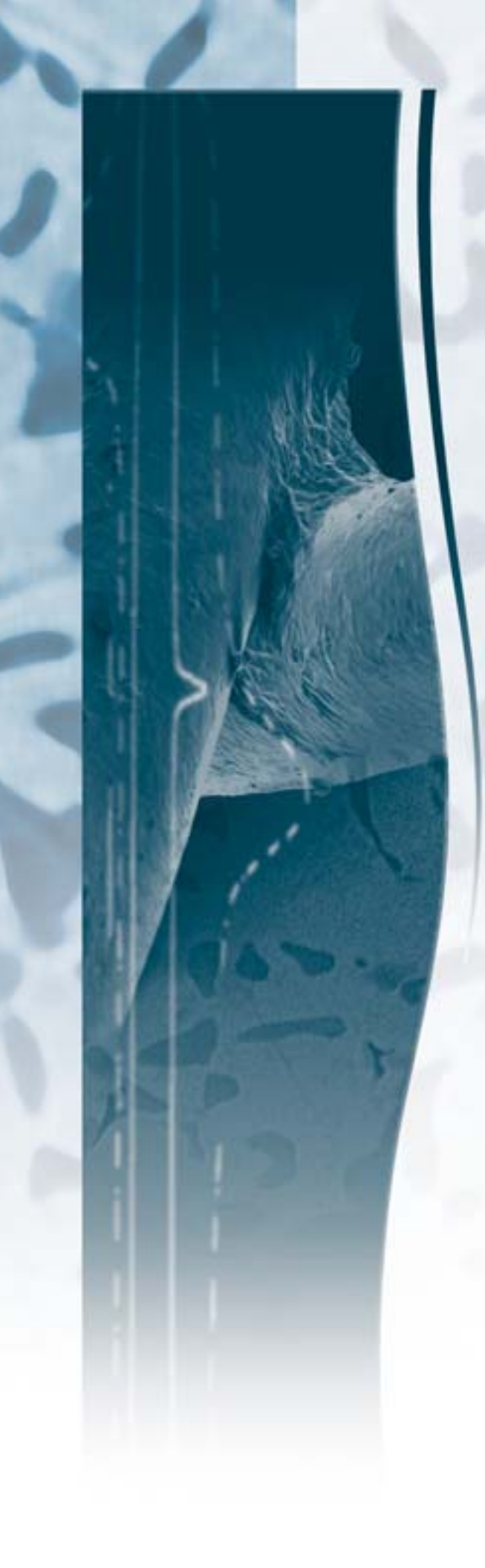

Technical Program

12th SPIE International Symposium

Smart Structures and Materials

Smart Structures & Materials/NDE Joint Conference

Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

10th SPIE International Symposium

Nondestructive Evaluation for Health Monitoring and Diagnostics

6–10 March 2005
Town and Country Resort & Convention Center
San Diego, California USA

Conferences • Courses • Poster Session • Exhibition

The International Society for Optical Engineering

Technical Program

12th SPIE International Symposium
Smart Structures and Materials

Smart Structures & Materials/NDE Joint Conference
Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

10th SPIE International Symposium
Nondestructive Evaluation for Health Monitoring and Diagnostics

6–10 March 2005
Town and Country Resort & Convention Center
San Diego, California USA

Coinciding with the 100th anniversary of Albert Einstein's "Miraculous Year," the events of the World Year of Physics 2005 aim to raise worldwide public awareness for physics and more generally for physical sciences.

Sponsored by
The International Society for Optical Engineering

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Journal of Intelligent Materials Systems and Structures/Sage Publications
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CSA Engineering, Inc.
ISIS Canada

Cooperating Organizations
Intelligent Materials Forum (Japan)
Jet Propulsion Laboratory
National Science Foundation

This program is based on commitments received up to the time of publication and is subject to change without notice.

SPIE's Event Manager for this symposium is Brian Thomas. For information about the technical program, email: meetinginfo@spie.org.

Cover images are used with permisson and can be found in Proceedings of SPIE Vol. 5387, paper 40. A. J. Muir Wood, V. Gergely, T. W. Clyne, authors.

Contents

SPIE would like to express its deepest appreciation to the program chairs, conference chairs, cochairs, program committees, and session chairs who have so generously given of their time and advice to make this symposium possible. The symposium, like our other conferences and activities, would not be possible without the dedicated contribution of our participants and members.

Welcome!

The Organizing Committees of SPIE's 12th Annual International Symposium on Smart Structures and Materials and SPIE's 10th Annual International Symposium on NDE for Health Monitoring and Diagnostics welcome you to attend what promises to be an exciting event. These unique international symposia offer many opportunities to network with colleagues from a variety of disciplines in academia, industry, and government. Over the last decade, this event has grown to become a premier technical meeting for the Smart Structures and Materials community and it includes the allied fields of NDE and Health Monitoring. The symposia are organized in many different parallel conferences. Some of the conferences are jointly organized with NDE related topics. These symposia include over 660 oral and poster papers presentations

There are 7 plenary speakers who were selected to inform and inspire the attendees. On Sunday before the start of the Symposia, we are planning to have an overview of the Technology and Applications. These are open to all symposium attendees and they intended to give the 'big picture' of the Smart Structures and NDE fields by identifying issues and opportunities for both the enabling technologies as well as the showcased applications.

The Symposium on Smart Structures and Materials covers all aspects of the enabling technologies, evolving materials, sensor/actuator design and fabrication, EAP materials (also known as artificial muscles), MEMS, NEMS and other micro-, nano- and bio- electronic devices, biomimetics, signal processing and control, systems concepts, wireless sensors and sensor networks, modeling and simulation, and applications of these technologies to cover the whole spectrum of life in the 21st century including commercial, medical, aerospace, military uses and many others.

The NDE for Health Monitoring and Diagnostics Symposium will bring together emerging technologies and advanced research in instrumentation, sensing, and measurement science with progressive management and diagnostic approaches and smart systems. The recent addition of a conference on NDE for Homeland Security will address the challenges and opportunities in this field of national importance. Focus areas of this symposium include application of micro- and nano-material systems, health monitoring of structural and biological systems, NDE for aerospace materials and applications, and NDE technologies for homeland security.

The conference chairs take this opportunity to thank Ms. Pat Wight and Mr. Brian Thomas of the SPIE staff and all the conference chairs whose hard work and dedication has made this event possible.

We invite you attend this exciting showcase for multidisciplinary research that will provide you an excellent opportunity to explore new research areas and team with new partners from other fields.

We look forward to seeing you in San Diego!

Smart Structures and Materials
Symposium Chairs

Vasundara V. Varadan,
The Pennsylvania State Univ.

Yoseph Bar-Cohen,
Jet Propulsion Lab.

NDE for Health Monitoring and Diagnostics
Symposium Chairs

Glenn Washer,
Univ. of Missouri/Columbia

Norbert Meyendorf,
Univ. of Dayton


FASHION VALLEY TROLLEY STATION
SAN DIEGO RIVER
FOOT BRIDGE
BRIDGE TO FASHION VALLEY SHOPPING CENTER
PROPERTY MAP
ROYAL PALM TOWER
GOLDEN BALLROOM
REGENCY ROAD
REGENCY TOWER
Audiovisual Desk
SPIE Registration
ATLAS BALLROOM
Internet Pavilion
Royal Palm Ballrooms
I
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SUNSHINE DELI
TERRACE CAFE
TERRACE PAVILION
Dover
Stratford
Sunset
Sunrise
Esquire
Towne
Meeting House/Executive Conference Center
Devonshire Room & Patio
REGENCY PROMENADE
REGENCY LANE
TRELLISES GARDEN GRILLE
TRELLISES COURTYARD
CHARLIE'S
LOBBY
PRIMO'S SALON & DAY SPA
KELLY'S STEAKHOUSE

Sunday 6 March

1:00 to 5:15 pm

Smart Structures and Materials and NDE for Health Monitoring and Diagnostics Technology and Applications Overviews

Golden West Ballroom

These technology and applications overviews are intended to give the 'big picture' of issues and opportunities of the enabling technologies such as materials, devices for sensors and actuators, control systems, power supplies, signal processing and systems integration that drive applications. The applications areas reflect the current trend of opportunities. This session should be of interest to all symposium attendees.

1:00 pm

Introduction

Vasundara V. Varadan, Univ. of Arkansas

1:10 to 3:00 pm

Enabling Technologies

- **Active Materials, Dimitris C. Lagoudas,** Texas A&M Univ.
- **Sensors**, **Vasundara V. Varadan,** Univ. of Arkansas
- **Actuators**, **Victor Giurgiutiu,** Univ. of South Carolina
- **Control, Signal Processing and Power Systems, Donald J. Leo,** Virginia Polytechnic Institute and State Univ.
- **Systems Integration, Vittal S. Rao,** National Science Foundation

3:00 to 3:20 pm

Coffee Break

3:20 to 5:00 pm

Applications

- **Homeland Security,** To be announced
- **Medicine, Vijay K. Varadan,** Univ. of Arkansas
- **Transportation Systems,** To be announced
- **Environment,** To be announced

5:05 to 5:15 pm

Concluding Remarks

Vasundara V. Varadan, Univ. of Arkansas

Monday 7 March

8:00 to 10:00 am

Award Presentations

Town & Country Ballroom

- Smart Structures and Materials Achievement Award
- NDE Achievement Award, see page 52.
- Nondestructive Evaluation Best Paper Award, see page 52.

SSM Plenary Presentation

The 'Smart' Path to the Future of Aeronautics

Town & Country Ballroom

Dr. Richard Wlezien, Director, Vehicle Systems Division, Aeronautics Research Mission Directorate, NASA Headquarters

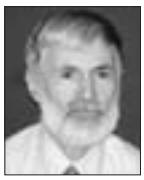
Abstract: Much of our expectation of the future is based on a linear extrapolation from the present. However history tells us time and again that it's the nonlinearities that make the big differences in predicting the future. New technologies like smart materials, MEMS, micro adaptive flow control, and nanotechnology all have the potential to have a big influence on the future of aeronautics. A forward-looking view of systems that can successfully integrate these technologies is a key part of making the future happen. A view of some new and exciting "game-changers" in aeronautics will be presented based on experience in industry, DARPA, and NASA.

Biography: **Dr. Wlezien** was born in Chicago IL. He earned his BS, MS, and Ph.D. in Mechanical and Aerospace Engineering, from the Illinois Institute of Technology in 1974, 1976, and 1981, respectively, where he specialized in fundamental studies of turbulence. He worked for the McDonnell Douglas Research Laboratories from 1980 to 1990 where he was responsible for noise research, working noise problems for acoustic issues for aircraft including the F-15 Eagle, F-18 Hornet, AV-8B Harrier, and MD-80, special projects including the F-15 STOL and Maneuvering Technology Demonstrator and the Ultra-High Bypass Engine Demonstrator. Between 1990 and 1992, he was Associate Professor of Mechanical and Aerospace Engineering at the Illinois Institute of Technology in Chicago. In 1992, he moved to High Technology Corporation where he worked as a senior scientist in aeronautics research, focusing on the coupling between sound and laminar boundary layers. He joined the staff at NASA-Langley in 1994 and has held a series of technical and management positions (progressing from Project Scientist to Branch Chief). He formed the Active Flow Control group and formulated the Aircraft Morphing Project, as it's first manager. He served as Program Manager at the Defense Advanced Research Projects Agency from 1999 to 2002. While at DARPA he ran the Quiet Supersonic Platform Program, which culminated in the demonstration of the first supersonic aircraft to fly with a quieted sonic boom. He also managed the Micro Adaptive Flow Control Program which demonstrated the first successful flight application of active flow control on the XV-15 aircraft and the first hovering micro air vehicle based on flapping wing technology, the MENTOR. Currently he is the Vehicle Systems Division Director in the Aeronautics Research Mission Directorate at NASA Headquarters in Washington, DC.

NDE Plenary Presentation

Optical and Laser NDE: More Than Meets the Eye

Town & Country Ballroom



Dr. Jean-Pierre Monchalin, Industrial Materials Institute/National Research Council Canada (Canada)

Light is certainly at the basis of the most widespread NDE technique: visual inspection. This technique is also likely to be the oldest one, dating back to prehistoric times when human beings started to fabricate rudimentary tools and objects. Presently, at the beginning of the third millennium, following the invention of the laser in 1960, the introduction of optical fibers for guiding light and computers for processing complex data and images, light-based techniques occupy a much larger place in the spectrum of NDE techniques and this is growing. Surface flaws and surface characteristics can now be analyzed by a range of advanced techniques that surpass simple visual inspection and are based on light scattering or optical profilometry. Techniques, such as Optical Coherence Tomography and Photon Density Waves Imaging, have also been developed to see through materials that are not transparent but only translucent. Also, from a single laser shot, Laser Induced Breakdown Spectroscopy could provide material composition and this in the most adverse industrial environment. Laser-based techniques, such as holography, shearography, speckle interferometry and laser-ultrasonics can even find flaws below the surface of completely opaque materials. In this presentation, a broad overview of all optics or laser-based NDE techniques will be presented, outlining their present industrial use and the perspectives.

Jean-Pierre Monchalin received a diploma in optical engineering in Paris in 1968 and the M.S. and Ph.D. degrees in lasers and optics from the Massachusetts Institute of Technology, Cambridge, in 1971 and 1976.

He is presently Principal Research Officer at the Industrial Materials Institute of the National Research Council of Canada in Boucherville, Québec, Canada and head of the Optical Techniques group at the Institute.

His doctoral work at MIT consisted of very accurate interferometric measurement in the infrared which led to a new value for the speed of light. He was then employed by École Polytechnique in Montréal and worked on chemical laser development, photoacoustic techniques and, in particular, on their application to the spectroscopy of powders. He has been involved with ultrasonic nondestructive evaluation since 1982. He is presently leading development work in laser and optical techniques to generate and detect ultrasound for industrial applications. He has published numerous papers and is the holder of sixteen patents in this field. He is a member of the Optical Society of America and of SPIE.

Special Events

Monday 7 March

5:00 to 6: 00 pm

EAP in Action

Town & Country Ballroom

Demonstrations on EAP applications, featuring the first human versus robot armwrestling match. See page 18 for further information.

6:00 to 7:30 pm

All-Conference Welcome Reception

Poolside by Terrace Pavilion

7:30 to 9:30 pm

Technical Group Meeting

Royal Palm IV

Chair: **Alison B. Flatau,** Univ. of Maryland/College Park

The Smart Structures and Materials Technical Group will meet to hear presentations from the six finalists in the Best Student Paper Contest. Following the presentations, technical working group members will vote to determine the 1st, 2nd, and 3rd place winning papers. The winners will be announced Tuesday morning at 8:00 am before the plenary presentations. This contest is sponsord by JIMSS/Sage Publications, Rhombus Consultants, and CSA Engineering.

All conference attendees are cordially invited to attend the Technical Working group Meeting.

Tuesday 8 March

8:00 to 8:55 am

Award Presentations

Town & Country Ballroom

- ASME Adaptive Structures and Materials Systems Best Paper Awards
- Smart Structures and Materials/ASME Best Student Paper Award

SSM Plenary Presentation

Research Opportunities in Nano and Microsystems Technology for Army Applications

Town & Country Ballroom

Dr. Paul B. Ruffin, U.S. Army Research, Development, and Engineering Command

Abstract: In an environment of new threats and challenges, the Army is being transformed into a lighter, faster, more agile force that can be deployed quickly. Trends in post-Cold War military conflicts suggest that increasing dominance of precision weapons, increasing the use and utility of unmanned aerial vehicles, and developing smaller missiles, guided rockets, and munitions will enhance the Army's capability to counter ballistics, sensory attack, and chemical/biological agents used in modern and future warfare by a diverse fleet of adversaries. The Army is investing a significant amount of research funds in the nanotechnology area to develop lightweight, strong, energy absorbing materials; smart, adaptive structures; micro-devices for sensing, situational awareness and information processing.

Biography: **Dr. Ruffin** graduated from Alabama A&M University with a BS degree in Physics, and from University of Alabama in Huntsville with a MS and Ph.D degrees in Physics. He is currently the Army's Senior Research Scientist for Micro-sensors and Systems. His patent that remedied problems associated with adverse temperature effects on Fiber Optics Gyroscope (FOG) performance, have been adopted and used in industry. Dr. Ruffin has received numerous awards including the highest honor that the Army gives for research and development from the Secretary of the Army, national acknowledgement as the Black Engineer of the Year: Special Recognition Award Recipient by the Council of Engineering Deans for Historically Black Universities, Technologist of the Year Award from the National Society of Black Engineers, Top Ten Army Materiel Command Personnel of the Year Award, Material Acquisition/Technology; Award from the American Defense Preparedness Association, and recognition for a Canadian Patent. SPIE is pleased to announce that Dr. Ruffin has just been elected as a SPIE Fellow, and he will be honored at the Annual Meeting, Optics and Photonics 2005.

NDE Plenary Presentation

Nondestructive Evaluation Technologies to Defend the Homeland[1]

Golden West Ballroom

Dr. Harry E. Martz, Jr., Lawrence Livermore National Lab.

Over the past 20 years, the Transportation Security Administration (TSA)[2]-formerly the Federal Aviation Administration (FAA)-invested extensively in the development of systems designed to protect the traveling public from attacks on the commercial aviation system using explosives. These efforts have resulted in the deployment of two kinds of technologies for screening of luggage: explosive detection systems (EDSs), which are certified by TSA to detect bulk quantities of explosives in checked luggage, and explosive trace detectors (ETDs), which are designed to detect vapor or particles of explosives that would be associated with passenger items or luggage as a result of bomb fabrication or transportation.

Events of September 11, 2001-terrorist destruction of the World Trade Center utilizing commercial aviation as a vehicle-have changed our country's view on the urgency and scope of the threats of terrorist acts against the United States.[3] The scope-of-threats extend beyond explosives and weapons to include radiological dispersal devices, and chemical, biological and nuclear weapons of mass destruction. Many different government entities, universities, and corporations are researching and developing technologies and methods for detection, identification, mitigation, and control of such threats. The presentation will summarize some of these efforts and focus somewhat on nondestructive evaluation technologies developed for detection and identification of explosive threats to aviation security, and how they may or may not apply to the expanding threats and other modes of transportation.

1 This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

2 The TSA, formerly under the Federal Aviation Administration (FAA) in the Department of Transportation, is charged with implementing technology for countering terrorist threats. In March of 2003, TSA was placed under the Department of Homeland Security (DHS).

3 "Making the Nation Safer, the Role of Science and Technology in Countering Terrorism" National Research Council of The National Academies, National Academies Press, Washington DC, 2002.

Dr. Harry E. Martz, Jr. is the Director for the Center for Nondestructive Characterization (CNDC) in the Engineering Department at the Lawrence Livermore National Laboratory (LLNL). He is responsible for leading the research and development efforts of different nondestructive measurement science methods including but not limited to x- and gamma-ray digital radiography and computed tomography

(CT), visual and infrared imaging, ultrasonics, micropower impulse radar imaging, and signal and image processing. This research and development includes the design and construction of instruments, and preprocessing, image reconstruction, analysis and visualization algorithms.

Harry received a B.S. degree in chemistry from Siena College, Loudonville, NY, in 1979. In 1983, he received a masters degree and in 1986 a Ph.D. degree both in nuclear/inorganic chemistry and physics from Florida State University, Tallahassee, FL. From 1982 to 1986 he was a participating guest in the Nuclear Structure Group at LLNL. After receiving his Ph.D. in 1986, he became a full-time employee at LLNL. From 1986 to 1988 he was a staff scientist in the Nondestructive Evaluation Section at LLNL. During this time he was engaged in x-ray and proton radiography and CT techniques for material characterization, and gamma-ray gauge studies for Treaty Verification applications. From 1988 to 1990 he was the computed tomography project leader and in 1991 he became the CT project manager in the NDE Section. In 1994 Harry became the NDE Thrust Area/Research Leader and became the Director of the Center for Nondestructive Characterization in 1999.

Dr. Martz received a 2000 R&D 100 award in the area of Waste Inspection Tomography using Nondestructive Assay. He received the LLNL 1998 Director's Performance Award for Active and Passive Computed Tomography. He was given the Federal Laboratory Consortium for Technology Transfer 1990 Award of Merit. Dr. Martz is a member of Alpha Chi Sigma and Sigma Pi Sigma-the National Physics Honor Society.

Noon to 1:00 pm

Student Pizza Lunch

Lower level Exhibition Hall

Join fellow students and conference organizers for a networking reception especially for you. This is a chance to meet distinguished professionals in your field, make new contacts, and help you make the most of the conference. Pizza will be served.

6:00 to 7:30 pm

Poster/Exhibition Reception

Lower level Exhibition Hall

The exhibition hall will be open Tuesday evening in conjunction with the poster session, to allow attendees specific exhibition and poster viewing time during the symposium. Take the opportunity to see the exhibits and talk with company representatives as well as review posters. Refreshments will be served.

Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed after 3 pm before the formal poster session begins at 6 pm.

Wednesday 9 March

8:00 to 8:55 am

Award Presentation

Town & Country Ballroom

Smart Structures Product Implementation Award

SSM Plenary Presentation

Engineering of Sub-Wavelength Photonic Meta Materials: A Route Towards Nano-Scale Plasmonics and Super Imaging

Town & Country Ballroom

Dr. Xiang Zhang, NSF Nano-Scale Science and Engineering Ctr. at Univ. of California/ Berkeley

Abstract: Recent theory predicts that artificial plasma and artificial magnetism enable a super lens that focuses far below the diffraction limit. This technology, if realized, will have profound impact in a wide range of applications such as nano-scale imaging, nanolithography, and integrated nano photonics. This presentation will discuss a few micro- and nano-fabrication technologies that were developed for engineering complex meta-structures and in the second part, sub-_ photonic "atoms" and "molecules" and the potential applications in nano-scale imaging and lithography. We demonstrated, for the first time, the high-frequency magnetic activity at THz generated by artificially structured "molecule resonance", as well as the artificial plasma. Our experiment also confirmed the key proposition of super lens theory by using surface plasmon. We indeed observed preliminary superlensing at near-field. This talk will be concluded with a vision of the nano manufacturing that will enable the new nano plasmonics and other applications.

Biography: **Dr. Xiang Zhang** is an Associate Professor and the Director of NSF Nano-scale Science and Engineering Center at University of California, Berkeley. He also serves as the Director of Department of Defense MURI Center on metamaterials and devices. He is a recipient of NSF CAREER Award (1997); Engineering Foundation Award (1997); SME Dell K. Allen Outstanding Young Manufacturing Engineer (1998) and ONR Young Investigator Award (1999). He was nominated in 2004 for the Millennium Technology Prize, the world's largest technology award. He was selected as a "Distinguished Lecturer" at University of Texas at Austin in 2004. His current research focused on nano-scale engineering, meta-materials, and nano-photonics and molecule engineering. He has published over 70 technical papers including one in "Science", and given more than 50 invited talks at international conferences and institutions. His research was featured by prestigious media such as BBC, Los Angeles Times, Science Daily, Photonics Spectra, Physics Today, He received Ph.D from University of California at Berkeley (1996) and MS/BS from Nanjing University, China.

NDE Plenary Presentation

Science and Technology Challenges in Screening for Radiological and Nuclear Materials

Golden West Ballroom

Dr. Michael Carter, Dept. of Homeland Security

Dr. Michael R. Carter of Virginia was appointed Chief Scientist in the Office of Plans, Programs and Budget in the Science and Technology Directorate of the Department of Homeland Security in March of 2004. Previously, Dr. Carter served as Director of the Radiological and Nuclear Countermeasures Portfolio in the Department of Homeland Security.

Prior to the start of the Department of Homeland Security, Dr. Carter served as a Technical Advisor to the Homeland Security Transition Planning Office with emphasis on Radiological and Nuclear Countermeasures.

Dr. Carter has been involved in research and development activities in support of National Security since 1987. Prior to his assignment in Washington, Dr. Carter served as Associate Division Leader for Proliferation Detection Systems at Lawrence Livermore National Laboratory (LLNL). At LLNL, Dr. Carter lead and managed programs in emerging technologies including nuclear, chemical and biological sensors, active and passive remote sensing systems, reconnaissance and surveillance systems, data exploitation and signal processing, high-bandwidth communications and distributed sensor systems. Previous experience at LLNL includes high-energy-density plasma physics research, x-ray lasers, nuclear test experimental physics and controlled thermonuclear fusion.

Dr. Carter received his Ph.D. in Applied Science from the University of California, Davis in 1987.

6:00 to 8:00 pm

Panel Discussion: Industry and Government Agencies Partnership in Sensor Technologies

Sunrise

Chairs: **Shih-Chi Liu,** National Science Foundation; **Rahmat A. Shoureshi,** Univ. of Denver

7:30 pm

SSM-NDE Women's Dinner

All women attendees are invited to attend dinner at a local restaurant (TBD). Each person is responsible for covering the cost of her meal. **Please sign up at the registration desk.** Join us!

Special Events

Thursday 10 March

8:00 to 8:55 am

SSM Plenary Presentation

Smart Structures and Materials Technology Applications for Network Centric Warfare Systems

Town & Country Ballroom

Dr. Jack H. Jacobs, Honeywell, Inc.

Abstract: Network Centric Warfare (NCW) relies on distributed sensor elements, computer processing power and networked communications technology to provide a shared awareness of the battle space for U.S. forces today. Shared awareness increases synergy for command and control, resulting in superior decision-making, and the ability to coordinate complex military operations over long distances for an overwhelming war-fighting advantage. NCW technology saw limited deployment in Afghanistan and, more recently, increased deployment in Operation Iraqi Freedom (OIF). Several DoD key programs are now underway for deployment throughout all services. Network Centric Warfare is driving many technological needs which include unattended sensor grids, autonomous UAV's , robotics, and system health management. A historical and future perspective on how today's smart structure, materials and sensing technologies could be applied to this critical mission is discussed as well as its implications to homeland security and national defense.

Biography: **Dr. Jack Jacobs** is the Manager of Technology for Honeywell's Defense and Space Electronics Division. He is responsible for the investment, development and insertion of new technologies in the application areas of Space, Aircraft and Surface vehicles. These technologies include such areas as MEMS sensors as well as completely autonomous UAV's. Prior to coming to Honeywell in 1997, he was a deputy team leader for the McDonnell Douglas phantom works in the area of smart structures and systems. Dr. Jacobs has over 25 publications and 14 patents. He leads the steering committee to integrate Honeywell technologies from both the defense and homeland security organizations into a network-centric warfare and defense portfolio for both DOD and the commercial sector. Also, he serves as the liaison between the Honeywell Labs organization, which performs R&D in critical infrastructure, homeland security, and defense systems, and the strategic business units, which implement these technologies into Honeywell's key products. His recent projects have been focused on distributed system architectures using network centric warfare concepts for both space and critical infrastructure protection. Dr. Jacobs received a B.S. in 1986 and M.S. in 1988 in Aeronautical and Astronautical Engineering from the Ohio State University, and in 1996 his Doctorate in Structural Mechanics from Washington University, St. Louis.

Daily Schedule

Sunday 6 March	Monday 7 March	Tuesday 8 March	Wednesday 9 March	Thursday 10 March

Smart Structures and Materials

5757 **Modeling, Signal Processing, and Control** *(Smith)*, p. 14-30

5758 **Smart Sensor Technology and Measurement Systems** *(Udd, Inaudi)*, p. 14-30

5759 **Electroactive Polymer Actuators and Devices (EAPAD)** *(Bar-Cohen)*, p. 14-34

5760 **Damping and Isolation** *(Wang)*, p. 14-32

5761 **Active Materials: Behavior and Mechanics** *(Armstrong)*, p. 15-32

5762 **Industrial and Commercial Applications of Smart Structures Technologies** *(White)*, p. 15-29

5763 **Smart Electronics, MEMS, BioMEMS, and Nanotechnology** *(Varadan)*, p. 15-34

5764 **Smart Structures and Integrated Systems** *(Flatau)*, p. 15-34

Smart Structures/NDE Joint Conference

5765 **Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems** *(Tomizuka)*, p. 35-39

NDE for Health Monitoring and Diagnostics

5768 **Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems IV** *(Kundu)*, p. 51-61

5769 **Nondestructive Detection and Measurement for Homeland Security III** *(Diaz, Aktan, Wu, Doctor, Bar-Cohen)*, p. 51-61

5767 **Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure IV** *(Shull, Gyekenyesi, Mufti)*, p. 50-64

5766 **Testing, Reliability, and Application of Micro- and Nano-Material Systems III** *(Geer, Meyendorf, Baaklini, Michel)*, p. 50-64

5770 **Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring** *(Meyendorf, Baaklini, Michel)*, p. 51-65

SPIE Professional Development Courses—*Register on-site!*

SC634 **Electroactive Polymer Actuators and Devices** (Bar-Cohen/ Madden/Su), $390 / $470 USD, 8:30 am to 5:30 pm

SC709 **Optical Fiber Sensing Technology for Structural Health Monitoring & Smart Structures** (Méndez/Baldwin), $390 / $470 USD, 8:30 am to 5:30 pm

EXHIBITION

Tues. 10:00 am to 4:00 pm, and 6:00 to 7:30 pm

Wed. 10:00 am to 4:00 pm

Stay up-to-date on industry trends —Visit the Exhibition!

12th SPIE International Symposium
Smart Structures and Materials

and

10th SPIE International Symposium
Nondestructive Evaluation for Health Monitoring and Diagnostics

Town and Country Resort & Convention Center
San Diego, California USA

Exhibition Hours:

Town and Country Resort & Convention Center
Lower Level Exhibition Hall

Tuesday 8 March 2005
10:00 am to 4:00 pm;
6:00 pm to 7:30 pm

Wednesday 9 March 2005
10:00 am to 4:00 pm

Exhibition/Poster Reception

Lower Level Exhibition Hall

Tuesday 8 March 2005
6:00 to 7:30 pm

The exhibition hall will be open Tuesday evening in conjunction with the poster session, to allow attendees specific exhibition and poster viewing time during the symposium. Take the opportunity to see the exhibits, talk with company representatives, and review posters. Refreshments will be served.

See the latest tools, instruments, devices, and components in:

- Materials, mathematics and control
- Sensing, actuation, and damping
- Integrated systems for civil infrastructures
- Systems for industrial and commercial structures
- Electro-active polymer actuators and devices
- And more!

Exhibitors as of 31 January 2005:

Aurora Scientific Inc.	112
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CSA Engineering, Inc.	110
IOP Publishing	223
ISIS Canada	116
LiComm Co., Ltd.	209
Luna Innovations	217
LxSix Photonics	219
Micron Optics, Inc.	211
MicroStrain, Inc.	204
Minus K Technology	106
NanoSonic, Inc.	109
Neubrex Co. Ltd.	120
Photonics Spectra - Laurin Publishing	114
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General Refreshment Sponsor Servet J.S.C.	111
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For information or to learn about exhibiting, visit **spie.org/events/ssmndeexhibit**

General Information

SPIE 12th International Symposium
Smart Structures and Materials
and *SPIE 10th International Symposium*
NDE for Health Monitoring and Diagnostics

Headquarters Hotel

Town & Country Resort andConvention Center
500 Hotel Circle North
San Diego, CA 92108
Hotel Phone: 619-291-7131
Hotel Fax: 619-291-3584

Registration Hours

San Diego Town & Country Resort and Convention Center, San Diego, California
Atlas Foyer

Sunday 6 March . . . . . 11:00 am to 4:00 pm
Monday 7 March . . . . . 7:00 am to 4:00 pm
Tuesday 8 March . . . . . 7:00 am to 4:00 pm
Wednesday 9 March . . . . . 7:30 am to 4:00 pm
Thursday 10 March . . . . . 7:30 am to 11:00 am

Technical Exhibition Hours

Lower Level Exhibition Hall

Tuesday 8 March . . . . . 10:30 am to 4:00 pm
. . . . . 6:00 to 7:30 pm
Wednesday 9 March . . . . . 10:00 am to 4:00 pm

- Meet managers and technicians to discuss your technology needs
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- Network with colleagues and exhibitors

For information about exhibiting at this symposium please contact Al Regan, SPIE Sales, (1) 360/676-3290 ext. 204 or email exhibits@spie.org.

Speakers Audiovisual Desk Hours

Terrace Salon I

Sunday . . . . . 11:00 am to 5:00 pm
Monday through Thursday . . . 7:30 am to 5:00 pm

Speakers using a laptop are requested to come to the Audiovisual Desk to confirm display compatibility with LCD projectors prior to their presentation. Speakers that did not pre-request required special audiovisual equipment are asked to stop at the Audiovisual Desk upon arrival to see if these special requests can be fulfilled.

Audio/Video/Digital Recording Policy

Due to copyright restrictions, strictly no recordings of any kind are permitted without prior written consent of the presenter in any conference session, short course or posters. Consent forms are available at the SPIE Audiovisual Desk and anyone wishing to record must have a written consent form signed and filed for each presenter being recorded. Individuals not complying with this policy will be asked to leave a given session and asked to surrender their film or recording media.

In the Exhibition Hall: For security and courtesy reasons, photographing or videotaping individual booths and displays in the exhibit hall is allowed ONLY with explicit permission from on-site company representatives. Individuals not complying with this policy will be asked to surrender their film and to leave the exhibition hall.

Coffee Breaks

Coffee will be served at the following locations at approximately these times (see your final program listing for specific coffee break times per conference). Breakfast baked goods and eggs will be served with the 10:00 am break each day.

10:00 to 10:30 am
Monday and Thursday: *Atlas Foyer*
Tuesday-Wednesday: *Lower Level Exhibition Hall*

3:00 to 3:40 pm
Sunday, Monday and Thursday: *Atlas Foyer*
Tuesday-Wednesday: *Lower Level Exhibition Hall*

Desserts

Dessert snacks will be served in the Lower Level Exhibition Hall Tuesday and Wednesday from 3:00 and 3:30 pm. Complimentary tickets for dessert snacks will be included in attendee registration packets.

All Conference Welcome Reception

Poolside by Terrace Pavilion

Monday 7 March . . . . . 6:00 to 7:30 pm

Sponsored by: San Diego Town & Country Resort and Convention Center, and SPIE.

All attendees are invited to relax, socialize and enjoy refreshments at the Town & Country resort poolside. Please remember to wear your conference registration badges. Dress is casual.

Poster/Exhibition Reception

Lower Level Exhibition Hall

Tuesday 8 March . . . . . 6:00 to 7:30 pm

The exhibition hall will be open Tuesday evening in conjunction with the poster session, to allow attendees specific exhibition and poster viewing time during the symposium. Take the opportunity to see the exhibits and talk with company representatives as well as review posters. Refreshments will be served.

Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed up until 4:00 pm. The Exhibition / Poster area will be closed from 4:00 to 6:00 pm and then reopen at 6:00 pm for the formal poster session and evening exhibition visiting hours.

Proceedings of SPIE

A full-manuscript, editor-reviewed Proceedings of SPIE volume will be published for each conference and will be available within eight to twelve weeks after the symposium. If you are unable to attend, you may order Proceedings now at reduced prepublication prices. See page 60 for details and order information.

Messages for Attendees

San Diego Town & Country Resort phone number: (619) 291-7131

The SPIE Message Board will be located near the Registration Desk. Messages will be taken during registration hours Saturday through Friday. To leave a message, call the hotel and ask the hotel operator for the SPIE Registration Desk.

SPIE Titles on Display

Atlas Foyer near registration

Open during registration hours

SPIE will have a wide range of scholarly books, tutorials, proceedings and CD-ROM's for professionals and educators in the fields of optics, photonics and imaging on display at the meeting near registration. Be sure to visit the display and browse the newest SPIE publications and take advantage of special meeting prices for ordering any of the display publications.

Internet Access

Monday through Wednesday . . . 7:00 am to 9:00 pm

Thursday . . . . . 7:00 am to 1:30 pm

Computers with Internet access and connections for laptops will be available during the times listed above. Please limit your time to 10 minutes when others are waiting.

Wireless Internet Access (Wi-Fi)

HIGH SPEED INTERNET: Guest rooms at The San Diego Town & Country Resort and Convention Center are equipped with high speed wireless internet, available at a special discounted rate of $4.95 for 24 hours for attendees to the Smart Structures/NDE Symposium. Laptops will need an appropriate wireless card and access is available in all guest room areas. Please contact internet call center at x1234 in order to get this discounted rate. You will need a credit card for this access. Note: WiFi service is not available in or near meeting rooms.

Properly secure your computer before accessing the Public Wireless network. Failure to do so may allow unauthorized access to your laptop.

Child Care

Marion's Child Care, 1-888-891-5029, or within San Diego call 619-582-5029,

SPIE does not imply an endorsement nor recommendation of this service. It is provided on an "information only" basis for your further analysis and decision. Other services may be available.

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Searching for top talent? Search no further. The SPIEWorks Career Center at Smart Structures/NDE is a great place to start. Place your open positions on the bulletin boards provided and review any resumes/CVs posted by meeting attendees.

If you can't wait for Smart Structures/NDE to fill your open position, SPIEWorks.com, the SPIE employment resource, can help you target a skilled group of professionals now. Contact Robert Dentel or Dave Baggenstos at +1 360 715 3705 or email sales@spieworks.com.

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Membership in SPIE is not required to post jobs or resumes and CVs, however, candidates or employers delivering materials onsite are encouraged to do so at the beginning of the conference to maximize exposure.

SPIE Digital Library

The SPIE Digital Library, one of the most extensive resources available on optics and photonics, contains more than 100,000 full-text papers from SPIE Journals and Proceedings published since 1998. It also includes citations and abstracts for most SPIE papers published since 1990.

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Links are also provided to INSPEC and MEDLINE records. Proceedings papers have assigned DOI numbers and thus may be linked from other sources in the technical literature. Outbound reference linking from SPIE Proceedings papers to references cited within the paper is planned for the future. SPIE is a member of CrossRef.

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The Article Collection feature allows users to mark papers of interest and assign their citations to personal Article Collection folders. This is useful for quick identification and storage of selected citations as well as for sharing bibliographies with other users.

Travel Information

Shuttle from and to San Diego Airport

San Diego International Airport is six miles from the Town & Country Resort. Cloud Nine Shuttle bus service to & from the Town & Country Resort is $9.50 per person one-way (prices subject to change). Reservations are required for transportation back to the airport. Cloud 9 Shuttle recommends a pickup time of at least 2 hours prior to flight departure time. Method of payment can be cash or credit card, but no checks. There is no roundtrip discount when traveling to/from hotels. Shuttle stops enroute to load/unload passengers. To book online www.cloud9shuttle.com or call 1-858-974-8885.

Taxi from and to San Diego Airport

Taxi service between the airport and the Town & Country Resort is approximately $23 one-way.

Parking

Complimentary outdoor self-parking has been arranged at the hotel for Smart Structures / NDE attendees.

Be sure to identify yourself as a Smart Structures 2005 attendee at check in to receive the complimentary parking! Your attendee badge can be shown when exiting the parking lot to receive the complimentary parking.

AmericanAirlines®

SPIE Thanks American Airlines for providing discounted rates to SPIE's Smart Structures and Materials/NDE Meeting 2005.

Car Rental

Hertz®

Hertz Car Rental has been selected as the official car rental agency for this Symposium. To reserve a car, identify yourself as a Smart Structures / Nondestructive Evaluation Conference attendee using the Hertz Meeting Code CV# 029B0007.

In the United States call 1-800-654-2240.

Local Attractions

Attendees wishing to arrange for tours/sightseeing for themselves, or traveling guests, may contact the hotel concierge prior to the meeting to make arrangements concierge@towncountry.com. Concierge services are offered on-site in the main lobby.

The hotel will also provide a special Concierge Services desk near SPIE registration for the convenience of SPIE's attendees, Sunday-Wednesday from 8:30 am to 10 am.

Services include:

- Discount tickets to San Diego Zoo and Seaworld
- Discount rates for Riverwalk Golf Course
- Priority seating at Hotel Restaurants and off property restaurants
- San Diego City, Mexico, wine tours or harbor excursions
- Public Transit Information, local driving directions/maps

San Diego Trolley/Light Rail
(Metropolitan Transit System)
The San Diego Trolley, i.e. the light rail, is referred to as the "moving landmark" and is a fun way to get around, serving a wide area from the International Border, to Centre City's shopping harbor, Mission Valley, Fashion Valley, Old Town, Downtown including the Gas Lamp Quarter, etc. Fares are based on the trip distance. The fare ranges from $1.25 to $3.00 depending on how many stations are traveled (fares are subject to change). The closest trolley stop is located between the Hotel and the Fashion Valley Mall, handy to Old Town, Downtown and even Tijuana. Check the website www.sdcommute.com for schedule information.

Fashion Valley Mall
Located directly behind the hotel the mall is a two-level outdoor garden accented center featuring over 300 specialty shops and restaurants and an 18 screen movie complex. It is the largest shopping area in San Diego!

Old Town
Take the Trolley or Hotel Shuttle to the founding site of San Diego with excellent Mexican dining and shopping at Bazaar Del Mundo.

Horton Plaza/Gas Lamp Quarter
Take the Trolley to downtown San Diego and enjoy shopping at Horton Plaza and/or the exciting nightlife of excellent restaurants and clubs of the Gas Lamp District.

Seaport Village
Situated on 22 acres of parkland at the water's edge, over 60 shops, galleries, and boutiques along with restaurants are found in this unique village.

1. QUALCOMM STADIUM
2. FASHION VALLEY MALL
3. SEAWORLD
4. HISTORIC OLD TOWN
5. SAN DIEGO ZOO & BALBOA PARK
6. SAN DIEGO INTERNATIONAL AIRPORT
7. HARBOR CRUISES
8. SAN DIEGO CONVENTION CENTER & SEAPORT VILLAGE
9. THE GASLAMP QUARTER
10. SAN DIEGO TROLLEY . . . . . .

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Continuing Education Units
SPIE is an authorized provider of Continuing Education Units (CEUs) through ICAET—The International Association of Continuing Education and Training. SPIE awards CEUs to participants who successfully attend courses, and complete and return the evaluation form within 30 days of the course presentation.

SPIE reserves the right to cancel a course due to insufficient advance registration. Please register early.

Electroactive Polymer Actuators and Devices

This course will provide an overview of the field of EAP covering the state of the art, challenges and potential. Two general classes of polymer materials are described, namely those that involve ionic mechanisms (Ionic EAP), and field activated materials (Electronic EAP). The basic mechanisms responsible for the electroactive behavior of EAP materials will be covered and compared with natural muscles. Analytical models, fabrication processes and methods of characterizing these materials will be described. Moreover, the currently considered applications will be reviewed including actuators, robotics, animatronics, medical, and biologically inspired mechanisms, so called biomimetics. The course begins with an overview of the field, current capabilities, potential and challenges. The course follows with a description of the currently available EAP materials and principles of operating them as actuators and artificial muscles. The course ends with a review of the future prospect of EAP as actuators in systems, mechanisms and smart structures for space, industrial and medical applications.

LEARNING OUTCOMES
This course will enable you to:
- identify EAP based available and emerging actuators
- understand the fundamentals of electroactive behavior in leading EAP materials
- describe the capabilities, limitations and benefits of electroactive polymers
- assess the applicability of current EAP actuators while accounting for their limitations
- understand mechanical analysis and design principles associated with EAP
- describe the future prospects of EAP materials as actuators and their applications

INTENDED AUDIENCE
Engineers, scientists and managers who need to understand the basic concepts of EAP, or are interested in learning, applying or engineering mechanisms or devices using EAP materials. Also those who wish to discover the excitement of research and development in EAP materials and their applications - present and future.

INSTRUCTORS
Yoseph Bar-Cohen is Senior Research Scientist and Group Leader for the NDE and Advanced Actuators (NDEAA) Technologies of JPL. Also, he is a Fellow of SPIE and ASNT and a leading expert in advanced actuators using electroactive polymer and ceramic. He is the author/coauthor of numerous publications having many listed patents and received many awards. Further information on: http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi.htm
John Madden is an Assistant Professor of Electrical & Computer Engineering at the University of British Columbia, Vancouver, Canada. His research areas include the application of EAPs to mimic insect flight and to assist in hydrodynamic propulsion, as well as the development and characterization of molecular and carbon nanotube actuators. http://www.ece.ubc.ca/~jmadden.
Ji Su is a Research Scientist at NASA Langley Research Center. His research is focused on electronic EAP materials such as ferroelectric, piezoelectric and electrostrictive polymers and their applications in electromechanical devices, artificial muscles and biomimetic technologies for aerospace and space missions. He has numerous publications and several issued patents related to EAP.

Course level: Introductory
SC634 CEU .65 $390 / $470 USD
Sunday 8:30 am to 5:30 pm

Optical Fiber Sensing Technology for Structural Health Monitoring & Smart Structures

New!

This course is divided into two parts. Part I provides a broad overview of optical fiber sensing principles and the associated components required for system integration. Emphasis is placed on reviewing the various sensor types and their use on practical applications. In Part II, a review of strain & stress measurement using optical fiber sensors— such as fiber Bragg gratings—is made, along with discussions on sensor placement & installation, data analysis and interpretation, design considerations and operational principles of Structural Health Monitoring (SHM). To reinforce the theoretical concepts and illustrate the practical aspects of the technology, a number of hands-on demonstrations of fiber-instrumented models and structural elements will be available.

LEARNING OUTCOMES
This course will enable you to:
- understand the operating principles, characteristics and advantages of fiber optic sensors
- review a wide range of sensor types for the measurement of materials properties and structural characteristics
- learn the required building blocks that make up a SHM system
- illustrate specific sensing solutions and their benefits in applications for civil structures, aerospace, composite materials, FRP elements, naval vessels, oil & gas, and others.
- obtain an overall view of fiber optic sensors, the SHM industry and its trends

INTENDED AUDIENCE
Technical managers, scientists, engineers, technicians and research students who wish to learn about structural health monitoring via fiber-sensing technology and review their implementation and applications. The course is also suitable to gain an overview on the field of smart structures and learn about the state-of-the-art in on-line monitoring techniques of civil engineering, aerospace and composite structures and components.

INSTRUCTORS
Alexis Méndez is President of MCH Engineering LLC, and has over 17 years of experience in optical fiber technology, sensors and instrumentation. He was the former Group Leader of the Fiber Optic Sensors Lab within ABB Corporate Research (USA), working on the development of new fiber optic sensing systems for electric utility and oil & gas applications. He has written over 30 technical publications, holds 3 US patents and is recipient of an R&D 100 award. Dr. Mendez holds a PhD. degree in Electrical Engineering from Brown University.
Christopher Baldwin is a Senior Research Engineer at Systems Planning & Analysis, Inc., and has over 10 years experience in the design, development, and implementation of fiber optic sensors and instrumentation systems. Much of this work has involved the use of fiber optic sensors for SHM applications. His experience includes multiple large-scale tests, in-field trials, and the development of various sensor attachment and sensor embedment procedures. Dr. Baldwin holds a Ph.D. degree in Mechanical Engineering from the University of Maryland, College Park.

Course level: Introductory
SC709 CEU .65 $390 / $470 USD
Sunday 8:30 am to 5:30 pm

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Since 1955, Event participants, through their collective talents, have influenced the future of optical, technical, and scientific discovery. For fifty years, their voice has helped to create the next generation of young researchers, who like Event participants, are captivated by the extraordinary promise of light.

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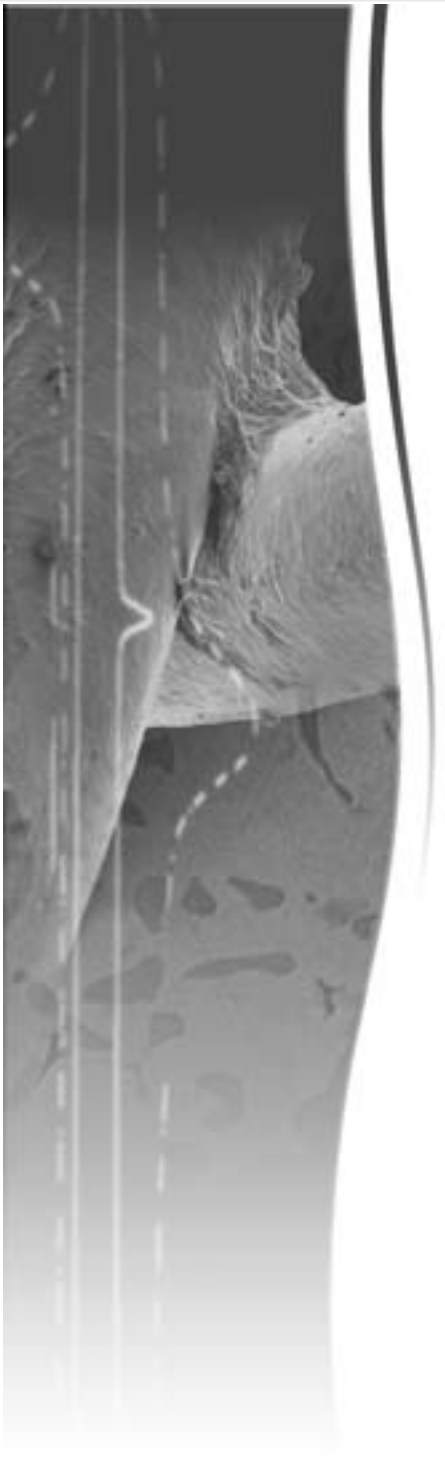

12th SPIE International Symposium

Smart Structures and Materials

6–10 March 2005
Town and Country Resort & Convention Center
San Diego, California USA

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SPIE 12th International Symposium on

Smart Structures and Materials

6–10 March 2005 • San Diego, CA

Conference 5757

Royal Palm III

Monday-Wednesday 7-9 March 2005
Proceedings of SPIE Vol. 5757

Modeling, Signal Processing, and Control

Conference Chair: **Ralph C. Smith**, North Carolina State Univ.

Cochair: **Robert L. Clark**, Duke Univ.

Program Committee: **Balakumar Balachandran**, Univ. of Maryland/College Park; **H. Thomas Banks**, North Carolina State Univ.; **Christian Boller**, Univ. of Sheffield (United Kingdom); **Frederic Bourquin**, Lab. Central des Ponts et Chaussees (France); **Fu-Kuo Chang**, Stanford Univ.; **Marcelo J. Dapino**, The Ohio State Univ.; **Mauricio C. de Oliveira**, Univ. of California/San Diego; **Michael A. Demetriou**, Worcester Polytechnic Institute; **Mary I. Frecker**, The Pennsylvania State Univ.; **Ulrich Gabbert**, Otto-von-Guericke Univ. Magdeburg (Germany); **Stephen C. Galea**, Defence Science and Technology Organisation (Australia); **Karolos M. Grigoriadis**, Univ. of Houston; **Hans Irschik**, Johannes Kepler Univ. Linz (Austria); **Ram V. Iyer**, Texas Tech Univ.; **Qing Jiang**, Univ. of California/Riverside; **Katharine J. Jones**, Rice Univ.; **Narendra S. Khot**, Air Force Research Lab.; **Noboru Kikuchi**, Univ. of Michigan; **Jaehwan Kim**, Inha Univ. (South Korea); **Sridhar Kota**, Univ. of Michigan; **Andrew J. Kurdila**, Univ. of Florida; **Reinhard Lerch**, Friedrich-Alexander Univ. Erlangen-Nürnberg (Germany); **Liviu I. Librescu**, Virginia Polytechnic Institute and State Univ.; **Douglas K. Lindner**, Virginia Polytechnic Institute and State Univ.; **Thomas J. Royston**, Univ. of Illinois/Chicago; **Stefan Seelecke**, North Carolina State Univ.; **Robert T. Skelton**, Univ. of California/San Diego; **Wieslaw J. Staszewski**, Univ. of Sheffield (United Kingdom); **Vasundara V. Varadan**, National Science Foundation; **Miao Yu**, Univ. of Maryland/College Park

Conference 5758

Golden West

Monday-Wednesday 7-9 March 2005
Proceedings of SPIE Vol. 5758

Smart Sensor Technology and Measurement Systems

Conference Chairs: **Eric Udd**, Blue Road Research;

Daniele Inaudi, SMARTEC SA (Switzerland)

Cochairs: **Brian Culshaw**, Univ. of Strathclyde (United Kingdom); **Wolfgang Ecke**, Institut für Physikalische Hochtechnologie e.V. (Germany); **Luc Thevenaz**, Swiss Federal Institute of Technology (Switzerland)

Program Committee: **Xiaoyi Bao**, Univ. of Ottawa (Canada); **Richard O. Claus**, Virginia Polytechnic Institute and State Univ.; **John P. Dakin**, Univ. of Southampton (United Kingdom); **Riccardo Falciai**, Istituto di Fisica Applicata (Italy); **Edward J. Friebele**, Naval Research Lab.; **Joseph Grant**, NASA Marshall Space Flight Ctr.; **Wolfgang R. Habel**, Bundesanstalt für Materialforschung und -prüfung (Germany); **Stephen T. Kreger**, Blue Road Research; **Marc Nikles**, Omnisens SA (Switzerland); **Kara J. Peters**, North Carolina State Univ.; **Nobuo Takeda**, Univ. of Tokyo (Japan)

Conference 5759

Town & Country and Golden West

Monday-Thursday 7-10 March 2005
Proceedings of SPIE Vol. 5759

Electroactive Polymer Actuators and Devices (EAPAD)

Conference Chair: **Yoseph Bar-Cohen**, Jet Propulsion Lab.

Cochair: **John D. W. Madden**, Univ. of British Columbia (Canada)

Program Committee: **Michael S. Banik**, Boston Scientific Corp.; **Ray H. Baughman**, Univ. of Texas/Dallas; **Paul D. Calvert**, Univ. of Massachusetts/Dartmouth; **Richard O. Claus**, Virginia Polytechnic Institute and State Univ.; **Pierre-Gilles de Gennes**, ESPCI (France); **Danilo De Rossi**, Univ. degli Studi di Pisa (Italy); **Rainer W. Gülch**, Eberhard-Karls-Univ. Tübingen (Germany); **Edwin W. Jager**, Micromuscle AB (Sweden); **Keiichi Kaneto**, Kyushu Institute of Technology (Japan); **Jaehwan Kim**, Inha Univ. (South Korea); **Kwang J. Kim**, Univ. of Nevada/Reno; **Roy D. Kornbluh**, SRI International; **Gabor Kovacs**, EMPA Duebendorf (Switzerland); **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **Wen-Liang Liu**, Industrial Technology Research Institute (Taiwan); **Chris Melhuish**, Univ. of the West of England (United Kingdom); **Jaedo Nam**, Sung Kyun Kwan Univ. (South Korea); **Siavouche Nemat-Nasser**, Univ. of California/San Diego; **Yoshihito Osada**, Hokkaido Univ. (Japan); **Toribio F. Otero**, Univ. Politécnica de Cartagena (Spain); **Mohsen Shahinpoor**, Univ. of New Mexico; **Elisabeth Smela**, Univ. of Maryland/College Park; **Peter Sommer-Larsen**, Risø National Lab. (Denmark); **Ji Su**, NASA Langley Research Ctr.; **Minoru Taya**, Univ. of Washington; **Gordon G. Wallace**, Univ. of Wollongong (Australia); **Qiming Zhang**, The Pennsylvania State Univ.; **Miklos Zrinyi**, Budapest Univ. of Technology and Economics (Hungary)

Conference 5760

Royal Palm I

Monday-Thursday 7-10 March 2005
Proceedings of SPIE Vol. 5760

Damping and Isolation

Conference Chair: **Kon-Well Wang**, The Pennsylvania State Univ.

Cochair: **William W. Clark**, Univ. of Pittsburgh

Program Committee: **Gregory S. Agnes**, Jet Propulsion Lab.; **Mehdi Ahmadian**, Virginia Polytechnic Institute and State Univ.; **Eric M. Austin**, Clemson Univ.; **H. Thomas Banks**, North Carolina State Univ.; **Amr M. Baz**, Univ. of Maryland/College Park; **Richard G. Cobb**, Air Force Institute of Technology; **Kenneth A. Cunefare**, Georgia Institute of Technology; **L. Porter Davis**, Honeywell Inc.; **Farhan Gandhi**, The Pennsylvania State Univ.; **Faramarz Gordaninejad**, Univ. of Nevada/Reno; **Roy Ikegami**, Acellent Technologies; **Daniel J. Inman**, Virginia Polytechnic Institute and State Univ.; **Conor D. Johnson**, CSA Engineering, Inc.; **Nikhil A. Koratkar**, Rensselaer Polytechnic Institute; **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **George A. Lesieutre**, The Pennsylvania State Univ.; **Wei-Hsin Liao**, Chinese Univ. of Hong Kong (Hong Kong China); **Arnold Lumsdaine**, Univ. of Tennessee/Knoxville; **Joseph R. Maly**, CSA Engineering, Inc.; **Samir A. Nayfeh**, Massachusetts Institute of Technology; **Roger Ohayon**, Conservatoire National des Arts et Métiers (France); **Zahidul H. Rahman**, Jet Propulsion Lab.; **Massimo Ruzzene**, Georgia Institute of Technology; **Steve I. Y. Shen**, Univ. of Washington; **Roger Stanway**, Univ. of Sheffield (United Kingdom); **Jian Q. Sun**, Univ. of Delaware; **Jiong Tang**, Univ. of Connecticut; **Geoffrey R. Tomlinson**, Univ. of Sheffield (United Kingdom); **Norman M. Wereley**, Univ. of Maryland/College Park

Conference 5761

California and Towne

Monday-Thursday 7-10 March 2005
Proceedings of SPIE Vol. 5761

Active Materials: Behavior and Mechanics

Conference Chair: **William D. Armstrong**, Univ. of Wyoming

Cochair: **Marcelo J. Dapino**, The Ohio State Univ.

Program Committee: **Gary L. Anderson**, Army Research Office; **Roshdy G. S. Barsoum**, Office of Naval Research; **Abhijit Bhattacharyya**, Univ. of Arkansas/ Little Rock; **James G. Boyd IV**, Texas A&M Univ.; **L. Catherine Brinson**, Northwestern Univ.; **Gregory P. Carman**, Univ. of California/Los Angeles; **Martin L. Dunn**, Univ. of Colorado/Boulder; **Qing Jiang**, Univ. of California/Riverside; **Marc Kamlah**, Forschungszentrum Karlsruhe (Germany); **Ibrahim Karaman**, Texas A&M Univ.; **Dimitris C. Lagoudas**, Texas A&M Univ.; **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **Christopher S. Lynch**, Georgia Institute of Technology; **Robert M. McMeeking**, Univ. of California/Santa Barbara; **Robert C. O'Handley**, Massachusetts Institute of Technology; **Zoubeida Ounaies**, Virginia Commonwealth Univ.; **Etienne Patoor**, Ecole Nationale Superieure d'Arts et Metiers (France); **Muhammad A. Qidwai**, Geo-Centers, Inc.; **John A. Shaw**, Univ. of Michigan; **Thomas W. Shield**, Univ. of Minnesota; **Thomas R. Shrout**, The Pennsylvania State Univ.; **Ralph C. Smith**, North Carolina State Univ.; **Nancy R. Sottos**, Univ. of Illinois/Urbana-Champaign

Conference 5762

San Diego

Monday-Wednesday 7-9 March 2005
Proceedings of SPIE Vol. 5762

Industrial and Commercial Applications of Smart Structures Technologies

Conference Chair: **Edward V. White**, Boeing Phantom Works

Cochair: **L. Porter Davis**, Honeywell Inc.

Program Committee: **Grigory Adamovsky**, NASA Glenn Research Ctr.; **Eric H. Anderson**, CSA Engineering, Inc.; **Christian Boller**, Univ. of Sheffield (United Kingdom); **Peter C. Chen**, Composite Mirror Applications, Inc.; **Arthur V. Cooke**, Active Signal Technologies; **Johannes K. Dürr**, DaimlerChrysler AG (Germany); **B. Kyle Henderson**, Air Force Research Lab.; **Jack H. Jacobs**, Honeywell, Inc.; **Mark R. Jolly**, Lord Corp.; **Chad H. Joshi**, Energen, Inc.; **Jayanth N. Kudva**, NextGen Aeronautics, Inc.; **Mark Lin**, Acellent Technologies, Inc.; **Douglas K. Lindner**, Virginia Polytechnic Institute and State Univ.; **John A. Main**, DARPA; **Anna-Maria R. McGowan**, NASA Langley Research Ctr.; **Marc E. Regelbrugge**, Rhombus Consultants Group; **W. Lance Richards**, NASA Dryden Flight Research Ctr.; **Brian P. Sanders**, Air Force Research Lab.; **Janet M. Sater**, Institute for Defense Analyses; **Jerry Schmidt**, Materials Systems, Inc.

Conference 5763

Royal Palm II

Monday-Thursday 7-10 March 2005
Proceedings of SPIE Vol. 5763

Smart Electronics, MEMS, BioMEMS, and Nanotechnology

Conference Chair: **Vijay K. Varadan**, The Pennsylvania State Univ.

Cochairs: **Pratul K. Ajmera**, Louisiana State Univ.; **Zeynep Celik-Butler**, Univ. of Texas/Arlington; **Laszlo B. Kish**, Texas A&M Univ.; **Babak Ziaie**, Univ. of Minnesota

Program Committee: **Vasu K. Aatre**, Defence Research & Development Organisation (India); **Steven W. Arms**, MicroStrain, Inc.; **John H. Belk**, Boeing Co.; **David L. Carroll**, Wake Forest Univ.; **Jung-Chih Chiao**, Univ. of Texas/ Arlington; **Sang H. Choi**, NASA Langley Research Ctr.; **Andras Der**, Biological Research Centre of the Hungarian Academy (Hungary); **Claes-Göran Granqvist, Sr.**, Uppsala Univ. (Sweden); **Peter Heszler, Sr.**, Uppsala Univ. (Sweden); **Michael H. Hoffmann**, Univ. Ulm (Germany); **Ajay P. Malshe**, Univ. of Arkansas; **William H. Marlow**, Texas A&M Univ.; **Conrad Masterson**, Nanotechnology Foundation of Texas, Inc.; **Kathryn M. McGrath**, Univ. of Otago (New Zealand); **Y. Eugene Pak**, Samsung Advanced Institute of Technology & CRI (South Korea); **Gabor Schmera**, Space and Naval Warfare Systems Command Ctr., San Diego; **Andrei M. Shkel**, Univ. of California/Irvine; **Sameer Sonkusale**, Texas A&M Univ.; **Ashok Srivastava**, Louisiana State Univ.; **Maria Strømme**, Uppsala Univ. (Sweden); **Robert Vajtai**, Rensselaer Polytechnic Institute; **Lode K. Vandamme**, Technische Univ. Eindhoven (Netherlands)

Conference 5764

Royal Palm V

Monday-Thursday 7-10 March 2005
Proceedings of SPIE Vol. 5764

Smart Structures and Integrated Systems

Conference Chair: **Alison B. Flatau**, Univ. of Maryland/College Park

Cochairs: **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **Yuji Matsuzaki**, Nagoya Univ. (Japan)

Program Committee: **Gregory S. Agnes**, Jet Propulsion Lab.; **Eric H. Anderson**, CSA Engineering, Inc.; **Gary L. Anderson**, Army Research Office; **Hiroshi Asanuma**, Chiba Univ. (Japan); **Balakumar Balachandran**, Univ. of Maryland/College Park; **Roshdy G. S. Barsoum**, Office of Naval Research; **Diann E. Brei**, Univ. of Michigan; **Allen J. Bronowicki**, Northrop Grumman Corp.; **Gregory P. Carman**, Univ. of California/Los Angeles; **Fu-Kuo Chang**, Stanford Univ.; **Aditi Chattopadhyay**, Arizona State Univ.; **Peter C. Chen**, Composite Mirror Applications, Inc.; **Seung-Bok Choi**, Inha Univ. (South Korea); **Ephrahim Garcia**, Cornell Univ.; **John M. Ginder**, Ford Motor Co.; **Victor Giurgiutiu**, Univ. of South Carolina; **Nesbitt W. Hagood**, Continuum Photonics; **T. Tupper Hyde**, NASA Goddard Space Flight Ctr.; **Daniel J. Inman**, Virginia Polytechnic Institute and State Univ.; **George A. Lesieutre**, The Pennsylvania State Univ.; **John A. Main**, DARPA; **David R. Martinez**, Sandia National Labs.; **Michihiro C. Natori**, Institute of Space and Astronautical Science (Japan); **Christopher Niezrecki**, Univ. of Florida; **Darryll J. Pines**, Univ. of Maryland/College Park; **Dale Ruebsamen**, Honeywell Inc.; **Roger Stanway**, Univ. of Sheffield (United Kingdom); **Friedrich K. Straub**, Boeing Co.; **Kon-Well Wang**, The Pennsylvania State Univ.; **Norman M. Wereley**, Univ. of Maryland/College Park; **Shoko Yoshikawa**, Phoenix Science and Technology; **Yung H. Yu**, NASA Ames Research Ctr.

Smart Structures and Materials

Conference 5757 | Conference 5758 | Conference 5759 | Conference 5760

Monday 7 March

8:00 to 10:00 am • *Town & Country Ballroom*

Award Presentations:

Smart Structures and Materials Achievement Award • NDE Achievement Award • Nondestructive Evaluation Best Paper Award

SSM&NDE Combined Plenary Presentations:

The 'Smart' Path to the Future of Aeronautics, Dr. Richard Wlezien, Director, Vehicle Systems Division, Aeronautics Research Mission Directorate, NASA Headquarters

Optical and Laser NDE: More Than Meets the Eye, Jean-Pierre Monchalin, Industrial Materials Institute/National Research Council Canada (Canada)

Coffee Break 10:00 to 10:30 am

SESSION 1
Royal Palm III
Mon. 10:30 am to 12:10 pm

Piezoceramic Materials

Chair: **Ralph C. Smith**, North Carolina State Univ.

10:30 am: **A stress-dependent hysteresis model for pre-stressed piezoceramic actuators,** B. L. Ball, R. Smith, North Carolina State Univ. . . . . [5757-01]

10:50 am: **A body-force analogy for dynamic piezoelasticity,** H. Irschik, M. Krommer, Johannes Kepler Univ. Linz (Austria) [5757-73]

11:10 am: **Computational multi-field mechanics model of piezoelectric micro-resonators,** S. Preidikman, B. Balachandran, Univ. of Maryland/College Park . . . [5757-03]

11:30 am: **Nonlinear forces oscillations of piezoelectric resonators,** H. Li, S. Preidikman, B. Balachandran, Univ. of Maryland/College Park . . . . . [5757-04]

11:50 am: **Analytical modeling and active vibration suppression of an adaptive circular composite plate with antisymmetric constraints,** S. Yan, M. Ghasemi Nejhad, Univ. of Hawaii/Manoa . . . . . [5757-05]

Lunch Break . . . . . 12:10 to 1:30 pm

SESSION 1
Golden West
Mon. 10:30 am to 12:10 pm

Fiber Bragg Grating Sensors I

Chairs: **Daniele Inaudi**, SMARTEC SA (Switzerland); **Eric Udd**, Blue Road Research

10:30 am: **Transverse strain sensitivity of fiber Bragg grating sensors,** M. Prabhugoud, K. J. Peters, North Carolina State Univ. . . . . [5758-01]

10:50 am: **Tuneable laser-based carbon composite strain sensing system using wavelength division multiplexed fiber Bragg grating sensors,** M. J. Connelly II, S. Moloney, P. Butler, Univ. of Limerick (Ireland) [5758-02]

11:10 am: **Adaptive multiplexed two-wave mixing array demodulator to monitor dynamic strains using fiber Bragg grating sensors,** Y. Zhou, Y. Qiao, S. Krishnaswamy, Northwestern Univ. . . . . [5758-03]

11:30 am: **Etched in-fiber Bragg gratings for temperature sensing at high temperatures,** K. H. Smith, B. L. Ipson, L. V. Crane, T. L. Lowder, S. M. Schultz, R. H. Selfridge, Brigham Young Univ. . . . . [5758-04]

11:50 am: **Processing of signals from fiber Bragg gratings using unbalanced interferometers,** G. Adamovsky, NASA Glenn Research Ctr. . . . . [5758-05]

Lunch Break . . . . . 12:10 to 1:30 pm

SESSION 1
Town & Country
Mon. 10:30 am to 12:10 pm

EAP as Emerging Actuators

Chairs: **Yoseph Bar-Cohen**, Jet Propulsion Lab.; **John D. W. Madden**, Univ. of British Columbia (Canada)

Keynote

10:30 am: **Artificial support and replacement of human organs *(Invited Paper)*,** P. Bonde, Johns Hopkins Univ. School of Medicine . . . . [5759-01]

11:10 am: **Biomimetics: mimicking and inspired-by biology,** Y. Bar-Cohen, Jet Propulsion Lab. . . . . [5759-02]

11:30 am: **Web-based actuator selection tool,** J. D. W. Madden, Univ. of British Columbia (Canada) . . . . . [5759-03]

11:50 am: **Eyeball pseudo-muscular actuators for an android face,** D. De Rossi, F. Carpi, A. Migliore, Univ. degli Studi di Pisa (Italy) . . . . . [5759-49]

Lunch Break . . . . . 12:10 to 1:30 pm

SESSION 1
Royal Palm I
Mon. 10:30 am to 11:50 pm

Vibration Isolation I

Chairs: **Kon-Well Wang**, The Pennsylvania State Univ.; **Samir A. Nayfeh**, Massachusetts Institute of Technology

10:30 am: **Switched-state control of a vibration isolation mount using ionomeric materials,** J. Mejia-Ariza, D. J. Leo, Virginia Polytechnic Institute and State Univ. [5760-01]

10:50 am: **Damping control of micromachined lowpass mechanical vibration isolation filters using electrostatic actuation with electronic signal processing,** R. N. Dean, Jr., G. Flowers, K. MacAllister, N. Sanders, S. Hodel, W. Johnson, Auburn Univ.; M. Kranz, Morgan Research Corp. . . . . [5760-02]

11:10 am: **Modeling and parameter identification of an active anti-vibration system,** F. Blum, S. Hurlebaus, Univ. Stuttgart (Germany); U. Stöbener, Halcyonics GmbH (Germany); L. Gaul, Univ. Stuttgart (Germany) . . . . . [5760-03]

11:30 am: **Launch vehicle payload adapter design with vibration isolation features,** G. R. Thomas, C. M. Fadick, ATA Engineering, Inc.; B. J. Fram, Air Force Research Lab. . [5760-04]

Lunch Break . . . . . 11:50 am to 1:30 pm

Smart Structures and Materials

Conference 5761 | Conference 5762 | Conference 5763 | Conference 5764

Monday 7 March

8:00 to 10:00 am • *Town & Country Ballroom*

Award Presentations:

Smart Structures and Materials Achievement Award • **NDE Achievement Award** • **Nondestructive Evaluation Best Paper Award**

SSM&NDE Combined Plenary Presentations:

The 'Smart' Path to the Future of Aeronautics, Dr. Richard Wlezien, Director, Vehicle Systems Division, Aeronautics Research Mission Directorate, NASA Headquarters

Optical and Laser NDE: More Than Meets the Eye, Jean-Pierre Monchalin, Industrial Materials Institute/National Research Council Canada (Canada)

Coffee Break 10:00 to 10:30 am

SESSION 1
California
Mon. 10:30 am to 12:10 pm

Nanostructured Active Composites I

Keynote

10:30 am: **Nanotube-based materials,** R. Barrera, Rice Univ. . . . . [5761-01]

11:10 am: **Automatic measurement of resistance of carbon nanotubes sheet actuators and the influence of the resistance on its actuation behavior,** S. Lanka, M. H. Haque, I. Kolaric, Fraunhofer-Technologie-Entwicklungsgruppe (Germany); X. Jiang, Univ. Siegen (Germany) . . . . . [5761-02]

11:30 am: **Electric field alignment of single-wall carbon nanotubes in polymers,** S. Banda, Z. Ounaies, Virginia Commonwealth Univ.; J. Wilkinson, Virginia Polytech Institute and State Univ.; C. Park, National Institute of Aerospace; J. S. Harrison, NASA Langley Research Ctr. . . . . [5761-03]

11:50 am: **Metal Rubber™ materials,** R. O. Claus, Virginia Polytechnic Institute and State Univ.; J. H. Lalli, J. B. Mecham, B. A. Davis, R. M. Goff, A. Hill, S. Subramanayan, NanoSonic, Inc. . . . . [5761-04]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 1
San Diego
Mon. 10:30 to 11:30 am

Novel Smart Material Applications

10:30 am: **Industrial and commercial applications of Metal Rubber™,** R. O. Claus, Virginia Polytechnic Institute and State Univ.; J. H. Lalli, B. A. Davis, J. B. Mecham, R. M. Goff, A. Hill, S. Subramanayan, NanoSonic, Inc. . . . . [5762-01]

10:50 am: **Self-healing cables and composites,** B. Esser, D. R. Huston, Univ. of Vermont . . . . . [5762-02]

11:10 am: **Stoichiometric study of $Tb_xDy_{(1-x)}Fe_{1.92}$ composites for passive vibration damping,** K. K. Ho, Fortis Technologies; G. P. Carman, Univ. of California/Los Angeles . . . . . [5762-03]

SESSION 2
San Diego
Mon. 11:30 am to 12:10 pm

Shape Memory Materials Applications I

11:30 am: **A high-temperature shape-memory alloy sensor for combustion monitoring and control,** G. S. Shaw, J. T. Snyder, T. S. Prince, M. C. Willett, Orbital Research Inc. [5762-04]

11:50 am: **Shape-memory polymer mandrels,** M. C. Everhart, Cornerstone Research Group, Inc. . . . . [5762-05]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 1
Royal Palm II
Mon. 10:30 am to 12:10 pm

Smart Electronics I

Chairs: **Ashok Srivastava**, Louisiana State Univ.; **K. A. Jose**, The Pennsylvania State Univ.

10:30 am: **Post-CMOS chip-level processing for high-aspect ratio microprobe fabrication utilizing pulse plating,** T. Xin, P. K. Ajmera, C. Zhang, A. Srivastava, Louisiana State Univ. . . . . [5763-01]

10:50 am: **Charge pump CMOS circuit based on internal clock voltage boosting for bio-medical applications,** R. R. Anantha, A. Srivastava, P. K. Ajmera, Louisiana State Univ. . . . . [5763-02]

11:10 am: **Remote power delivery for hybrid integrated bio-implantable electrical stimulation system,** V. R. Gaddam, J. Yernagula, R. R. Anantha, S. Kona, S. Kopparthi, P. K. Ajmera, A. Srivastava, Louisiana State Univ. . . . . [5763-03]

11:30 am: **Extending PAD (Power Allocation and Distribution),** K. D. Song, W. T. Golembiewski, Norfolk State Univ.; G. C. King, S. H. Choi, NASA Langley Research Ctr. . . . . [5763-04]

11:50 am: **Wireless microsensor network for solutions for neurological implantable device,** J. K. Abraham, A. K. Whitchurch, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-05]

Lunch Break . . . . . 12:10 to 1:30 pm

SESSION 1
Royal Palm V
Mon. 10:30 to 11:50 am

Advanced Actuation Concepts I

Chairs: **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **HuiRu Shih**, Jackson State Univ.

10:30 am: **A comprehensive model for NiMnGa magnetic shape-memory alloy behavior,** R. N. Couch, Univ. of Maryland/College Park . . . . . [5764-01]

10:50 am: **Actuation performance of conducting shape-memory polyurethane actuators,** I. H. Paik, N. S. Goo, K. J. Yoon, J. H. Cho, Konkuk Univ. (South Korea) . . [5764-03]

11:10 am: **Integrated system for stimulation of mechanosensitive cells using polymeric bender elements,** X. He, M. Kreke, D. J. Leo, A. Goldstein, P. Vlachos, Virginia Polytechnic Institute and State Univ. . . . . [5764-04]

11:30 am: **Development of a piezoelectric induced-strain actuator with an innovative internal amplifying structure,** C. S. Yung, S. W. Or, D. Li, H. L. W. Chan, Hong Kong Polytechnic Univ. (Hong Kong China); P. K. Choy, P. C. K. Liu, ASM Assembly Automation Ltd. (Hong Kong China) . . . . . [5764-05]

Lunch Break . . . . . 11:50 am to 1:30 pm

Smart Structures and Materials

Conference 5757

SESSION 2
Royal Palm III
Mon. 1:30 to 3:10 pm

Control Design I

Chair: **Mary I. Frecker**, The Pennsylvania State Univ.

1:30 pm: **Optimization of actuator placement and hybrid controller design in flexible plates using PZT actuators,** M. A. Demetriou, Worcester Polytechnic Institute . . . [5757-06]

1:50 pm: **Comparison of laplace transform, integral equation, and assumed modes approaches for piezo-patch control of beams,** J. C. Bruch, Jr., O. Kayacik, J. M. Sloss, Univ. of California/Santa Barbara; S. Adali, Univ. of KwaZulu-Natal (South Africa); I. Sadek, American Univ. of Sharjah (United Arab Emirates) . . . . . [5757-07]

2:10 pm: **Nonlinear electronic compensation for position control of a magnetostrictor actuator,** D. K. Lindner, C. Howells, H. Zhu, Virginia Polytechnic Institute and State Univ. [5757-08]

2:30 pm: **Stability of a nonlinear electronic controller for an electrostrictor actuator,** D. K. Lindner, C. Howells, G. Zvonar, Virginia Polytechnic Institute and State Univ. [5757-09]

2:50 pm: **Exact boundary controllability of a multilayer sandwich beam,** S. W. Hansen, Iowa State Univ. . . . . [5757-10]

Coffee Break . . . . . 3:10 to 3:40 pm

Conference 5758

SESSION 2
Golden West
Mon. 1:30 to 3:10 pm

Fiber Bragg Grating Sensors II

Chairs: **Eric Udd**, Blue Road Research; **Daniele Inaudi**, SMARTEC SA (Switzerland)

1:30 pm: **Process for mounting and packaging of fiber Bragg grating strain sensors for use in harsh environment applications,** V. P. Wnuk, Hitec Products Inc.; A. Méndez, MCH Engineering, LLC; S. Ferguson, T. W. Graver, Micron Optics Inc. . . . . [5758-06]

1:50 pm: **Development of high-speed optical wavelength interrogation system for damage detection in composite materials,** K. Seiji, S. Komatsuzaki, A. Hongo, Hitachi Cable, Ltd. (Japan); N. Takeda, Univ. of Tokyo (Japan) . . . . . [5758-07]

2:10 pm: **In situ simultaneous strain and temperature measurement of adaptive composite materials using a fiber Bragg grating based sensor,** H. Yoon, Korea Advanced Institute of Science and Technology (South Korea); D. M. Costantini, V. J. Michaud, H. G. Limberger, J. E. Månson, R. Salathé, Ecole Polytechnique Fédérale de Lausanne (Switzerland); C. Kim, C. Hong, Korea Advanced Institute of Science and Technology (South Korea) . . . . . [5758-08]

2:30 pm: **Demodulating interferometric and FBG sensors in the spectral domain,** D. Inaudi, B. Glisic, D. Posenato, SMARTEC SA (Switzerland); T. Haber, J. W. Miller, Micron Optics, Inc. . . . . [5758-09]

2:50 pm: **Modeling of transverse loading effect on Bragg grating signals,** S. A. Mastro, Drexel Univ. and Naval Surface Warfare Ctr.; M. A. El-Sherif, Drexel Univ. . . . . [5758-10]

Coffee Break . . . . . 3:10 to 3:40 pm

Conference 5759

SESSION 2
Town & Country
Mon. 1:30 to 3:50 pm

Ionic EAP I

Chairs: **Danilo De Rossi**, Univ. degli Studi di Pisa (Italy); **Jaedo Nam**, Sung Kyun Kwan Univ. (South Korea)

1:30 pm: **Ionic polymer-metal composites: recent advances *(Invited Paper),*** K. J. Kim, Univ. of Nevada/Reno . . . . . [5759-05]

2:10 pm: **Operation of ionic polymer-metal composites in water,** J. W. Paquette, K. J. Kim, S. Heo, Univ. of Nevada/Reno; W. Yim, Univ. of Nevada/Las Vegas . . . . . [5759-06]

2:30 pm: **Self-oscillatory behavior of ionic polymer-metal composite (IPMC): a new finding,** D. Kim, K. J. Kim, J. Paquette, Univ. of Nevada/Reno . . . . . [5759-07]

2:50 pm: **Frequency response analysis of IPMC actuators by an IR system,** C. Bonomo, L. Fortuna, P. Giannone, S. Graziani, Univ. degli Studi di Catania (Italy) . . . . . [5759-08]

3:10 pm: **Recent advances in ionic-polymer conductor composite materials as distributed nanosensors, nanoactuators, and artificial muscles *(Invited Paper),*** M. Shahinpoor, Environmental Robots Inc. and Univ. of New Mexico and Artificial Muscle Research Institute . . . . . [5759-09]

Conference 5760

SESSION 2
Room: Royal Palm I
Mon. 1:30 to 3:10 pm

MR/ER Fluid Damping I

Chairs: **Roger Stanway**, Univ. of Sheffield (United Kingdom); **Jian Q. Sun**, Univ. of Delaware

1:30 pm: **A study on MR fluids subjected to high-shear rates and high velocities,** F. D. Goncalves, M. Ahmadian, Virginia Polytechnic Institute and State Univ. . . . . [5760-07]

1:50 pm: **Pressurized magnetorheological dampers for train suspension,** W. Liao, Y. Lau, Chinese Univ. of Hong Kong (Hong Kong China) . . . . . [5760-08]

2:10 pm: **Semi-active controller dynamics in a magnetorheological tuned vibration absorber,** J. Koo, M. Ahmadian, Virginia Polytechnic Institute and State Univ.; M. H. Elahinia, Univ. of Toledo . . . . . [5760-09]

2:30 pm: **Design and performance optimization of magnetorheological oleopneumatic landing gear,** D. C. Batterbee, N. D. Sims, R. Stanway, Univ. of Sheffield (United Kingdom) . . . . . [5760-10]

2:50 pm: **Experimental investigation on the effectiveness of of a magnetorheological fluid squeeze film damper,** C. Zhu, Zhejiang Univ. (China) . . . . . [5760-11]

Coffee Break . . . . . 3:10 to 3:40 pm

Smart Structures and Materials

Conference 5761

Conference 5762

Conference 5763

Conference 5764

Monday 7 March

Sessions 2 and 5 run concurrently.

SESSION 2
California
Mon. 1:30 to 3:10 pm

Nanostructured Active Composites II

1:30 pm: **Nano-coating with controllable reflectance spectrum,** O. Aktsipetrov, T. Murzina, M. Murzina, J. P. Farrell, Brookhaven Technology Group, Inc. . . . . [5761-05]

1:50 pm: **Dielectric constant measurements of nanoscale thickness polymeric films,** R. Asmatulu, W. B. Spillman, Jr., R. O. Claus, Virginia Polytechnic Institute and State Univ. . . . . [5761-06]

2:10 pm: **Improving the lifespan of aircraft skins against corrosion attacks by using polymeric nanocomposites,** R. Asmatulu, Virginia Polytechnic Institute and State Univ. . . . . [5761-07]

2:30 pm: **Characterization and release of surface tension energy in nanoparticles,** O. Aktsipetrov, T. Murzina, J. P. Farrell, M. V. Murzina, Brookhaven Technology Group, Inc. . . . . [5761-08]

2:50 pm: **Carbon nanotubes-coated electroactive paper (EAPap) as hybrid high-displacement actuator,** S. Yun, J. Kim, Inha Univ. (South Korea); Z. Ounaies, T. St Clair, Virginia Commonwealth Univ. . . . . [5761-09]

Sessions 2 and 5 run concurrently.

SESSION 5
Towne
Mon. 1:30 to 3:10 pm

Magnetic Composites

Chairs: **William D. Armstrong**, Univ. of Wyoming; **Julie C. Slaughter**, Etrema Products, Inc.

1:30 pm: **Applications of magnetically active fiber reinforced composites,** J. A. Etches, I. Bond, P. Mellor, Univ. of Bristol (United Kingdom) . . . . . [5761-18]

1:50 pm: **Characterization of quasi-static and dynamic properties of Terfenol-D composites,** A. P. Mortensen, M. J. Dapino, The Ohio State Univ. . . . . [5761-19]

2:10 pm: **Degradation of Terfenol-D particle epoxy composites under low-frequency cyclic magneto-mechanical loading: comparisons of matrix polymer,** W. D. Armstrong, Univ. of Wyoming . . . . . [5761-20]

2:30 pm: **Magnetic sensor for high temperature using a laminate composite of magnetostrictive material and piezoelectric materials,** T. Ueno, T. Higuchi, Univ. of Tokyo (Japan) . . . . . [5761-21]

2:50 pm: **Genetic algorithms for rheological parameter identification of magnetorheological fluids,** A. Chaudhuri, N. M. Wereley, Univ. of Maryland/College Park . . . . . [5761-22]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 3
San Diego
Mon. 1:30 to 2:30 pm

Shape Memory Materials Applications II

1:30 pm: **Elastic Memory Composites (EMC) for deployable space structures,** M. L. Tupper, N. A. Munshi, M. S. Lake, S. C. Arzberger, R. Barrett, P. N. Keller, W. H. Francis, D. Campbell, Composite Technology Development, Inc.; K. A. Gall, Univ. of Colorado/Boulder . . . . . [5762-06]

1:50 pm: **Light-activated shape-memory polymers and associated applications,** T. H. Tong, E. Havens, Cornerstone Research Group, Inc. . . . . [5762-07]

2:10 pm: **Research and design of a remotely activated SMA actuated naval tie-down system,** R. Shydo, Jr., Ithaca Mechanical Systems, Inc.; E. Garcia, Cornell Univ.; J. Harris, Ithaca Mechanical Systems Inc. . . . . [5762-08]

SESSION 4
San Diego
Mon. 2:30 to 4:20 pm

Sensor Applications

2:30 pm: **A nondestructive method to estimate moisture content in grain from RF impedance measurements with a parallel-plate sensor,** C. V. Kandala, C. L. Butts, USDA Agricultural Research Service . . . . . [5762-09]

2:50 pm: **Design and analysis of an ultrasonic horn for an ultrasonic/sonic driller/corer (USDC),** Z. Chang, S. Sherrit, M. Badescu, X. Q. Bao, Y. Bar-Cohen, Jet Propulsion Lab. [5762-10]

Coffee Break . . . . . 3:10 to 3:40 pm

3:40 pm: **Development and optimization of novel sensors for inline measurement of sand filling and compaction stages in lost foam casting,** M. J. Whelan, K. D. Janoyan, Clarkson Univ. . . . . [5762-11]

4:00 pm: **Structural sensor testing for space vehicle applications,** J. Q. Huang, J. Rose, J. Gordon, Boeing Co. . . . . [5762-12]

SESSION 2
Royal Palm II
Mon. 1:30 to 3:10 pm

Smart Electronics II

Chairs: **Sang H. Choi**, NASA Langley Research Ctr.; **Hargsoon Yoon**, The Pennsylvania State Univ.

1:30 pm: **Design and testing of flexible dipole rectennas,** K. D. Song, W. T. Golembiewski, K. Henderson, Norfolk State Univ.; G. C. King, S. H. Choi, NASA Langley Research Ctr.; J. Kim, Inha Univ. (South Korea); W. Craft, North Carolina A&T State Univ. . . . . [5763-06]

1:50 pm: **A ku-band Wilkinson power divider implemented on a surface-stabilized high-resistivity Si substrate,** T. Ji, H. Yoon, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-07]

2:10 pm: **Design of 3-bit MEMS phase shifter,** H. Yoon, T. Ji, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-08]

2:30 pm: **Stacked phased array antenna systems monolithically integrated on silicon,** T. Ji, H. Yoon, K. A. Jose, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-09]

2:50 pm: **Organic thin-film transistor and electronics: a review,** J. Xie, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-10]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 2
Royal Palm V
Mon. 1:30 to 3:10 pm

Advanced Actuation Concepts II

Chairs: **Diann E. Brei**, Univ. of Michigan; **Yuri M. Shkel**, Univ. of Wisconsin/Madison

1:30 pm: **Piezocomposite transducers for smart structure applications,** A. J. Schoenecker, T. Roedig, S. Gebhardt, U. Keitel, Fraunhofer IKTS (Germany); T. P. Daue, Smart Material Corp. . . . . [5764-06]

1:50 pm: **Effect of electrode pattern on the performance of unimorph piezoelectric diaphragm actuators,** R. M. Wright, Univ. of Pittsburgh; C. Mo, Sangju National Univ. (South Korea); W. W. Clark, Univ. of Pittsburgh . . . . . [5764-07]

2:10 pm: **Micro-tailoring micro and nano composites toward variable orthotropy for biomimicking applications,** D. K. Moeller, Y. M. Shkel, Univ. of Wisconsin/Madison . . . . . [5764-08]

2:30 pm: **The fabrication and material characterization of PZT-based functionally graded piezoceramics,** P. W. Alexander, D. E. Brei, J. W. Halloran, Univ. of Michigan . . . . . [5764-09]

2:50 pm: **Studies on a multifunctional actuation system for lightweight space structures,** U. A. Korde, C. H. M. Jenkins, J. W. Sears, M. J. Husman, South Dakota School of Mines and Technology . . . . . [5764-10]

Coffee Break . . . . . 3:10 to 3:40 pm

Smart Structures and Materials

Conference 5757

Conference 5758

Conference 5759

Conference 5760

Monday 7 March

SESSION 3
Royal Palm III
Mon. 3:40 to 5:40 pm

Optimization

Chair: **Douglas K. Lindner**, Virginia Polytechnic Institute and State Univ.

3:40 pm: **Optimization of a piezoelectric acoustical compressor,** R. A. Dickens, DRS Signal Solutions, Inc.; A. M. Baz, Univ. of Maryland/College Park . . . . . [5757-11]

4:00 pm: **Parallel algorithm for optimal design of a morphing aircraft wing,** S. Bharti, M. Frecker, G. A. Lesieutre, D. Ramrakhyani, The Pennsylvania State Univ. . . . . [5757-12]

4:20 pm: **Simultaneous structure and control optimization of tensegrities,** M. Masic, R. E. Skelton, Univ. of California/San Diego . . . . . [5757-13]

4:40 pm: **Topology optimization of active control vibration damping layers,** M. Parsons, J. Jiang, A. Lumsdaine, Univ. of Tennessee/ Knoxville . . . . . [5757-14]

5:00 pm: **An automated approach to design shape morphing strategies for reconfigurable surfaces,** N. Srinivasa, R. S. Ross, HRL Labs., LLC . . . . . [5757-15]

5:20 pm: **Piezoresistive sensor design using topology optimization,** E. C. N. Silva, Univ. de São Paulo (Brazil); S. Nishiwaki, Kyoto Univ. (Japan) . . . . . [5757-16]

SESSION 3
Golden West
Mon. 3:40 to 5:40 pm

Structural Health Monitoring and Deformation Measurements I

Chairs: **Nobuo Takeda**, Univ. of Tokyo (Japan); **Kara J. Peters**, North Carolina State Univ.

3:40 pm: **Use of multidimensional fiber grating strain sensors for damage detection in composite pressure vessels,** M. Kunzler, E. Udd, Blue Road Research . . . . . [5758-11]

4:00 pm: **Damage growth detection of composite laminate structure using embedded FBG sensor/PZT actuator hybrid system,** T. Ogisu, M. Shimanuki, S. Kiyoshima, Fuji Heavy Industries Ltd. (Japan); Y. Okabe, N. Takeda, Univ. of Tokyo (Japan) . . . . . [5758-12]

4:20 pm: **Identification of impact damage in sandwich structures by application of high-speed MEMS-OSA to FBG sensors,** Y. Okabe, S. Minakuchi, N. Takeda, Univ. of Tokyo (Japan) . . . . . [5758-13]

4:40 pm: **On-line characterization of impacts on electrical train current collectors using integrated optical fiber grating sensor network,** W. Ecke, K. Schroeder, M. Kautz, IPHT Jena e.V. (Germany); P. Joseph, S. Willet, Morganite Electrical Carbon Ltd. (United Kingdom); T. Bosselmann, Siemens AG (Germany); M. Jenzer, BLS Loetschbergbahn AG (Switzerland) . . . . . [5758-14]

5:00 pm: **Residual stress and debonding analyses using fiber Bragg grating in a model composite specimen,** G. R. Dunkel, F. Colpo, L. Humbert, J. I. Botsis, EPFL (Switzerland) . . . . . [5758-15]

5:20 pm: **Lamb-wave sensing using fiber Bragg grating sensors for delamination detection in composite laminates,** N. Takeda, Y. Okabe, J. Kuwahara, Univ. of Tokyo (Japan); S. Kojima, Hitachi Cable, Ltd. (Japan)[5758-16]

EAP in Action
Town & Country

Preparation: 4:00 to 5:00 pm

EAP-in-Action Session and Demonstrations: 5:00 to 6:00 pm

This session, held annually as part of the SPIE EAPAD conference, is intended to turn the spotlight on Electroactive Polymers (EAP) materials and their applications as well as increase the recognition of their potential for smart structures. New materials and applications are continuing to emerge and this session is intended to provide an opportunity for interaction between technology developers and potential users and a demonstration of state-of-the-art EAP materials in action.

This conference will mark a milestone for the field of EAP where the first wrestling match of human and EAP-Robot arms will be held. A robot win will be a major milestone accomplishment for biomimetics, namely demonstrating the ability to emulate human physical capabilities. Recently, four organizations have announced they believe they have the potential capability to make such an arm. Three of these organizations have made an EAP-Robot arm and are ready for the competition this year. They are: **International, Environmental Robots Inc. (ERI), and Swiss Federal Labs. for Materials Testing and Research (EMPA),** and a group of students from **Virginia Tech., Engineering and Mechanics Department.**

Table for the Armwrestling Competition

A standard professional armwrestling table will be provided for this competition by **Dave Devoto** who is a pioneer and leading representative of the United States ArmSports.

The Armwrestling Match of EAP Robotic Arm Against Human (AMERAH) Competition Judges*

The following are the members of the AMERAH Organization Committee and will act as competition judges:

Chair: **Yoseph Bar-Cohen,** Senior Research Scientist and Group Supervisor (Act.), Jet Propulsion Lab.

Dave Devoto, Pioneer and Leading Representative, **United States ArmSports**

Richard Landon, Co-Author of a chapter in the book *Biologically Inspired Intelligent Robots,* **Stan Winston Studio** (SWS designed and created the robots and makeups for Spielberg's movie AI).

John D. W. Madden, Univ. of British Columbia (Canada)

Joanne Pransky, World's First Robotic Psychiatrist

Brian Thomas, Senior Event Manager, **SPIE**

The Human Opponent

Panna Felsen, has volunteered to be the human opponent for the match with EAP actuated robotic arms. Panna is a straight-A high-school student from the San Diego School District who is a robotics hobbyist.

**Please note that commitments for equipment and participation were accurate at time of publication, but are subject to change.*

SESSION 3
Royal Palm I
Mon. 3:40 to 6:00 pm

Characterization and Modeling

Chairs: **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **Wei-Hsin Liao**, Chinese Univ. of Hong Kong (Hong Kong China)

3:40 pm: **Experimental and finite element analysis of stand-off layer damping treatments for beams,** J. M. H. Yellin, I. Shen, P. Reinhall, Univ. of Washington . . [5760-12]

4:00 pm: **Low-wave-speed media for damping at high-temperature,** S. A. Nayfeh, Massachusetts Institute of Technology . . . . . [5760-13]

4:20 pm: **On the damping behavior and stiffness of 8 wt% yttria-stabilized zirconia coatings deposited by APS and EB-PVD techniques,** N. Tassini, Univ. of Sheffield (United Kingdom); K. Lambrinou, Katholieke Univ. Leuven (Belgium); S. Patsias, Univ. of Sheffield (United Kingdom); O. Van der Biest, Katholieke Univ. Leuven (Belgium); R. Stanway, Univ. of Sheffield (United Kingdom) . . . . . [5760-14]

4:40 pm: **A variational model of ionomeric polymer actuators and sensors,** M. A. Buechler, D. J. Leo, Virginia Polytechnic Institute and State Univ. . . . . [5760-15]

5:00 pm: **Nonlinear finite element modeling of vibration control of composite piezolaminated composite plates and shells,** R. Schmidt, RWTH-Aachen (Germany) . . . . . [5760-16]

5:20 pm: **Study of damping capacities of nitinol shape-memory alloys in Martensite, Austenite, and Martensite-Austenite co-existence phases,** G. Song, N. Ma, Univ. of Houston . . . . . [5760-17]

5:40 pm: **Electrostatic tuning of the bending stiffness of simple slender multi-layer composite structures,** A. E. Bergamini, R. Christen, M. Motavalli, Swiss Federal Labs. for Materials Testing and Research (Switzerland) . . . . . [5760-18]

Smart Structures and Materials

Conference 5761

Sessions 3 and 4 run concurrently with Session 6..

SESSION 3
California
Mon. 3:40 to 5:00 pm

Electrochemical Polymer Actuation

3:40 pm: **Modeling the electrical impedance of ionic polymer transducers,** K. M. Farinholt, D. J. Leo, Virginia Polytechnic Institute and State Univ. . . . . [5761-10]

4:00 pm: **Role of inherent polarization and ion transport in the actuation of cellulose-based EAP,** J. Kim, Y. Kang, S. Yun, Inha Univ. (South Korea); Z. Ounaies, Virginia Commonwealth Univ. . . . . [5761-11]

4:20 pm: **Electrochemical-based solid state actuation mechanisms based on reversible Li compound formation,** W. Barvosa-Carter, HRL Labs., LLC; C. G. Massey, HRL Labs., LLC and Univ. of Southern California; G. P. McKnight, P. Liu, HRL Labs., LLC . . . . . [5761-12]

4:40 pm: **Photoresponsive thin films containing Azobenzene,** C. J. Barrett, McGill Univ. (Canada) . . [5761-13]

SESSION 4
California
Mon. 5:00 to 6:20 pm

Modeling Issues in Active Materials

5:00 pm: **Monte Carlo analysis of ionic polymers with cluster morphology,** L. M. Weiland, D. J. Leo, Virginia Polytechnic Institute and State Univ. . . . . [5761-14]

5:20 pm: **Chemo-mechanical model of biological membranes for actuation mechanisms,** V. B. Sundaresan, D. J. Leo, D. Hopkinson, H. Tan, Virginia Polytechnic Institute and State Univ. . . . . [5761-15]

5:40 pm: **Three-dimensional atomistic computational model for electrostrictive graft elastomer,** C. Zhang, Y. Wang, Kansas State Univ.; J. Su, NASA Langley Research Ctr. . . . [5761-16]

6:00 pm: **Variable stiffness materials for reconfigurable surface applications,** G. P. McKnight, C. Henry, HRL Labs., LLC . . . . . [5761-17]

SESSION 6
Towne
Mon. 3:40 to 6:00 pm

Iron-Gallium Alloys

Chairs: **Marcelo J. Dapino**, The Ohio State Univ.; **Toshiyuki Ueno**, Univ. of Tokyo (Japan)

3:40 pm: **Elevated temperature aging of stress annealed of Fe-Ga transduction alloys,** M. Wun-Fogle, J. B. Restorff, Naval Surface Warfare Ctr.; A. E. Clark, Clark Associates, Inc.; E. M. Summers, Etrema Products, Inc. . . . . [5761-23]

4:00 pm: **Effect of cyclic stresses and magnetic fields on stress-annealed Galfenol alloys,** J. C. Slaughter, J. Raim, Etrema Products, Inc.; M. Wun-Fogle, J. B. Restorff, Naval Surface Warfare Ctr.; A. E. Clark, Clark Associates . [5761-24]

4:20 pm: **Magnetostriction and surface-energy-induced selective grain growth in rolled Galfenol doped with sulfur,** S. Na, A. B. Flatau, Univ. of Maryland/College Park . . [5761-25]

4:40 pm: **Investigation of magneto-mechanical properties of Galfenol for coil-less magnetic force control using inverse magnetostrictive effect,** T. Ueno, Univ. of Tokyo (Japan); E. M. Summers, Etrema Products, Inc.; T. Higuchi, Univ. of Tokyo (Japan) . . . . . [5761-26]

5:00 pm: **Dynamic property determination of magnetostrictive iron-gallium alloys,** L. M. Twarek, D. K. Pullen, A. B. Flatau, Univ. of Maryland/College Park [5761-27]

5:20 pm: **Texture and magnetomechanical behavior of polycrystalline Fe-Ga samples,** J. Atulasimha, A. Flatau, Univ. of Maryland/College Park; E. Summers, Etrema Products, Inc. . . . . [5761-28]

5:40 pm: **Generalized free-energy model for hysteresis in ferroelectric and ferromagnetic materials with application to single crystal iron-gallium alloy actuators,** J. Atulasimha, A. Flatau, Univ. of Maryland/College Park . . . . . [5761-29]

Conference 5762

SESSION 5
San Diego
Mon. 4:20 to 5:40 pm

Aircraft Applications I

4:20 pm: **NASA's research morphing technologies for aircraft,** A. R. McGowan, NASA Langley Research Ctr. . . . . [5762-13]

4:40 pm: **UAV visual signature suppression via adaptive materials,** R. M. Barrett, J. A. Melkert, Technische Univ. Delft (Netherlands) . . . . . [5762-15]

5:00 pm: **A new class of piezoelectric grid-fin flight control actuators enabling high-speed autonomous VTOL MAVs,** R. M. Barrett, R. D. Breuker, Technische Univ. Delft (Netherlands); R. McMurtry, Imperial College (United Kingdom); P. Tiso, E. Jansen, Technische Univ. Delft (Netherlands) . . . . . [5762-16]

5:20 pm: **Optimization of selective piezoelectric actuator activation on a flexible fin using a genetic algorithm,** A. A. Rader, Carleton Univ. (Canada) and National Research Council Canada (Canada); A. Yousefi-Koma, National Research Council Canada (Canada); F. F. Afagh, Carleton Univ. (Canada); D. G. Zimcik, National Research Council Canada (Canada) . . . . . [5762-17]

Conference 5763

SESSION 3
Royal Palm II
Mon. 3:40 to 5:40 pm

Fabrication and Characterization

Chairs: **Taeksoo Ji**, The Pennsylvania State Univ.; **Kyo D. Song**, Norfolk State Univ.

3:40 pm: **The Nanostructured Origami™ 3D fabrication and assembly process for nanopatterned 3D structures,** H. J. In, W. Arora, H. I. Smith, G. Barbastathis, Massachusetts Institute of Technology . . . . . [5763-11]

4:00 pm: **Hierarchical MEMS synthesis and optimization,** Y. Zhang, S. Graf, R. Kamalian, A. M. Agogino, Univ. of California/Berkeley . . . . . [5763-12]

4:20 pm: **Evaluation of novel tooling for nanoscale injection molding,** S. Yoon, J. Lee, J. L. Mead, C. M. F. Barry, Univ. of Massachusetts/Lowell . . . . . [5763-13]

4:40 pm: **Variable surface enhanced Raman spectroscopy of molecular motors,** O. Inya-Agha, J. M. Cooper, T. Davies, Univ. of Glasgow (United Kingdom) . [5763-14]

5:00 pm: **Material property measurement of micro-size cantilevers using the AFM,** S. Ko, H. Lee, J. Han, H. Park, POSTECH (South Korea) . . . . . [5763-15]

5:20 pm: **Microstereolithography for 3D microstructures,** T. Ji, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-16]

Conference 5764

SESSION 3
Royal Palm V
Mon. 3:40 to 6:00 pm

Advanced Sensor Concepts

Chairs: **Nii O. Attoh-Okine**, Univ. of Delaware; **Jin-Hyeong Yoo**, Univ. of Maryland/College Park

3:40 pm: **Smart sensory system for rapid detection and identification of pedestrian impacts,** A. C. Kim, F. Chang, Stanford Univ. . . . . [5764-11]

4:00 pm: **Investigation of the touch sensitivity of ER fluid-based tactile display,** Y. Liu, R. Davidson, P. M. Taylor, Univ. of Newcastle upon Tyne (United Kingdom) . . . . . [5764-12]

4:20 pm: **Application of iron-gallium alloy as magnetostrictive sensors,** S. Datta, A. B. Flatau, Univ. of Maryland/College Park . . . . . [5764-13]

4:40 pm: **Development of vibratory gyro-sensor using Galfenol,** J. Yoo, A. B. Flatau, Univ. of Maryland/College Park [5764-14]

5:00 pm: **Bending behavior of iron-gallium (Galfenol) alloys for sensor applications,** P. R. Downey, A. B. Flatau, Univ. of Maryland/College Park [5764-15]

5:20 pm: **Principle, modeling, and testing of a magnetorheological fluid damper with an integrated relative velocity sensor,** D. Lai, D. Wang, Chongqing Univ. (China) . . . . . [5764-16]

5:40 pm: **Monitoring the performance of geosynthetic materials within pavement systems using MEMS,** N. O. Attoh-Okine, A. Ayenu-Prah, S. Mensah, Univ. of Delaware . . . . . [5764-17]

Smart Structures and Materials

Conference 5757 | Conference 5758 | Conference 5759 | Conference 5760

Tuesday 8 March

8:00 to 8:55 am • *Town & Country Ballroom*

Award Presentations:

ASME Adaptive Structures and Materials Systems Best Paper Awards • Smart Structures and Materials/ASME Best Student Paper Award

SSM Plenary Presentation:

Research Opportunities in Nano and Microsystems Technology for Army Applications
Dr. Paul B. Ruffin, U. S. Army Research, Development, and Engineering Command (ARDEC)

Exhibition: 10:00 am to 4:00 pm, and 6:00 to 7:30 pm

SESSION 4
Royal Palm III
Tues. 9:00 to 10:00 am

Tensegrity Structures

Chair: **Thomas R. Braun**, North Carolina State Univ.

9:00 am: **Interaction of a turbulent channel flow with a compliant-tensegrity fabric,** H. Luo, T. R. Bewley, Univ. of California/San Diego . . . . . [5757-17]

9:20 am: **A new topology of tensegrity towers with uniform force distribution,** M. C. de Oliveira, R. E. Skelton, Univ. of California/San Diego . . . . . [5757-19]

9:40 am: **Integrated optimal-control design and sensor/actuator selection for a tensegrity beam,** R. Skelton, F. Li, Univ. of California/San Diego . . . . . [5757-18]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 5
Royal Palm III
Tues. 10:30 am to 12:10 pm

Sensors and Sensing

Chair: **Brian L. Ball**, North Carolina State Univ.

10:30 am: **Optimal sensing strategy for adaptive control of optical systems,** S. Moon, R. L. Clark, Duke Univ. . . . . [5757-20]

10:50 am: **Assessment of wavelet analysis of signal processing for smart structures,** K. J. Jones, Rice Univ. . . . . [5757-21]

11:10 am: **Nonlinear analysis of sensor diaphragm under initial tension,** M. Yu, B. Balachandran, Univ. of Maryland/College Park . . . . . [5757-22]

11:30 am: **Shape sensing a morphed wing with an optical fiber Bragg grating,** H. Tai, NASA Langley Research Ctr. . . . . [5757-23]

11:50 am: **Signal feature extraction for impact damage detection in composite materials,** S. Mahzan, W. J. Staszewski, M. S. Found, Univ. of Sheffield (United Kingdom) . . . . [5757-24]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 4
Golden West
Tues. 9:00 to 10:00 am

Structural Health Monitoring and Deformation Measurements II

Chairs: **Kara J. Peters**, North Carolina State Univ.; **Nobuo Takeda**, Univ. of Tokyo (Japan)

9:00 am: **Airplane structure health monitoring by the optical frequency modulation Brillouin distributed measuring method,** T. Yari, M. Ishioka, K. Nagai, Mitsubishi Heavy Industries, Ltd. (Japan) . . . . . [5758-17]

9:20 am: **Thermo-acoustic emission method of failure prediction of composites,** E. G. Nesvijski, Univ. of Minnesota . . . . [5758-18]

9:40 am: **Mobile instrument for intelligent leak detection and location on underground water supply pipelines,** Y. Wen, P. Li, W. Lu, J. Yang, Chongqing Univ. (China) . . . [5758-19]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 5
Golden West
Tues. 10:30 to 11:10 am

Structural Health Monitoring and Deformation Measurements III

Chairs: **Kara J. Peters**, North Carolina State Univ.; **Nobuo Takeda**, Univ. of Tokyo (Japan)

10:30 am: **Damage evaluation and analysis of composite pressure vessels using fiber Bragg gratings to determine structural health,** M. Kunzler, E. Udd, Blue Road Research[5758-20]

10:50 am: **Optical technique for examining materials' elastic properties,** B. Sorazu, B. Culshaw, Univ. of Strathclyde (United Kingdom); S. G. Pierce, Univ. of Sheffield (United Kingdom); P. Jun, Univ. of Strathclyde (United Kingdom) . . . . . [5758-21]

SESSION 6
Golden West
Tues. 11:10 to 11:50 am

Impact Monitoring, Vibration, and Structural Measurements I

Chairs: **Brian Culshaw**, Univ. of Strathclyde (United Kingdom); **Luc Thevenaz**, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

11:10 am: **An innovative method for monitoring impact events on complicated structures using system identification technique,** J. Park, Stanford Univ. . [5758-22]

11:30 am: **Distributed sensing of composite over-wrapped pressure vessel using fiber Bragg gratings at ambient and cryogenic temperatures,** J. Grant, NASA Marshall Space Flight Ctr. . . . . [5758-61]

Lunch/Exhibition . . . . . 11:50 am to 1:30 pm

SESSION 4
Town & Country
Tues. 9:00 am to 12:10 pm

Electronic EAP I

Chairs: **Keiichi Kaneto**, Kyushu Institute of Technology (Japan); **Ray H. Baughman**, Univ. of Texas/Dallas

9:00 am: **A new contractile linear actuator made of dielectric elastomers *(Invited Paper),*** F. Carpi, A. Migliore, D. De Rossi, Univ. degli Studi di Pisa (Italy) . . . . . [5759-10]

9:40 am: **Actuation performance of cellulose-based electroactive papers,** J. Kim, C. Song, Inha Univ. (South Korea); W. Craft, North Carolina A&T State Univ. . . . . [5759-11]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **Viscoelastic model of axisymmetric dielectric elastomer membranes,** E. Yang, M. I. Frecker, E. M. Mockensturm, The Pennsylvania State Univ. . . . . [5759-12]

10:50 am: **A modified electroactive polymer-ceramic hybrid actuation system (HYBAS) for aerodynamic control applications,** J. Su, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace . . . . . [5759-13]

11:10 am: **Enhanced thickness-mode electroactive polymer actuators and their applications,** H. Prahlad, R. Pelrine, R. D. Kornbluh, S. Chhokar, J. Eckerle, SRI International; M. A. Rosenthal, N. Bonwit, Artificial Muscle, Inc. . . . . [5759-14]

11:30 am: **PEDOT-electroded PVDF,** J. T. Polasik, H. V. Schmidt, Montana State Univ. . . . . [5759-70]

11:50 am: **Stacked liquid crystalline elastomer films as artificial muscles,** C. M. Spillmann, J. Naciri, B. D. Martin, Naval Research Lab.; W. A. Farahat, M. Popovic, H. M. Herr, Massachusetts Institute of Technology; B. R. Ratna, Naval Research Lab. . . . . [5759-16]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 4
Royal Palm I
Tues. 9:00 to 10:00 am

Damping Composites I

Chairs: **William W. Clark**, Univ. of Pittsburgh; **Andrew N. Vavreck**, The Pennsylvania State Univ.

9:00 am: **Characterization of carbon nanotube polycarbonate composites,** J. Suhr, N. A. Koratkar, Rensselaer Polytechnic Institute . . . . . [5760-19]

9:20 am: **On the damping charateristics of polymeric composites with randomly oriented single-walled carbon nanorope fillers,** A. Liu, K. Wang, C. E. Bakis, The Pennsylvania State Univ. . . . . [5760-20]

9:40 am: **Optimization of carbon nanotube reinforced composite laminated structures for vibration damping,** S. M. Damu, A. Lumsdaine, M. Parsons, Univ. of Tennessee . . . . . [5760-21]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 5
Royal Palm I
Tues. 10:30 am to 12:10 pm

MR/ER Fluid Damping II

Chairs: **Norman M. Wereley**, Univ. of Maryland/College Park; **Neil D. Sims**, Univ. of Sheffield (United Kingdom)

10:30 am: **Physical therapy applications of MR fluids and intelligent control,** S. Dong, K. Lu, J. Q. Sun, K. Rudolph, Univ. of Delaware . . . . . [5760-22]

10:50 am: **An experimental analysis of suitability of various semiactive control methods for magnetorheological vehicle suspensions,** M. Ahmadian, C. Sandu, F. D. Goncalves, Virginia Polytechnic Institute and State Univ. . . . . [5760-23]

11:10 am: **Viscoelastic behavior of a magnetorheological fluid-elastomer composite under oscillatory compression,** X. Wang, F. Gordaninejad, Univ. of Nevada/Reno; G. Hitchcock, Advanced Materials and Devices, Inc. . . . . [5760-24]

11:30 am: **Dynamic property of magnetorheological elastomer-based sandwich beam,** G. Zhou, Q. Wang, Univ. Central Florida . . . . . [5760-25]

11:50 am: **Theoretical and experimental investigation into dynamics characteristics of a rotor supported on a disk-type magnetorheological fluid damper,** C. Zhu, Zhejiang Univ. (China) . . . . . [5760-26]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

Smart Structures and Materials

Conference 5761 | Conference 5762 | Conference 5763 | Conference 5764

Tuesday 8 March

8:00 to 8:55 am • *Town & Country Ballroom*

Award Presentations:

ASME Adaptive Structures and Materials Systems Best Paper Awards • **Smart Structures and Materials/ASME Best Student Paper Award**

SSM Plenary Presentation:

Research Opportunities in Nano and Microsystems Technology for Army Applications
Dr. Paul B. Ruffin, U. S. Army Research, Development, and Engineering Command (ARDEC)

Exhibition: 10:00 am to 4:00 pm, and 6:00 to 7:30 pm

SESSION 7
California
Tues. 9:00 am to 12:30 pm

Ferroelectric Actuator Materials and Composites

9:00 am: **Integration of active Fiber composite (AFC) sensors/actuators in GFRP laminates,** M. Melnykowycz, Swiss Federal Labs. for Material Testing (Switzerland) and Swiss Federal Institute of Technology (Switzerland); X. Kornmann, ABB Switzerland Ltd. (Switzerland); C. Huber, A. J. Brunner, M. Barbezat, Swiss Federal Labs. for Material Testing (Switzerland) . . . . . [5761-30]

9:20 am: **Degradation prediction of piezocomposite actuator,** S. Herry, K. J. Yoon, N. S. Goo, H. C. Park, Konkuk Univ. (South Korea) . . . . . [5761-31]

9:40 am: **Boundary condition effects on piezoelectric diaphragm actuators for synthetic jet applications,** P. Mane, K. Moss, Virginia Commonwealth Univ.; R. Bryant, NASA Langley Research Ctr. . . . . [5761-32]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **Characterization and modeling of phase transitions in relaxor single crystals,** T. Liu, C. S. Lynch, Georgia Tech.; E. A. McLaughlin, Naval Research Lab. . [5761-33]

10:50 am: **Advanced piezoelectric single-crystal-based actuators,** X. Jiang, P. W. Rehrig, W. S. Hackenberger, TRS Technologies, Inc.; E. C. Smith, The Pennsylvania State Univ.; S. Dong, D. D. Viehland, Virginia Polytechnic Institute and State Univ.; J. D. Moore, Jr., B. G. Patrick, SRS Technologies . . . . . [5761-34]

11:10 am: **Advanced piezoelectric single-crystal-based transducers for naval sonar applications,** P. W. Rehrig, W. S. Hackenberger, X. S. Jiang, TRS Technologies, Inc.; R. J. Meyer, Jr., The Pennsylvania State Univ. . . . . [5761-35]

11:30 am: **Electric-field-induced phase transitions of ‹001›-oriented $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ single crystals,** W. Ren, R. Wicks, G. Yang, B. K. Mukherjee, Royal Military College of Canada (Canada) . . . . . [5761-36]

11:50 am: **High-temperature piezoelectric materials for actuators and sensors,** S. Zhang, R. E. Eitel, C. A. Randall, T. R. Shrout, The Pennsylvania State Univ.; E. Alberta, P. W. Rehrig, W. Hackenberger, TRS Technologies . . . . . [5761-37]

12:10 pm: **A model for frequency dependent characteristics of piezoceramic materials,** W. Seemann, Univ. Karlsruhe (Germany) . . . . . [5761-38]

Lunch/Exhibition Break . . . 12:30 to 1:30 pm

SESSION 6
San Diego
Tues. 9:00 to 10:00 am

Aircraft Applications II

9:00 am: **Adaptive wing structures,** C. D. Hemmelgarn, Cornerstone Research Group, Inc. . . . . [5762-18]

9:20 am: **Mechanical properties of shape-memory polymers for morphing aircraft applications,** B. P. Sanders, Air Force Research Lab. . . . . [5762-19]

9:40 am: **Topology design and optimization of an active airfoil in a flow field,** D. K. Lindner, M. Abdulla, Z. Gurdal, Virginia Polytechnic Institute and State Univ.; M. I. Frecker, The Pennsylvania State Univ. . . . . [5762-20]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 7
San Diego
Tues. 10:30 am to 12:10 pm

Actuators I

10:30 am: **The Ultrasonic/Sonic Driller/Corer (USDC) as a subsurface drill, sampler, and lab-on-a-drill for planetary exploration applications,** Y. Bar-Cohen, Z. S. Chang, S. Sherrit, M. Badescu, X. Bao, Jet Propulsion Lab. . . . . [5762-21]

10:50 am: **Adapting the Ultrasonic/Sonic Driller/Corer (USDC)for walking/climbing robotic applications,** M. Badescu, Jet Propulsion Lab. and California Institute of Technology; Y. Bar-Cohen, X. Q. Bao, Z. Chang, B. E. Dabiri, B. A. Kennedy, S. Sherrit, California Institute of Technology . [5762-22]

11:10 am: **Design of torque actuators based on ferromagnetic shape-memory alloy composites,** T. B. Burklin, V. J. Cheng, M. Taya, Univ. of Washington . . . . . [5762-23]

11:30 am: **Design of membrane actuators based on ferromagnetic shape-memory alloy composite for synthetic jet applications,** Y. Liang, Y. Kuga, M. Taya, Univ. of Washington . . . . . [5762-24]

11:50 am: **Miniature thin film NiTi hydraulic actuator with MEMS microvalves,** G. P. McKnight, L. A. Momoda, HRL Labs., LLC; D. Croft, Raytheon Systems Co.; D. Lee, D. D. Shin, G. P. Carman, Univ. of California/Los Angeles . . . . . [5762-25]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 4
Royal Palm II
Tues. 9:00 to 10:00 am

Nanotechnology

Chairs: **Laszlo B. Kish**, Texas A&M Univ.; **Yong Rae Roh**, Kyungpook National Univ. (South Korea)

9:00 am: **Knowledge engineering for the 21st Century war fighters through exploitation of nanotechnology *(Presentation Only),*** D. C. Oberlander, U.S. Army Black Hawk Helicopters; L. Hall, Intergraph Solutions Group; E. Fuller, U.S. Army Ulitity Helicopter Project . . . . . [5763-17]

9:20 am: **Development of a nanowire array for wireless neural probe,** J. K. Abraham, J. Xie, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-18]

9:40 am: **Nanotechnology in medicine,** V. K. Varadan, K. A. Jose, The Pennsylvania State Univ. . . . . [5763-19]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 5
Royal Palm II
Tues. 10:30 am to 12:30 pm

Nanotubes and Applications

Chairs: **Nikhil A. Koratkar**, Rensselaer Polytechnic Institute; **Jining Xie**, The Pennsylvania State Univ.

10:30 am: **Engineering carbon nanotube for device applications,** B. Wei, Louisiana State Univ. . . . . [5763-20]

10:50 am: **Synthesis of aligned conducting polymer nanotubes,** J. Xie, V. K. Varadan, The Pennsylvania State Univ.; G. N. Mathur, R. Dube, Defense Materials & Science Research (India) . . . . . [5763-21]

11:10 am: **Finite-length nanotubes, ground-state degeneracy, single-electron spectra, and conductivity,** M. M. Mestechkin, Consultant; V. A. Zubkov, LSI Logic Corp. . . . . [5763-22]

11:30 am: **Synthesis of carbon nanotubes from C60 and their applications in medicine,** K. Mukhopadhyay, J. Yadev, G. N. Mathur, Defense Materials & Science Research (India); J. Xie, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-23]

11:50 am: **Functionalized carbon nanotubes as bio sensors,** N. Zhang, J. Xie, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-24]

12:10 pm: **High-perfromance sensor platform based on electroactive polymers,** S. Li, Z. Li, L. Orona, Z. Cheng, Auburn Univ. . . [5763-25]

Lunch/Exhibition Break . . . 12:30 to 1:30 pm

SESSION 4
Royal Palm V
Tues. 9:00 to 10:00 am

Aerodynamic Systems I

Chairs: **Ron Barrett**, Auburn Univ.; **Hoon Cheol Park**, Konkuk Univ. (South Korea)

9:00 am: **Design and evaluation of LIPCA-actuated flapping device,** M. Syaifuddin, H. C. Park, N. S. Goo, K. J. Yoon, Konkuk Univ. (South Korea) . . . . . [5764-18]

9:20 am: **Airfoil drag elimination and stall suppression via tangential piezoelectric synthetic jet actuators,** R. M. Barrett, L. M. Prothero, Auburn Univ. . . . . [5764-19]

9:40 am: **Active aerodynamic control OF MAVs,** S. Ugrina, Univ. of Maryland/College Park . . . . . [5764-20]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 5
Royal Palm V
Tues. 10:30 am to 12:10 pm

Aerodynamic Systems II

Chairs: **Martin R. Waszak**, NASA Langley Research Ctr.; **Yuji Matsuzaki**, Nagoya Univ. (Japan)

10:30 am: **Feasibility study on rotorcraft blade morphing in hovering,** C. Testa, A. Concilio, S. Leone, S. Ameduri, Italian Aerospace Research Ctr. (Italy) . . . [5764-21]

10:50 am: **Development of an active twist rotor blade with distributed actuation and orthotropic material,** P. Wierach, J. Riemenschneider, S. Keye, DLR (Germany) . . . . . [5764-22]

11:10 am: **Longitudinal dynamics of a perching aircraft concept,** A. M. Wickenheiser, E. Garcia, Cornell Univ.; M. R. Waszak, NASA Langley Research Ctr.[5764-23]

11:30 am: **Flutter boundary prediction of an adapting smart wing,** Y. Matsuzaki, Nagoya Univ. (Japan); H. Torii, Meijo Univ. (Japan) . . . . . [5764-24]

11:50 am: **Finite element study of flutter detection and control for a simply supported flat panel,** N. Sebastijanovic, T. Ma, H. T. Yang, Univ. of California/Santa Barbara . . . . . [5764-25]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

Smart Structures and Materials

Conference 5757

Conference 5758

Conference 5759

Conference 5760

Tuesday 8 March

SESSION 6
Royal Palm III
Tues. 1:30 to 3:10 pm

Control Design II

Chair: **Katharine J. Jones**, Rice Univ.

1:30 pm: **Sensorless position estimation of a linear voice-coil transducer using sliding mode observers,** B. C. Glenn, C. Bouton, Battelle Memorial Institute .... [5757-25]

1:50 pm: **Tensor diagonalization and distributed control,** R. V. Iyer, Texas Tech Univ. ..... [5757-26]

2:10 pm: **Transducer placement for robustness to variations in boundary conditions for active structural acoustic control,** J. D. Sprofera, R. L. Clark, Duke Univ.; R. H. Cabell, G. P. Gibbs, NASA Langley Research Ctr. ..... [5757-27]

2:30 pm: **Robust control design for nonlinear smart systems,** R. C. Smith, W. Oates, North Carolina State Univ. [5757-28]

2:50 pm: **Experimental verification of an analytical bound H-inf collocated control approach,** R. J. Sweeney, M. A. Demetriou, Worcester Polytechnic Institute; K. M. Grigoriadis, Univ. of Houston ... [5757-29]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 7
Royal Palm III
Tues. 3:40 to 5:40 pm

Shape Memory Alloys

Chair: **Ram V. Iyer**, Texas Tech Univ.

3:40 pm: **A model for ferromagnetic shape memory thin-film actuators,** K. Lee, S. Seelecke, North Carolina State Univ. ..... [5757-30]

4:00 pm: **Segmented binary control of multi-axis SMA array actuators,** K. Cho, H. Asada, Massachusetts Institute of Technology ..... [5757-31]

4:20 pm: **Testing of the thermomechanical response of shape memory alloy hybrid composite beams,** B. A. Davis, North Carolina State Univ.; T. L. Turner, NASA Langley Research Ctr.; S. Seelecke, North Carolina State Univ. ..... [5757-74]

4:40 pm: **Shock absorption capability of woven-SMA skin,** A. Masuda, A. Sone, T. Yamamura, Q. Ni, R. Zhang, Kyoto Institute of Technology (Japan) ..... [5757-33]

5:00 pm: **Modeling of ferroelastic behavior of shape memory alloys,** T. Ikeda, Nagoya Univ. (Japan) ..... [5757-34]

5:20 pm: **The nonlinear fully coupled thermodynamic model of martensitic micro-shells and their application to the design of a targeted drug delivery system,** P. Kloucek, Rice Univ.; D. Reynolds, Lawrence Livermore National lab. ..... [5757-35]

SESSION 7
Golden West
Tues. 1:30 to 2:30 pm

Impact Monitoring, Vibration, and Structural Measurements II

Chairs: **Luc Thevenaz**, Ecole Polytechnique Fédérale de Lausanne (Switzerland); **Brian Culshaw**, Univ. of Strathclyde (United Kingdom)

1:30 pm: **Camera-based digital real-time static and dynamic testing of deployable/inflatable structures,** P. F. Pai, J. Hu, Univ. of Missouri/Columbia ..... [5758-24]

1:50 pm: **Design of a distributive load sensor using PZT,** G. Georgiades, O. Oyadiji, Z. Liu, Univ. of Manchester (United Kingdom) ..... [5758-25]

2:10 pm: **Digital phase modulation and demodulation techniques based on low-coherence fiber-optic interferometry and phase-measurement interferometry,** M. Yu, Univ. of Maryland/College Park ..... [5758-26]

SESSION 8
Golden West
Tues. 2:30 to 3:10 pm

Pressure Sensors

Chairs: **Brian Culshaw**, Univ. of Strathclyde (United Kingdom); **Luc Thevenaz**, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

2:30 pm: **Fiber pressure sensors based on periodical mode coupling effects,** D. T. Schaafsma, H. Lotem, W. C. Wang, M. Wang, IPITEK, Inc.; R. B. Skolnick, General Atomics ..... [5758-27]

2:50 pm: **Geotechnical pressure cell using a long-term reliable high-precision fiber optic sensor head,** R. Gloetzl, Gloetzl GmbH (Germany); W. R. Habel, D. Hofmann, F. Basedau, Bundesanstalt für Materialforschung und -prüfung (Germany) [5758-28]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 9
Golden West
Tues. 3:40 to 5:40 pm

Biological and Chemical Sensors

Chairs: **Xiaoyi Bao**, Univ. of Ottawa (Canada); **Marc Niklès**, Omnisens SA (Switzerland)

3:40 pm: **Demonstration of an intelligent hydrogel-based diffraction grating,** R. Zhang, A. Bowyer, R. Eisenthal, J. Hubble, Univ. of Bath (United Kingdom) ..... [5758-30]

4:00 pm: **ORB: an airborne microsensor observing platform,** M. L. Adams, J. T. Manobianco, ENSCO, Inc. ..... [5758-31]

4:20 pm: **Gas sensor with starburst dendrimers: molecular recognition and molecular structure,** L. L. Lee, Univ. of Oklahoma; D. S. Wilson, Florida State Univ. ..... [5758-32]

4:40 pm: **Fiber optic pH sensor for early detection of danger of corrosion in steel-reinforced concrete structures,** N. Dantan, W. R. Habel, Bundesanstalt für Materialforschung und -prüfung (Germany); O. S. Wolfbeis, Univ. Regensburg (Germany) [5758-33]

5:00 pm: **Cable-free wearable systems using conductive fabrics transmitting signals and power,** E. R. Wade, H. Asada, Massachusetts Institute of Technology ..... [5758-34]

5:20 pm: **Self-sensing structures for control of micro and nano-cantilevers,** Y. M. Shkel, B. R. Barmish, Univ. of Wisconsin/Madison . [5758-35]

SESSION 5
Town & Country
Tues. 1:30 to 3:10 pm

Electronic EAP II

Chairs: **Roy D. Kornbluh**, SRI International; **Geoffrey M. Spinks**, Univ. of Wollongong (Australia)

1:30 pm: **Novel multilayer electrostatic solid state actuators with elastic dielectric *(Invited Paper),*** H. F. Schlaak, M. Jungmann, M. Matysek, P. Lotz, Technische Univ. Darmstadt (Germany) ..... [5759-17]

2:10 pm: **The strain response of silicone dielectric elastomer actuators,** G. Yang, W. Ren, B. K. Mukherjee, G. Yao, G. Akhras, Royal Military College of Canada (Canada); J. Szabo, Defence Research and Development Canada (Canada) ..... [5759-18]

2:30 pm: **A new type of carbon-nanotube yarn for artificial muscle and other multifunctional material applications *(Invited Paper),*** R. H. Baughman, M. Zhang, M. Kozlov, Univ. of Texas/Dallas; K. R. Atkinson, CSIRO Textile & Fibre Technology (Australia) ..... [5759-19]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 6
Town & Country
Tues. 3:40 to 6:00 pm

Ionic EAP II

Chairs: **Donald J. Leo**, Virginia Polytechnic Institute and State Univ.; **Qibing Pei**, Univ. of California/Los Angeles

3:40 pm: **Electroactive polymer hydrogels for bio-inspired actuators *(Invited Paper),*** S. J. Kim, S. I. Kim, I. Y. Kim, Hanyang Univ. (South Korea) ..... [5759-21]

4:20 pm: **Ionic electroactive hybrid transducers,** B. J. Akle, M. D. Bennett, D. J. Leo, Virginia Polytechnic Institute and State Univ. ..... [5759-22]

4:40 pm: **Experimental study of Nafion-based ionic polymer-metal composites (IPMCs) with glycerol as solvent,** S. Zamani, S. Nemat-Nasser, Univ. of California/San Diego ..... [5759-23]

5:00 pm: **Computational model of ion transport and electromechanical transduction in ionomeric polymer materials *(Invited Paper),*** D. J. Leo, Virginia Polytechnic Institute and State Univ.; T. Wallmersperger, Univ. Stuttgart (Germany); K. Farinholt, Virginia Polytechnic Institute and State Univ. ..... [5759-24]

5:40 pm: **Circular prestrained dielectric elastomer actuator: modeling, simulation, and experimental verification,** M. T. Wissler, EMPA Duebendorf (Switzerland); E. Mazza, ETH Zurich (Switzerland); G. Kovacs, EMPA Duebendorf (Switzerland) ..... [5759-25]

SESSION 6
Royal Palm I
Tues. 1:30 to 3:10 pm

MR/ER Fluid Damping III

Chairs: **Faramarz Gordaninejad**, Univ. of Nevada/Reno; **Eric M. Austin**, Clemson Univ.

1:30 pm: **An automotive suspension strut using compressible magnetorheological fluids,** G. Wang, W. Hu, Univ. of Maryland/College Park; J. B. Niemczuk, Systems Planning and Analysis, Inc.; N. M. Wereley, Univ. of Maryland/College Park ..... [5760-27]

1:50 pm: **Designing an adaptive semi-active magnetorheological seat suspension for heavy truck applications,** M. Ahmadian, Virginia Polytechnic Institute and State Univ.; X. Song, Eaton Corp.; C. Sandu, Virginia Polytechnic Institute and State Univ. ..... [5760-28]

2:10 pm: **Characterization of a commercial magnetorheological brake/damper in oscillatory motion,** A. N. Vavreck, C. Ho, The Pennsylvania State Univ. ..... [5760-29]

2:30 pm: **On the development of fuzzy skyhook control for semi-active magnetorheological systems,** M. Ahmadian, Virginia Polytechnic Institute and State Univ. ..... [5760-30]

2:50 pm: **Torsional vibration control with an MR fluid brake,** S. Ye, K. A. Williams, Univ. of Alabama ..... [5760-31]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 7
Royal Palm I
Tues. 3:40 to 6:00 pm

Active and Semi-active Vibration Control I

Chairs: **Amr M. Baz**, Univ. of Maryland/College Park; **Jiong Tang**, Univ. of Connecticut

3:40 pm: **New semi-active damping concept using eddy currents,** H. A. Sodano, Virginia Polytechnic Institute and State Univ.; J. Bae, Korea Institute of Energy Research (South Korea); D. J. Inman, Virginia Polytechnic Institute and State Univ. ..... [5760-32]

4:00 pm: **Viscoelastic behavior and the design of a delayed-resonator vibration absorber,** J. Q. Cowans, E. M. Austin, Clemson Univ. [5760-33]

4:20 pm: **Active vibration damping using an electrodynamic actuator with internal velocity sensor,** C. K. Paulitsch, P. Gardonio, S. J. Elliott, Univ. of Southampton (United Kingdom)[5760-34]

4:40 pm: **Vibration reduction and power flow using passive and active resonant devices,** R. M. Glaese, E. H. Anderson, CSA Engineering, Inc. [5760-35]

5:00 pm: **Vibration damping of piezoactuated structures with electric circuits containing a negative capacitance: new developments,** G. Caruso, Consiglio Nazionale delle Ricerche (Italy); P. Bisegna, Univ. degli Studi di Roma Tor Vergata (Italy) ..... [5760-36]

5:20 pm: **Vibration suppression of scale model of railway car body with piezoelectric elements: a new implementation method of shunt circuit considering large vibration amplitude and generated voltage,** T. Takigami, T. Tomioka, Railway Technical Research Institute (Japan) . [5760-37]

5:40 pm: **Vibration control of a beam using linear magnetostrictive actuators,** S. Moon, C. Lim, B. Kim, Korea Institute of Machinery & Materials (South Korea); Y. Park, Korea Advanced Institute of Science and Technology (South Korea) [5760-38]

Smart Structures and Materials

Conference 5761

Conference 5762

Conference 5763

Conference 5764

Tuesday 8 March

SESSION 8
California
Tues. 1:30 to 5:20 pm

Behavior, Design, and Reliability Modeling Tools

1:30 pm: **Anisotropic fracture in ferroelectric relaxor PZN-4.5%PT single crystals,** W. S. Oates, C. S. Lynch, Georgia Institute of Technology; A. B. Kounga Njiwa, D. Lupascu, Technische Univ. Darmstadt (Germany) . . . . . [5761-39]

1:50 pm: **Toughening behavior of ferroelectric ceramics under different poling conditions,** J. Wang, C. M. Landis, Rice Univ. . . . . [5761-40]

2:10 pm: **Finite element analysis of a multilayer piezoelectric actuator taking into account the ferroelectric and ferroelastic behaviors,** M. Elhadrouz, E. Patoor, Ecole Nationale Superieure d'Arts et Métiers (France) . . . . . [5761-41]

2:30 pm: **An experimental study of domain switching criterion for soft PZT piezoceramics subjected to coaxial proportional electromechanical loading,** D. Zhou, M. Kamlah, Z. Wang, Forschungszentrum Karlsruhe (Germany) . . . . . [5761-42]

2:50 pm: **Monte Carlo simulation of ferroelectric relaxor crystals at morphotropic phase boundary,** J. Li, Univ. of Nebraska/Lincoln; K. Bhattacharya, California Institute of Technology . . . . . [5761-43]

Coffee Break . . . . . 3:10 to 3:40 pm

3:40 pm: **From crystals to devices *(Invited Paper),*** C. S. Lynch, T. Liu, Georgia Institute of Technology . . . . . [5761-44]

4:10 pm: **Morphing needs and requirements *(Invited Paper),*** J. N. Kudva, NextGen Aeronautics, Inc. . . . . [5761-45]

4:40 pm: **Smart material/actuator needs in extreme space environments,** S. Sherrit, Jet Propulsion Lab. . . . . [5761-48]

5:00 pm: **New innovative multi-layer type of bender,** S. Ouchouche, Noliac A/S. [5761-82]

SESSION 8
San Diego
Tues. 1:30 to 3:10 pm

Health Monitoring

1:30 pm: **Practical issues in real-world implementation of SHM Systems,** S. Beard, A. Kumar, P. X. Qing, I. H. L. Chan, D. C. Zhang, Acellent Technologies, Inc.; T. K. Ooi, Univ. of Alabama in Huntsville . . . . . [5762-26]

1:50 pm: **Concept verificaiton testing of an in-flight deformation monitoring system for uninhabited autonomous vehicles overview,** C. M. Bielmeier, W. L. Ko, W. L. Richards, A. Parker, A. Piazza, NASA Dryden Flight Research Ctr. . . . . [5762-27]

2:10 pm: **Structural health monitoring of advanced grid structure using multi-point FBG sensors,** H. Takeya, T. Ozaki, Mitsubishi Electric Corp. (Japan); N. Takeda, Univ. of Tokyo (Japan) . . . . . [5762-28]

2:30 pm: **Piezoelectric structural acoustic leak detection for pressurized pipelines,** J. Pretorius, M. C. van Schoor, M. Hugo, Midé Technology Corp. . . . . [5762-29]

2:50 pm: **Reliability of resonant packaged piezoelectric power generators for machinery health monitoring,** A. J. du Plessis, Midé Technology Corp.; F. M. Discenzo, Rockwell Automation; M. J. Huigsloot, R. L. Spangler, Midé Technology Corp. . . . . [5762-30]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 9
San Diego
Tues. 3:40 to 5:20 pm

Active Damping and Control

3:40 pm: **Optical table with embedded active vibration dampers (smart table),** V. M. Ryaboy, P. S. Kasturi, A. S. Nastase, T. K. Rigney, Newport Corp. . . . . [5762-31]

4:00 pm: **Miniature vibration isolation system for space application: ground test results,** M. Gonzalez, Honeywell Inc.[5762-32]

4:20 pm: **High-precision active distortion control of thin membrane windows,** D. R. Huston, J. O. Plumpton, B. Esser, Univ. of Vermont . . . . . [5762-33]

4:40 pm: **Multi-mode vibration reduction concept for machine tools and automotive applications,** H. Kunze, R. Neugebauer, W. Drossel, B. Kranz, Fraunhofer-Institut für Werkzeugmaschinen und Umfo (Germany) . . . . . [5762-34]

5:00 pm: **Hexapod geometry optimization for passive payload isolation,** S. Hadden, M. Gonzalez, Honeywell Inc. . . . . [5762-35]

5:20 pm: **Simultaneous separation, seaming, and sealing using brazing (S3B) for sample containerization and planetary protection,** Y. Bar-Cohen, J. Wu, S. Bley, A. K. Olorunsola, T. P. Rivellini, J. E. Wincentsen, R. Gershman, Jet Propulsion Lab. . . . . [5762-43]

SESSION 6
Royal Palm II
Tues. 1:30 to 2:50 pm

Nanomaterials and Nanowires

Chairs: **Cheng Luo**, Louisiana Tech Univ.; **Hargsoon Yoon**, The Pennsylvania State Univ.

1:30 pm: **A novel approach to fabricate metallic nano-cantilevers,** C. Luo, A. Chakraborty, Louisiana Tech Univ. . [5763-26]

1:50 pm: **New carbon nanofiber smart materials,** Y. Yun, M. Atul, I. Kang, P. He, S. B. Jain, S. Narasimhadevara, D. L. Hurd, S. Subramaniam, D. Shi, J. Boerio, V. Shanov, M. J. Schulz, Univ. of Cincinnati . . . . . [5763-27]

2:10 pm: **Nanostructured electrodes for efficient gas ionization,** N. A. Koratkar, Rensselaer Polytechnic Institute . . [5763-28]

2:30 pm: **Photoconductivity of structures nanodimensional Ge/c-Si.,** R. S. Udovitskaya, S. V. Kondratenko, O. V. Vakulenko, National Taras Shevchenko Univ. of Kyiv (Ukraine) . . . . . [5763-30]

Coffee Break . . . . . 2:50 to 3:40 pm

SESSION 7
Royal Palm II
Tues. 3:40 to 5:40 pm

Microsensors, Actuators, and MEMS I

Chairs: **Pratul K. Ajmera**, Louisiana State Univ.; **K. A. Jose**, The Pennsylvania State Univ.

3:40 pm: **Feasibility of a self-powered piezoelectric microaccelerometer,** W. Zhou, W. Liao, W. J. Li, Chinese Univ. of Hong Kong (Hong Kong China) . . . . . [5763-31]

4:00 pm: **A new type of microcantilever-based mass sensors,** C. Luo, X. Liu, A. Francis, Louisiana Tech Univ. . . . . [5763-32]

4:20 pm: **Analysis and design of a novel double piezoelectric beam-driven torsional micro actuator,** J. H. Huang, J. Chen, Feng Chia Univ. (Taiwan) . . . . . [5763-34]

4:40 pm: **Ultrasoft FeAlSiBCuNb nanocomposites for GMI sensor applications,** M. Phan, H. Peng, M. R. Wisnom, Bristol Univ. (United Kingdom); S. Yu, Chungbuk National Univ. (South Korea) . . . . . [5763-35]

5:00 pm: **Power management for energy harvesting wireless sensors,** S. W. Arms, C. P. Townsend, D. L. Churchill, J. H. Galbreath, MicroStrain, Inc. . . . . [5763-36]

5:20 pm: **Thin film piezoelectric MEMS accelerometer and pressure sensor,** B. Sun, Cape Peninsula Univ. of Technology (South Africa) and Jinan Univ. (China) . . . . [5763-33]

SESSION 6
Royal Palm V
Tues. 1:30 to 3:10 pm

Morphing Structural Systems

Chairs: **Sergio L. dos Santos e Lucato**, Univ. of California/Santa Barbara; **Hilary Bart-Smith**, Univ. of Virginia

1:30 pm: **Design and demonstration of a small expandable morphing wing,** Y. Heryawan, H. C. Park, N. S. Goo, K. J. Yoon, Konkuk Univ. (South Korea) . . . . . [5764-26]

1:50 pm: **Design of a shape-memory alloy actuated macro-scale morphing aircraft mechanism,** J. Manzo, E. Garcia, Cornell Univ. . . . . [5764-27]

2:10 pm: **A new concept for active bistable twisting structures,** M. R. Schultz, NASA Langley Research Ctr. and National Research Council . . . . . [5764-28]

2:30 pm: **The analysis of tensegrity structures for the design of a morphing wing,** K. W. Moored III, H. Bart-Smith, Univ. of Virginia . . . . . [5764-29]

2:50 pm: **Load capacity and deformation optimization of a Kagome-based high-authority shape morphing structure,** S. L. dos Santos e Lucato, R. M. McMeeking, A. G. Evans, Univ. of California/Santa Barbara . . . . . [5764-30]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 7
Royal Palm V
Tues. 3:40 to 5:20 pm

Mechanical Systems

Chairs: **Andrew R. Johnson**, Univ. of Sheffield (United Kingdom); **Marcelo J. Dapino**, The Ohio State Univ.

3:40 pm: **Compact actuation through magnetorheological flow control and rectification of magnetostrictive vibrations,** D. Nosse, M. J. Dapino, The Ohio State Univ. . . . . [5764-31]

4:00 pm: **Investigation of active materials as driving elements of a hydraulic,** J. A. Ellison, J. Sirohi, I. Chopra, Univ. of Maryland/College Park . . . . . [5764-33]

4:20 pm: **Analysis and testing of a THUNDER piezoelectric actuator as an actuator in an air flow control valve,** J. C. Rodgers, W. W. Clark, J. S. Vipperman, Univ. of Pittsburgh [5764-34]

4:40 pm: **Validation of computational models and experimental facility of a robot actuator using twin-ER clutches,** A. R. Johnson, R. Stanway, Univ. of Sheffield (United Kingdom) . . . . . [5764-36]

5:00 pm: **Integrated modeling of the Ultrasonic/Sonic Drill/Corer (USDC): procedure and analysis results,** M. Badescu, Jet Propulsion Lab. and California Institute of Technology; X. Bao, Y. Bar-Cohen, Z. Chang, S. Sherrit, California Institute of Technology . . . . . [5764-37]

Smart Structures and Materials

Conference 5757

Conference 5758

Conference 5759

Conference 5760

Tuesday 8 March

✔ Posters-Tuesday

The following posters will be displayed in the formal Poster Session and Exhibition Reception on Tuesday evening from 6:00 to 7:30 pm. Authors will be present during this time for discussion. Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed after 4 pm before the formal poster session begins at 6:00 pm.

✔ **On the applications of orthogonal functions in pattern recognition,** M. Razzaghi, Mississippi State Univ. . . . . [5757-57]

✔ **Sensor calibration using density estimation-based error model,** M. Potkonjak, J. Feng, Univ. of California/Los Angeles . . . . . [5757-58]

✔ **Sensor calibration based on external stimulus actuation,** M. Potkonjak, J. Feng, Univ. of California/Los Angeles . . . . . [5757-59]

✔ **Finite element analysis of a ring-type ultrasonic motor,** W. Duan, S. T. Quek, National Univ. of Singapore (Singapore) . . . . . [5757-61]

✔ **Designing a smart damping system to mitigate structure vibration part 1: experimental approval of unified Lyapunov control algorithm,** G. Heo, Konyang Univ. (South Korea); G. Lee, W. Lee, Chungnam National Univ. (South Korea); D. Lee, Konyang Univ. (South Korea) . . . . . [5757-62]

✔ **Virtual and flexible digital signal processing system based on software PnP and component works,** T. He, Hubei Polytechnic Univ. (China) . . . . [5757-69]

✔ **Verified models of multi-agent systems for vehicle health management,** A. C. Esterline, Jr., B. P. Gandluri, M. J. Sundaresan, North Carolina A&T State Univ. . . . . [5757-71]

✔ **Implementaion of wavelet transform-based image compression using altera Max Plus II and EPF10K70,** N. Garg, S. K. Soni, A. Aggarwal, Sant Longowal Institute of Engineering and Technology (India) . . . . . [5757-64]

✔ **An application of data fusion technology in structural health monitoring and damage identification,** X. Chun, Wuhan Univ. of Technology (China) . . . [5758-55]

✔ **A resonant coding passive wireless SAW sensor array system,** P. Li, Y. Wen, Chongqing Univ. (China) . . . . . [5758-56]

✔ **Simulation of micro-cooling system with measuring and controlling function,** X. Liu, R. Chuai, G. Zhang, X. Wang, H. Ni, Harbin Institute of Technology (China) . . . . . [5758-57]

✔ **Pavement deflection vehicle weighing method with embedded piezoelectric sensor,** L. Guo, C. R. Liu, Univ. of Houston . . . [5758-59]

✔ **Real-time highway vehicle pullover monitoring using fiber microbending-loss reflectometry,** K. Wang, B. Chen, H. Cui, Stevens Institute of Technology . . [5758-46]

✔ **Electrical response characterization of interpenetrating polymer network hydrogels as an actuator,** H. I. Kim, B. K. Gu, M. K. Shin, S. Park, S. Yoon, I. Kim, S. I. Kim, S. Kim, Hanyang Univ. (South Korea) . . . . . [5759-39]

✔ **Characterization of Nafion and Flemion with several new ionic liquids,** J. Andexler, M. O. LeGuilly, C. Xu, L. Liu, M. Taya, Univ. of Washington . . . . . [5759-55]

✔ **Electromechanical behavior of IPMC based on chitosan/polyaniline,** M. Kim, C. Lee, S. Shin, S. Lee, S. I. Kim, Hanyang Univ. (South Korea); G. M. Spinks, Univ. of Wollongong (Australia); S. Kim, Hanyang Univ. (South Korea) . . . . . [5759-59]

✔ **Electrochemistry of ionic polymer-metal composite,** D. Kim, K. J. Kim, Univ. of Nevada/Reno . . . . . [5759-69]

✔ **Modeling PVDF actuators with conducting polymer electrodes,** L. M. Lediaev, H. Schmidt, Montana State Univ. . . . . [5759-71]

✔ **Mechanical and electrical properties of electroactive papers and its potential application,** J. Kim, W. Jung, Inha Univ. (South Korea); W. Craft, J. Shelton, North Carolina A&T State Univ.; K. D. Song, Norfolk State Univ.; S. H. Choi, NASA Langley Research Ctr. . . . . [5759-72]

✔ **Limited-angle motor using ionic polymer metal composite,** K. Takagi, Z. Luo, The Institute of Physical and Chemical Research (RIKEN) (Japan); K. Asaka, National Institute of Advanced Industrial Science and Technology (Japan); K. Tahara, The Institute of Physical and Chemical Research (RIKEN) (Japan) . . . . . [5759-73]

✔ **The effect of ionic-membrane properties on the performance of ionic polymer-metal composite (IPMC) actuator,** J. Y. Jho, Seoul National Univ. (South Korea) . . . . . [5759-74]

✔ **Morphological characterization of ionic liquid/Nafion polymer composites,** M. D. Bennett, D. J. Leo, Virginia Polytechnic Institute and State Univ. . . . . [5759-76]

✔ **Electro-deposited vanadium oxide as a counter-electrode for PProDOT-Me2 based electrochromic devices (ECDs),** C. Kaneko, C. Xu, L. Liu, D. Ning, M. Taya, Univ. of Washington . . . . . [5759-77]

✔ **Photo-active self-assembled PD interlayer polymer films,** J. Su, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace; G. A. Miner, D. M. Stoakley, NASA Langley Research Ctr.; M. M. Caruso, Elon Univ. . . . . [5759-78]

✔ **Ferroelectric characterization of polymer blends with sensing and actuating dual functionality,** J. W. Paquette, Univ. of Nevada/Reno; J. Su, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace; K. J. Kim, Univ. of Nevada/Reno . . . . . [5759-79]

✔ **Experimental characterization of non-linear viscoelastic dielectric elastomer membranes,** E. Yang, M. I. Frecker, E. M. Mockensturm, The Pennsylvania State Univ. [5759-80]

✔ **Study on bending behavior of ionic polymer metal composites with various organic solvents and cationic species,** Y. Yoo, B. Nam, Konkuk Univ. (South Korea) . . . . . [5759-81]

✔ **Novel solid polymer electrolyte systems for PEDOT conducting polymer actuators,** M. S. Cho, Sung Kyun Kwan Univ. (South Korea) . . . . . [5759-83]

✔ **pH sensors based on polyelectrolytic hydrogels,** M. Guenther, G. Gerlach, J. Sorber, G. Suchaneck, K. Arndt, A. Richter, Dresden Univ. of Technology (Germany) [5759-84]

✔ **Structural investigation of PF6-doped polypyrrole as a function of oxidation state,** M. Warren, J. D. W. Madden, The Univ. of British Columbia (Canada); R. Z. Pytel, E. L. Thomas, I. W. Hunter, Massachusetts Institute of Technology . . . . . [5759-86]

✔ **Magnetic field analysis of disk-type magnetorheologic fluid dampers,** C. Zhu, Zhejiang Univ. (China) . . . . . [5760-67]

✔ **Sliding liquid surface in earthquake isolation bearing,** F. Bartolozzi, Consultant . [5760-69]

✔ **Predictive semi-active control of shock isolation system using magnetorheological damper,** W. Yim, G. Babu, V. Subramaniam, S. N. Singh, Univ. of Nevada/Las Vegas . . . . . [5760-70]

✔ **Vibration isolation of a ship's seat,** M. Agahi, Univ. of Wollongong (Australia) and Sharif Univ. of Technology (Iran); M. Bahrami Samani, Univ. of Wollongong (Australia); M. Behzad, Sharif Univ. of Technology (Iran) . . . [5760-05]

Smart Structures and Materials

Conference 5761

Conference 5762

Conference 5763

Conference 5764

Tuesday 8 March

✔ Posters-Tuesday

The following posters will be displayed in the formal Poster Session and Exhibition Reception on Tuesday evening from 6:00 to 7:30 pm. Authors will be present during this time for discussion. Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed after 4 pm before the formal poster session begins at 6:00 pm.

✔ **A finite element approach for domain wall dynamics in ferroelectric materials,** Y. Su, C. M. Landis, Rice Univ. [5761-77]

✔ **Active fiber composites: optimization of the manufacturing process and their poling behaviour,** C. Huber, M. M. Melnykowycz, A. J. Brunner, M. Barbezat, EMPA Duebendorf (Switzerland)[5761-78]

✔ **Modeling of particulate Fe/NiTi alloy (FSMA) composites,** S. Gururaja, M. Taya, Univ. of Washington . . . . . [5761-79]

✔ **Vibration characteristics in a smart bridge model using shape-memory alloy fiber reinforced composite,** A. Shimamoto, Saitama Institute of Technology (Japan); H. Zhao, Anshan Univ. of Science and Technology (China) . . . . . [5761-81]

✔ **Stability analysis of carbon nanotubes via continuum models,** Q. Wang, Univ. of Central Florida; K. Varadan, The Pennsylvania State Univ.; G. Zhou, Univ. of Central Florida . . . . . [5763-66]

✔ **Design, fabrication, and simulation of cantilever-type electrostatic micromechanical switch,** V. Ostasevicius, R. Dauksevicius, S. Tamulevicius, A. Bubulis, A. Palevicius, Kaunas Univ. of Technology (Lithuania); V. Grigaliunas, Institute of Physical Electronics (Lithuania) . . . . . [5763-67]

✔ **Generation mechanism of micro/nano machined surfaces based on molecular dynamics,** Y. Tang, Shenyang Jianzhu Univ. (China) and Harbin Insititute of Technology (China); Y. Liang, D. Huo, J. Dou, Harbin Institute of Technology (China) . . . . . [5763-52]

✔ **Mechanical properties of metal-core piezoelectric fiber,** H. Sato, National Institute of Advanced Industrial Science (Japan); M. Nagamine, Nagamine Manufacturing Co., Ltd. (Japan)[5764-69]

✔ **A thin-film Nitinol heart valve,** L. L. Stepan, D. S. Levi, G. P. Carman, Univ. of California/Los Angeles . . . . . [5764-70]

✔ **Characterization of energy harvesting potential of Terfenol-D and Galfenol,** M. E. Staley, A. B. Flatau, Univ. of Maryland/College Park . . . . . [5764-72]

✔ **Analytical, numerical, and experimental investigation of self resonance in vibration excitation systems,** K. Ragulskis, R. Palevicius, M. Ragulskis, D. Rubliauskas, A. Palevicius, Kaunas Univ. of Technology (Lithuania) . . . . [5764-73]

✔ **Vibration isolation modeling of Stewart platform through Newton-Euler approach,** P. Xu, D. Wang, Chongqing Univ. (China) . . . . . [5764-74]

✔ **Dynamic and control characteristics of 3-axis active mount using piezoelectric actuators,** S. Choi, J. Kim, J. Shon, Inha Univ. (South Korea) . . . . . [5764-75]

✔ **Integration of novel MEMs valve for improvement of piezohydraulic actuator performance,** R. M. Tieck, D. G. Lee, G. Carman, Univ. of California/Los Angeles . . . . . [5764-76]

✔ **A new technology for fabrication, excitation, and control of high-density actuators,** A. R. Bowles, A. Rahman, J. G. Gore, P. Morris, T. Jarman, QinetiQ (United Kingdom) . . . . . [5764-77]

✔ **Direct adaptive control of a smart projectile fin by piezoelectric,** W. Yim, S. Mani, S. N. Singh, Univ. of Nevada/Las Vegas . . . . . [5764-78]

✔ **Unsteady fluid flow in smart material actuated,** S. John, C. Cadou, Univ. of Maryland/College Park . . . . . [5764-80]

Smart Structures and Materials

Conference 5757 | Conference 5758 | Conference 5759 | Conference 5760

Wednesday 9 March

8:00 to 8:55 am • *Town & Country Ballroom*

Award Presentation: **Smart Structures Product Implementation Award**

SSM Plenary Presentation:

Engineering of Sub-Wavelength Photonic Meta Materials: A Route Towards Nano-Scale Plasmonics and Super Imaging,
Xiang Zhang, NSF Nano-Scale Science and Engineering Ctr. at Univ. of California/Berkeley

Exhibition: 10:00 am to 4:00 pm

SESSION 8
Royal Palm III
Wed. 9:00 to 10:00 am

Polymers and Tissue

Chair: **Robert L. Clark**, Duke Univ.

9:00 am: **Characterization of the solvent-induced nonlinear response of ionic polymer actuators,** C. S. Kothera, D. J. Leo, Virginia Polytechnic Institute and State Univ. [5757-37]

9:20 am: **Application of Monte Carlo simulations to the prediction of the effective elastic moduli of hydrated Nafion,** L. M. Weiland, Virginia Polytechnic Institute and State Univ.; E. K. Lada, Statistical and Applied Mathematical Sciences Institute; J. Mathews, R. C. Smith, North Carolina State Univ.; D. J. Leo, Virginia Polytechnic Institute and State Univ. . . . . [5757-36]

9:40 am: **Implementation techniques for a ferromagnetic hysteresis model,** R. C. Smith, T. R. Braun, North Carolina State Univ. . . . . [5757-68]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 9
Royal Palm III
Wed. 10:30 am to 12:10 pm

Composite Structures

Chair: **Marcelo J. Dapino**, The Ohio State Univ.

10:30 am: **Hysteresis in a smart plate: identification and simulation,** B. Fan, Univ. of Houston . . . . . [5757-39]

10:50 am: **Modeling of acoustic reflection and radiation fields generated from elastic boundary using MHSV model reduction,** W. Chang, National Univ. of Singapore (Singapore) . . . . . [5757-40]

11:10 am: **Active damping of piezolaminated composite beams using combined extension and shear piezoelectric mechanisms,** H. Abramovich, L. Edery-Azulay, Technion, I.I.T. (Israel) . . . . . [5757-41]

11:30 am: **A fully thermoelectromechanicaly coupled FE analysis for the dynamic behavior of smart plates using discrete-layer kinematics,** G. Giannopoulos, J. Vantomme, Royal Military Academy (Belgium) . [5757-42]

11:50 am: **Finite-element computation of dispersion in piezoelectric waveguides,** P. W. Loveday, M. Shatalov, CSIR (South Africa) . . . . . [5757-43]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 10
Golden West
Wed. 9:00 to 9:40 am

Image and Vision Systems

Chairs: **Marc Niklès**, Omnisens SA (Switzerland); **Xiaoyi Bao**, Univ. of Ottawa (Canada)

9:00 am: **Musca domestica inspired machine vision system with hyperacuity,** D. Riley, S. F. Barrett, Univ. of Wyoming; M. Wilcox, U.S. Air Force Academy; C. H. Wright, Univ. of Wyoming . . . . . [5758-36]

9:20 am: **Methodology for image-based tracking of seismic-induced motions,** T. C. Hutchinson, K. Doerr, F. Kuester, Univ. of California/Irvine . . . . . [5758-37]

Coffee Break . . . . . 9:40 to 10:30 am

SESSION 11
Golden West
Wed. 10:30 am to 12:10 pm

New Material Sensors

Chairs: **Stephen T. Kreger**, Blue Road Research; **Riccardo Falciai**, Istituto di Fisica Applicata (Italy)

10:30 am: **Metal Rubber™ sensors,** R. O. Claus, Virginia Polytechnic Institute and State Univ.; J. H. Lalli, B. A. Davis, J. B. Mecham, R. M. Goff, A. Hill, S. Subramanayan, NanoSonic, Inc. . . . . [5758-39]

10:50 am: **Nondestrtuctive damage sensitity of functionalized carbon nanotube and nanofiber/epoxy composites using electrical resistance measurement,** J. Park, J. Jung, S. Kim, Gyeongsang National Univ. (South Korea); T. Kim, Korea Institute of Machinery and Materials (South Korea) . . . . . [5758-40]

11:10 am: **Polarization plane's weak rotation amplifiers and polarization azimuth stabilizers,** A. H. Gevorgyan, Yerevan State Univ. (Armenia); A. Kocharian, California State Univ./Northridge; Z. B. Khachatryan, S. A. Mkhitaryan, Yerevan State Univ. (Armenia); G. A. Vardanyan, Intercontinental State Univ. . . . . [5758-41]

11:30 am: **Ferroelectric-based multiple radiations source for in situ multifunctional analytical instruments,** Y. Bar-Cohen, S. Lih, X. Q. Bao, S. Sherrit, Jet Propulsion Lab. . . . . [5758-42]

11:50 am: **Electrode shape design for multi-mode sensors using genetic algorithm,** C. H. Park, K. Lee, H. C. Park, Pohang Univ. of Science and Technology (South Korea) . . . . . [5758-43]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 7
Town & Country
Wed. 9:00 am to 12:10 pm

Conductive Ploymers and Nanotubes

Chairs: **Jaehwan Kim**, Inha Univ. (South Korea); **Minoru Taya**, Univ. of Washington

9:00 am: **Multiwalled carbon nanotube/IPMC nanocomposite,** K. J. Kim, Univ. of Nevada/Reno; D. Y. Lee, Daelim College of Engineering (South Korea); S. Heo, Univ. of Nevada/Reno; M. Lee, Korea Institute of Ceramic Engineering and Technology (South Korea) . . . . . [5759-26]

9:20 am: **Multi-walled carbon-nanotubes-sheet actuators: theoretical and experimental investigations,** M. H. Haque, I. Kolaric, Fraunhofer-Technologie-Entwicklungsgruppe (Germany); U. Vohrer, Fraunhofer-Institut für Grenzflächen- und Bioverfahrenstechnik (Germany); T. Wallmersperger, M. D'Ottavio, B. Kröplin, Univ. Stuttgart (Germany)[5759-27]

9:40 am: **Carbon nanotube-polymer composites as electroactive sensors/actuators,** O. Zoubeida, P. Ricardo, Virginia Commonwealth Univ.; C. Park, J. S. Harrison, NASA Langley Research Ctr. . . . . [5759-28]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **Conducting polymer as smart interfaces for cultured neurons,** A. Ahluwalia, I. Mauricio, A. Mazzoldi, G. Serra, F. Bianchi, Univ. degli Studi di Pisa (Italy) . . . . [5759-29]

10:50 am: **Porous polypyrrole films for better performance of artificial muscles,** K. Kaneto, Kyushu Institute of Technology (Japan) . . . . . [5759-30]

11:10 am: **Conducting polymer actuator utilizing novel planar patterned flexible supporting electrode,** R. E. Askin III, K. Asai, N. Matsukawa, M. Yamamoto, K. Yokoyama, Matsushita Electric Industrial Co., Ltd. (Japan) . . . . . [5759-31]

11:30 am: **Integrating conjugated polymer microactuators with CMOS sensing circuitry for studying living cells,** Y. Liu, N. Nelson, P. Abshire, E. Smela, Univ. of Maryland/College Park . . . . . [5759-32]

11:50 am: **Bi-layer polypyrrole artificial muscle valves for drug delivery systems,** H. A. Tsai, H. Xu, J. V. Zoval, M. J. Madou, Univ. of California/Irvine . . . . . [5759-33]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 8
Royal Palm I
Wed. 9:00 to 10:00 am

Damping Composites II

Chairs: **Daniel J. Inman**, Virginia Polytechnic Institute and State Univ.; **George A. Lesieutre**, The Pennsylvania State Univ.

9:00 am: **Optimization of constrained layer damping,** A. M. Baz, Univ. of Maryland/College Park . . . . . [5760-39]

9:20 am: **Embedding viscoelastic damping materials in low-cost VRTM composite structures,** J. B. Kosmatka, M. Robinson, Univ. of California/San Diego . . . . . [5760-40]

9:40 am: **Chamber-core structures for fairing noise mitigation,** E. V. Ardelean, Science Applications International Corp.; A. Williams, B. K. Henderson, S. Lane, Air Force Research Lab.; R. E. Richard, Boeing-SVS, Inc. [5760-41]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 9
Royal Palm I
Wed. 10:30 am to 12:30 pm

Active and Semi-active Vibration Control II

Chairs: **Roger Ohayon**, Conservatoire National des Arts et Métiers (France); **Arnold Lumsdaine**, Univ. of Tennessee

10:30 am: **Modified LMS feed-forward control for active vibration with limited actuator authority,** S. A. Nayfeh, L. Zuo, Massachusetts Institute of Technology . . . . . [5760-42]

10:50 am: **Vibration disturbance rejection through left Eigen-vector assignment and piezoelectric circuits,** T. Wu, K. Wang, The Pennsylvania State Univ. . . . . [5760-43]

11:10 am: **Hybrid multivariable controller architecture,** M. A. Hopkins, Rochester Institute of Technology; D. A. Smith, P. Vallone, R. Sandor, ITT Industries, Inc. . . . . [5760-44]

11:30 am: **Tuning the switch timing of pulse-switched piezoelectric shunts for vibration control,** J. Schoenly, W. W. Clark, Univ. of Pittsburgh . . . . . [5760-45]

11:50 am: **Averaging analysis of state-switched piezoelectric structural systems,** A. J. Kurdila, Univ. of Florida; G. A. Lesieutre, The Pennsylvania State Univ.; X. Zhang, C. Prazenica, Univ. of Florida . . . . . [5760-46]

12:10 pm: **Suboptimal bang-bang control of buildings using piezoelectric friction dampers,** H. Li, J. Li, Dalian Univ. of Technology (China); G. Song, Univ. of Houston . . . . . [5760-47]

Lunch/Exhibition Break . . . 12:30 to 1:30 pm

Smart Structures and Materials

Conference 5761

Conference 5762

Conference 5763

Conference 5764

Wednesday 9 March

8:00 to 8:55 am • *Town & Country Ballroom*

Award Presentation: **Smart Structures Product Implementation Award**

SSM Plenary Presentation:

Engineering of Sub-Wavelength Photonic Meta Materials: A Route Towards Nano-Scale Plasmonics and Super Imaging,
Xiang Zhang, NSF Nano-Scale Science and Engineering Ctr. at Univ. of California/Berkeley

Exhibition: 10:00 am to 4:00 pm

SESSION 9
California
Wed. 9:00 am to 12:10 pm

Shape Memory Alloys

Keynote

9:00 am: **A three-phase model of shape-memory alloys undergoing complex thermomechanical loading paths,** D. C. Lagoudas, P. Popov, Texas A&M Univ. . . . . [5761-46]

9:40 am: **Direct experimental observation of high-rate dynamic buckling of shape-memory thin cylindrical shells,** S. Nemat-Nasser, J. Y. Choi, J. B. Isaacs, D. W. Lischer, Univ. of California/San Diego . . . . . [5761-47]

Coffee/Exhibition Break . 10:00 to 10:30 am

10:30 am: **Strain-rate effects on TiNi and TiNiCu shape-memory alloys,** H. Nakayama, M. Taya, Y. Zhao, Univ. of Washington; W. W. Chen, Univ. of Arizona; Y. Urushiyama, S. Suzuki, Honda R&D Co., Ltd. . . . . [5761-49]

10:50 am: **Properties and potential of two (Ni,Pt)Ti alloys for use as high-temperature actuator materials,** R. D. Noebe, D. Gaydosh, S. A. Padula II, T. Biles, NASA Glenn Research Ctr.; A. Garg, Univ. of Toledo . . . . . [5761-50]

11:10 am: **Characterization of ternary NiTiPt high-temperature shape-memory alloys,** O. Rios, Univ. of Florida; R. Noebe, T. Biles, NASA Glenn Research Ctr.; A. Garg, Univ. of Toledo; A. Palczer, NASA Glenn Research Ctr.; M. Kaufman, Univ. of North Texas . [5761-51]

11:30 am: **Observed dependencies of the large thermal-compressive response of a NiTi shape-memory alloy fiber aluminum metal matrix composite,** W. D. Armstrong, Univ. of Wyoming . . . . . [5761-52]

11:50 am: **Analytical model for predicting internal stress and deformation of shape-memory alloy composite,** G. Murasawa, Yamagata Univ. (Japan) . . . . . [5761-53]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

SESSION 10
San Diego
Wed. 9:00 to 9:20 am

Magnetorheological Fluid Applications

9:00 am: **Design and fabrication of a novel settled and laminated testing instrument for magnetorheological fluid,** X. Guan, J. Li, J. Ou, Harbin Institute of Technology (China) . . . . . [5762-36]

SESSION 11
San Diego
Wed. 9:20 to 11:10 am

Actuators II

9:20 am: **A two-stage actuation system using DC motors and piezoelectric/magnetostrictive actuators for controllable industrial and automotive brakes and clutches,** V. A. Neelakantan, G. N. Washington, The Ohio State Univ. . [5762-39]

9:40 am: **High-power Inchworm® actuators for extended range precision positioning,** G. D. Powers, Q. Xu, T. Guidarelli, J. A. Smith, EXFO . . . . . [5762-40]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **Development of miniaturized piezo-hydraulic pumps,** S. L. Herdic, C. S. Lynch, E. G. Chapman, Georgia Institute of Technology . . . . . [5762-41]

10:50 am: **Hierarchical actuator systems,** D. R. Huston, B. Esser, Univ. of Vermont . . . . . [5762-42]

■ Conference 5762 End.

SESSION 8
Royal Palm V
Wed. 9:00 to 10:00 am

Energy Harvesting

Chairs: **GyuHae Park**, Los Alamos National Lab.; **Yi-Chung Shu**, National Taiwan Univ. (Taiwan)

9:00 am: **A comparison between several approaches of piezoelectric energy harvesting,** E. Lefeuvre, A. Badel, C. L. Richard, D. Guyomar, INSA de Lyon (France) . . . . . [5764-38]

9:20 am: **A universal semi-passive technique for smart applications: vibration damping, acoustic-wave control, and energy harvesting,** D. Guyomar, C. L. Richard, L. Petit, E. Lefeuvre, INSA de Lyon (France) . . . . . [5764-39]

9:40 am: **Modeling of piezoelectric power generator with adaptive energy harvesting circuit,** Y. Shu, I. Lien, National Taiwan Univ. (Taiwan) . . . . . [5764-40]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 9
Royal Palm V
Wed. 10:30 am to 12:10 pm

Dynamic Systems and Control I

Chairs: **Faramarz Gordaninejad**, Univ. of Nevada/Reno; **Massimo Ruzzene**, Georgia Institute of Technology

10:30 am: **Dynamic shape control of sandwich beams with chiral prismatic core,** M. Ruzzene, A. Spadoni, Georgia Institute of Technology; F. L. Scarpa, Univ. of Sheffield (United Kingdom) . . . . . [5764-41]

10:50 am: **Diagnosis and control of 3D elastic mechanical structures,** I. Krajcin, D. Söffker, Univ. Duisburg-Essen (Germany) . . [5764-42]

11:10 am: **Mulitmodal active vibration suppression of a flexible structure by loop shaping,** V. Sethi, M. A. Franchek, G. Song, Univ. of Houston . . . . . [5764-43]

11:30 am: **Fuzzy control of a HMMWV suspension system using magnetorheological fluid damper,** Y. Liu, F. Gordaninejad, C. A. Evrensel, S. Karakas, U. Dogruer, Univ. of Nevada/Reno . . . [5764-44]

11:50 am: **Vibration suppression of HDD spindle-disk system using piezoelectric shunt damping,** S. Choi, S. Lim, Inha Univ. (South Korea); Y. Park, Yonsei Univ. (South Korea) . . . . . [5764-45]

Lunch/Exhibition Break . . . 12:10 to 1:30 pm

Smart Structures and Materials

Conference 5757

Conference 5758

Conference 5759

Conference 5760

Wednesday 9 March

SESSION 10
Royal Palm III
Wed. 1:30 to 3:10 pm

Control Design III

Chair: **Michael A. Demetriou**, Worcester Polytechnic Institute

1:30 pm: **Vibration confinement of flexible structures using piezoceramic actuators,** A. Punhani, H. Yoon, G. Washington, The Ohio State Univ. . . . . [5757-44]

1:50 pm: **Applications of neuro-PID adaptive controller based on RBF,** Z. Gu, O. Oyadiji, Univ. of Manchester (United Kingdom) . . . . . [5757-45]

2:10 pm: **MIMO adaptive control of thruster-firing-induced aibration of satellites using multifunctional platforms,** K. Ma, M. N. Ghasemi-Nejhad, Univ. of Hawaii/ Manoa . . . . . [5757-46]

2:30 pm: **Damage detection and gain-scheduled control of CFRP smart board mounting the metal core assisted piezoelectric fiber,** K. Takagi, H. Sato, M. Saigo, National Institute of Advanced Industrial Science and Technology (Japan) . . . . . [5757-47]

2:50 pm: **Tracking control of a piezo-actuated stage based on frictional model,** Y. Huang, National Changhua Univ. of Education (Taiwan) . . . . . [5757-48]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 11
Royal Palm III
Wed. 3:40 to 5:40 pm

Structural Analysis

Chair: **William Oates**, North Carolina State Univ.

3:40 pm: **The development of variably compliant haptic systems using magnetorheological fluids,** F. Ahmadkhanlou, G. N. Washington, Y. Wang, S. E. Bechtel, The Ohio State Univ. . . . . [5757-49]

4:00 pm: **Orthotropic deflection model for corner-supported plates with segmented in-plane actuators,** J. E. Massad, H. Sumali, P. M. Chaplya, G. Washington, Sandia National Labs. . . . . [5757-50]

4:20 pm: **Mechanical modeling of failure in surface coatings,** B. A. Slavin, S. P. Levitan, G. Buxton, Univ. of Pittsburgh . . . . . [5757-52]

4:40 pm: **SMARTSIM: an integrated design tool for smart structures,** M. M. Panahandeh, Berkeley Applied Science and Engineering Inc.; F. Rostamabadi, U.S. Army Tank-automotive and Armaments Command; E. S. Budiman, Berkeley Applied Science and Engineering, Inc.; E. P. Kasper, California Polytechnic State Univ./San Luis Obispo . . . . . [5757-53]

5:00 pm: **Transient analysis of delaminated smart-composite structures by incorporating Fermi-Dirac distribution function,** H. S. Kim, Inha Univ. (South Korea); A. Ghoshal, United Technologies Research Ctr.; J. Kim, S. Choi, Inha Univ. (South Korea) . . . . . [5757-54]

5:20 pm: **Analytical study on the influence of the normalized Bouc-Wen model parameters on hysteresis loops,** F. Ikhouane, J. Rodellar, A. Rodriguez, Univ. Politecnica de Catalunya (Spain) . . . . . [5757-55]

■ Conference 5757 End.

SESSION 12
Golden West
Wed. 1:30 to 2:50 pm

Sensor Systems

Chairs: **Riccardo Falciai**, Istituto di Fisica Applicata (Italy); **Stephen T. Kreger**, Blue Road Research

1:30 pm: **Efficient electromechanical network model for wireless acoustic-electric feed-throughs,** S. Sherrit, M. Badescu, X. Q. Bao, Y. Bar-Cohen, Z. Chang, Jet Propulsion Lab. . . . . [5758-44]

1:50 pm: **Identifying dynamic characteristics of structures to estimate the performance of a smart wireless MA system,** G. Heo, Konyang Univ. (South Korea); W. Lee, G. Lee, Chungnam National Univ. (South Korea); D. Lee, Konyang Univ. (South Korea) . [5758-45]

2:10 pm: **An improved fiber optic strain sensor with RF interferometric and I & Q demodulation techniques,** F. Dong, B. Culshaw, Univ. of Strathclyde (United Kingdom) . . . . . [5758-47]

2:30 pm: **Spatial resolution enhancement of a Brillouin scattering-based fiber optic distributed sensor using a pulse base,** J. J. Lee, Korea Advanced Institute of Science and Technology (South Korea) . . . . . [5758-48]

Coffee Break . . . . . 2:50 to 3:40 pm

SESSION 13
Golden West
Wed. 3:40 to 6:00 pm

Reliability and Standards for Fiber Optic Sensors

Chairs: **Wolfgang Ecke**, Institut für Physikalische Hochtechnologie e.V. (Germany); **Joseph Grant**, NASA Marshall Space Flight Ctr.

3:40 pm: **Fiber optic sensor reliability and survivability issues in structural health monitoring *(Invited Paper),*** F. Ansari, Univ. of Illinois/Chicago . . . . . [5758-49]

4:10 pm: **Long-term reliability testing of packaged strain sensors,** D. Inaudi, SMARTEC SA (Switzerland) . . . . . [5758-50]

4:30 pm: **Failure mechanisms of fiber optic sensors placed in composite materials,** E. Udd, Blue Road Research . . . . . [5758-51]

4:50 pm: **Reliability of components for fiber optic sensors *(Invited Paper),*** F. Berghmans, SCK•CEN (Belgium) . . . . . [5758-52]

5:15 pm: **Validation of space flight fiber components *(Invited Paper),*** M. N. Ott, NASA Goddard Space Flight Ctr. . . . . [5758-53]

5:40 pm: **Radiation and cladding modes as independent measurements of Bragg grating sensor integrity,** M. Prabhugoud, J. Pearson, K. J. Peters, M. Zikry, North Carolina State Univ. . . . . [5758-54]

■ Conference 5758 End.

SESSION 8
Town & Country
Wed. 1:30 to 3:10 pm

Fabrication Methods

Chairs: **James J. Pak**, Korea Univ. (South Korea); **Kwang J. Kim**, Univ. of Nevada/ Reno

1:30 pm: **Metal Rubber™ electrodes for active polymer devices,** R. O. Claus, Virginia Polytechnic Institute and State Univ. and NanoSonic, Inc; J. H. Lalli, B. A. Davis, J. B. Mecham, R. M. Goff, A. Hill, S. Subramanayan, NanoSonic, Inc. . . [5759-34]

1:50 pm: **Interfacial layer: a new mechanism for electromechanical response,** Z. Li, Z. Cheng, Auburn Univ. . . . . [5759-35]

2:10 pm: **High-contrast ratio and long-lifetime polymer electrochromic devices (ECDs),** D. Ning, C. Xu, L. Liu, C. Kaneko, M. Taya, Univ. of Washington . . . . . [5759-36]

2:30 pm: **Co-fabrication techniques in the development of an artificial pectoral fish fin from conducting polymers,** N. Davidson, L. Proctor, P. A. Anquetil, I. W. Hunter, Massachusetts Institute of Technology . . . . . [5759-37]

2:50 pm: **Fabrication of polypyrrole nanoactuators,** Y. Berdichevsky, Y. Lo, Univ. of California/San Diego . . . . . [5759-38]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 9
Town & Country
Wed. 3:40 to 5:40 pm

Characterization

Chairs: **Ji Su**, NASA Langley Research Ctr.; **Siavouche Nemat-Nasser**, Univ. of California/San Diego

3:40 pm: **The construction and characterization of a fish-like conducting polymer actuator for microAUVs,** W. M. Megill, Univ. of Bath (United Kingdom) . . . . . [5759-40]

4:00 pm: **Toward standarization of EAP actuators test procedures,** D. Fernández, EADS Astrium CRISA (Spain); L. Moreno, J. Baselga, Univ. Carlos III de Madrid (Spain) . . . . . [5759-41]

4:20 pm: **Mechanical characterization and implementation of antagonistically,** J. Koo, H. Choi, Sung Kyun Kwan Univ. (South Korea) . . . . . [5759-42]

4:40 pm: **Characterization of conducting polymer actuators in room-temperature ionic liquids,** P. A. Anquetil, N. A. Vandesteeg, I. W. Hunter, Massachusetts Institute of Technology . . . . . [5759-43]

5:00 pm: **Polypyrrole/gold bilayer characterization,** S. Fanning, Y. Liu, E. Smela, Univ. of Maryland/College Park . . . [5759-44]

5:20 pm: **Quasi-static and dynamic inflation of a dielectric elastomer membrane for an artificial heart pump,** N. C. Goulbourne, M. I. Frecker, E. M. Mockensturm, The Pennsylvania State Univ. . . . . [5759-45]

SESSION 10
Royal Palm I
Wed. 1:30 to 2:30 pm

MR/ER Fluid Damping IV

Chairs: **Mehdi Ahmadian**, Virginia Polytechnic Institute and State Univ.; **Gregory S. Agnes**, Jet Propulsion Lab.

1:30 pm: **Friction factor of magnetorheological fluid flow in channels with porous walls,** B. M. Kavlicoglu, F. Gordaninejad, X. Wang, Univ. of Nevada/ Reno; G. Hitchcock, Advanced Materials and Devices, Inc. . . . . [5760-48]

1:50 pm: **Effective design strategy of a magnetorheological damper using a nonlinear flow model,** M. Mao, Y. Choi, N. M. Wereley, Univ. of Maryland/College Park . . . . . [5760-49]

2:10 pm: **Transient response of MR fluids subjected to magnetic fields under constant shear conditions,** O. Oyadiji, W. W. Chooi, Univ. of Manchester (United Kingdom) . . . . . [5760-50]

Coffee Break . . . . . 2:30 to 3:40 pm

SESSION 11
Royal Palm I
Wed. 3:40 to 6:00 pm

Dampers and Actuators

Chairs: **Nikhil A. Koratkar**, Rensselaer Polytechnic Institute; **Wolfgang G. Luber**, DaimlerChrysler AG (Germany)

3:40 pm: **Particle impact damping,** V. K. Kinra, R. R. Bijai, B. L. Witt, Texas A&M Univ. . . . . [5760-52]

4:00 pm: **Investigation of a model vertical motion liquid,** C. Papadopoulos, H. Tabatabai, Univ. of Wisconsin/Milwaukee; C. Buechel, Univ. of Wisconsin/Milwaukee and Pierce Engineers, Inc. . . . . [5760-53]

4:20 pm: **Modeling and motion control of inchworm considering nonlinearities,** Y. Kim III, I. Kim, K. Kim, Kumoh National Univ. of Technology (South Korea) . . . . . [5760-54]

4:40 pm: **Static electromechanical response of piezoelectric tubes,** J. H. Huang, Y. Shiah, Feng Chia Univ. (Taiwan) . . . . . [5760-55]

5:00 pm: **A novel tunable mass damper based on giant magnetostrictive composites,** D. Li, S. W. Or, C. S. Yung, H. L. W. Chan, Hong Kong Polytechnic Univ. (Hong Kong China); P. K. Choy, P. C. K. Liu, ASM Assembly Automation Ltd. (Hong Kong China) [5760-56]

5:20 pm: **Application of LIPCA as smart actuator for active vibration control of dynamic structures,** A. Suhariyono, N. S. Goo, H. C. Park, K. J. Yoon, Konkuk Univ. (South Korea) . . . . . [5760-57]

5:40 pm: **Design of a novel magnetostrictive-viscous damper,** X. Guan, J. Li, J. Ou, Harbin Institute of Technology (China) . . . [5760-58]

Conference 5761

Conference 5763

Conference 5764

Wednesday 9 March

SESSION 10
California
Wed. 1:30 to 2:50 pm

SMA

1:30 pm: **Pressurized shape-memory thin foils and films,** Y. Shu, National Taiwan Univ. (Taiwan) . . . . . [5761-54]

1:50 pm: **Hybrid micro-macro-mechanical constitutive model for shape-memory alloys,** F. Wong, Defence Research Development Canada/ Valcartier (Canada); O. Boissonneault, P. Terriault, Ecole de Technologie Supérieure (Canada) . [5761-55]

2:10 pm: **Control of shape recovery force in SMA fiber reinforced composite materials,** K. Yamashita, A. Shimamoto, Saitama Institute of Technology (Japan) . . . . . [5761-57]

2:30 pm: **Structural applications of SMA/ superelastic materials,** E. I. Rivin, Wayne State Univ. . . . . [5761-58]

Coffee Break . . . . . 2:50 to 3:40 pm

SESSION 11
California
Wed. 3:40 to 6:00 pm

SMA and FMSM

3:40 pm: **Dynamic buckling and recovery of shape-memory thin-cylindrical shells,** M. R. Amini, S. Nemat-Nasser, Univ. of California/ San Diego . . . . . [5761-59]

4:00 pm: **Magnetic and conventional shape-memory characteristics of Co38Ni33Al29 and Ni2MnGa shape-memory alloys,** H. E. Karaca, B. Basaran, I. Karaman, Texas A&M Univ.; Y. I. Chumlyakov, Siberian Physical-Technical Institute (Russia); H. Maier, Univ. Paderborn (Germany) . . . . . [5761-60]

4:20 pm: **Modeling of the magnetic field-induced martensitic variant reorientation in and the associated magnetic shape-memory effect in MSMAs,** B. Kiefer, D. C. Lagoudas, Texas A&M Univ. . . . . [5761-61]

4:40 pm: **Multiscale constitutive model of magnetic shape-memory alloys,** V. M. Stoilov, Univ. of Windsor (Canada) . . . . . [5761-62]

5:00 pm: **Characterization of piezoelectrically induced actuation of Ni-Mn-Ga single crystals,** J. M. Chambers, S. R. Hall, R. C. O'Handley, D. C. Bono, Massachusetts Institute of Technology . . . . . [5761-63]

5:20 pm: **Mechanical efficiency of acoustic-assisted, magnetic-induced-strain in ferromagnetic shape-memory alloy actuators,** B. W. Peterson, R. C. O'Handley, S. M. Allen, Massachusetts Institute of Technology . . . . . [5761-64]

5:40 pm: **Inductive measurement of combined acoustic and magnetic actuation,** R. Techapiesancharoenkij, B. W. Peterson, J. M. Chambers, J. Feuchtwanger, D. C. Bono, S. M. Allen, R. C. O'Handley, Massachusetts Institute of Technology . . . . . [5761-65]

SESSION 8
Royal Palm II
Wed. 1:50 to 2:30 pm

Microsensors, Actuators, and MEMS II

Chairs: **Ananth Selvarajan**, Indian Institute of Science (India); **Vijay K. Varadan**, The Pennsylvania State Univ.

1:50 pm: **Analysis of a nonuniform cantilever beam MOEM accelerometer under closed-loop operation,** A. Selvarajan, Indian Institute of Science (India); N. Jagannath, Research Ctr. Imarat (India); S. Talabattula, Indian Institute of Science (India); D. V. K. Sastry, Research Ctr. Imarat (India) . . . . . [5763-37]

2:10 pm: **Feedback controlled nano-positioner using the fiber optic EFPI sensor with novel demodulation technique,** S. W. Park, C. G. Kim, Korea Advanced Institute of Science and Technology (South Korea) . . . . . [5763-40]

Coffee Break . . . . . 2:30 to 3:40 pm

SESSION 9
Royal Palm II
Wed. 3:40 to 5:40 pm

Biosensors and BioMEMS I

Chair: **Tian-Bing Xu**, National Institute of Aerospace

3:40 pm: **Development of an SH-SAW sensor for detection of DNA immobilization and hybridization,** Y. Roh, Y. Hur, Kyungpook National Univ. (South Korea); Y. E. Pak, Samsung Advanced Institute of Technolgy (South Korea) . . . . . [5763-42]

4:00 pm: **Piezoelectric polymer micro-sensor for biomass detection,** T. Xu, National Institute of Aerospace; N. M. Holloway, J. Su, NASA Langley Research Ctr. . . . . [5763-43]

4:20 pm: **Ultra-high-aspect-ratio electrochemical probe array for biological cellular monitoring,** Y. Tao, R. J. Fasching, F. B. Prinz, Stanford Univ. . . . . [5763-44]

4:40 pm: **An innovative all-polymeric drug-supply device,** C. Luo, R. Poddar, Louisiana Tech Univ.; J. Currie, M. Paranjape, Georgetown Univ. . . . . [5763-45]

5:00 pm: **Biosensor-based magnetostrictive microcantilever,** Z. Li, S. Li, Z. Cheng, Auburn Univ. . . . . [5763-46]

5:20 pm: **Synthesis and characterization of block copolymeric vesicles integrated with energy transducing biomolecules,** D. Ho, B. B. Chu, H. Lee, K. Kuo, C. D. Montemagno, Univ. of California/Los Angeles . . . [5763-47]

SESSION 10
Royal Palm V
Wed. 1:30 to 3:10 pm

Dynamic Systems and Control II

Chairs: **Antonio Concilio**, Italian Aerospace Research Ctr. (Italy); **Mehrdad N. Ghasemi-Nejhad**, Univ. of Hawaii/ Manoa

1:30 pm: **Piezoelectric-based vibration control optimization in nonlinear composite structures,** S. J. John, J. J. Cao, T. Molyneaux, RMIT Univ. (Australia) . . . . . [5764-46]

1:50 pm: **Active vibration suppression of a satellite frame using an adaptive composite thruster platform,** N. Antin, M. N. Ghasemi-Nejhad, Univ. of Hawaii/Manoa . . . [5764-47]

2:10 pm: **The Fraunhofer MAVO FASPAS for smart system design for automotive and machine tool engineering,** T. Melz, M. Matthias, Fraunhofer-Institut für Betriebsfestigkeit LBF (Germany) . [5764-48]

2:30 pm: **Design of smart actuator based on magnetorheological elastomer sandwich beam,** G. Zhou, Q. Wang, Univ. of Central Florida . . . . . [5764-49]

2:50 pm: **An MRF-based device able to control the torque stiffness of all movable vertical tails,** S. Ameduri, A. Concilio, A. Gianvito, Italian Aerospace Research Ctr. (Italy) . . . . . [5764-50]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 11
Royal Palm V
Wed. 3:40 to 5:40 pm

SMA/FEM

Chair: **Reginald DesRoches**, Georgia Institute of Technology

3:40 pm: **The effect of mechanical training on the properties of superelastic shape-memory alloys for seismic applications,** J. P. McCormick, L. Barbero, R. DesRoches, Georgia Institute of Technology . . . [5764-51]

4:00 pm: **Design of composite structures with high-energy absorption,** Y. Zhao, M. Taya, Univ. of Washington . . . . . [5764-52]

4:20 pm: **Effect of ambient temperature on the performance of shape-memory alloy seismic devices,** B. O. Andarwes, R. DesRoches, Georgia Institute of Technology . . . . . [5764-53]

4:40 pm: **Finite element analysis of adaptive inflatable structures with SMA strip actuator,** J. Roh, J. Han, I. Lee, Korea Advanced Institute of Science and Technology (South Korea) . . . . . [5764-54]

5:00 pm: **Experimental and numerical characterization of multi-actuator piezoelectric device designs using topology optimization,** R. C. Carbonari, E. C. N. Silva, G. Nader, Univ. de São Paulo (Brazil); S. Nishiwaki, Kyoto Univ. (Japan) . . . . [5764-55]

5:20 pm: **Three-dimensional electromagnetic finite element models of actuator driven by a magnetostrictive iron-gallium rod,** J. G. Benatar, A. B. Flatau, Univ. of Maryland/ College Park . . . . . [5764-56]

Conference 5759 | Conference 5760

Thursday 10 March

8:00 to 8:55 am • *Town & Country Ballroom*

SSM Plenary Presentation:
Smart Structures and Materials Technology Applications for Network Centric Warfare Systems,
Dr. Jack H. Jacobs, Honeywell, Inc.

Sessions 10 and 11 run concurrently.

SESSION 10
Town & Country
Thurs. 9:00 am to 12:10 pm

Applications of EAP I

Chairs: **Hsing-Lin Wang**, Los Alamos National Lab.; **Alan J. Snyder**, The Pennsylvania State Univ.

9:00 am: **In pursuit of high-force/high-stroke conducting polymer actuators *(Invited Paper),*** G. M. Spinks, B. Xi, T. Campbell, P. Whitten, V. Mottaghitalab, M. Bahrami Samani, G. Wallace, Univ. of Wollongong (Australia) . . . . . [5759-46]

9:40 am: **Reversible work by electrochemical intercalation of graphitic materials,** C. G. Massey, HRL Labs., LLC and Univ. of Southern California; G. P. McKnight, W. Barvosa-Carter, P. Liu, HRL Labs., LLC . . . . . [5759-47]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **IPMC actuator array for a 3D haptic display,** H. Bleuler, Ecole Polytechnique Federale de Lausanne (Switzerland); M. Nakano, Ecole Polytechnique Federale de Lausanne (Switzerland) and Univ. of Tokyo (Japan); A. Mazzone, ETH Zürich (Switzerland) . . . . . [5759-48]

10:50 am: **Biomimetic actuator,** V. Bouda, Czech Technical Univ. (Czech Republic) . . . . . [5759-68]

11:10 am: **Progress in design of EAP pumps,** A. J. Snyder, A. M. Tews, K. Pope, E. Yeager, The Pennsylvania State Univ. [5759-50]

11:30 am: **A bio-inspired EAP actuator design methodology,** D. Fernandez, EADS Astrium CRISA (Spain); L. Moreno, J. Baselga, Univ. Carlos III de Madrid (Spain) . . . . . [5759-51]

11:50 am: **Wirelessly controllable inflated electroactive polymer (EAP) reflectors,** X. Q. Bao, Y. Bar-Cohen, Z. Chang, S. Sherrit, M. Badescu, Jet Propulsion Lab. . . . . [5759-52]

SESSION 11
Golden West
Thurs. 9:00 to 11:50 am

EAP Materials and their Characteristics

Chairs: **Michael S. Banik**, Boston Scientific Corp.; **Hsing-Lin Wang**, Los Alamos National Lab.

9:00 am: **Electro-driven polypyrrole actuators working in air,** H. Okuzaki, T. Saido, Univ. of Yamanashi (Japan) . . . . . [5759-53]

9:20 am: **Bending response of an artificial muscle in high-pressure water environments,** Y. Nakabo, K. Takagi, T. Mukai, The Institute of Physical and Chemical Research (RIKEN) (Japan); H. Yoshida, Japan Agency for Marine-Earth Science and Technology (Japan); K. Asaka, National Institute of Advanced Industrial Science and Technology (Japan) . . . . . [5759-54]

9:40 am: **Improving adhesion of polypyrrole on Au for long-term actuation,** Y. Liu, Q. Gan, S. Baig, E. Smela, Univ. of Maryland/College Park . . . . . [5759-75]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **Electromechanical response of P(VDF-TrFE)-P(VDF-CTFE) blends,** Y. Wang, Z. Li, Z. Cheng, Auburn Univ. . [5759-85]

10:50 am: **Understanding ion transport in conjugated polymers,** X. Wang, E. Smela, B. Shapiro, Univ. of Maryland/College Park . . . . . [5759-57]

11:10 am: **Application of polypyrrole(PPy) as the media material for the release and the detection of a neurotransmitter,** J. J. Pak, J. H. Son, J. H. Chang, D. B. Kim, Korea Univ. (South Korea); S. Lee, Dankook Univ. (South Korea) . . . . . [5759-58]

11:30 am: **A robotic architecture composed entirely of EAP components,** M. R. Blackburn, Space and Naval Warfare Systems Ctr., San Diego; S. Ozcelik, Texas A&M Univ. . . . . [5759-64]

Lunch Break . . . . . 11:50 am to 1:30 pm

SESSION 12
Royal Palm I
Thurs. 9:00 to 9:40 am

Vibration Isolation II

Chairs: **Conor D. Johnson**, CSA Engineering, Inc.; **Andrew J. Kurdila**, Univ. of Florida

9:00 am: **Experimental analysis of wave propagation in periodic grid-like structures,** M. Ruzzene, S. M. Jeong, Georgia Institute of Technology . . . . . [5760-59]

9:20 am: **Vibration isolation of automotive vehicle engine mounting systems,** S. A. Asiri, King Abdulaziz Univ. (Saudi Arabia) [5760-61]

9:40 am: **The reduced order optimum method for the placement and control law design of control devices between two adjacent structures,** J. Teng, Shenzhen Graduate School of HIT (China) . . . . . [5760-06]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 13
Royal Palm I
Thurs. 10:30 to 11:50 am

Damping Composites III

Chairs: **Massimo Ruzzene**, Georgia Institute of Technology; **Jin H. Huang**, Feng Chia Univ. (Taiwan)

10:30 am: **Damping of a composite drive shaft,** H. A. Ghoneim, Rochester Institute of Technology . . . . . [5760-62]

10:50 am: **Chiral hexagonal cellular sandwich structures: a vibro-acoustic assessment,** T. L. Lew, Univ. of Sheffield (United Kingdom); A. Spadoni, Georgia Institute of Technology; F. Scarpa, Univ. of Sheffield (United Kingdom); M. Ruzzene, Georgia Institute of Technology . . . . . [5760-63]

11:10 am: **Impact response of flexible cylindrical tubes filled with a shock absorbing composite,** G. Georgiades, O. Oyadiji, J. Wright, J. T. Turner, Univ. of Manchester (United Kingdom) . . . . [5760-64]

11:30 am: **Predicting the effectiveness of viscoelastic damping pockets in beams,** N. Butler, O. Oyadiji, Univ. of Manchester (United Kingdom) . . . . . [5760-65]

■ Conference 5760 End.

Smart Structures and Materials

Conference 5761

Conference 5763

Conference 5764

Thursday 10 March

8:00 to 8:55 am • *Town & Country Ballroom*

SSM Plenary Presentation:

Smart Structures and Materials Technology Applications for Network Centric Warfare Systems,
Dr. Jack H. Jacobs, Honeywell, Inc.

SESSION 12
California
Thurs. 9:00 to 11:50 am

FMSM

9:00 am: **Damping of polycrystalline ferromagnetic shape alloy bulk and sputtered thin film,** D. A. Ruggles, G. P. Carman, Univ. of California/Los Angeles . . . . . [5761-66]

9:20 am: **Temperature effect on the damping capacity of Ni-Mn-Ga/polymer composites,** J. Feuchtwanger, M. L. Richard, D. C. Bono, S. M. Allen, R. C. O'Handley, Massachusetts Institute of Technology . . . . . [5761-67]

9:40 am: **Energy absorption and damping in NiMnGa composites,** E. Gans, G. P. Carman, Univ. of California/Los Angeles . . . [5761-68]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **Fabrication of magnetic shape-memory alloy/polymer composites,** R. Hamsu, J. Healey, R. Underhill, S. Farrell, L. Cheng, C. Hyatt, Defence Research and Development Canada/Atlantic (Canada); R. Rogge, M. Gharghouri, National Research Council of Canada (Canada) . . . . . [5761-69]

10:50 am: **Reversible strain in Ni-Mn-Ga with collinear field and stress,** L. E. Faidley, M. J. Dapino, G. N. Washington, The Ohio State Univ.; T. A. Lograsso, Iowa State Univ. and DOE Ames Lab. . . . . [5761-70]

11:10 am: **Magnetic shape-memory fatigue,** O. Heczko, L. Straka, Helsinki Univ. of Technology (Finland); K. Ullakko, Adaptamat Oy (Finland); S. Hannula, Helsinki Univ. of Technology (Finland) . . . . . [5761-72]

11:30 am: **Constitutive modeling and related experimentation for MR fluids,** N. G. Naganathan, Univ. of Toledo . . . . . [5761-83]

■ Conference 5761 End.

SESSION 10
Royal Palm II
Thurs. 9:00 to 9:40 am

Biosensors and BioMEMS II

Chairs: **Glen C. King**, NASA Langley Research Ctr.; **Hargsoon Yoon**, The Pennsylvania State Univ.

9:00 am: **Real-time PCR detction with nanofabricated SERS microchips,** N. Elejalde, N. Atkins, O. Inya-Agha, J. M. Cooper, Univ. of Glasgow (United Kingdom) . . . . . [5763-48]

9:20 am: **Nanowire sensor array for the detection and identification of bio-hazards,** H. Yoon, T. Ji, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-50]

Coffee Break . . . . . 9:40 to 10:30 am

SESSION 11
Royal Palm II
Thurs. 10:30 to 11:50 am

Sensor Modeling and Simulation

Chairs: **S. M. Yang**, National Cheng Kung Univ. (Taiwan); **Jining Xie**, The Pennsylvania State Univ.

10:30 am: **Double-microcantilever design for surface stress measurement in biochemical sensor,** T. Yin, S. M. Yang, National Cheng Kung Univ. (Taiwan) . . . . . [5763-51]

10:50 am: **Optimization of microfluidic mixing using multiobjective evolution strategies,** T. S. Mautner, Consultant, Technology Development . . . . . [5763-53]

11:10 am: **Molecular dynamics simulations of single-walled carbon nanotube tips impact processes on a silicon (001) surface,** J. Dou, Harbin Institute of Technology (China) . . . . . [5763-54]

11:30 am: **Simulation and design of self-heating continuous-flow PCR chip,** W. Chen, Harbin Institute of Technology (China) . . . . . [5763-55]

Lunch Break . . . . . 12:30 to 1:30 pm

SESSION 12
Royal Palm V
Thurs. 9:00 to 10:00 am

Health Monitoring I

Chairs: **Victor Giurgiutiu**, Univ. of South Carolina; **Mark M. Derriso**, Air Force Research Lab.

9:00 am: **Early detection of local buckling in structural members,** B. Ali, North Carolina A&T State Univ. . . . . [5764-57]

9:20 am: **A benchmark problem for structural health monitoring based on a real bridge structure,** W. Zhou, H. Li, J. Ou, Harbin Institute of Technology (China) . . . [5764-58]

9:40 am: **Development of specifications for an integrated piezoelectric wafer active sensors system,** C. J. Jenkins, V. Giurgiutiu, Univ. of South Carolina . . . . . [5764-59]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 13
Royal Palm V
Thurs. 10:30 am to 12:30 pm

Health Monitoring II

Chairs: **David Chelidze**, Univ. of Rhode Island; **Dirk Söffker**, Univ. Duisburg-Essen (Germany)

10:30 am: **Fault tolerant design and improved availability of active composite elastic structures,** D. Söffker, I. Krajcin, K. Wolters, Univ. Duisburg-Essen (Germany) . . [5764-60]

10:50 am: **Decision uncertainty in a structural health monitoring system,** M. P. DeSimio, iCAD, Inc.; S. E. Olson, Univ. of Dayton Research Institute; M. M. Derriso, Air Force Research Lab. . . . . [5764-61]

11:10 am: **Damage criticality assessment in complex geometric structures using strain and dynamic response-based signal processing techniques,** M. Deivasigamani, A. Kesavan, RMIT Univ. (Australia); I. Herszberg, CRC-ACS (Australia); S. J. John, RMIT Univ. (Australia) . . . . . [5764-62]

11:30 am: **Flow-variance method for damage identification,** D. Chelidze, M. Liu, Univ. of Rhode Island . . . . . [5764-63]

11:50 am: **Structural health monitoring(SHM) of co-cured composite structures using fiber Bragg grating (FBG) sensors,** R. Sundaram, G. M. Kamath, N. Gupta, M. Subbarao, National Aerospace Labs. (India) . . . . . [5764-64]

12:10 pm: **Elastic wave propagation in delaminated composites using piezoelectric-wafer actuators and sensors,** X. Zhou, A. Chattopadhyay, Arizona State Univ. [5764-83]

Lunch Break . . . . . 12:30 to 1:30 pm

Wednesday 9 March

SESSION 12
Town & Country
Thurs. 1:30 to 4:20 pm

Applications of EAP II

Chairs: **Richard O. Claus**, Virginia Polytechnic Institute and State Univ.; **Toribio F. Otero**, Univ. Politécnica de Cartagena (Spain)

1:30 pm: **Proposal of new actuators using ion gels driven at low-voltage under atmospheric conditions,** M. Watanabe, S. Nanjo, Yokohama National Univ. (Japan) . . [5759-60]

2:10 pm: **Development of a tactile array with the utilization of dielectric electroactive polymers,** G. Chakrabarti, Dalient; R. Chakraborty, Thermefficient . . . . . [5759-61]

2:30 pm: **Actuation behavioral studies on polyaniline-cellophane based electroactive paper actuator,** S. D. Deshpande, C. Song, Q. Li, J. Kim, Inha Univ. (South Korea) [5759-62]

2:50 pm: **Low-voltage driven dry soft actuators using carbon-anotube gels with ionic liquids,** K. Asaka, National Institute of Advanced Industrial Science and Technology (Japan); T. Fukushima, A. Kosaka, A. Takuzo, Japan Science and Technology Corp. (Japan) . . . . . [5759-63]

Coffee Break . . . . . 3:10 to 3:40 pm

3:40 pm: **Design and performance analysis of a novel IPMC-driven micropump,** S. K. Lee, K. Kim, S. Heo, K. Choe, Univ. of Nevada/Reno; H. C. Park, Konkuk Univ. (South Korea) . . . . . [5759-65]

4:00 pm: **Smart actuators based on electromechanically active conjugated polymer diodes,** G. Dennler, R. Schwoediauer, S. Bauer, N. S. Sariciftci, Johannes Kepler Univ. (Austria); H. Reiss, Univ. of California/Los Angeles . . . [5759-67]

■ Conference 5759 End.

SESSION 12
Royal Palm II
Thurs. 1:30 to 2:50 pm

Microsensor, Actuators, and MEMS III

Chair: **Cheng Luo**, Louisiana Tech Univ.

1:30 pm: **An experimental structural neural system,** V. Shinde, G. R. Kirikera, M. J. Schulz, Univ. of Cincinnati; M. J. Sundaresan, North Carolina A&T State Univ. . . . . [5763-56]

1:50 pm: **An analytical relationship to determine compressive residual stress in a doubly-clamped microbeam according to its buckled shape,** C. Luo, A. Francis, X. Liu, K. Varahramyan, Louisiana Tech Univ. [5763-57]

2:10 pm: **The micro-patterned device for cell attachment using new extracellular matrix,** S. Chae, Korea Advanced Institute of Science and Technology (South Korea) . . . . [5763-59]

2:30 pm: **Reinforcement of PDMS using oxide-coated silicon plates,** C. Luo, F. Meng, Y. Guo, A. Govindaraju, Louisiana Tech Univ. . . . . [5763-60]

Coffee Break . . . . . 2:50 to 3:40 pm

SESSION 13
Royal Palm II
Thurs. 3:40 to 4:40 pm

RF MEMS

Chair: **Vijay K. Varadan**, The Pennsylvania State Univ.

3:40 pm: **Lifetime characterization of capacitive RF MEMS switches,** A. Ziaei, T. Dean, Thales Research and Technology (France) . . . . . [5763-61]

4:00 pm: **Millimeter-wave GaAs stepped-impedance hairpin resonator filters using surface micromachining,** J. Lee, J. Cho, T. Yun, K. Kim, Kwangwoon Univ. (South Korea); T. Baek, D. Shin, B. Ko, Dongguk Univ. (South Korea) . . . . . [5763-62]

4:20 pm: **Applicability of holographic technique for analysis of nonlinear dynamics of MEMS switch,** V. Ostasevicius, M. Ragulskis, A. Palevicius, V. Kravcenkiene, G. Janusas, Kaunas Univ. of Technology (Lithuania) . . . . . [5763-63]

SESSION 14
Royal Palm II
Thurs. 4:40 to 5:20 pm

Applications

Chair: **Vijay K. Varadan**, The Pennsylvania State Univ.

4:40 pm: **Identification of soft drinks using MEMS-IDT microsensors,** J. K. Abraham, S. Karjatkar, V. K. Varadan, The Pennsylvania State Univ. . . . . [5763-64]

5:00 pm: **Smart Vest for physiological monitoring,** V. K. Varadan, J. K. Abraham, A. K. Whitchurch, The Pennsylvania State Univ.; G. N. Mathur, Defense Materials and Science Research (India) . . . . . [5763-65]

■ Conference 5763 End.

SESSION 14
Royal Palm V
Thurs. 1:30 to 3:10 pm

Health Monitoring III

Chairs: **Wieslaw J. Staszewski**, Univ. of Sheffield (United Kingdom); **Aditi Chattopadhyay**, Arizona State Univ.

1:30 pm: **Wave-based signature characterization of damage using response-surface method,** S. Das, X. Zhou, A. Chattopadhyay, A. Papandreou-Suppappola, Arizona State Univ. . . . . [5764-65]

1:50 pm: **Crack detection using vibro-acousto-ultrasonics,** W. J. Staszewski, Univ. of Sheffield (United Kingdom) . . . . . [5764-66]

2:10 pm: **Monitoring of crack growth in aluminum 7075 T6 using distributed sensor,** G. Grandhi, North Carolina A&T State Univ. . . . . [5764-67]

2:30 pm: **Life prediction and life extension of composite specimens,** F. Nkrumah, North Carolina A&T State Univ. . . . . [5764-68]

2:50 pm: **Characterization of impact damage in laminate composites with numcerical simulation for health monitoring,** S. J. Kim, S. H. Paik, S. H. Park, Seoul National Univ. (South Korea) . . . . . [5764-82]

■ Conference 5764 End.

Conference 5765 • Sunrise and Towne

Monday-Thursday 7-10 March 2005 • Proceedings of SPIE Vol. 5765

Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

Cosponsor: SISTeC, KAIST

Conference Chair: **Masayoshi Tomizuka**, Univ. of California/Berkeley

Cochairs: **ChungBang Yun**, Korea Advanced Institute of Science and Technology (South Korea); **Victor Giurgiutiu**, Univ. of South Carolina; **Jan-Ming Ko**, Hong Kong Polytechnic Univ. (Hong Kong China); **Akira Mita**, Keio Univ. (Japan); **Robert X. Gao**, Univ. of Massachusetts/Amherst; **Billie F. Spencer, Jr.**, Univ. of Illinois/Urbana-Champaign

Program Committee: **H. Harry Asada**, Massachusetts Institute of Technology; **Amr M. Baz**, Univ. of Maryland/College Park; **Fabio Casciati**, Univ. degli Studi di Pavia (Italy); **Chih-Chen Chang**, Hong Kong Univ. of Science and Technology (Hong Kong China); **Fu-Kuo Chang**, Stanford Univ.; **Genda Chen**, Univ. of Missouri/Rolla; **Reginald DesRoches**, Georgia Institute of Technology; **Shirley J. Dyke**, Washington Univ.; **Silvia Ferrari**, Duke Univ.; **Yozo Fujino**, Univ. of Tokyo (Japan); **Henri P. Gavin**, Duke Univ.; **Steven D. Glaser**, Univ. of California/Berkeley; **Faramarz Gordaninejad**, Univ. of Nevada/Reno; **B. Kyle Henderson**, Air Force Research Lab.; **Dryver R. Huston**, Univ. of Vermont; **Kumar Jata**, Air Force Research Lab.; **Jeong-Tae Kim**, Pukyong National Univ. (South Korea); **Ki S. Kim**, Hoseo Univ. (South Korea); **Shih-Chi Liu**, National Science Foundation; **Chin-Hsiung Loh**, National Taiwan Univ. (Taiwan); **Sami F. Masri**, Univ. of Southern California; **Siavouche Nemat-Nasser**, Univ. of California/San Diego; **Irving J. Oppenheim**, Carnegie Mellon Univ.; **Jinping Ou**, Harbin Institute of Technology (China); **Ser-Tong Quek**, National Univ. of Singapore (Singapore); **Tadanobu Sato**, Kyoto Univ. (Japan); **Rahmat A. Shoureshi**, Univ. of Denver; **Andrew W. Smyth**, Columbia Univ.; **Meihua Tai**, Polytechnic Univ.; **Angela Trego**, The Boeing Co.; **T. C. Tsao**, Univ. of California/Los Angeles; **Kevin K. Tseng**, Vanderbilt Univ.; **Ming L. Wang**, Univ. of Illinois/Chicago; **John T. Wen**, Rensselaer Polytechnic Institute; **Zhishen Wu**, Ibaraki Univ. (Japan); **You-Lin Xu**, Hong Kong Polytechnic Univ. (Hong Kong China); **Hiroyuki Yamanouchi**, Building Research Institute (Japan); **Bojidar S. Yanev**, New York City Department of Transportation; **Lily L. Zhou**, Nanjing Univ. of Aeronautics and Astronautics (China)

Monday 7 March

Opening Remarks ..... **Mon. 10:30 am**

Chairs: **ChungBang Yun**, Korea Advanced Institute of Science and Technology (South Korea); **Victor Giurgiutiu**, Univ. of South Carolina

SESSION 1

Sunrise ..... **Mon. 10:40 am to 12:00 pm**

Invited Lectures

Chairs: **ChungBang Yun**, Korea Advanced Institute of Science and Technology (South Korea); **Victor Giurgiutiu**, Univ. of South Carolina

10:40 am: **Recent developments in MEMS *(Invited Paper, Presentation Only)*,** A. Duwel, Draper Lab. ..... [5765-01]

11:20 am: **What do earthquakes do? Measurement and control challenges for earthquake engineering *(Invited Paper)*,** S. Mahin, Univ. of California/Berkeley ..... [5765-02]

Lunch Break ..... 12:00 to 1:30 pm

SESSION 2

Sunrise ..... **Mon. 1:30 to 3:10 pm**

Piezoelectric and Intergrated Sensors

Chairs: **Robert C. Anderson**, Texas Tech Univ.; **Xinchun Guan**, Harbin Institute of Technology (China)

1:30 pm: **Temperature and humidity variation of specific resistance of carbon fiber-reinforced cement,** X. Guan, B. Han, J. Ou, Harbin Institute of Technology (China) ..... [5765-03]

1:50 pm: **Computational tool for the design of structures with built-in piezoelectric-based sensor networks,** Y. Kim, F. Chang, Stanford Univ. ..... [5765-126]

2:10 pm: **An improved damage identification method using tunable piezoelectric transducer circuitry,** L. Jiang, Pennsylvania State Univ.; J. Tang, Univ. of Connecticut; K. Wang, Pennsylvania State Univ. ..... [5765-05]

2:30 pm: **Characterization of concrete stress by measuring dissipation factors of embedded piezoelectric ceramic discs,** Y. Wen, Y. Chen, P. Li, H. Guo, Chongqing Univ. (China) [5765-06]

2:50 pm: **Integrated charge sensors for electrostatic MEMS,** R. C. Anderson, K. Ragulan, S. Maithripala, J. M. Berg, R. O. Gale, Jr., M. Holtz, W. P. Dayawansa, M. J. Donohue, Texas Tech Univ. ..... [5765-07]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 3

Sunrise ..... **Mon. 3:40 to 6:00 pm**

Novel Sensors I

Chairs: **Ser-Tong Quek**, National Univ. of Singapore (Singapore); **Jeong-Tae Kim**, Pukyong National Univ. (South Korea)

3:40 pm: **Dynamic displacement measurement accuracy of GPS for monitoring large civil engineering structures,** W. S. Chan, Y. L. Xu, X. L. Ding, Y. L. Xiong, W. J. Dai, The Hong Kong Polytechnic Univ. (Hong Kong China) ..... [5765-08]

4:00 pm: **High-speed hybrid active system,** I. F. Gonzalez, Univ. Politecnica de Madrid (Spain) and Stanford Univ.; F. Chang, Stanford Univ. ..... [5765-09]

4:20 pm: **Concrete-filled steel pipes inspection using electro-magnetic acoustic transducer (EMAT),** W. Na, Pukyong National Univ. (South Korea); T. Kundu, Univ. of Arizona; Y. Ryu, J. Kim, Pukyong National Univ. (South Korea) ..... [5765-10]

4:40 pm: **Control of distributed sensors by dynamic Bayesian networks,** S. Ferrari, M. Qian, Duke Univ. ..... [5765-11]

5:00 pm: **Forisome as a biomimetic smart materials,** A. Shen, Washington Univ. .. [5765-12]

5:20 pm: **Health monitoring of a reinforced concrete bridge bent-cap using piezoceramic materials,** H. Gu, Univ. of Houston ..... [5765-13]

5:40 pm: **Monitoring liquid and solid polymers through electroactive response,** H. Y. Lee, Y. Peng, Y. M. Shkel, Univ. of Wisconsin/Madison ..... [5765-14]

Smart Structures and Materials, and NDE *Joint Conference*

Tuesday 8 March

Sessions 4, 5, 6 and 7 run concurrently with Sessions 8, 10 and 11.

SESSION 4

Sunrise ..... Tues. 9:00 to 10:00 am

Monitoring Systems

Chairs: **Hans Irschik**, Johannes Kepler Univ. Linz (Austria); **Xiaoyan Han**, Wayne State Univ.

9:00 am: **Design of sensors/actuators for structural control of continuous CMA systems,** H. Irschik, M. Krommer, U. Pichler, Johannes Kepler Univ. Linz (Austria) ..... [5765-15]

9:20 am: **Sonic infrared imaging NDE,** X. Han, Wayne State Univ. ..... [5765-16]

9:40 am: **Development of vehicle intelligent monitoring system (VIMS),** Y. Fujino, K. Kitagawa, H. Ishii, Univ. of Tokyo (Japan) ..... [5765-17]

Coffee Break ..... 10:00 to 10:30 am

SESSION 5

Sunrise ..... Tues. 10:30 am to 12:30 pm

Wireless Sensors

Chairs: **Jerome P. Lynch**, Univ. of Michigan; **Angela Trego**, Boeing Co.

10:30 am: **Development of a multi-variable wireless sensor for structural health monitoring in civil engineering,** Y. Yu, Harbin Institute of Technology (China) ..... [5765-18]

10:50 am: **Energy efficiency analysis of a self-powered acoustic wireless pressure sensor: a bond graph approach,** Y. Cui, R. X. Gao, Univ. of Massachusetts/Amherst; D. O. Kazmer, Univ. of Masachusetts/Lowell ..... [5765-19]

11:10 am: **Development of wireless smart sensor for structural health monitoring,** L. Liu, F. Yuan, North Carolina State Univ. ..... [5765-20]

11:30 am: **The SHM system using self-diagnosis material and wireless data measurement device,** M. Shiraishi, H. Kumagai, Shimizu Corp. (Japan); H. Inada, Ohsaki Research Institute (Japan); Y. Okuhara, H. Matsubara, Japan Fine Ceramics Ctr. (Japan) ..... [5765-21]

11:50 am: **Development of an off-the-shelf field programmable gate array-based wireless sensing unit for structural health monitoring,** C. Kapoor, J. Pei, Univ. of Oklahoma; T. L. Graves-Abe, Princeton Univ. ..... [5765-22]

12:10 pm: **Health dynamic measurement of tall building using wireless sensor network,** J. Ou, H. Li, Harbin Institute of Technology (China); Q. Li, City Univ. of Hong Kong (Hong Kong China) ..... [5765-23]

Lunch/Exhibition Break ..... 12:30 to 1:30 pm

SESSION 6

Sunrise ..... Tues. 1:30 to 3:10 pm

Sensor Networks

Chairs: **Irving J. Oppenheim**, Carnegie Mellon Univ.; **Bogdan I. Epureanu**, Univ. of Michigan/Ann Arbor

1:30 pm: **Flexibility-based damage identification algorithm embedded in sensor network emvironment,** A. Masuda, A. Sone, Y. Hashimoto, Kyoto Institute of Technology (Japan) . [5765-24]

1:50 pm: **An energy-efficient data processing scheme for wireless sensor networks,** Z. Fan, R. X. Gao, Univ. of Massachusetts/Amherst ..... [5765-25]

2:10 pm: **Sensitivity vector fields for damage detection and sensing,** A. I. Hashmi, B. I. Epureanu, Univ. of Michigan/Ann Arbor ..... [5765-26]

2:30 pm: **Prototype of sensor network with embedded local data processing,** Y. Hashimoto, A. Masuda, A. Sone, Kyoto Institute of Technology (Japan) ..... [5765-27]

2:50 pm: **Architecture optimization for wireless sensor networks,** F. Casciati, L. Faravelli, Univ. degli Studi di Pavia (Italy); R. Rossi, Paviasystem (Italy) ..... [5765-28]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 7

Sunrise ..... Tues. 3:40 to 6:00 pm

Lamb Waves for SHM

Chairs: **Fuh-Gwo Yuan**, North Carolina State Univ.; **Carlos E. Cesnik**, Univ. of Michigan/Ann Arbor

3:40 pm: **Simulation of the Lamb-wave interaction between piezoelectric wafer active sensors and host structure,** V. Giurgiutiu, G. Bottai, Univ. of South Carolina ..... [5765-29]

4:00 pm: **Efficient electromechanical (E/M) impedance measuring method for active sensor structural health monitoring,** B. Xu, V. Giurgiutiu, Univ. of South Carolina ..... [5765-30]

4:20 pm: **Use of Lamb waves to monitor plates: experiments and simulations,** D. W. Greve, J. J. Neumann, Carnegie Mellon Univ.; J. H. Nieuwenhuis, Technical Univ. of Vienna (Austria); I. J. Oppenheim, Carnegie Mellon Univ. ..... [5765-31]

4:40 pm: **Validation of a Lamb wave-based structural health monitoring system for aircraft applications,** S. S. Kessler, A. B. Size, Metis Design Corp. ..... [5765-32]

5:00 pm: **Interdigitated PVDF transducer for crack and corrosion detection,** H. Gu, G. M. Lloyd, M. L. Wang, Univ. of Illinois/Chicago ..... [5765-33]

5:20 pm: **Finite-actuator modeling for piezoelectric-based Lamb-wave structural health monitoring,** A. Raghavan, C. E. Cesnik, Univ. of Michigan/Ann Arbor ..... [5765-34]

5:40 pm: **Wavelet-based built-in delamination detection for composites,** G. Yan, L. L. Zhou, Nanjing Univ. of Aeronautics and Astronautics (China); F. Yuan, North Carolina State Univ. ..... [5765-35]

SESSION 8

Towne ..... Tues. 9:00 to 10:00 am

Modeling and Design of Smart Systems

Chairs: **Yozo Fujino**, Univ. of Tokyo (Japan); **Yunfeng Zhang**, Lehigh Univ.

9:00 am: **Finite element model updating of structures using a mixed optimization technique,** Z. Duan, Y. Liu, J. Ou, Harbin Institute of Technology (China) ..... [5765-36]

9:20 am: **A new approach to designing multilayer feedforward neural networks for modeling nonlinear restoring forces,** J. Pei, Univ. of Oklahoma; A. W. Smyth, Columbia Univ. . [5765-37]

9:40 am: **A new design strategy for optimal distribution of dampers in smart building structures,** H. Kazama, A. Mita, Keio Univ. (Japan) ..... [5765-38]

Coffee/Lunch/Exhibition Break ..... 10:00 am to 1:30 pm

SESSION 10

Towne ..... Tues. 1:30 to 3:10 pm

Novel Sensors II

Chairs: **Jeong-Tae Kim**, Pukyong National Univ. (South Korea); **Silvia Ferrari**, Duke Univ.

1:30 pm: **Efficient use of Lamb waves and their wavelet coefficients for damage detection of steel plates,** S. Park, Korea Advanced Institute of Science and Technology (South Korea); C. Yun, Korea Advenced Institute of Science and Technology (South Korea); Y. R. Roh, Kyungpook National Univ. (South Korea) ..... [5765-39]

1:50 pm: **Distributed sensing of RC beams with HCFRP sensors,** C. Yang, Z. Wu, L. Ye, Ibaraki Univ. (Japan) ..... [5765-40]

2:10 pm: **A heterogeneous network of vertical seismic arrays,** M. Chen, S. D. Glaser, Univ. of California/Berkeley ..... [5765-41]

2:30 pm: **Application of EM stress sensors in large steel cables,** G. Wang, M. L. Wang, Y. Zhao, Univ. of Illinois/Chicago ..... [5765-42]

2:50 pm: **Toward crack mapping of reinforced concrete members with distributed cable sensors for their coupled flexural-shear-torsional behavior,** A. Belarbi, G. G. Greene, R. McDaniel, G. Chen, S. Sun, D. J. Pommerenke, Univ. of Missouri/Rolla ..... [5765-43]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 11

Towne ..... Tues. 3:40 to 6:00 pm

Novel Sensors III

Chairs: **Genda Chen**, Univ. of Missouri/Rolla; **Ming L. Wang**, Univ. of Illinois/Chicago

3:40 pm: **Conductivity-based strain monitoring and damage characterization of cementitious structural components,** J. P. Lynch, T. Hou, Univ. of Michigan ..... [5765-44]

4:00 pm: **Smart RC elements for long-life monitoring of civil infrastructure,** D. Zonta, O. S. Bursi, M. Pozzi, Univ. degli Studi di Trento (Italy) ..... [5765-46]

4:20 pm: **SMA-based smart damper/displacement transducer,** C. Mao, H. Li, Harbin Institute of Technology (China) ..... [5765-47]

4:40 pm: **Design, characterization, and experimental use of an optimized MEMS acoustic emission device,** D. Ozevin, Lehigh Univ.; D. W. Greve, I. J. Oppenheim, Carnegie Mellon Univ.; S. P. Pessiki, Lehigh Univ. ..... [5765-48]

5:00 pm: **GPS monitoring in urban zones: calibration and quantification of multipath effects,** M. Kochly, T. Kijewski-Correa, Univ. of Notre Dame; J. Stowell, Leica Geosystems Inc.[5765-49]

5:20 pm: **Wireless sensors for wildfire monitoring,** D. M. Doolin, N. Sitar, Univ. of California/Berkeley ..... [5765-50]

✔ Posters-Tuesday

The following posters will be displayed in the formal Poster Session and Exhibition Reception on Tuesday evening from 6:00 to 7:30 pm. Authors will be present during this time for discussion. Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed after 4 pm before the formal poster session begins at 6:00 pm.

✔ **Review of in-situ fabrication methods of piezoelectric wafer active sendor for sensing and actuation applications,** B. Lin, V. Giurgiutiu, Univ. of South Carolina . . . [5765-04]

✔ **Nonlinear observability of the extended Kalman filter,** J. Pan, Zhejiang Univ. (China); R. Wang, Univ. of California/Irvine . . . . . [5765-114]

✔ **Self-diagnosing and self-healing mortar using conductive additives and microcapsules,** S. Park, Daejeon Univ. (South Korea) . . . . . [5765-116]

✔ **Studies on the mechanical properties of carbon fiber reinforced porous concrete for planting,** S. B. Park, Chungnam National Univ. (South Korea); J. Kim, Hanil Eco-Concrete Co. (South Korea) . . . . . [5765-118]

✔ **Strain transfer of embedded fiber Bragg grating sensors,** D. Li, H. Li, Dalian Univ. of Technology (China) . . . . . [5765-120]

✔ **Piezoelectric paint sensor for real-time structural health monitoring,** Y. Zhang, S. Zhu, Lehigh Univ. . . . . [5765-121]

✔ **A new, low-cost, stress sensor for battery-free wireless sensor applications,** A. R. Bowles, J. G. Gore, QinetiQ (United Kingdom); J. G. Tomka, Charles Darwin Univ. (Australia) . . . . . [5765-122]

✔ **A novel fiber Bragg grating-based geophone for seismic exploration,** Y. Zhang, H. Cui, Z. Yin, Stevens Institute of Technology . . . . . [5765-123]

✔ **A new kind of ice-pressure sensor based on FBG,** Z. Zhou, C. Lan, J. Ou, Harbin Institute of Technology (China) . . . . . [5765-124]

✔ **Healable polymer composites,** T. A. Plaisted, J. B. Isaacs, S. Nemat-Nasser, Univ. of California/San Diego . . . . . [5765-125]

✔ **Influence of optical fiber coating damage in the light-transmissivity characteristics of microbend sensors,** F. Campero Verdun, Florida Institute of Technology and GFA International; P. J. Cosentino, Florida Institute of Technology . . . . . [5765-128]

✔ **Development of automatic data collection for PWAS-based structural health monitoring,** W. Liu, V. Giurgiutiu, Univ. of South Carolina . . . . . [5765-129]

✔ **An initial investigation of the large strain and fatigue behavior of piezoelectric wafer active sensors,** J. E. Doane, V. Giurgiutiu, Univ. of South Carolina . . . . . [5765-130]

✔ **Embedded wavelet packet-based signal compression algorithm in wireless sensors for structural health monitoring,** J. Ou, Harbin Institute of Technology (China); H. Li, Q. S. Li, City Univ. of Hong Kong (Hong Kong China) . . . . . [5765-131]

Smart Structures and Materials, and NDE *Joint Conference*

Wednesday 9 March

Sessions 12, 13, 14 and 15 run concurrently with Sessions 16, 17, 18 and 19.

SESSION 12

Sunrise . . . . . **Wed. 9:00 to 10:00 am**

Corrosion Detection

Chairs: **Sharon L. Wood**, Univ. of Texas/Austin; **Russell D. Braunling**, Honeywell Technology Ctr.

9:00 am: **Corrosion and corrosivity monitoring system,** R. D. Braunling, P. F. Dietrich, Honeywell International . . . . . [5765-51]

9:20 am: **Wireless low-cost corrosion monitoring sensors for reinforced concrete structures,** N. P. Dickerson, J. T. Simonen, M. Ardringa, S. L. Wood, D. P. Neikirk, Univ. of Texas/Austin . . [5765-52]

9:40 am: **Quantitative corrosion monitoring and detection using ultrasonic Lamb waves,** G. A. Gordon, R. D. Braunling, Honeywell International . . . . . [5765-53]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 13

Sunrise . . . . . **Wed. 10:30 am to 12:30 pm**

Fiber Optic Sensors for SHM I

Chairs: **Reginald DesRoches**, Georgia Institute of Technology; **Kara J. Peters**, North Carolina State Univ.

10:30 am: **Distributed strain measurement of a large-scale reinforced concrete beam-column assembly under cycle loading,** G. Chen, B. Xu, R. D. McDaniel, X. Ying, D. J. Pommerenke, Univ. of Missouri/Rolla; Z. Wu, Ibaraki Univ. (Japan) . . . . . [5765-55]

10:50 am: **Fiber optic sensor protection system and its practical for structural integrity monitoring of concrete structures,** J. Leng, Harbin Institute of Technology (China); D. Winter, A. Hameed, R. A. Barnes, G. C. Mays, G. F. Fernando, Cranfield Univ. (United Kingdom) . . . . . [5765-56]

11:10 am: **Failure and damage identification in woven composites with fiber Bragg grating sensors,** J. Pearson, M. Prabhugoud, M. A. Zikry, K. J. Peters, M. Sitar, L. Davis, North Carolina State Univ. . . . . [5765-57]

11:30 am: **Fiber Bragg grating array calibration,** A. M. Abdi, S. Suzuki, A. Schülzgen, A. R. Kost, Optical Sciences Ctr./Univ. of Arizona . . . . . [5765-58]

11:50 am: **Characterization of long-gauge fiber optics sensors for broad-based structural dynamic measurements,** S. Li, Z. Wu, B. Xu, Ibaraki Univ. (Japan) . . . . . [5765-59]

12:10 pm: **A novel intensity and wavelength-division multiplexing FBG sensor system,** Z. Li, J. Tang, Y. Zhao, Yanshan Univ. (China) . . . . . [5765-54]

Lunch/Exhibition Break . . . . . 12:30 to 1:30 pm

SESSION 14

Sunrise . . . . . **Wed. 1:30 to 3:10 pm**

Fiber Optic Sensors for SHM II

Chairs: **Zhishen Wu**, Ibaraki Univ. (Japan); **Nicole Metje**, Univ. of Birmingham (United Kingdom)

1:30 pm: **Health monitoring of Binzhou Yellow River Highway Bridge using fiber Bragg gratings,** J. Ou, X. Zhao, Z. Zhou, H. Li, Z. Zhang, C. Wang, Harbin Institute of Technology (China) . . [5765-60]

1:50 pm: **Application of fiber Bragg grating sensors for structural integrity test of nuclear power plant containment structure,** K. S. Kim, Hoseo Univ. (South Korea) . . . . . [5765-61]

2:10 pm: **Damage detection from dynamic SOFO experimental data,** S. M. Casciati, M. Domaneschi, Univ. degli Studi di Pavia (Italy); D. Inaudi, SMARTEC SA(Switzerland) . . . [5765-62]

2:30 pm: **A Brillouin smart FRP material and a strain data post processing software for structural health monitoring through laboratory testing and field application on a highway bridge,** F. Bastianini, F. Matta, N. Galati, A. Nanni, Univ. of Missouri/Rolla . . . . . [5765-63]

2:50 pm: **Discontinuous Brillouin strain monitoring of small concrete bridges: comparison between near-to-surface and 'smart' FRP fiber installation techniques,** F. Bastianini, A. Rizzo, U. Deza, N. Galati, A. Nanni, Univ. of Missouri/Rolla . . . . . [5765-64]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 15

Sunrise . . . . . **Wed. 3:40 to 6:00 pm**

Fiber Optic Sensors for SHM III

Chairs: **Ki S. Kim**, Hoseo Univ. (South Korea); **Filippo Bastianini**, Istituto Univ. of Venezia (Italy)

3:40 pm: **Structural health monitoring system using FBG sensor for simultaneous detection of acceleration and strain,** H. Hayano, A. Mita, Keio Univ. (Japan) . . . . . [5765-65]

4:00 pm: **Using fiber Bragg gratings to measure dynamic soil-shear response,** L. Overbey, M. D. Todd, Univ. of California/San Diego; M. E. Seaver, Naval Research Lab.; L. He, A. Elgamal, Univ. of California/San Diego . . . . . [5765-66]

4:20 pm: **Development of a new structural monitoring system using optical fiber technology,** N. Metje, D. N. Chapman, C. D. F. Rogers, S. N. Kukureka, P. Miao, Univ. of Birmingham (United Kingdom); P. Henderson, Smart Fibres Ltd. (United Kingdom); M. Beth, Sol Data (France) . . . . . [5765-67]

4:40 pm: **Identification of damage location in advanced- grid structures using fiber Bragg grating sensor,** M. Amano, I. Takahashi, Y. Okabe, N. Takeda, Univ. of Tokyo (Japan); S. Hahn, H. Takeya, T. Ozaki, Mitsubishi Electric Corp. (Japan) . . . . . [5765-68]

5:00 pm: **Polymer-based optical fiber sensors for health monitoring of engineering structures,** K. S. C. Kuang, S. Quek, M. Maalej, National Univ. of Singapore (Singapore) . . . . . [5765-69]

5:20 pm: **Applications of FBG sensors on bridge cables,** Z. Zhou, X. Zhao, C. Wang, Z. Zhang, J. Ou, Harbin Institute of Technology (China) . . . . . [5765-70]

5:40 pm: **Demonstration of a fiber grating based SHM system for bridges,** S. G. Calvert, J. Mooney, J. de la Harpe, M. Louie, C. Quinlan, Blue Road Research; J. P. Conte, Univ. of California/San Diego . . . . . [5765-71]

SESSION 16

Towne . . . . . **Wed. 9:00 to 10:00 am**

Structural Control

Chairs: **Jann N. Yang**, Univ. of California/Irvine; **Tadanobu Sato**, Kyoto Univ. (Japan)

9:00 am: **Design guidelines for open-loop vibration control of stay cables using MR dampers,** Y. Duan, Y. Ni, J. Ko, Hong Kong Polytechnic Univ. (Hong Kong China) . . . . . [5765-72]

9:20 am: **Modeling of a full-scale MR damper and its application in open-loop vibration control of stay cables,** J. Ko, Y. Duan, Y. Ni, Hong Kong Polytechnic Univ. (Hong Kong China) . . . . . [5765-73]

9:40 am: **Smart systems for short-duration impulse loads,** A. Rajaraman, Indian Institute of Technology Madras (India) . . . . . [5765-74]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 17

Towne . . . . . **Wed. 10:30 am to 12:30 pm**

System Identification and SHM

Chairs: **Jan-Ming Ko**, Hong Kong Polytechnic Univ. (Hong Kong China); **John T. DeWolf**, Univ. of Connecticut

10:30 am: **Educating next-generation civil engineers about smart structures technology,** Y. Zhang, Lehigh Univ. . . . . [5765-75]

10:50 am: **Auxiliary particle filtering for structural system identification,** H. Tang, Kyoto Univ. (Japan); T. Sato, Kyoyo Univ. (Japan) . . . . . [5765-76]

11:10 am: **Support vector regression for structural identification,** J. Zhang, T. Sato, Kyoto Univ. (Japan) . . . . . [5765-77]

11:30 am: **An adaptive extended Kalman filter with unknown inputs for on-line identification of structural parameters,** J. N. Yang, S. Pan, S. Lin, Univ. of California/Irvine . . . . . [5765-78]

11:50 am: **System identification of buildings equipped with closed-loop control devices,** A. Mita, Keio Univ. (Japan); M. Kamibayashi, East Japan Railway Co. (Japan) . . . . . [5765-79]

12:10 pm: **Application of a maximum entropy method to estimate the probability density function of nonlinear or chaotic behavior in structural health monitoring data,** R. A. Livingston, Federal Highway Administration; S. Jin, Wiss, Janney, Elstner . . . . . [5765-80]

Lunch/Exhibition Break . . . . . 12:30 to 1:30 pm

SESSION 18

Towne . . . . . **Wed. 1:30 to 3:10 pm**

SHM for Composite Materials

Chairs: **Kumar Jata**, Air Force Research Lab.; **Francesco Lanza di Scalea**, Univ. of California/San Diego

1:30 pm: **A guided-wave system for monitoring the wing skin-to-spar bond in unmanned aerial vehicles,** H. M. Matt, F. Lanza di Scalea, A. Marzani, S. Coccia, J. A. Oliver, J. B. Kosmatka, P. Rizzo, G. Restivo, Univ. of California/San Diego . . . . . [5765-81]

1:50 pm: **Terahertz plasmonic composites,** A. V. Amirkhizi, S. C. Nemat-Nasser, W. J. Padilla, S. Nemat-Nasser, Univ. of California/San Diego . . . . . [5765-82]

2:10 pm: **Verification of a built-in health monitoring system,** J. Yang, J. Park, F. Chang, Stanford Univ. . . . . [5765-83]

2:30 pm: **Mechanical properties of composite materials with integrated embedded sensor networks,** K. L. Schaaf, S. Nemat-Nasser, A. F. Starr, B. Cook, Univ. of California/San Diego; F. Ghezzo, Univ. degli Studi di Bologna (Italy) . . . . . [5765-84]

2:50 pm: **Sensing technology for integrated embedded sensor networks in composite materials,** A. F. Starr, S. Nemat-Nasser, P. Rye, Univ. of California/San Diego . . . . . [5765-85]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 19

Towne . . . . . **Wed. 3:40 to 5:40 pm**

Vibration SHM and Other Sensors

Chairs: **Harry H. Asada**, Massachusetts Institute of Technology; **Robert X. Gao**, Univ. of Massachusetts/Amherst

3:40 pm: **Generalized harmonic wavelet as an adaptive filter for machine system health diagnosis,** R. Yan, R. X. Gao, Univ. of Massachusetts/Amherst . . . . . [5765-87]

4:00 pm: **Vibration-based piezoelectric micro-power generator: design and optimization,** R. X. Gao, Y. Cui, Univ. of Massachusetts/Amherst . . . . . [5765-86]

4:20 pm: **Development of multivariate statistical tools for damage detection of bladed disks,** J. Tang, Univ. of Connecticut . . . . . [5765-89]

4:40 pm: **Active motion artifact cancellation for wearable health monitoring sensors using collocated MEMS accelerometers,** P. T. Gibbs, H. H. Asada, Massachusetts Institute of Technology . . . . . [5765-90]

5:00 pm: **Detection of crack in thin cylindrical pipes using piezoactuated Lamb waves,** S. Quek, P. Tua, National Univ. of Singapore (Singapore); Q. Wang, Univ. of Central Florida . . . . . [5765-91]

5:20 pm: **Performance of MICA2 Mote for civil engineering applications,** N. Kurata, Kajima Corp. (Japan); B. F. Spencer, Jr., Univ. of Illinois/Urbana-Champaign; M. Ruiz-Sandoval, Univ. Autonoma Metropolitana-Azcapotzalco (Mexico); T. Nagayama, Univ. of Illinois/Urbana-Champaign [5765-92]

Panel Discussion: Industry and Government Agencies Partnership in Sensor Technologies

Chairs: **Shih-Chi Liu**, National Science Foundation; **Rahmat A. Shoureshi**, Univ. of Denver

Sunrise ..... **Wed. 6:00 to 8:00 pm**

Sensor technologies and multifunctional structures: Air Force perspective, Clark L. Allred, B. Les Lee, Air Force Office of Scientific Research

Wireless sensing systems for machines and structures, Steven W. Arms, MicroStrain, Inc.

Development and application of sensors at the Federal Highway Administration, Richard A. Livingston, Federal Highway Administration

Programs on sensors and sensing technologies at the National Science Foundation, Shih-Chi Liu, National Science Foundation; Masayoshi Tomizuka, Univ. of California/Berkeley

Sensors and controls for energy efficiency in industry, public/private partnerships in the national interest, Timothy J. McIntyre, Oak Ridge National Lab.

Smart actuators for steerable munitions, Darryll J. Pines, Univ. of Maryland/College Park

To be announced, K. Thirumalai, U.S. Department of Transportation

Use of fiber optic grating sensors for nondestructive evaluation of composite structures, Eric Udd, Blue Road Research

Thursday 10 March

SESSION 20

Sunrise ..... **Thurs. 9:00 to 10:00 am**

Application to Civil Infra-structures

Chairs: **Jinping Ou**, Harbin Institute of Technology (China); **Akira Mita**, Keio Univ. (Japan)

9:00 am: **Offshore platform real-time health monitoring system based on fieldbus CAN and OPC,** L. He, Harbin Institute Technology (China) ..... [5765-94]

9:20 am: **Adaptive systems for truss and tower systems,** A. Rajaraman, Indian Institute of Technology Madras (India); T. Rengaraja, RMD Engineering College (India) ..... [5765-95]

9:40 am: **Advanced technologies monitoring safety of water conservancy and hydropower engineering,** Z. Wu, C. Gu, H. Su, H. Guo, Hohai Univ. (China) ..... [5765-93]

Coffee Break ..... 10:00 to 10:30 am

SESSION 21

Sunrise ..... **Thurs. 10:30 am to 12:30 pm**

Signal Processing and Damage Detection I

Chairs: **Andrew W. Smyth**, Columbia Univ.; **Kevin S. C. Kuang**, National Univ. of Singapore (Singapore)

10:30 am: **Statistical detection method for time of arrival and frequency of waves,** S. W. Shin, Univ. of Illinois/Chicago and Korea Advanced Institute of Science and Technology (South Korea); G. M. Lloyd, Jr., M. L. Wang, Univ. of Illinois/Chicago ..... [5765-96]

10:50 am: **Wavelet coefficient analysis for the quantitative determination of damage in tendons and cables,** P. Rizzo, F. Lanza di Scalea, Univ. of California/San Diego .... [5765-97]

11:10 am: **Multicomponent signal decomposition techniques for structural health monitoring,** C. Chang, Z. Sun, C. Poon, K. Sze, Hong Kong Univ. of Science and Technology (Hong Kong China) ..... [5765-98]

11:30 am: **Identification of nonlinear normal modes of structures using the empirical-mode decomposition method,** C. Poon, C. Chang, Hong Kong Univ. of Science and Technology (Hong Kong China) ..... [5765-99]

11:50 am: **Structural damage detection using wavelet packet decomposition and probabilistic neural network,** G. Yan, Z. Duan, J. Ou, Harbin Institute of Technology (China) .... [5765-100]

12:10 pm: **Bridge health assessment system based on fuzzy logic algorithms,** X. Wang, M. L. Wang, Y. Zhao, Univ. of Illinois/Chicago ..... [5765-101]

Lunch Break ..... 12:30 to 1:30 pm

SESSION 22

Sunrise ..... **Thurs. 1:30 to 3:10 pm**

Signal Processing and Damage Detection II

Chairs: **Chih-Chen Chang**, Hong Kong Univ. of Science and Technology (Hong Kong China); **Piervincenzo Rizzo**, Univ. of California/San Diego

1:30 pm: **Performance of neural networks for simulation and prediction of temperature-induced modal variability,** H. Zhou, Y. Ni, J. Ko, Hong Kong Polytechnic Univ. (Hong Kong China) ..... [5765-102]

1:50 pm: **Damage assessment of bending structures using support vector machine,** M. Shimada, A. Mita, Keio Univ. (Japan) ..... [5765-103]

2:10 pm: **Structural health monitoring using FFT,** K. E. Loewke, D. A. Meyer, A. F. Starr, S. Nemat-Nasser, Univ. of California/San Diego ..... [5765-104]

2:30 pm: **High-precision photogrammetric technique for structural response measurement,** C. Chang, Y. Ji, Hong Kong Univ. of Science and Technology (Hong Kong China) ..... [5765-105]

2:50 pm: **Metadata and network API aspects of a framework for storing and retrieving civil infrastructure monitoring data,** J. Wong, B. Stojadinovic, Univ. of California/Berkeley ..... [5765-106]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 23

Sunrise ..... **Thurs. 3:40 to 6:00 pm**

SHM for Bridges

Chairs: **Yi-Qing Ni**, Hong Kong Polytechnic Univ. (Hong Kong China); **Richard A. Livingston**, Federal Highway Administration

3:40 pm: **Development and implementation of a nondestructive monitoring system on a composite steel box-girder bridge in Connecticut,** J. T. DeWolf, Univ. of Connecticut; C. D. Virkler, Macchi Engineers, LLC ..... [5765-107]

4:00 pm: **Structural health monitoring of bridges using effective two-step identification approaches,** J. Lee, K. Koo, C. Yun, Korea Advanced Institute of Science and Technology (South Korea) ..... [5765-108]

4:20 pm: **Instrumentation for durability monitoring of a long-span cable-stayed bridge,** X. Hua, Y. Q. Ni, H. F. Zhou, J. M. Ko, The Hong Kong Polytechnic Univ. (Hong Kong China) ..... [5765-109]

4:40 pm: **Intelligent health monitoring systems for cable-stayed bridges,** H. Li, J. Ou, Harbin Institute of Technology (China) ..... [5765-110]

5:00 pm: **Structural health monitoring and risk alarming in plate-girder bridges under uncertain temperature condition,** J. Kim, W. Na, J. Park, Pukyong National Univ. (South Korea); J. S. Lee, Korea Infrastructure Safety & Technology Corp. (South Korea) ..... [5765-111]

5:20 pm: **A bridge structural health monitoring information system based on GIS technology,** W. Z. Shi, Hong Kong Polytechnic Univ. (Hong Kong China) ..... [5765-112]

5:40 pm: **In-service inspection of deck beam bridge,** R. Wang, Wuhan Univ. (China) [5765-113]

■ Conference 5765 End.

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Smart Structures and Materials Participants

Names appearing in boldface are SPIE Members.

H

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Smart Structures and Materials Participants

Names appearing in boldface are SPIE Members.

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Smart Structures and Materials Participants

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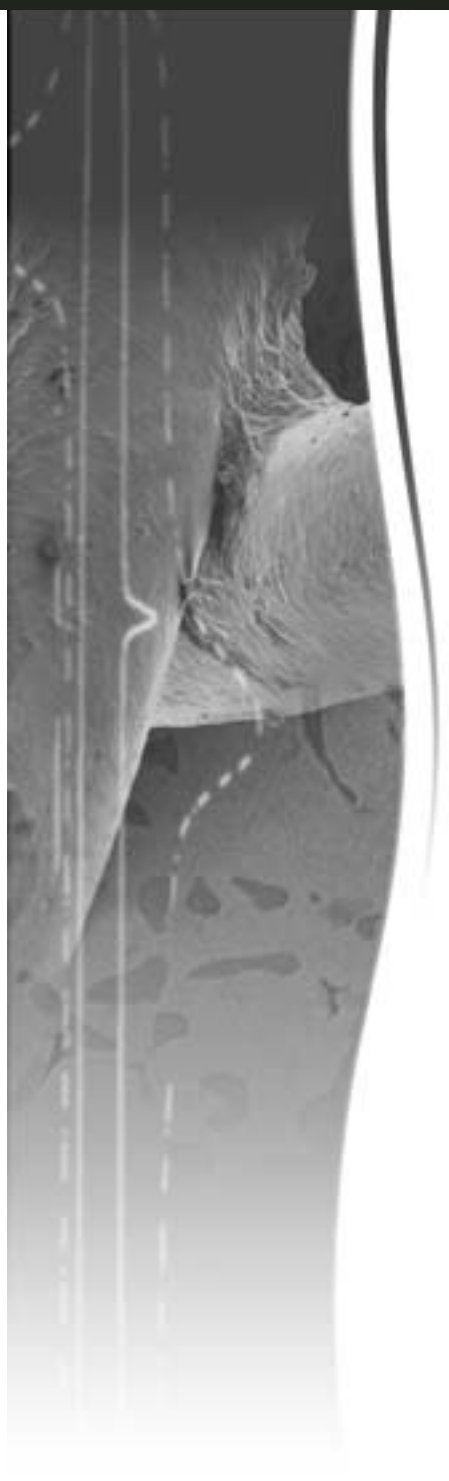

10th SPIE International Symposium

Nondestructive Evaluation for Health Monitoring and Diagnostics

6–10 March 2005
Town and Country Resort & Convention Center
San Diego, California USA

Nondestructive Evaluation Executive Committee

NDE Lifetime Achievement Award

This award will be presented to an individual whose contributions have led to significant advances in research, development, or applications of NDE specifically related to NDE for health monitoring and diagnostics. The selection of this award will be made by the NDE Symposium Planning Committee.

For 2005, we are honored to present this award to:

Professor Jan Achenbach, Northwestern Univ.

Jan Achenbach is Murphy Professor and Distinguished McCormick School of Civil and Environmental Engineering Professor, and Director of the Center for Quality Engineering and Failure Prevention. A thirty-nine year Northwestern faculty member, he is a member of the National Academy of Sciences and the National Academy of Engineering. His research interests include propagation of mechanical disturbances in solids, ultrasonic methods in quantitative nondestructive evaluation, damage mechanisms in composites and vibrations of complex structures. His work with the Institute has involved nondestructive testing and evaluation of bridges with emphasis on testing and modeling of bridge hanger pins and assemblies.

In recent years Professor Achenbach has developed methods for flaw detection and characterization by using contact transducers, imaging techniques and laser-based ultrasonics. He has also developed methods for thin-layer characterization by acoustic microscopy. Work is both analytical and experimental in nature, with extensive cooperation with investigators from other universities and from industrial organizations on theoretical experimental projects. Work in fracture mechanics has been primarily on dynamic fracture. He also carries out research on structural acoustics and on the mechanical behavior of composite materials.

Conference 5766 • San Diego

Wednesday-Thursday 9-10 March 2005
Proceedings of SPIE Vol. 5766

Testing, Reliability, and Application of Micro- and Nano-Material Systems III

Conference Chairs:

Robert E. Geer, Univ. at Albany/SUNY

Norbert Meyendorf, Univ. of Dayton

George Y. Baaklini, NASA Glenn Research Ctr.

Bernd Michel, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

Program Committee: **Joachim F. Baumann**, Siemens AG (Germany); **Bharat Bhushan**, The Ohio State Univ.; **James L. Blackshire**, Air Force Research Lab.; **Jürg Dual**, Swiss Federal Institute of Technology (Switzerland); **Lukas M. Eng**, Technische Univ. Dresden (Germany); **Manfred P. Hentschel**, Bundesanstalt für Materialforschung und -prüfung (Germany); **Thorsten Hesjedal**, Paul Drude Institute (Germany); **D. C. Hurley**, National Institute of Standards and Technology; **Chih-Hao Lee**, National Tsing Hua Univ. (Taiwan); **Eric Lifshin**, Univ. at Albany/SUNY; **Joseph A. Turner**, Univ. of Nebraska/Lincoln; **Matthias R. Werner**, Deutsche Bank AG (Germany); **Klaus-Jürgen Wolter**, Technische Univ. Dresden (Germany); **Kazushi Yamanaka**, Tohoku Univ. (Japan)

Conference 5767 • Royal Palm IV

Tuesday-Thursday 8-10 March 2005
Proceedings of SPIE Vol. 5767

Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure IV

Conference Chairs: **Peter J. Shull**, The Pennsylvania State Univ.; **Andrew L. Gyekenyesi**, NASA Glenn Research Ctr.; **Aftab A. Mufti**, Univ. of Manitoba (Canada)

Program Committee: **Ali Abdul-Aziz**, NASA Glenn Research Ctr. and Cleveland State Univ.; **George Y. Baaklini**, NASA Glenn Research Ctr.; **David K. Hsu**, Iowa State Univ.; **Francesco Lanza di Scalea**, Univ. of California/San Diego; **Richard E. Martin**, Cleveland State Univ. and NASA Glenn Research Ctr.; **Chiaki Miyasaka**, The Pennsylvania State Univ.; **Peter B. Nagy**, Univ. of Cincinnati; **Donald J. Roth**, NASA Glenn Research Ctr.; **Jaswinder S. Sandhu**, Santec Systems, Inc.; **Jerzy T. Sawicki**, Cleveland State Univ.; **Steven M. Shepard**, Thermal Wave Imaging, Inc.; **Graham H. Thomas**, Lawrence Livermore National Lab.; **Bernhard R. Tittmann**, The Pennsylvania State Univ.

Conference 5768 • Royal Palm VI

Monday-Wednesday 7-9 March 2005
Proceedings of SPIE Vol. 5768

Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems IV

Conference Chair: **Tribikram Kundu**, Univ. of Arizona

Cochairs: **Ajit K. Mal**, Univ. of California/Los Angeles; **Yoseph Bar-Cohen**, Jet Propulsion Lab.

Program Committee: **Jürgen Bereiter-Hahn**, J.W. Goethe Univ. (Germany); **Fu-Kuo Chang**, Stanford Univ.; **Yuris A. Dzenis**, Univ. of Nebraska/Lincoln; **Victor Giurgiutiu**, Univ. of South Carolina; **Wolfgang Grill**, Univ. Leipzig (Germany); **Roy Ikegami**, Acellent Technologies; **Sridhar Krishnaswamy**, Northwestern Univ.; **Francesco Lanza di Scalea**, Univ. of California/San Diego; **Michel B. Lemistre**, ONERA (France); **Shih-Chi Liu**, National Science Foundation; **Perngjin F. Pai**, Univ. of Missouri/Columbia; **Dominique Placko**, Ecole Normale Supérieure de Cachan (France); **Reiner Salzer**, Technische Univ. Dresden (Germany); **Christian P. Schultz**, Bruker Optics Inc.; **Amit Shukla**, Miami Univ.; **Bernhard R. Tittmann**, The Pennsylvania State Univ.; **Stephen T. Trickey**, Naval Research Lab.; **Joseph A. Turner**, Univ. of Nebraska/Lincoln; **Wei-Chih Wang**, Univ. of Washington; **Hwai-Chung Wu**, Wayne State Univ.; **George Zentai**, Varian Medical Systems, Inc.

Conference 5769 • Sunset

Monday-Wednesday 7-9 March 2005
Proceedings of SPIE Vol. 5769

Nondestructive Detection and Measurement for Homeland Security III

Conference Chairs:

Aaron A. Diaz, Pacific Northwest National Lab.;

A. Emin Aktan, Drexel Univ.

H. Felix Wu, National Institute of Standards and Technology

Steven R. Doctor, Pacific Northwest National Lab.

Yoseph Bar-Cohen, Jet Propulsion Lab.

Program Committee: **George Y. Baaklini**, NASA Glenn Research Ctr.; **Louise K. Comfort**, Univ. of Pittsburgh; **Sheila Duwadi**, Federal Highway Administration; **Forrest R. Frank**, Institute for Defense Analyses; **Tribikram Kundu**, Univ. of Arizona; **Steven McCabe**, National Science Foundation; **Bernd Michel**, Fraunhofer-Institut für Zuverlässigkeit und Mikroi (Germany); **Kam W. Ng**, Office of Naval Research; **Paul D. Panetta**, Pacific Northwest National Lab.; **Masanobu Shinozuka**, Univ. of California/Irvine; **Glenn A. Washer**, Federal Highway Administration; **Amy M. Waters**, Lawrence Livermore National Lab.; **George Zentai**, Varian Medical Systems, Inc.

Conference 5770 • Room: Sunset

Wednesday-Thursday 9-10 March 2005
Proceedings of SPIE Vol. 5770

Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring

Cooperating Organizations:
Airbus Industries (France)
NASA Glenn Research Ctr.
Ctr. for Materials Diagnostics/Univ. of Dayton
Fraunhofer Institute for Nondestructive Testing (Germany)

Conference Chairs: **Norbert Meyendorf**, Univ. of Dayton

George Y. Baaklini, NASA Glenn Research Ctr.

Bernd Michel, Fraunhofer-Institut for Reliability and Microintegration (Germany)

Program Committee: **Mark Bashkansky**, Naval Research Lab.; **Bharat Bhushan**, The Ohio State Univ.; **James L. Blackshire**, Air Force Research Lab.; **Richard D. Finlayson**, Physical Acoustics Corp.; **Gerald U. Gerlach**, Technische Univ. Dresden (Germany); **Neil J. Goldfine**, JENTEK Sensors, Inc.; **Manfred P. Hentschel**, Bundesanstalt für Materialforschung und -prüfung (Germany); **Albrect Jander**, NVE Corp.; **Silvio Kruger**, National Research Council Canada (Canada); **Stanislave I. Rokhlin**, The Ohio State Univ.; **Jaswinder S. Sandhu**, Santec Systems, Inc.; **Carl Smith**, NVE Corp.; **Holger Speckmann**, Airbus Deutschland GmbH (Germany)

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Conference 5768 | Conference 5769 | Conference 5770

Monday 7 March

8:00 to 10:00 am

Award Presentations

Smart Structures and Materials Achievement Award • NDE Achievement Award • Nondestructive Evaluation Best Paper Award

SSM&NDE Combined Plenary Presentations:

The 'Smart' Path to the Future of Aeronautics, Dr. Richard Wlezien, Director, Vehicle Systems Division, Aeronautics Research Mission Directorate, NASA Headquarters

Optical and Laser NDE: More Than Meets the Eye, Jean-Pierre Monchalin, Industrial Materials Institute/National Research Council Canada (Canada)

Coffee Break 10:00 to 10:30 am

SESSION 1

Royal Palm VI . . Mon. 10:30 am to 12:10 pm

Biological/Medical Applications I

Chairs: **Tribikram Kundu**, Univ. of Arizona; **Wolfgang Grill**, Univ. Leipzig (Germany)

10:30 am: **The pressure and temperature fields generated by focused ultrasound in biological materials,** A. K. Mal, F. Feng, Univ. of California/Los Angeles . . . . . [5768-01]

10:50 am: **The elastic properties of hamster kidney cells evaluated by ultrasonic atomic force microscopy,** B. R. Tittmann, The Pennsylvania State Univ. . . . . [5768-02]

11:10 am: **In-vivo investigation of protein absorption on implant surfaces,** R. Salzer, Technische Univ. Dresden (Germany) . . . . . [5768-03]

11:30 am: **Acoustic phase micrographs in mesoscale materials characterization,** W. Ngwa, W. Luo, Univ. of Central Florida; W. Grill, Univ. Leipzig (Germany); T. Kundu, Univ. of Arizona . . . . . [5768-04]

11:50 am: **Biosystem damage using thermal infrared imagery,** G. La Rosa, A. Risitano, Univ. di Catania (Italy); G. Grasso, S. Avondo, Univ. of Catania (Italy) . . . . . [5768-05]

Lunch Break . . . . . 12:10 to 1:30 pm

SESSION 2

Royal Palm VI . . . . . Mon. 1:30 to 2:50 pm

Biological/Medical Applications II

Chairs: **Reiner Salzer**, Technische Univ. Dresden (Germany); **Wei-Chih Wang**, Univ. of Washington

1:30 pm: **Polymer grating micro pressure sensor,** C. Huang, W. Wang, Univ. of Washington . . . . . [5768-06]

1:50 pm: **Determination of biological cell properties using acoustic microscope,** T. Kundu, Univ. of Arizona; C. Blase, J. Bereiter-Hahn, J. W. Goethe Univ. (Germany) . . . . . [5768-07]

2:10 pm: **Sizing of microbubbles in blood stream based on ultrasound velocity,** B. Kanani, B.K. Pulse Ltd. (United Kingdom) . . . . . [5768-09]

2:30 pm: **Non-destructive testing (NDT) of Sree Chitra heart valves by using holographic interferometry,** P. T. Ajithkumar, S. Ambadiyil, G. Prasannan, Ctr. for Development of Imaging Technology (India) . . . . . [5768-10]

Coffee Break . . . . . 2:50 to 3:30 pm

SESSION 1

Sunset . . . . . Mon. 1:30 to 4:40 pm

Detection and Measurement Techniques in Homeland Security

Chair: **Amy M. Waters**, Lawrence Livermore National Lab.

1:30 pm: **Creating a trusted information network for homeland security *(Invited Paper),*** Z. Baird, Markle Task Force on National Security; T. Lemmey, LENS Ventures . . . . . [5769-01]

2:10 pm: **A new vacuum insulated tandem accelerator for detection of explosives and special nuclear materials,** J. P. Farrell, M. V. Murzina, J. R. Powell, Brookhaven Technology Group, Inc. . . . . [5769-02]

2:30 pm: **Visual identification system for homeland security and law enforcement operations support,** T. J. Samuel, D. Edwards, Pacific Northwest National Lab. . . . . [5769-03]

2:50 pm: **Functional optical brain sensor to monitor deception,** S. C. Bunce, A. Devaraj, M. A. Izzetoglu, B. K. Onaral, K. Pourrezaei, Drexel Univ. . . . . [5769-04]

Coffee Break . . . . . 3:10 to 3:40 pm

Conference 5766

Conference 5767

Tuesday 8 March

8:00 to 8:55 am
NDE Plenary Presentation:
Nondestructive Evaluation Technologies to Defend the Homeland1, Harry E. Martz, Jr., Lawrence Livermore National Lab.

SESSION 1

Royal Palm IV ..... Tues. 9:00 to 11:50 am

NDE of Composite Materials

Chairs: **Bernhard R. Tittmann**, The Pennsylvania State Univ.; **Ali Abdul-Aziz**, NASA Glenn Research Ctr.

9:00 am: **In-situ ultrasonic monitoring of crack growth under static and dynamic loading conditions,** T. E. Michaels, J. E. Michaels, B. Mi, Georgia Institute of Technology .. [5767-01]

9:20 am: **Evaluation of impact-induced damage of CF/AF hybrid fabric composites with scanned image microscopy,** C. Miyasaka, The Pennsylvania State Univ.; H. Kasano, Takushoku Univ. (Japan); P. J. Shull, The Pennsylvania State Univ.[5767-02]

9:40 am: **Composite structures with pre-stress subject to low velocity impact damage,** B. O. Whittingham, Monash Univ. (Australia) ..... [5767-03]

Coffee Break ..... 10:00 to 10:30 am

10:30 am: **Identification of failure modes in composite materials using AET and neural network,** F. Nkrumah, G. Grandhi, B. P. Gandluri, M. J. Sundaresan, North Carolina A&T State Univ. ..... [5767-04]

10:50 am: **Evaluation of stress-induced martensite phase in ferromagnetic shape memory alloy Fe-30.2at%Pd by non-destructive Barkhausen noise,** T. Okazaki, Y. Furuya, Hirosaki Univ. (Japan); M. R. Wuttig, Univ. of Maryland/College Park ..... [5767-05]

11:10 am: **Comparison of normal and phase stepping shearographic NDE,** A. Andhee, J. Gryzagoridis, D. M. Findeis, Univ. of Cape Town (South Africa) ..... [5767-06]

11:30 am: **Use of high frequency dielectric measurements in the NDE of adhesively bonded aluminium joints,** R. A. Pethrick, D. Hayward, B. McConnell, Univ. of Strathclyde (United Kingdom); R. L. Crane, Air Force Research Lab. .... [5767-07]

Lunch Break ..... 11:50 am to 1:30 pm

Conference 5768 | Conference 5769 | Conference 5770

Monday 7 March

SESSION 3

Royal Palm VI ..... Mon. 3:30 to 6:10 pm

Emerging Sensor Technologies

Chairs: **Jerome P. Lynch**, Univ. of Michigan; **Amit Shukla**, Miami Univ.

3:30 pm: **Design of a low-power wireless structural monitoring system for collaborative computational algorithms,** Y. Wang, Stanford Univ.; J. P. Lynch, Univ. of Michigan; K. H. Law, Stanford Univ. ..... [5768-11]

3:50 pm: **Wireless sensor seismic response monitoring system implemented on top of NEESgrid,** J. Wong, B. Stojadinovic, J. Goethals, Univ. of California/Berkeley ..... [5768-12]

4:10 pm: **Wireless structural health monitoring of cyclically loaded bridge piers,** J. P. Lynch, T. Hou, G. Parra-Montesinos, Univ. of Michigan ..... [5768-13]

4:30 pm: **Methodologies for quantifying changes in diffuse ultrasonic signals with applications to structural health monitoring,** J. E. Michaels, Y. Lu, T. E. Michaels, Georgia Institute of Technology ..... [5768-14]

4:50 pm: **Real-time seismic monitoring and functionality assesment of a building,** M. Celebi, U.S. Geological Survey ..... [5768-15]

5:10 pm: **Investigation of data quality in a wireless sensing unit composed of off-the-shelf components,** J. Pei, C. Kapoor, Univ. of Oklahoma; T. L. Graves-Abe, Princeton Univ.; J. P. Lynch, Univ. of Michigan; C. Chu, Y. P. Sugeng, Univ. of Oklahoma ..... [5768-16]

5:30 pm: **Monitoring of bolt preload using piezoelectric active devices,** D. Mascarenas, G. Park, C. R. Farrar, Los Alamos National Lab. ..... [5768-17]

5:50 pm: **Bio-inspired design of sensor system for damage prognosis,** A. Shukla, Miami Univ. ..... [5768-18]

3:40 pm: **Straddle carrier portal,** E. S. Andersen, T. J. Samuel, O. D. Mullen, Pacific Northwest National Lab. ..... [5769-05]

4:00 pm: **Advanced ultrasonic measurement methodology for on-invasive interrogation and identification of fluids in sealed containers,** B. J. Tucker, A. A. Diaz, T. J. Samuel, Pacific Northwest National Lab. ..... [5769-06]

4:20 pm: **Portable source identification device,** E. S. Andersen, T. J. Samuel, K. Gervais, Pacific Northwest National Lab. ..... [5769-07]

Tuesday 8 March

8:00 to 8:55 am

NDE Plenary Presentation:

Nondestructive Evaluation Technologies to Defend the Homeland1, Harry E. Martz, Jr., Lawrence Livermore National Lab.

SESSION 4

Royal Palm VI ..... Tues. 9:00 to 10:00 am

Aerospace Applications

Chairs: **Michel B. Lemistre**, ONERA (France); **Sridhar Krishnaswamy**, Northwestern Univ.

9:00 am: **Identification of damage in a standoff metallic thermal protection system panel subjected to combined thermo-acoustic excitation,** R. J. Hundhausen, Los Alamos National Lab.; D. E. Adams, Purdue Univ.; M. M. Derriso, Air Force Research Lab. ... [5768-19]

9:20 am: **Fusion of visual and eddy current inspection results for the evaluation of corrosion damage in aircraft lap joints,** Z. Liu, D. S. Forsyth, S. Safizadeh, A. Marincak, National Research Council Canada (Canada) ..... [5768-20]

9:40 am: **Feature selection for partial discharge diagnosis,** W. Yan, K. F. Goebel, GE Global Research Ctr. ..... [5768-56]

Coffee/Exhibition Break ..... 10:00 to 10:30 am

SESSION 5

Royal Palm VI ..... Tues. 10:30 am to 12:10 pm

Novel Devices

Chairs: **Ajit K. Mal**, Univ. of California/Los Angeles; **George Zentai**, Varian Medical Systems, Inc.

10:30 am: **Modular dry-coupled ultrasonic probes for field inspections of multi-layered aircraft structures,** I. N. Komsky, Northwestern Univ. ..... [5768-22]

10:50 am: **Scanning-laser-source and microcantilever receiver for detection of surface flaws in microdevices,** Y. Sohn, S. Krishnaswamy, Northwestern Univ. ..... [5768-23]

11:10 am: **Quantitative magneto-optic imager for non destructive evaluation,** M. B. Lemistre, ONERA (France) and ENS-Cachan (France); P. Joubert, J. Pinassaud, ENS-Cachan (France) .. [5768-24]

11:30 am: **NDT of wafer direct bonding by non-confocal transmission phase sensitive acoustic microscopy,** E. Twerdowski, R. Wannemacher, W. Grill, Univ. Leipzig (Germany) ..... [5768-25]

11:50 am: **Hybrid electromagnetic method for NDE of GFRP and CFRP composite materials,** M. B. Lemistre, ONERA (France) and ENS-Cachan (France) ..... [5768-26]

Lunch/Exhibition Break ..... 12:10 to 1:30 pm

SESSION 2

Sunset ..... Tues. 9:00 to 11:30 am

Wireless Sensor Technology for Homeland Security

Chairs: **H. Felix Wu**, National Institute of Standards and Technology; **Maria Q. Feng**, Univ. of California/Irvine

9:00 am: **Wireless structural monitoring for homeland security applications *(Invited Paper),*** A. Kiremijdian, Stanford Univ.; G. K. Kiremidjian, B. Benco, Sensametrics, Inc.; E. Caryer, Stanford Univ. ..... [5769-08]

9:40 am: **Detection of chemical, biological, and radiological hazard materials on highway transportation systems using nanotechnology-based wireless sensors,** M. Saafi, P. Shansez, P. Romine, Alabama A&M Univ. ..... [5769-10]

Coffee Break ..... 10:00 to 10:30 am

10:30 am: **Managed traffic evacuation using distributed sensor processing,** S. Biswas, P. Ramuhalli, Michigan State Univ. ..... [5769-11]

10:50 am: **CREM monitoring: a wireless RF application,** J. D. Valencia, B. J. Burghard, J. R. Skorpik, K. L. Silvers, Pacific Northwest National Lab. ..... [5769-12]

11:10 am: **DuraNode: wireless network sensor for structural safety monitoring,** H. Chung, ImageCat, Inc.; C. Park, Q. Xie, P. H. Chou, M. Shinozuka, Univ. of California/Irvine .. [5769-13]

Lunch Break ..... 11:30 am to 1:30 pm

Conference 5766

Conference 5767

Tuesday 8 March

SESSION 2

Royal Palm IV ..... Tues. 1:30 to 3:10 pm

Guided Wave Inspection of Materials

Chairs: **Ali Abdul-Aziz**, NASA Glenn Research Ctr.; **Richard E. Martin**, Cleveland State Univ.

1:30 pm: **Novel guided-wave based damage detection method for arbitrary defects,** M. Yang, P. Qiao, Univ. of Akron ..... [5767-09]

1:50 pm: **Traverse and longitudinal crack detection in the head of rail tracks using Rayleigh wave-like wideband guided ultrasonic waves,** S. B. Palmer, S. Dixon, R. Edwards, X. Jian, Univ. of Warwick (United Kingdom) ..... [5767-10]

2:10 pm: **Experimental investigation of damage detection on composite plates using wave analysis,** W. Lestari, P. Qiao, Univ. of Akron ..... [5767-11]

2:30 pm: **Response of FBG sensors to Lamb wave propagation and its application to active sensing,** H. Tsuda, National Institute of Advanced Industrial Science and Technology (Japan) ..... [5767-12]

2:50 pm: **Estimation of corrosion damage in steel reinforced concrete using wave guides,** H. L. Reis, B. Ervin, D. A. Kuchma, J. T. Bernhard, Univ. of Illinois/Urbana-Champaign ..... [5767-13]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 3

Royal Palm IV ..... Tues. 3:40 to 6:20 pm

ISIS Canada Session on Data Management and Damage Detection

Chair: **Ashutosh Bagchi**, Concordia Univ. (Canada)

3:40 pm: **Damage detection on a steel-free bridge deck using random vibration,** Z. Zhou, L. D. Wegner, B. Sparling, Univ. of Saskatchewan (Canada) ..... [5767-14]

4:00 pm: **Application of artificial neural networks in vibration based damage detection,** H. Xu, J. M. Humar, Carleton Univ. (Canada) ..... [5767-15]

4:20 pm: **Improved iterative regularization for vibration-based damage detection,** B. Weber, P. Paultre, J. Proulx, Univ. of Sherbrooke (Canada) ..... [5767-16]

4:40 pm: **Characterization of system sensitivity in SHM event-detection systems,** L. Card, D. K. McNeill, Univ. of Manitoba (Canada) ..... [5767-17]

5:00 pm: **Developing an SHM system for FRP-strengthened beams,** J. P. Newhook, Dalhousie Univ. (Canada) .. [5767-18]

5:20 pm: **Rugged and affordable wireless micromachined sensors for civil infrastructure,** M. Saafi, P. Shansez, P. Romie, Alabama A&M Univ. ..... [5767-19]

5:40 pm: **Comparison of strain measurements using polyimide and acrylate recoated FBG sensors,** D. J. Thomson, E. Rivera, A. A. Mufti, Univ. of Manitoba (Canada) . [5767-20]

6:00 pm: **Determination of residual stresses using laser-generated surface skimming longitudinal waves,** J. Monchalin, C. Bescond, D. Levesque, A. Gilbert, R. Talbot, M. Ochiai, National Research Council Canada (Canada) [5767-58]

Conference 5768 | Conference 5769 | Conference 5770

Tuesday 8 March

SESSION 6

Royal Palm VI ..... Tues. 1:30 to 3:10 pm

Signal Processing for Diagnosis and Prognosis I

Chairs: **Stephen T. Trickey**, Naval Research Lab.; **Shivan Haran**, Arkansas State Univ.

1:30 pm: **Analysis of chaotic vibrations for damage detection in structures,** L. M. Pecora, L. Moniz, J. M. Nichols, S. T. Trickey, M. E. Seaver, Naval Research Lab. ..... [5768-27]

1:50 pm: **Exploring damage sensitivity of state-space-based prediction error methods for structural health monitoring,** L. Overbey, C. C. Olson, M. D. Todd, Univ. of California/San Diego ..... [5768-28]

2:10 pm: **Sensitivity and computational comparison of state-space methods for structural health monitoring,** C. C. Olson, L. A. Overbey, M. D. Todd, Univ. of California/San Diego ..... [5768-29]

2:30 pm: **Piezoelectric active sensing using chaotic excitations and state space reconstruction,** T. R. Fasel, M. D. Todd, Univ. of California/San Diego; G. Park, Los Alamos National Lab.; H. Sohn, Carnegie-Mellon Univ.; C. R. Farrar, Los Alamos National Lab. ..... [5768-30]

2:50 pm: **Detecting nonlinearity in a frame experiment with measures of information flow and interdependence,** M. D. Todd, Univ. of California/San Diego; J. M. Nichols, Naval Research Lab.; L. Overbey, C. C. Olson, Univ. of California/San Diego ..... [5768-31]

Coffee/Exhibition Break ..... 3:10 to 3:40 pm

SESSION 7

Royal Palm VI ..... Tues. 3:40 to 6:00 pm

Guided Waves

Chairs: **Francesco Lanza di Scalea**, Univ. of California/San Diego; **Joseph A. Turner**, Univ. of Nebraska/Lincoln

3:40 pm: **High-speed defect detection in rails by non-contact guided ultrasonic testing,** F. Lanza di Scalea, I. Bartoli, P. Rizzo, Univ. of California/San Diego; M. A. Fateh, Federal Railroad Administration ..... [5768-32]

4:00 pm: **Underground pipe inspection by guided waves using wavelet analysis,** R. Ahmad, S. Banerjee, T. Kundu, Univ. of Arizona ..... [5768-33]

4:20 pm: **Health monitoring of composite structures using Lamb waves,** A. K. Mal, Univ. of California/Los Angeles; F. Shih, Seattle Univ.; S. Banerjee, Univ. of California/Los Angeles ..... [5768-34]

4:40 pm: **Improved attenuation calculation algorithm for multi-mode, transient leaky Lamb waves and its use in material characterization,** K. Luangvilai, L. J. Jacobs, Georgia Institute of Technology; J. Qu, Goergia Institute of Technology ..... [5768-35]

5:00 pm: **Novel methods of Lamb wave detection for material damage detection and location,** G. J. Thursby, B. Sorazu, Univ. of Strathclyde (United Kingdom); D. C. Betz, DaimlerChrysler AG (Germany); B. Culshaw, Univ. of Strathclyde (United Kingdom) ..... [5768-36]

5:20 pm: **Elastic wave propagation in corrugated plates,** S. Banerjee, T. Kundu, Univ. of Arizona ..... [5768-37]

5:40 pm: **Three-dimensional guided waves in laminated composite plates excited from a point source,** P. Banerji, S. Nayak, Indian Institute of Technology Bombay (India) ..... [5768-38]

SESSION 3

Sunset ..... Tues. 1:30 to 3:10 pm

Condition Assessment of Civil Infrastructure in Homeland Security

Chairs: **Maria Q. Feng**, Univ. of California/Irvine; **H. Felix Wu**, National Institute of Standards and Technology

1:30 pm: **The role of uncertainty in evaluating condition and vulnerability of constructed systems,** K. Ciloglu, Q. Pan, K. A. Grimmelsman, Drexel Univ.; F. N. Catbas, Univ. of Central Florida; A. E. Aktan, Drexel Univ. ..... [5769-14]

1:50 pm: **Fatigue crack propagation of magnesium alloy in biaxial stress fields,** Y. Itoh, National Research Institute of Police Science (Japan); A. Shimamoto, Saitama Institute of Technology (Japan) ..... [5769-15]

2:10 pm: **Some issues in condition assessment of large structures using dynamic measurements,** F. N. Catbas, Univ. of Central Florida; A. E. Aktan, Drexel Univ. ..... [5769-16]

2:30 pm: **Global structural condition assessment of highway bridges,** M. Q. Feng, Y. Chen, Univ. of California/Irvine; C. Tan, Wayne State Univ. ..... [5769-17]

2:50 pm: **Acoustic emission monitoring of structural perturbations with serially multiplexed optical fiber sensors,** Y. Liang, Northwestern Univ.; C. Sun, Dalian Univ. of Technology (China); F. Ansari, Univ. of Illinois/Chicago ..... [5769-18]

Coffee Break ..... 3:10 to 3:40 pm

SESSION 4

Sunset ..... Tues. 3:40 to 5:20 pm

Structural Health Monitoring in Homeland Security

Chair: **Brian J. Tucker**, Pacific Northwest National Lab.

3:40 pm: **Dynamic hyperspectral imaging,** M. V. Murzina IV, J. P. Farrell, Brookhaven Technology Group, Inc. .... [5769-20]

4:00 pm: **Hyperspectral characterization of adjustable nano-coating systems,** M. V. Murzina IV, J. P. Farrell, O. A. Aksipetrov, T. V. Murzina, Brookhaven Technology Group, Inc. ..... [5769-21]

4:20 pm: **Detection of gas leaks in the subsurface environment,** M. Ghandehari, Polytechnic Univ.; G. Khalil, Univ. of Washington ..... [5769-22]

4:40 pm: **SMART sensing solutions for homeland security,** H. Chan, Acellent Technologies, Inc.; H. F. Wu, National Institute of Standards and Technology; A. Kumar, S. J. Beard, X. Qing, M. Hamilton, C. Zhang, Acellent Technologies, Inc. [5769-23]

5:00 pm: **A conceptual framework for intelligent monitoring systems: a response to terrorist attack or catastrophic accidents in critical infrastructure,** R. D. Finlayson, Physical Acoustics Corp.; J. N. Meegoda, T. M. Juliano, New Jersey Institute of Technology ..... [5769-24]

Conference 5766 | Conference 5767

Tuesday 8 March

✔ Posters-Tuesday

The following posters will be displayed in the formal Poster Session and Exhibition Reception on Tuesday evening from 6:00 to 7:30 pm. Authors will be present during this time for discussion. Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed after 4:00 pm before the formal poster session begins at 6:00 pm.

Conference 5768 | Conference 5769 | Conference 5770

Tuesday 8 March

✔ Posters-Tuesday

The following posters will be displayed in the formal Poster Session and Exhibition Reception on Tuesday evening from 6:00 to 7:30 pm. Authors will be present during this time for discussion. Poster authors will be able to set up their poster papers between 10:00 am and 4:00 pm Tuesday. Poster papers can be previewed after 4:00 pm before the formal poster session begins at 6:00 pm.

Conference 5766

Conference 5767

Wednesday 9 March

8:00 to 8:55 am

NDE Plenary Presentation:
Science and Technology Challenges in Screening for Radiological and Nuclear Materials,
Michael Carter, Dept. of Homeland Security

SESSION A

Royal Palm II . . . . . Wed. 9:00 am

Chair Welcome and Opening Remarks

Chair: **Robert E. Geer**, Univ. at Albany/SUNY

SESSION 1

Royal Palm II . . . . . Wed. 9:20 to 11:50 am

X-ray Tomography and Small-Angle Scattering for Nondestructive Testing/ Reliability I

Keynote

9:20 am: **X-ray refraction topography and computed tomography for NDE of lightweight materials,** B. R. Müller, A. Lange, M. Harwardt, M. P. Hentschel, B. J. Illerhaus, J. Goebbels, Bundesanstalt für Materialforschung und-prüfung (Germany); J. Bamberg, F. Heutling, Technische Univ. München (Germany) . . . . . [5766-01]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **X-ray diffraction topography images materials by molecular probe,** M. P. Hentschel, A. Lange, J. Schors, O. Wald, Bundesanstalt für Materialforschung und-prüfung (Germany) . . . . . [5766-02]

10:50 am: **Micro-mechanical properties of fiber composites characterized by X-ray-refraction *(Invited Paper),*** V. Trappe, M. P. Hentschel, Bundesanstalt für Materialforschung und-prüfung (Germany) . . . . . [5766-03]

11:30 am: **Direct iterative reconstruction of computed tomography trajectories (DIRECTT),** M. P. Hentschel, A. Lange, J. Schors, Bundesanstalt für Materialforschung und-prüfung (Germany) . . . . . [5766-04]

Lunch Break . . . . . 11:50 am to 1:30 pm

SESSION 2

San Diego . . . . . Wed. 1:30 to 3:10 pm

X-ray Tomography and Small-Angle Scattering for Nondestructive Testing/ Reliability II

1:30 pm: **X-ray reflectometry and small-angle X-ray scattering *(Invited Paper),*** R. J. Matyi, National Institute of Standards and Technology . . . . . [5766-05]

2:10 pm: **Nondestructive characterization of nanoparticles in solid states by Raman spectroscopy and small angle x-ray scattering,** M. Herms, Fraunhofer-Institut für Zerstörungsfreie Prüfverfa (Germany); G. Irmer, Technische Univ. Freiberg (Germany); P. Verma, Osaka Univ. (Japan); G. Goerigk, DESY Hamburg (Germany) and Forschungszentrum Jülich (Germany) . . . . . [5766-06]

2:30 pm: **High-resolution x-ray microscopy for NDE of micro- and nano-structrues *(Invited Paper),*** S. Wang, Xradia, Inc. . . . . [5766-07]

Coffee Break . . . . . 3:10 to 3:40 pm

SESSION 4

Royal Palm IV . . . Wed. 9:00 am to 12:10 pm

ISIS Canada Session on Field Application of SHM Systems

Chair: **John P. Newhook**, Dalhousie Univ. (Canada)

9:00 am: **Some practical issues in remote structural health monitoring,** L. Han, Univ. of Manitoba (Canada) and ISIS Canada (Canada); J. P. Newhook, Dalhousie Univ. (Canada) and ISIS Canada (Canada); A. Mufti, Univ. of Manitoba (Canada) and ISIS Canada (Canada) . . . . . [5767-21]

9:20 am: **The implementation of civionics in a second generation steel free bridge deck,** C. Klowak, Univ. of Manitoba (Canada) and ISIS Canada (Canada); E. Rivera, Univ. of Manitoba (Canada); A. A. Mufti, Univ. of Manitoba (Canada) and ISIS Canada (Canada) . . . . . [5767-22]

9:40 am: **Impact resonance method for fatigue damage detection in RC beams strengthened with CFRPs,** C. Gheorghiu, Univ. of Manitoba (Canada); P. Labossiere, J. E. Rhazi, Univ. de Sherbrooke (Canada) . . . . . [5767-23]

Coffee Break . . . . . 10:00 to 10:30 am

10:30 am: **SHM data interpretation and structural condition assessment of the Manitoba Golden Boy,** B. A. Bogdabovic, A. A. Mufti, Univ. of Manitoba (Canada); A. Bagchi, Concordia Univ. (Canada) . . . . . [5767-24]

10:50 am: **Application of vibration-based damage detection to an integral abutment bridge,** A. B. Siddique, L. D. Wegner, B. Sparling, Univ. of Saskatchewan (Canada) . . . . . [5767-25]

11:10 am: **Electromagnetic and elastic wave scattering and imaging for multi-mode nondestructive testing of concrete,** K. J. Langenberg, Univ. Kassel (Germany) . . . . . [5767-26]

11:30 am: **Distributed cable sensors with memory feature for post-disaster damage assessment,** G. Chen, R. McDaniel, S. Sun, D. J. Pommerenke, Univ. of Missouri/Rolla . . . [5767-27]

11:50 am: **Characterization of dented pipelines utilizing ultrasonic velocity measurements,** P. D. Panetta, Pacific Northwest National Lab.; G. Alers, EMAT Consulting [5767-28]

Lunch Break . . . . . 12:10 to 1:30 pm

SESSION 5

Royal Palm IV . . . . . Wed. 1:30 to 3:10 pm

NDE Modeling: Aerospace Materials

Chairs: **Louis J. Ghosn**, Ohio Aerospace Institute; **Laura M. Cosgriff**, Cleveland State Univ.

1:30 pm: **Modeling of active fiber composite for delamination sensing,** K. T. Ajay, P. J. Guruprasad, D. Harursampath, Indian Institute of Science (India) . . . . . [5767-29]

1:50 pm: **Structural assessment of metal foam,** L. J. Ghosn, Ohio Aerospace Institute; A. Abdul-Aziz, NASA Glenn Research Ctr.; P. G. Young, Univ. of Exeter (United Kingdom); R. W. Rauser, Univ. of Toledo . . . . . [5767-30]

2:10 pm: **Application of finite element modelling to predicting the effects of short-term post-weld heat treatments on residual stresses in flashbutt welds,** D. Tawfik, Monash Univ. (Australia) . . . . . [5767-31]

2:30 pm: **Finite element calibration of pulse phase IR thermography for the NDE of composite structures,** M. Krishnapillai, Monash Univ. (Australia) . . . . . [5767-32]

2:50 pm: **Detection of micro scale changes in structures from vibration data,** K. V. Singh, G. Li, Louisiana State Univ. . . . . [5767-33]

Coffee Break . . . . . 3:10 to 3:40 pm

Conference 5768 | Conference 5769 | Conference 5770

Wednesday 9 March

8:00 to 8:55 am

NDE Plenary Presentation:
Science and Technology Challenges in Screening for Radiological and Nuclear Materials,
Michael Carter, Dept. of Homeland Security

SESSION 8

Royal Palm VI ..... Wed. 9:00 to 10:00 am

Civil Engineering and Infrastructure Applications

Chairs: **Hwai-Chung Wu**, Wayne State Univ.; **Masoud Ghandehari**, Polytechnic Univ.

9:00 am: **Study of embedded wireless sensors network for application to SHM of bridges,** S. Haran, J. Cole, B. Hampton, Arkansas State Univ. ..... [5768-39]

9:20 am: **Noise reduction in wireless strain sensors,** D. J. Thomson, J. Chuang, G. E. Bridges, Univ. of Manitoba (Canada) ..... [5768-40]

9:40 am: **FBG sensors for the measurement of the dynamic response of offshore storage tank platform model,** S. Li, H. N. Li, Dalian Univ. of Technology (China) ..... [5768-41]

Coffee/Exhibition Break ..... 10:00 to 10:30 am

SESSION 9

Royal Palm VI .. Wed. 10:30 am to 12:10 pm

Signal Processing for Diagnosis and Prognosis II

Chairs: **Shivan Haran**, Arkansas State Univ.; **Stephen T. Trickey**, Naval Research Lab.

10:30 am: **Structural health monitoring and life prediction system for fatigue damaged components,** L. Sun, S. S. Kulkarni, S. Krishnaswamy, B. J. Moran, J. D. Achenbach, Northwestern Univ. ..... [5768-42]

10:50 am: **Important factors of input excitation in vibration based damage detection,** S. T. Trickey, J. M. Nichols, M. E. Seaver, Naval Research Lab. ..... [5768-43]

11:10 am: **Examining coupling in structural dynamics using information flow,** J. M. Nichols, Naval Research Lab. [5768-44]

11:30 am: **On a bifurcation theory based prognosis methodology for characterizing multiple damage mechanisms,** P. Mejia, A. Shukla, Miami Univ. .... [5768-45]

11:50 am: **Damage assessment of an isolation system,** L. W. Salvino, Naval Surface Warfare Ctr. ..... [5768-46]

Lunch/Exhibition Break ..... 12:10 to 1:30 pm

SESSION 10

Royal Palm VI .....Wed. 1:30 to 3:10 pm

Damage Detection for Diagnosis and Prognosis

Chairs: **Victor Giurgiutiu**, Univ. of South Carolina; **Perngjin F. Pai**, Univ. of Missouri/Columbia

1:30 pm: **Effect of geometric non-linearity on acoustic modulation,** H. Wu, Wayne State Univ. ..... [5768-47]

1:50 pm: **Multi-damage detection with embedded ultrasonic structural radar algorithm using piezoelectric wafer active sensors through advanced signal processing,** L. Yu, V. Giurgiutiu, Univ. of South Carolina ..... [5768-48]

2:10 pm: **Thermo-acoustic emission method of failure prediction of composites,** E. G. Nesvijski, Univ. of Minnesota ..... [5768-49]

2:30 pm: **Dynamics-based model-independent local inspection method for damage detection of large structures,** P. F. Pai, L. Huang, Univ. of Missouri/Columbia ... [5768-50]

2:50 pm: **Vision system using linear CCD cameras in fluorescent magnetic particle inspection of axles of railway wheelsets,** H. Hao, L. Li, Tsinghua Univ. (China) ... [5768-51]

■ Conference 5768 End.

SESSION 5

Sunset ..... Wed. 9:00 to 10:50 am

Science and Technology Needs in Homeland Security: Government-Industry-Academia Partnerships

Chairs: **Eric S. Andersen**, Pacific Northwest National Lab.; **Harry E. Martz**, Lawrence Livermore National Lab.; **Michael R. Carter**, Dept. of Homeland Security and Lawrence Livermore National Lab.; **Laura Petonito**, Dept. of Homeland Security; **Kenneth Blank**, Drexel Univ.; **Masanobu Shinozuka**, Univ. of California/Irvine; **H. Felix Wu**, National Institute of Standards and Technology

Coffee Break ..... 9:00 to 9:30 am

Homeland Security Panel Discussion

Wed. 9:00 am to 12:00 pm

THEME: "Science and Technology Needs in Homeland Security: Government-Industry-Academia Partnerships

Facilitator: **Eric S. Andersen,** Pacific Northwest National Lab.

Distinguished Panelists: **Harry Martz,** Lawrence Livermore National Lab.; **Michael Carter, Laura Petonito,** Dept. of Homeland Security; **Ken Blank,** Drexel Univ.; **Masanobu Shinozuka,** Univ. of California/Irvine; **H. Felix Wu,** National Institute of Standards and Technology

Agenda:

9:00 am: **Opening Remarks and Introductions**
9:10 to 10:10 am: **Panelist Presentations**
9:10 am: **Dr. Martz**
9:20 am: **Dr. Carter**
9:30 am: **Dr. Petonito**
9:40 am: **Dr. Blank**
9:50 am: **Dr. Shinozuka**
10:00 am: **Dr. Wu**
10:10 to 10:30 am: Coffee Break
10:30 am to 12:00 pm: **Open Panel Forum** (Questions and Audience Participation)

■ Conference 5769 End.

SESSION 1

Sunset .....Wed. 1:30 to 3:10 pm

Applications of Electro-magnetic Sensors

Chair: **Norbert Meyendorf**, Univ. of Dayton

1:30 pm: **Magnetoresistive sensors for nondestructive evaluation *(Invited Paper),*** A. Jander, Oregon State Univ. and NVE Corp.; C. Smith, R. Schneider, NVE Corp. ..... [5770-01]

2:10 pm: **Health monitoring using MWM®-Array and IDED-Array sensor networks,** A. P. Washabaugh, D. Grundy, D. E. Schlicker, I. Shay, N. J. Goldfine, JENTEK Sensors, Inc. ..... [5770-02]

2:30 pm: **Transient magnetic flux leakage NDT technique for ferro-magnetic materials inspection,** G. Y. Tian, S. Zairi, A. Sophian, Univ. of Huddersfield (United Kingdom) . [5770-03]

2:50 pm: **Radar sensor for monitoring the injection moulding processes,** C. Sklarczyk, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); M. Knoblauch-Xander, Fraunhofer-Institut für Chemische Technologie (Germany) ..... [5770-04]

Coffee Break ..... 3:10 to 3:40 pm

Conference 5766

Conference 5767

Wednesday 9 March

SESSION 3

San Diego . . . . . Wed. 3:40 to 5:40 pm

Electron/Ion/Photon Techniques for Characterization of Nanoscale and Microscale Materials and Structures

3:40 pm: **Self-regulating charge control for ultra high-resolution scanning electron microscopy *(Invited Paper),*** M. Toth, FEI Company; B. Thiel, Univ. at Albany/SUNY; W. R. Knowles, FEI Company . . . . . [5766-08]

4:20 pm: **FIB based measurements for material characterization on MEMS structures,** D. W. Vogel, D. Lieske, B. Michel, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration Berlin (Germany) . . . . . [5766-09]

4:40 pm: **3D reconstructive imaging of Cu/W/SiO2 integrated circuit interconnect structures through FIBSEM *(Invited Paper),*** J. Evertsen, E. Lifshin, Univ. at Albany/SUNY [5766-10]

5:20 pm: **Application of photo and particle acoustic methods,** B. Koehler, F. Schubert, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); A. Peiffer, EADS Deutschland GmbH (Germany); G. Hentges, Siemens AG (Germany); N. Meyendorf, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany) . . . . . [5766-11]

SESSION 6

Royal Palm IV . . . . . Wed. 3:40 to 5:40 pm

NDE and Health Monitoring of Aerospace Structures I

Chairs: **Jerzy T. Sawicki**, Cleveland State Univ.; **Andrew L. Gyekenyesi**, NASA Glenn Research Ctr.

3:40 pm: **Fatigue and damage tolerance evaluation of an aircraft spoiler,** S. Hurlebaus, L. Gaul, Univ. Stuttgart (Germany) . . . . . [5767-34]

4:00 pm: **Evaluation of modal-based damage detection techniques for composite aircraft sandwich structures,** J. B. Kosmatka, J. Oliver, Univ. of California/San Diego . [5767-35]

4:20 pm: **Application of modal analysis with Hilbert-Huang transforms for spar-skin disbond detection in a lightweight composite aircraft wings,** J. B. Kosmatka, J. Oliver, Univ. of California/San Diego . . . . . [5767-36]

4:40 pm: **Impact damage detection in composite structures using Lamb waves and scanning laser vibrometry,** W. J. Staszewski, F. L. Scarpa, Univ. of Sheffield (United Kingdom) . . . . . [5767-37]

5:00 pm: **Application of nonlinear dynamic analysis for diagnosis of cracked rotor vibration signatures,** J. T. Sawicki, X. Wu, Cleveland State Univ.; A. L. Gyekenyesi, G. Y. Baaklini, NASA Glenn Research Ctr. . . . . [5767-38]

5:20 pm: **Finite element design study of a bladed, flat rotating disk to simulate cracking in a typical turbine disk,** A. Abdul-Aziz, J. J. Trudell, G. Y. Baaklini, NASA Glenn Research Ctr. . . . . [5767-39]

Thursday 10 March

8:00 to 8:55 am

Plenary Presentation:
Smart Structures and Materials Technology Applications for Network Centric Warfare Systems,
Dr. Jack H. Jacobs, Honeywell, Inc.

SESSION 4

San Diego . . . . . Thurs. 9:00 am to 12:30 pm

Acoustic and Nanomechanical Analyses of Nanoscale and Microscale Materials and Structures I

9:00 am: **Elastic modulus of nanomaterials: resonant contact-AFM measurement and reduced-size effects *(Invited Paper),*** B. Nysten, S. Cuenot, Univ. Catholique de Louvain (Belgium); C. Frétigny, ESPCI/CNRS UMR (France) . . . . . [5766-12]

9:40 am: **Ultrasonic characterization of the mechanical properties of thin film coatings,** F. Zhang, S. Krishnaswamy, Northwestern Univ.; D. Fei, D. A. Rebinsky, Caterpillar Inc. . . . . [5766-13]

Coffee Break . . . . . 10:00 to 10:30 am

SESSION 7

Royal Palm IV . . Thurs. 9:00 am to 12:10 pm

NDE and Health Monitoring of Aerospace Structures II

Chairs: **Richard E. Martin**, Cleveland State Univ.; **Laura M. Cosgriff**, Cleveland State Univ.

9:00 am: **Quadrupole resonance as a nondestructive evaluation technique for aerospace materials,** C. R. Ward, S. A. Vierkotter, Quantum Magnetics, Inc. . . . . [5767-40]

9:20 am: **Inspecting multilayered air space structures using ultrasonic narrowband spectroscopy,** T. Stepinski, M. Jonsson, Uppsala Univ. (Sweden) . . . . . [5767-41]

9:40 am: **Phased array transducers for damage detection in aircraft structures,** J. Pena Macias, Gamesa Desarrollos Aeronauticos (Spain); C. Perez, R. Martinez-Ona, Tecnatom, S.A. (Spain); Y. Gomez, F. Montero, Instituto de Acustica (Spain); G. Kawiecki, Gamesa Desarrollos Aeronauticos (Spain) . . . . . [5767-42]

Coffee Break . . . . . 10:00 to 10:30 am

Conference 5770

Wednesday 9 March

SESSION 2

Sunset ..... Wed. 3:40 to 5:40 pm

Sensors for Vehicle Monitoring

Chair: **Albrecht Jander**, Oregon State Univ.

3:40 pm: **Using magnetoresistive sensors for a sensitivity quantum leap in aircraft nondestructive evaluation (NDE) *(Invited Paper),*** R. D. Rempt, Boeing Phantom Works[5770-05]

4:20 pm: **Hollow shaft integrated health monitoring system for railroad wheels,** B. Frankenstein, D. Hentschel, E. Pridoehl, F. Schubert, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany) .....[5770-06]

4:40 pm: **Development of acoustic health monitoring for railroad tank cars,** R. Finlayson, V. Godinez, R. Gostautas, Jr., A. Pollock, Physical Acoustics Corp.; J. Pena, Federal Railroad Association ..... [5770-07]

5:00 pm: **Characterization of sensor performance and durability for structural health monitoring systems,** J. L. Blackshire, Air Force Research Lab.; V. Giurgiutiu, Univ. of South Carolina; A. Cooney, Air Force Research Lab.; J. Doane, Univ. of South Carolina .....[5770-08]

5:20 pm: **The use of embedded sensors for the monitoring of adhesive joints in marine environments,** S. T. McGovern, G. M. Spinks, G. G. Wallace, Univ. of Wollongong (Australia) .....[5770-09]

Thursday 10 March

8:00 to 8:55 am

Plenary Presentation:
Smart Structures and Materials Technology Applications for Network Centric Warfare Systems,
Dr. Jack H. Jacobs, Honeywell, Inc.

SESSION 3

Sunset ..... Thurs. 9:00 to 10:00 am

Applications of Special Sensing Principles

Chair: **George Y. Baaklini**, NASA Glenn Research Ctr.

9:00 am: **Smart coatings for health monitoring and nondestructive evaluation *(Invited Paper),*** T. J. Bencic, NASA Glenn Research Ctr.; J. I. Eldridge, NASA Glenn Research Ctr ..... [5770-10]

9:40 am: **Materials investigations of gallium arsenide for direct converting energy sensitive x-ray detectors,** M. Kroening, I. Besse, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); T. Baumbach, Forschungszentrum Karlsruhe GmbH (Germany); A. Berthold, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); R. G. Melkadze, T. M. Lezhneva, L. V. Khvedelidze, G. D. Kalandadzes, Tbilisi State Univ. (Georgia) ..... [5770-11]

Coffee Break ..... 10:00 to 10:30 am

Thursday 10 March

Conference 5766

10:30 am: **Nondestructive mechanical imaging of carbon nanotubes,** Y. Zheng, B. Sankaran, R. E. Geer, Univ. at Albany/SUNY . . . . . [5766-14]

10:50 am: **High-resolution imaging of ferroelectric domain structure by ultrasonic atomic force microscopy *(Invited Paper),*** T. Tsuji, Tohoku Univ. (Japan); H. Ogiso, J. Akedo, National Institute of Advanced Industrial Science and Technology (Japan); S. Saito, K. Fukuda, K. Yamanaka, Tohoku Univ. (Japan) . . . . . [5766-15]

11:30 am: **Quantitative nanomechanical imaging with contact-resonance-frequency AFM,** D. C. Hurley, A. B. Kos, P. Rice, M. Kopycinska-Mueller, National Institute of Standards and Technology . . . . . [5766-16]

11:50 am: **Numerical time-domain simulation of wave propagation and scattering in acoustic microscopy for subsurface defect characterization,** F. Schubert, B. Koehler, Fraunhofer-Institut für Zerstörungsfreie Prüfverfa (Germany); P. Zinin, Univ. of Hawaii/Honolulu . . . . . [5766-17]

12:10 pm: **Damage detection in polymer composites with mechanochromatic nanoparticles,** B. F. McCaughey, Beckman Institute . . . . . [5766-18]

Lunch Break . . . . . 12:30 to 1:30 pm

SESSION 5

San Diego . . . . . Thurs. 1:30 to 1:50 pm

Acoustic and Nanomechanical Analyses of Nanoscale and Microscale Materials and Structures II

1:30 pm: **Shearographic technique for NDE analysis of high frequency bending vibrations of microstructures,** L. Ragulskis, Vytautas Magnus Univ. (Lithuania); M. Ragulskis, A. Palevicius, V. Ostasevicius, R. Palevicius, Kaunas Univ. of Technology (Lithuania) . . . . . [5766-19]

SESSION 6

San Diego . . . . . Thurs. 1:50 to 4:40 pm

Near-field Optical Approaches for Nanoscale Analysis of Materials, Structures and Devices

1:50 pm: **Near-field Raman microscopy and spectroscopy *(Invited Paper),*** L. Novotny, N. Anderson, Univ. of Rochester . . . . . [5766-20]

2:30 pm: **Direct observation of molecular vibrations by tip-enhanced near-field scanning optical microscopy *(Invited Paper),*** N. Hayazawa, RIKEN-The Institute of Physical and Chemical Research (Japan); S. Kawata, RIKEN-The Institute of Physical and Chemical Research (Japan) and Osaka Univ. (Japan) . . . . . [5766-21]

Coffee Break . . . . . 3:10 to 3:40 pm

3:40 pm: **Antenna-based near-field scanning optical microscopy *(Invited Paper),*** H. F. Hamann, IBM Thomas J. Watson Research Ctr. . . . . [5766-22]

4:20 pm: **Near-field nano-Raman imaging of Si device structures,** R. E. Geer, J. Atesang, Univ. at Albany/SUNY . . . . . [5766-23]

■ Conference 5766 End.

Conference 5767

10:30 am: **Impedance based detection of corrosion,** G. E. Simmers, Jr., H. A. Sodano, Virginia Polytechnic Institute and State Univ.; G. Park, Los Alamos National Lab.; D. J. Inman, Virginia Polytechnic Institute and State Univ. . . . . [5767-43]

10:50 am: **Recent developments in absolute optical fiber sensors for static and dynamic performance evaluation of ceramic matrix composites at elevated temperature,** J. A. Greene, C. Paye, M. Belcher, Lambda Instruments, Inc. . . . . [5767-44]

11:10 am: **A smart composite patch for aircraft structure repair,** C. K. Wakha, D. J. Pines, P. D. Samuel, Univ. of Maryland/College Park . . . . . [5767-45]

11:30 am: **Application of Hilbert-Huang transform for improved defect detection in terahertz NDE of shuttle tiles,** R. F. Anastasi, E. I. Madaras, NASA Langley Research Ctr. . . . . [5767-46]

11:50 am: **Thermographic characterization of impact damage in SiC/SiC composite materials,** L. M. Cosgriff, Cleveland State Univ. and NASA Glenn Research Ctr.; R. T. Bhatt, S. R. Choi, D. S. Fox, NASA Glenn Research Ctr. . . . . [5767-47]

■ Conference 5767 End.

Conference 5770

Thursday 10 March

SESSION 4

Sunset ..... Thurs. 10:30 am to 12:10 pm

Applications of Acoustic Sensors

Chair: **Michael Kroening**, Fraunhofer-Institut for Nondestructive Testing (Germany)

10:30 am: **Structural damage assessment of propulsion system components by impedance based health monitoring,** R. E. Martin, Cleveland State Univ. and NASA Glenn Research Ctr.; J. T. Sawicki, Cleveland State Univ.; A. L. Gyekneyesi, NASA Glenn Research Ctr. and Ohio Aerospace Institute; G. Y. Baaklini, NASA Glenn Research Ctr. ..... [5770-12]

10:50 am: **Air-coupled ultrasonic NDE of automotive tires,** B. R. Tittmann, J. Du, I. Lucas, The Pennsylvania State Univ. ..... [5770-13]

11:10 am: **Non-uniformity correction and dynamic range extension for acoustography,** D. J. Roth, NASA Glenn Research Ctr.; J. Sandhu, A. Mandlik, Santec Systems Inc.; L. Hertert, The Ohio State Univ.; R. E. Martin, Cleveland State Univ. ..... [5770-14]

11:30 am: **Advancement of wave generation and signal transmission in wire waveguides for structural health monitoring applications,** M. Kropf, M. Pedrick, G. Facco, B. R. Tittmann, The Pennsylvania State Univ. . [5770-15]

11:50 am: **Acoustic emission (AE) health monitoring of diaphragm type couplings using neural network analysis,** R. D. Finlayson, V. Godinez, F. Shu, Physical Acoustics Corp. ..... [5770-16]

Lunch Break ..... 12:10 to 1:30 pm

SESSION 5

Sunset ..... Thurs. 1:30 to 3:10 pm

Sensor Systems for Reliability Problems

Chair: **Bernd Michel**, Fraunhofer-Institut for Reliability and Microintegration (Germany)

1:30 pm: **Sensor modules for structural health monitoring and reliability of components,** M. Kroening, A. Berthold, N. Meyendorf, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany) ..... [5770-17]

1:50 pm: **Microsystem for signal processing applications,** B. Frankenstein, K. Froehlich, D. Hentschel, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); G. Reppe, RHe Microsystems (Germany) [5770-18]

2:10 pm: **Nanoscale deformation measurements for reliability analysis of sensors,** J. Keller, A. Gollhardt, D. Vogel, B. Michel, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany) ..... [5770-19]

2:30 pm: **Smart measurement transducer and information technologies through task of NDE for HMAD,** G. A. Abramchuk, K. Abramchuk, Measurements & Metrologies (Canada) ..... [5770-20]

2:50 pm: **Calibration of GPS for dynamic displacement measurement of long span cable-supported bridges in vertical direction,** W. Chan, Y. Xu, X. Ding, Y. Xiong, W. Dai, The Hong Kong Polytechnic Univ. (Hong Kong China)[5770-21]

Coffee Break ..... 3:10 to 3:30 pm

SESSION 6

Sunset .....Thurs. 3:30 to 4:50 pm

Applications of Optical Sensors and Sensor Systems

Chair: **James L. Blackshire**, Air Force Research Lab.

3:30 pm: **Real-time nondestructive structural health monitoring using support vector machines and wavelets,** A. Bulut, A. K. Singh, Univ. of California/Santa Barbara; P. Shin, T. Fountain, H. Jasso, San Diego Supercomputer Ctr.; L. Yan, A. Elgamal, Univ. of California/San Diego ..... [5770-22]

3:50 pm: **Tunable infrared filter based on elastic polymer springs,** W. Zhang, Univ. of California/Irvine; M. Almasri, Georgia Institute of Technology; A. Kine, J. LaRue, R. D. Nelson, Univ. of California/Irvine ..... [5770-24]

4:10 pm: **Optical fiber gas sensor for remote detection of CH_4 gas in underground mines,** S. Li, Z. Yin, H. Cui, Stevens Institute of Technology ..... [5770-25]

4:30 pm: **Development of tube-packaged FBG strain sensor and application in the vibration experiment of submarine pipeline model,** L. Ren, Dalian Univ. of Technology (China); H. Li, Dalian Univ.of Technology (China); S. Li, D. Li, Dalian Univ. of Technology (China) ..... [5770-26]

■ Conference 5770 End.

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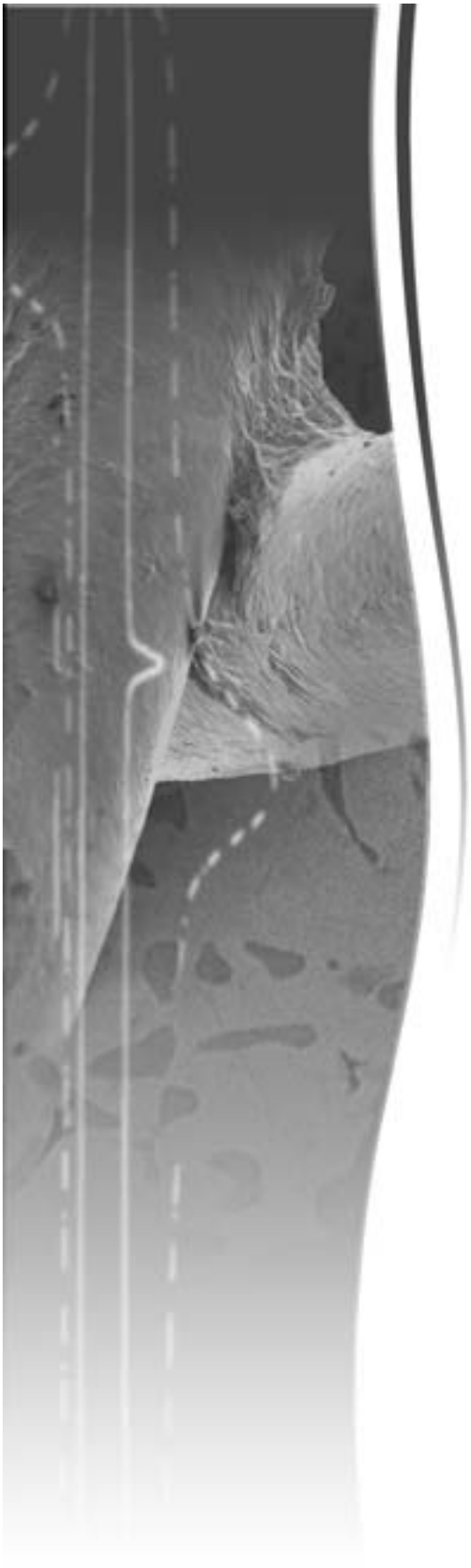

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Conference 5757: Modeling, Signal Processing, and Control

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5757-01, Session 1

A stress-dependent hysteresis model for pre-stressed piezoceramic actuators

B. L. Ball, R. Smith, North Carolina State Univ.

This paper presents a stress-dependent polarization model that quantifies the asymmetries present in the hysteretic behavior exhibited by high performance prestressed piezoceramic (PZT) transducers operating in nonlinear regimes. Several applications (accelerometers, flow control, high speed switches and valves, nanopositioning and electro-optical scanning) require transducers capable of generating large forces and strains while operating in highly nonlinear regimes. Transducers such as THUNDER (\underline{Th}in Layer \underline{Un}imorph Ferroelectric \underline{D}river and S\underline{e}nso\underline{r}) and RAINBOW (\underline{R}educed \underline{a}nd \underline{In}ternally \underline{B}iased \underline{O}xide \underline{W}afer) are prestressed during their manufacturing process making them durable and capable of use in high performance applications. The prestressing process also influences the orientation of the dipole domain structure in the PZT \cite{OMSB}. Therefore, the stress-dependence and the hysteretic behavior of such prestressed transducers must be quantified to achieve accurate models and subsequent control designs.

5757-03, Session 1

Computational multi-field mechanics model of piezoelectric micro-resonators

S. Preidikman, B. Balachandran, Univ. of Maryland/College Park

Micromechanical systems (MEMS) that employ active piezoelectric materials show promise for a variety of applications and are currently the subject of research. The development of increasingly complex devices demands sophisticated simulation techniques for design and optimization of these systems. MEMS devices typically involve multiple coupled energy domains and media that can be modeled by using a set of partial differential equations, including spatial and time variables. In this work, a computational multi-field mechanics model of a composite micro-structure with piezoelectric actuation and piezoelectric sensing has been developed as a design tool for micro-resonators. These devices are to be used as frequency filters and other signal processing applications. The developed dynamic model of MEMS resonators accounts for structural properties and the electromechanical coupling effect through finite element analysis. It is assumed that the deflection is large and that the geometric nonlinearity must be included. The mechanical strain, however, is assumed to be small so that the linear constitutive relations are still valid. The dynamic admittance model is derived by combining the linear piezoelectric constitutive equations with the modal transfer function of the multilayered micro-resonator structure. The overall transfer function describing the admittance between the driven input and the sense output of the micro-resonator is obtained, and in the frequency domain, this function is expressed as the product of the mechanical force-displacement transfer function for the composite micro-structure, the electromechanical coupling at the input port, and the electromechanical coupling at the output port. The resonator receptance matrix is constructed through modal summation by considering only a limited number of dominant modes. The electromechanical coupling determination at the input and output ports makes use of the converse and direct piezoelectric effects. The resonators considered in this work typically range in lengths from 100 μm to 400 μm. In the development of the finite-element models, boundary conditions, electrodes shaping, and factors such as varying elastic modulus across the length of the beam for the multilayered structure has been taken into account. Moreover, the coupled model can be used to carry out sensitivity studies with respect to the following: (i) the resonator beam thickness and length; (ii) the influence of constant axial forces on the transverse vibrations of clamped-clamped micro-resonators; (iii) geometry of the drive and sense electrodes; and (iv) imperfect boundary conditions due to mask imperfections and fabrication procedure. For micromechanical resonators, these modeling uncertainties come in large part from manufacturing tolerance, residual stresses, irregular surface topology, and material property variations, among others. The developed model has been validated by comparing it with results available in the literature for clamped-clamped resonators.

5757-04, Session 1

Nonlinear forces oscillations of piezoelectric resonators

H. Li, S. Preidikman, B. Balachandran, Univ. of Maryland/College Park

Forced oscillations of piezoelectric, micro-electromechanical (MEMS) resonators fabricated as clamped-clamped composite structures are studied in this effort. Piezoelectric actuation is used to excite these structures on the input side and piezoelectric sensing is carried out on the output side. Each resonator structure is modeled as an Euler-Bernoulli beam with axially varying properties across the length and distributed actuation. A nonlinear integro-partial differential system is derived to describe the micro-resonator. For weak damping and weak forcing, the method of multiple scales is used to obtain an approximate solution of the system about a post-buckling position. The different modeling assumptions made are presented and discussed, and the analytical result is compared with experimental observations.

5757-05, Session 1

Analytical modeling and active vibration suppression of an adaptive circular composite plate with antisymmetric constraints

S. Yan, M. Ghasemi Nejhad, Univ. of Hawaii/Manoa

Adaptive composite panels have great potentials to be used as common structures in various industrial fields and main components of future space-crafts. As a result, the knowledge of their modal behavior has to be explored in order to establish a technological roadmap for their applications. As a basic stepping stone, numerous models have been developed recently to describe the dynamics of adaptive composite panels with surface-mounted piezoelectric (PZT) patches using various methods. Although, much research has been performed on the dynamics of beams and rectangular plates, less research has been performed on circular plates.

In this paper, the dynamic analysis of a circular plate with antisymmetric constraints with respect to the angular coordinate system is investigated. Due to the antisymmetric constrains, the dynamics of the circular plate could not be simply solved from the partial differential equation by ignoring the angular dependency. Using the method of separation of variables, the mode shapes are expanded in Bessel Series. The validation of the theoretical model is performed by comparing the developed analytical mode shapes with FEM mode shapes.

Also, employing the developed model, the simulation of the vibration control is implemented on the circular plate with one central simply support and three edge simply supports using LQR controller.

The proposed mathematical method provides the mode shape analysis of the circular plate with various constrain conditions. Also, this method can be applied to the three-dimensional case. Therefore, the proposed method provides design reference for adaptive composite material applications, such as an antenna or a satellite dish.

5757-73, Session 1

A body-force analogy for dynamic piezoelasticity

H. Irschik, M. Krommer, Johannes Kepler Univ. Linz (Austria)

In the linear theory of thermoelasticity, the body force analogy dates back to Duhamel. In its classical form, it reads: Consider the static deformation of an isotropic linear thermoelastic body under the action of a given temperature. Then the thermal stresses can be obtained by addition of an imaginary pressure to the isothermal stresses, which follow by solving the isothermal governing equations with certain imaginary body forces and surface tractions. Moreover, the thermal displacements due to the given temperature are identical to the isothermal displacements due to the imaginary body forces and surface tractions.

Due to a well-known similarity between thermal expansion strains and the actuating strains in a piezoelastic body, the question of a dynamic extension of the above static body force analogy has gained interest in connection with the compensation of force-induced vibrations in a linear elastic body by smart actuation. This field is also known as shape control in the literature, see e.g. the review papers by Irschik [1] and Ziegler [2]. Smart actuation involves non-mechanical entities as actuating effects, particularly the electric field in a piezoelastic body. A proper linear mapping of the electric field is often called an

actuation stress for convenience. It has been shown by Irschik and Pichler [3] that vibrations induced by transient forces in an anisotropic linear elastic body can be exactly compensated when a statically admissible transient stress is used as actuation stress. A statically admissible stress represents a stress, which is in temporal equilibrium with the transient body forces and surface tractions. Now, assuming the electric field to be given and re-inserting the corresponding actuation stress in the equilibrium equation and boundary conditions for the statically admissible stress, imaginary body forces and surface tractions can be computed, such that the displacements due to the electric field are exactly compensated. Reversing the direction of the forces, the latter result immediately suggests a straightforward dynamic extension of the classical static body force analogy. The present paper is devoted to a more detailed study of this strategy. We give a 3D mathematical formulation of the corresponding dynamic piezoelastic body force analogy, and we study the influence not only of the converse, but also of the direct piezoelectric effect upon our formulation, i.e the influence of coupling. Finally, a structural example considering vibrations of a beam is presented.

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5757-06, Session 2

Optimization of actuator placement and hybrid controller design in flexible plates using PZT actuators

M. A. Demetriou, Worcester Polytechnic Institute

The objective of this investigation is to provide a computational scheme for the optimal placement of actuating devices in flexible plates that utilize piezoceramic patches as actuators. In addition to controllability criteria, the candidate locations are required to also exhibit robustness with respect to the spatial distribution of disturbances. These PZT actuators are bonded at optimal locations that are determined by statically minimizing the optimal value of a disturbance-to-output transfer function with respect to the worst distribution of disturbances. Once the optimal actuator locations are determined, that in addition to performance specifications also satisfy a spatial robustness criterion, a suitable LQG-based compensator is designed using a single velocity sensor. At a given interval of time, only one PZT is activated and the remaining ones are kept dormant. The rationale of actuator/controller switching is to demonstrate the better vibration alleviation characteristics of switching between actuators over the use of a single actuator that is always in continuous use. The optimality of switching is with respect to a cost-to-go performance index that corresponds to each actuating device. Extensive computer simulations with repeatable spatiotemporally varying disturbance profiles, reveal that this algorithm offers better performance over the non-switched case.

5757-07, Session 2

Comparison of laplace transform, integral equation, and assumed modes approaches for piezo-patch control of beams

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Use of piezoelectric patches as sensors and actuators for the vibration control of beams is a well established technology. Various techniques developed to analyze these problems range from analytical to computational ones and have different levels of complexity and accuracy. In the present paper three techniques, namely, Laplace Transform, integral equation and assumed modes are applied to the vibration control problem involving a cantilever beam with piezoelectric patches attached to the top and bottom surfaces. These patches act as sensors and actuators providing a feedback control mechanism for the damping of vibrations.

The Laplace Transform involves the transform of the space part of the partial differential equation governing the motion of the beam and an inverse transform to find the exact solution. The integral equation approach transforms the differential equation formulation to an integral equation formulation which, in turn, is replaced by an infinite system of equations. As such this method provides an approximate solution, the accuracy of which depends on the size of the system of linear equations involved. The assumed modes method is quite widely used because of its ease of application, and its accuracy depends on the number of terms in the series approximation used to express the solution.

These solution methods are summarized and difficulties, drawbacks and advantages associated with each method are discussed. The accuracy of each technique is compared and assessed in the context of a vibrating cantilever beam with a single patch. The results are given in a comparative manner which also includes the exact solutions.

5757-08, Session 2

Nonlinear electronic compensation for position control of a magnetostrictor actuator

D. K. Lindner, C. Howells, H. Zhu, Virginia Polytechnic Institute and State Univ.

It is well known that the first order material nonlinearity between current and position is a magnetostrictive actuator is quadratic. By proper biasing of the magnetic field and using only small sinusoidal command signals, the position of the actuator does not exhibit significant second order harmonics. However, if the position of the actuator is commanded over its full range of deflection, then the position of the actuator exhibits a significant second order harmonic due to the quadratic material nonlinearity. This nonlinear response is highly undesirable for precise positioning applications.

In this paper we propose a simple nonlinear feedback scheme in the drive amplifier that corrects for the quadratic material nonlinearity. This nonlinear feedback law is suggested by the linear feedback inherent in the switching drive amplifier. By changing the feedback law from linear to a quadratic, the position of the actuator will be forced to incorporate the quadratic behavior of the magnetostrictive material, generating a linear response for high drive levels. The performance of this amplifier is demonstrated through simulation.

This nonlinear control law is very attractive because of its simplicity in implementation. This control law is achieved by the simple modification of the linear control loops that already exist in the drive amplifier. Basically, all that is required is an electronic multiplier chip.

5757-09, Session 2

Stability of a nonlinear electronic controller for an electrostrictor actuator

D. K. Lindner, C. Howells, G. Zvonar, Virginia Polytechnic Institute and State Univ.

Electrostrictor actuators are attractive because of their (relatively) large displacements. However, they exhibit a quadratic nonlinearity between the charge and displacement as well as a arctan relationship between charge and voltage. These nonlinearities limit the usage range of the linear displacements. For example, in acoustic applications, these nonlinearities limit the range of displacements that do not generate higher order harmonics.

In this paper we describe a nonlinear electronic controller that has been introduced previously to mitigate the effects of the material nonlinearity, and demonstrate its performance. Then we provide a stability proof for the nonlinear controller. This proof is based on a Lyapunov stability proof for a nonlinear capacitor, with modifications. This stability proof supports the performance observed in the lab.

5757-10, Session 2

Exact boundary controllability of a multilayer sandwich beam

S. W. Hansen, Iowa State Univ.

The three-layer Rao-Nakra sandwich

beam model consists of two relatively stiff face plates and a much more compliant core layer. In this talk we first describe a natural generalization of this model to any number of alternating stiff and compliant layers. Linear viscous damping due to shear motions in the compliant layer is included. This results in a well-posed PDE in the time domain. We then consider the problems of exponential stability/stabilization and exact boundary controllability. It turns out that the system is already exponentially stable for boundary conditions that do not admit inertial motions provided the wave speeds of the layers are not identical. The exact controllability question is analyzed by reduction to an associated moment problem. We find that exact controllability holds with enough control placed on one boundary provided the time is large enough for the waves from each layer to travel twice the length of the beam. At the cost of losing a Sobolev order, improved controllability results (with less control, or in a faster time) can also be proved.

Conference 5757: Modeling, Signal Processing, and Control

5757-11, Session 3

Optimization of a piezoelectric acoustical compressor

R. A. Dickens, DRS Signal Solutions, Inc.; A. M. Baz, Univ. of Maryland/College Park

A one-dimensional, axisymmetric, linear finite element model describing a fluid interacting with a piezoelectric actuator is developed. This system is used to generate finite amplitude standing waves in an acoustic cavity with rigid walls. The model includes the effects of viscous and thermal damping of the fluid at the boundary of the cavity, and material damping in the piezoelectric actuator. Two types of piezoelectric actuators are considered, a stacked layer actuator, and a bending bimorph actuator. The resulting finite element equations are used to determine the optimum shape for the acoustic cavity that results in the highest pressure for the least input power. Optimal chambers were found that could generate  19 psi at 1700 Hz for 50 watts of power using air as a working fluid and  70 psi at 950 Hz for 42 watts of power using R-134A as a working fluid. The optimization results were verified against the commercial finite element code ANSYS and published experimental data.

The potential of the transition of the developed technology to other fields is viable and is only limited by our imagination as it includes numerous applications such as the inflation of inflatable structures, inflation of tires, refrigeration, and air-conditioning.

5757-12, Session 3

Parallel algorithm for optimal design of a morphing aircraft wing

S. Bharti, M. Frecker, G. A. Lesieutre, D. Ramrakhyani, The Pennsylvania State Univ.

The idea of an aircraft with morphing wings has generated considerable interest in recent years due to its inherent advantages of possessing high maneuverability and efficiency under different flight conditions such as take off, cruise and loiter. Structural morphing in conventional aircrafts has been accomplished by using control surfaces connected with hinged and sliding joints. Effort is currently being made to achieve wing morphing that is continuous along the wing surface, as opposed to the conventional “discrete” shape change. This is desirable in order to prevent surface discontinuities resulting in increased drag.

The present research aims to achieve continuous wing morphing by employing a wing structure comprising of an optimized internal layout of cables and struts. Cables are used as actuators while struts provide rigidity to the wing. Struts and cables are connected by flexure joints so as to form a compliant mechanism. In addition to achieving continuous morphing by changing cable length, this structure has the advantage of being light in weight.

An important aspect of this research is determining an optimal layout of the cables and struts that would produce increased morphing with minimal actuation effort. Optimization procedures using Genetic Algorithm are used to find the best wing structure for the problem. Wing morphing has been quantitatively defined as deflection of one or more points of the wing. Shape change is accomplished by shortening of cables while the structure is subjected to aerodynamic loads. The conflicting need for the wing to be stiff enough to withstand the air loads and at the same time be flexible enough to morph is one of the challenges in the design.

In our previous work we have developed a genetic algorithm to optimize the cable and strut layout in the wing body. The current paper focuses on a new optimization formulation which includes variable cable actuation and reversible actuation. The objective function is the weighted sum of deflection under actuation and deflection under air loads. A parallel processing algorithm is developed, resulting in increased program efficiency and reduced computational costs. Results from the serial and the parallel program are compared.

5757-13, Session 3

Simultaneous structure and control optimization of tensegrities

M. Masic, R. E. Skelton, Univ. of California/San Diego

This paper concerns prestress optimization of a tensegrity structure for its optimal dynamic performance. A linearized dynamic model of the structure is derived. The force density variables that parameterize the prestress of the structure appear linearly in the model. A feasible region for these parameters is defined in terms of the extreme directions of the prestress cone. A numerical method for computing this basis for a structure prestress cone is proposed. Several properties of the problem are established inside the feasible region of the parameters motivating a solution algorithm. The problem is solved using a gradient method that provides a monotonic decrease of the objective function inside the feasible region. A numerical example of a cantilevered planar tensegrity beam is shown.

5757-14, Session 3

Topology optimization of active control vibration damping layers

M. Parsons, J. Jiang, A. Lumsdaine, Univ. of Tennessee/Knoxville

Piezoelectric materials can provide effective vibration suppression in an active control system. Among the many studies on using piezoelectrics in vibration suppression, little research has focused on optimizing the shape of the piezoelectric actuator to achieve “optimum” damping characteristics of a mechanical structure. Generally, piezoelectric material optimization has focused on the location and/or the number of actuators and involved expensive global optimal solution algorithms. Moreover, studies focusing on piezoelectric topology optimization using homogenization models have only been used to determine the optimal microstructure [1], the optimal topology of a piezoelectric sensor [2], and optimal topology of a piezoelectric sensor on a static beam [3]. However, to the author’s knowledge no previous studies have determined the optimal topology of a piezoelectric actuator under dynamic loading to maximize vibration damping characteristics.

Topology optimization is growing field and has been proven to provide efficient designs of various structures. Bendsoe and Kikuchi [4] first introduced the homogenization method for finding the optimal topology of a structural problem. Further work was done by Silva and Kikuchi [5]; they applied topology optimization in the design of piezoelectric structures. Drenckhan and Lumsdaine [3] investigated the optimum topology of a piezoelectric actuator mounted to a cantilever beam under a concentrated static load at the tip. The study results showed improvements in beam stiffness based on the percentage of material used in the piezoelectric actuator layer (for examples of some optimal topologies see Figure 1). Using the previous work of Drenckhan and Lumsdaine, this study expands their static analysis to dynamic analysis.

In the field of modeling and analysis for piezoelectrics, a good overview has been done by Naillon and Besnier [6], who describe a method to analyze a piezoelectric structure by a finite element method. Guyan [7] removed the electric degree of freedom by using a condensation matrix, and the control is applied over the remaining translational and rotational degrees of freedom.

Recently, much work has been done on implementing the control law between piezoelectric sensors and actuators in smart structures. Tzou and Tseng [8] described a distributed sensor/actuator design by a finite element approach. Ha et al. [9] performed an analysis of structures with piezoelectric sensors and actuators, and compared the results with experiments. Baz and Ro [10] performed similar work; they analyzed the performance of active constrained layer damping (ACLD), where piezoelectric and viscoelastic materials (VEM) were used. Veley and Rao [11] built on these results to make a comparison of active, passive and hybrid damping. Vardan et al. [12] described a closed loop finite element modeling of active damping in vibration control. The vibration and actuation characteristics of structures with piezoceramic actuators have been examined by Han [13], and compared with experimental results. Drenckhan and Lumsdaine [3] developed a method of modeling the active control law and used it for the optimization of piezoelectric sandwich beams. Most of these studies use their own codes, which limit their applicability.

This research investigates the optimum topology of a piezoceramic (PZT) active damping actuator bonded to a base beam under a steady-state dynamic load. The piezoelectric material is applied to a cantilever elastic base beam and applied as both an actuator and a sensor layer of the active control system. The piezoelectric material is modeled using homogenization techniques which allows the optimal topology to be determined using a local optimization algorithm. The main focus of this work is to implement the control law into the commercial finite element code ABAQUS by manually modifying the stiffness matrix and to study the topology using a sequential linear programming (SLP) algorithm.

The control law is implemented into ABAQUS in three steps. The stiffness matrices for each piezoelectric element are constructed. These matrices are then passed to Matlab, and a proportional (displacement) control law is applied. Finally, the modified stiffness matrices are passed back to ABAQUS to determine the steady-state dynamic solution.

The actuator topology is broken into elements as shown in Figure 2 (heights of piezoelectric elements are exaggerated for viewing clarity). The elements in the actuator layer could be manipulated with several optimization techniques. The first possibility is to model the system as a binary discrete variable optimization; each element would contain either piezoelectric material or a void. However, this approach would require the use of a global optimization algorithm, and the computational requirement for a reasonable density mesh would be exorbitant. The alternative approach, and the method of this work, is to allow the material properties of each element to vary, making the design variables continuous. Then, the design variables are the volume fraction of material (PZT) in each

element. The homogenization method assumes that the material consists of infinitesimal microvoids that are periodically distributed over the domain. This distribution results in macroscopic properties that show the homogenized values of different constituents.

When solving the homogenized optimization problem, a sequential linear programming (SLP) algorithm is used. In SLP, the optimization problem is linearized around the current design point in each iteration, and the next design is found by linear programming. SLP provides a robust code that will handle the large number of local minima [14]. The commercial code VisualDoc is used to perform the SLP algorithm. The optimization results show a substantial increase in the loss factor for the first mode.

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5757-15, Session 3

An automated approach to design shape morphing strategies for reconfigurable surfaces

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Reconfigurable and morphing structures have attracted attention for potentially providing a range of new functionalities including system optimization over broad operational conditions and multi-mission capability. One promising approach for creating large deformation morphing structures uses variable stiffness components to provide large deformation without large energy input to the system. In this paper, we present an automated approach to design shape morphing strategies for reconfigurable surfaces composed of variable stiffness components. Variable stiffness components create an ill-posed control problem and generally have multiple solutions for any given morphing task. We formulate this problem as an optimization search using genetic algorithms (GA) to efficiently search the design space and rapidly arrive at a family of plausible solutions. Our novel approach can simultaneously satisfy a broad range of design constraints including structural properties, mechanical loading, boundary conditions and shape. Critical to GA searching is an accurate and computationally efficient variable stiffness surface model. Computer simulation of the reconfigurable surface was performed using a physics based model of the variable stiffness surface. The surface is modeled as a thin elastic plate in which the stretching and bending elastic moduli are treated separately and as arbitrary functions defined over the surface. This allows for large deformations including complete foldings. The resulting non-linear difference equations are solved using various preconditioned global search based relaxation algorithms. The results of our simulations show that our approach not only allows us to verify the feasibility of morphing tasks of variable stiffness surfaces, but also enables us to efficiently explore much larger design spaces resulting in unique and non-obvious morphing strategies.

5757-16, Session 3

Piezoresistive sensor design using topology optimization

E. C. N. Silva, Univ. de São Paulo (Brazil); S. Nishiwaki, Kyoto Univ. (Japan)

Piezoresistive materials, materials whose resistivity properties change when subjected to a mechanical stresses, currently have wide industry application in pressure sensors, accelerometers, inclinometers, MEMS, and load cells.

A basic piezoresistive sensor consists of piezoresistive material bonded to a flexible structure, such as a cantilever, membrane, or compliant mechanism, where the flexible structure transfers pressure, force, or inertial force (due to acceleration), thereby causing a stress that changes the resistivity of the piezoresistive material. By applying a voltage to the material, its resistivity can be measured and correlated with the degree of applied pressure or force. A classical problem in piezoresistive sensor design is to determine the optimal location for the piezoresistive material in the flexible structure, to obtain the highest possible response. Although there is considerable literature concerning piezoresistive sensor manufacturing, published research that addresses piezoresistive sensor modeling and design, and the application of analytical techniques and FEM modelling, is scarce.

This suggests that systematic design methods, such as topology optimization, can offer important contributions, and in the work presented here, a topology optimization formulation has been applied to the design of piezoresistive sensors. As an initial problem, a load cell design is considered. Load cells are widely used in industry to measure force, often in the form of "strain gages" that are essentially one-dimensional applications of piezoresistive material. The optimization problem is posed as the design of a flexible structure that bonded to the piezoresistive material generates the maximum response in terms of resistivity change (or output voltage).

5757-17, Session 4

Interaction of a turbulent channel flow with a compliant-tensegrity fabric

H. Luo, T. R. Bewley, Univ. of California/San Diego

A non-trivial influence of the compliant surface on the statistics of near-wall turbulence has been found by direct numerical simulations of a channel flow at $Re_\tau=150$ passing over a "tensegrity fabric" surface. Inspired from nature, this compliant surface model is special truss system having tensile members distinguished from the compressive members, as we have presented at previous APS meetings. Validated by a variety of flows, a pseudospectral/finite-difference flow solver with a 3D coordinate transformation is coupled with a C++ code calculating the dynamics of the tensegrity fabric to simulate the flow/structure interaction. Simulation results show that, when the structure has high stiffness and damping, the flow acts as if the interface were a solid flat wall. When the structure's stiffness and damping are reduced, it may resonate under the excitation of the flow disturbances. The resonating flow/structure interface forms a streamwise wave reminiscent of air-water interface but traveling at a much faster phase speed, a few times of the viscous velocity u_τ. Although the wave's amplitude is small, $y_w^+\approx 2$, it changes the near-wall turbulence significantly. Drag on the compliant surface is increased by about 17\% where form drag accounts for only one third of the drag increase due to the small wall deformation. Various domain sizes have been tried in order to make sure that the structure's vibration mode is correct.

5757-18, Session 4

Integrated optimal-control design and sensor/actuator selection for a tensegrity beam

R. Skelton, F. Li, Univ. of California/San Diego

In structure control, sensor/actuator selection is traditionally separated from control design, despite that they are not independent decisions. From a system design point of view, by enlarging the design space, more freedoms can be utilized to achieve a more optimal or economic design scheme. This paper integrates sensor/actuator precision allocation and output feedback control design. Two different sensor/actuator noise models are employed, i.e., the conventional white noise model and the FSN (finite signal to noise ratio)model. Three competitive factors, namely, the output performance, the input cost and the total sensor/actuator precisions are optimized over the controller design and precision allocation scheme. This problem turned out to be convex. Furthermore, it can be converted to an LMI optimization. A five-stage tensegrity beam is studied as an application of this algorithm.

5757-19, Session 4

A new topology of tensegrity towers with uniform force distribution

M. C. de Oliveira, R. E. Skelton, Univ. of California/San Diego

This work investigates the design of a new class of three dimensional tensegrity structures whose nodes lie in a cylinder. The proposed structure is a member of the so called shell class of tensegrity structures. It is constructed by stacking up modules in a regular fashion. These modules are called stages, each stage containing an arbitrary number of bars greater than three. The distinctive aspect of this particular topology is the fact that all bars in a stage are oriented in the same way, clockwise or counterclockwise, whereas in existing tensegrity tower structure designs the bars in adjacent stages must have opposite orientation. This feature brings at least two advantages. First, it simplifies the actual construction of the structure. Second, and more important from the point of view of design, it brings major simplifications to the mathematical equilibrium conditions. This second advantage is explored in detail.

Computing solutions to the equilibrium conditions for tensegrity structures amounts at solving a large number of complicated nonlinear algebraic equations. In general, these equations do not have closed form solutions, being solved by an iterative numerical algorithm, such as the Newton-Raphson. A complicating factor is that geometrically symmetric tensegrity structures may not necessarily exhibit force symmetry. In the present work we show that there exists solutions to the equilibrium conditions of the proposed tensegrity tower topology which present force symmetry whenever the structure has geometric symmetry. More importantly, we show how to enforce a particular symmetric force arrangement such that the equilibrium conditions for structures with any number of intermediate stages can be computed by solving only three vector algebraic equations, regardless of the number of intermediate stages. This is accomplished by enforcing that the unloaded structure configuration be such that corresponding members in all intermediate stages should experience the exact same force. In other words, that the structure presents an uniform force distribution when unloaded. We show that such solution is indeed a stable equilibrium solution.

This theoretical result is of great practical importance. First it implies that intermediate stages are made of identical modules which can be added or removed from the structure without affecting the overall equilibrium. This feature is desirable for manufacturing purposes, allowing modular construction. Second, the simplicity of the equilibrium equations can be used to develop effective decentralized control strategies. These control laws can achieve structure deployment or disturbance rejection and regulation.

5757-20, Session 5

Optimal sensing strategy for adaptive control of optical systems

S. Moon, R. L. Clark, Duke Univ.

Optical jitter degrades the pointing and imaging performance of precision optical systems. Practical active control has been used to achieve jitter reduction. Adaptive control approaches are advantageous in the presence of time-varying or uncertain disturbances. When a correlated measurement of the disturbance is available, control performance can be improved.

In this research, adaptive optimal sensing strategy for structural vibration of optical system is proposed. An array of sensors makes it possible to estimate the disturbance and model the disturbance-to-performance paths. The least-square algorithm is applied for the disturbance estimation. A genetic optimization algorithm is then used to chooses a set of well-correlated sensors with disturbance. The feedforward of the disturbance measurement sensor signals are used for the optimal compensator design. An array of accelerometer sensors is chosen to measure the structural vibration of optical elements. The control mechanism is the reduction of the structural vibration of optical components because reducing the level of structural vibration results in reduction of the corresponding jitter. The proposed technique will be applied to the demonstration system test bed.

5757-21, Session 5

Assessment of wavelet analysis of signal processing for smart structures

K. J. Jones, Rice Univ.

This effort will assess progress as well as future challenges using wavelet signal porcessing in Smart Structures. Wavelet signal processing allows noise reduction as well as data compression. Of particular importance in this context is the use of the Morlet wavelet transform to determine phase in interferometric fringes used to sense deformation, i.e. wavefront sensors. Present Smart Structures technology continues to rely heavily on Fiber Optic (FO) sensors and Fiber Bragg Grating Sensors (FBGS) with constraints heavily dependent on materials. Wavelets could increase resolution as well as reduce constraints.

Wavelet analysis of signal processing has provided two major capabilities: noise reduction and data compression. A capability which might significantly impact Smart Structures is phase determination using the Morlet wavelet transform. Many wavefront sensors are based on interferometry: a phase step in one of the arms of an interferometer induces a phase shift in the interferogram. Using an algorithm, it is possible to recover the phase map of an image and compute the deformation of an object of interest. Here, the phase properties of the Morlet wavelet trasnform are used to compute the phase of the signal.

Past papers by this author on use of wavelets in Smart Structures include:

'Wavelet edge detection applied to be used with composite embedded fiber optci sensors, 3986-52, 2000; and Wavelet crack detection algorithm for Smart Structures, 4328-32, 2001. The first paper used wavelet edge detection on embedded optical fibers and noise reduction on the output of a grating. The second paper extended edge detection to an algorithm.

There are many challenges for the future implementation of wavelet analysis in Smart Structures. Wavelets are particularly suited for the detection of transitory phenonmena as well as data where high resolution is required. One type of sensor is the Fiber Bragg Grating, i.e. birefringent optical fibers, multiaxis optical fibers or FBG rosettes. These are used for crack or damage detection, and the detection of certain wavelengths is crutial. Filter banks might be used to demultiplex output of FBG rosettes to increase resolution. Time-frequency experiments could use spectrograms of the Morlet wavelet transform to increase resolution.

This paper will assess progress as well as define future challenges in Smart Structures using wavelet analysis. For example, using the Morlet wavelet transform, it is possible to determine the phase of a 1-D signal from a 2-D interferogram and hence the deformation or strain on the object. Other promising wavelet approaches will also be presented.

5757-22, Session 5

Nonlinear analysis of sensor diaphragm under initial tension

M. Yu, B. Balachandran, Univ. of Maryland/College Park

In this paper, recent efforts conducted to investigate the dynamic behavior of a sensor diaphragm under initial tension are presented. A comprehensive mechanics model based on a plate with in-plane tension is presented and analyzed to examine the transition from plate behavior to membrane behavior. It is shown that for certain tension parameter values, it is appropriate to model the diaphragm as a plate-membrane structure rather than as a membrane. In the nonlinear analysis, the effect of cubic nonlinearity is studied when the excitation frequency is close to 1/3 of the first resonance or the first resonance itself. These nonlinear effects limit the sensor bandwidth and dynamic range. Study shows that both of these two nonlinear effects can be attenuated by decreasing the diaphragm thickness and applying an appropriate tension to keep the first natural frequency while reducing the strength of the nonlinear effect. These analyses and related results should be valuable to carry out the design of circular diaphragms for various sensor applications especially for designing sensors on small scales.

5757-23, Session 5

Shape sensing a morphed wing with an optical fiber Bragg grating

H. Tai, NASA Langley Research Ctr.

Abstract: We suggest using distributed fiber Bragg sensors systems which were developed locally at Langley Research Center carefully placed on the wing surface to collect strain component information at each location. Then we used the fact that the rate change of slope in the definition of linear strain is very small and can be treated as a constant. Thereby the strain distribution information of a morphed surface can be reduced into a distribution of local slope information of a flat surface. In other words a morphed curve surface is replaced by the collection of individual flat surface of different slope. By assembling the height of individual flat surface, the morphed curved surface can be approximated. A more sophisticated graphic routine can be utilized to restore the curved morphed surface. With this information, the morphed wing can be further adjusted and controlled. A numerical demonstration is presented.

5757-24, Session 5

Signal feature extraction for impact damage detection in composite materials

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The introduction of composite materials challenges the existing maintenance technologies in relation to damage detection. It is well known that impact with ground support equipment is one of the major causes of in-service damage to composites. Damage detection in composite materials has direct relevance to the problem of impact detection. An accurate method of locating and quantifying impacts essentially solves the impact detection problem. There is strong evidence that damage detection can be correlated with impact energy, with no damage occurring below a certain energy threshold. The previous work by the current authors was concerned with applications of neural networks which could locate and quantify impact damage in various types of composite structures. The study involved the application of smart composite panels with embedded and/or bonded piezoceramic sensors. It appears that signal processing is one of the major difficulties in such applications. This includes the process of data feature extraction for neural network analysis. The choice of features from impact strain data is a trade-off between the computational feasibility associated with low-level features and extensive pre-processing required for high-level features.

The paper reports the application of different signature analysis techniques for feature extraction from impact strain data. A simple FE model of a composite plate and an impacting body is used to obtain impact strain data. More than fifteen parameters extracted from the data are used in the study. This includes time and frequency domain features. The focus is on parameters which increase monotonically with the impact energy. The study aims to assess various data features for impact location problem based on neural networks and a modified triangulation procedure.

5757-25, Session 6

Sensorless position estimation of a linear voice-coil transducer using sliding mode observers

B. C. Glenn, C. Bouton, Battelle Memorial Institute

There are numerous applications where a voice coil actuator is used for position control where it is not desirable to have position measurement for feedback This paper proposes a technique for sensorless position estimation of a linear voice coil transducer. The method exploits the fact that as the coil moves along its axis it can experience different reluctances due to its geometrical properties, thus causing a change in coil inductance. Using a sliding mode observer that incorporates the nonlinear inductance of the transducer allows the coil position to be observed from a current measurement. The sliding mode observer is attractive for this application because it is robust to measurement noise and parameter uncertainty. The experimental model validation and real-time observer results are presented and discussed.

5757-26, Session 6

Tensor diagonalization and distributed control

R. V. Iyer, Texas Tech Univ.

The diagonalization of symmetric matrices has been studied in the past in the context of distributed control of a row of smart actuators and sensors. For distributed control using a two dimensional array of actuators and sensors, it is more natural to describe the system transfer function as a complex tensor rather than a complex matrix. In this paper, we study the problem of diagonalizing a symmetric tensor and study its application to a distributed control problem for a smart structure.

5757-27, Session 6

Transducer placement for robustness to variations in boundary conditions for active structural acoustic control

J. D. Sprofera, R. L. Clark, Duke Univ.; R. H. Cabell, G. P. Gibbs, NASA Langley Research Ctr.

The study of control strategies aimed at the reduction of turbulent boundary layer noise transmission into the fuselage of an aircraft has been a topic of academic and industrial research for several years. There has been a great deal of knowledge culled from these research projects that has added to the understanding of the fundamental and application physics involved. However, there has been very little in the way of practical realization of these strategies. The problem with this lies in the limitations that the previously completed research encounters when examined in a practical application setting. This work focuses on an approach that will attempt to address the issue of uncertainties found in panel boundary conditions and the effect these uncertainties have on transducer optimization for active control.

The focus of this project is the development of an adaptive-structures based control system that, through the use of efficient mathematical modeling and a minimized number of transducers, exhibits robustness to uncertainty in the structure resulting from bounded variations in boundary conditions. This robustness is achieved through the optimization of transducer placement with respect to maximizing control over the desired range of conditions. This project incorporates the energy based modeling of the structure, the simulation of electromechanical piezo coupling, balanced model reduction, radiation filter modeling, and control analysis through the use of Hankel Singular Value (HSV) estimates and a genetic optimization technique. Through these methods the research addresses uncertainty associated with the physical structure, particularly that of boundary conditions.

The final goal of this work is the design of an adaptive aircraft panel structure that can reduce turbulent boundary layer noise transmission through the use of a completely adaptive, single-input, single-output control system focused on controlling radiated sound power. The feasibility of this goal is demonstrated through the creation of a detailed analytical solution, followed by the creation of a test model that is implemented in the transmission loss apparatus at the Structural Acoustics Branch of the NASA Langley Research Center. Successfully realizing a control system that is robust to variations in boundary conditions can lead to the design and implementation of practical adaptive structures that could be used to control the transmission of sound to the interior of aircraft.

The impact of model uncertainties, uncertain boundary conditions in particular, on the selection of actuator and sensor locations for structural acoustic control are considered herein. Results from this research effort indicate that it is possible to optimize the design of actuator and sensor location and aperture, which minimizes the impact of boundary conditions on the desired structural acoustic control.

5757-28, Session 6

Robust control design for nonlinear smart systems

R. C. Smith, W. Oates, North Carolina State Univ.

To achieve the performance requirements dictated by many present smart material applications, transducers are required to operate in highly nonlinear and hysteretic regimes. This necessitates the development of either nonlinear control laws or linear control designs employing nonlinear feedforward or feedback filters. In this talk, we will address the design of both nonlinear optimal control designs and linear H2 and H-Infinity designs employing model based filters. The performance of the designs for applications employing piezoceramic, magnetic and shape memory alloy compounds will be illustrated through numerical and experimental examples.

5757-29, Session 6

Experimental verification of an analytical bound H-inf collocated control approach

R. J. Sweeney, M. A. Demetriou, Worcester Polytechnic Institute; K. M. Grigoriadis, Univ. of Houston

The objective of this paper is to provide an experimental verification of a new H-infinity control scheme on a flexible beam which uses a collocated PZT actuator/sensor pair. We use an analytical bound approach that provides an explicit expression of an upper bound on the H-infinity norm of the closed-loop system and an explicit parametrization of the corresponding output feedback control gains. The method has great computational advantages for large scale structural systems where the solution of H-infinity optimization problems using standard tools could be computationally prohibitive. Both experimental and computational results are presented which compare the performance and the computational requirements on the controller design using the standard H-infinity formulation and the proposed analytical bound approach.

5757-30, Session 7

A model for ferromagnetic shape memory thin-film actuators

K. Lee, S. Seelecke, North Carolina State Univ.

The last decade has witnessed the discovery of materials combining shape memory behavior with ferromagnetic properties (FSMAs), see James & Wuttig, 1998, James et al., 1999, Ullakko et al., 1996. These materials feature the so-called giant magnetostrain effect, which, in contrast to conventional magnetostriction is due motion of martensite twins. This effect has motivated the development of a new class of active materials transducers, which combine intrinsic sensing capabilities with superior actuation speed and improved efficiency when compared to conventional shape memory alloys.

Currently, thin film technology is being developed intensively in order to pave the way for applications in micro- and nanotechnology. As an example, Kohl et al., 2004a, recently proposed a novel actuation mechanism based on NiMnGa thin film technology, which makes use of both the ferromagnetic transition and the martensitic transformation allowing the realization of an almost perfect antagonism in a single component part. The implementation of the mechanism led to the award-winning development of an optical microscanner (Kohl et al., 2004b). Possible applications in nanotechnology arise, e.g., by combination of smart NiMnGa actuators with scanning probe technologies.

The research presented in this paper aims at the development of a model that simulates the material behavior of the above device. It uses a model originally developed for conventional shape memory alloy behavior, (Mueller & Achenbach, 1985, Achenbach, 1989, Seelecke, 2002, Seelecke & Mueller, 2004) and couples it with a simple expression for the nonlinear temperature- and position-dependent effective magnetic force. Even though this early and strongly simplified version does not account for coupling between SMA behavior and ferromagnetism yet, and does not incorporate the hysteretic character of the magnetization phenomena either. As an example, however, it shows the potential to predict the effect of different Curie temperatures on the device performance and will eventually allow optimizing material properties for a specific application.

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5757-31, Session 7

Segmented binary control of multi-axis SMA array actuators

K. Cho, H. Asada, Massachusetts Institute of Technology

A new approach to designing and controlling multiple artificial muscle actuators using Segmented Binary Control (SBC) is presented and is implemented using shape memory alloys(SMA). Segmented Binary Control is a method of controlling the actuators by dividing them into multiple segments and controlling each segment independently in a binary manner. This Segmented Binary Control uses basic characteristics of SMA wires. Namely, the resultant motion, i.e. displacement at one end of the wire, is the integration of the strain along the whole wire, or the summation of individual displacements contributed by all the segments. As far as the value of the integral remains the same, the resultant displacement does not vary although some segments have larger strains than others, or the strain is uniformly distributed along the wire. Therefore, we do not have to control the strain or phase of the wire as a whole, but can generate the same total displacement by heating or cooling local segments of the wire. The advantage is that pushing the phase of specific segments to all austenite phase or all martensite phase, rather than keeping the phase of the entire wire somewhere between the two extremes, would make the SMA wire insensitive to complex nonlinearity and hysteresis.

A two-dimensionally segmented structure is designed to control multiple actuators in a coordinated manner. Each segment creates different length of motion for different actuators and creates a streamlined and coordinated motion of multiple actuators.

One drawback of SBC is complexity of the control and drive system. Although each control loop regulating the phase of an individual segment is rather simple, many loops are needed. SBC may not be useful nor can practically be justifiable, if it entails many feedback loops for controlling individual segments of each axis. For single axis case, number of segments can be reduced by setting the length of each segment to be 1, 2, 4, 8,....., instead of equal length, without deteriorating the resolution of the actuator. For multi axis case, the number of segments can be reduced by activating adjacent SMA wires with coupled segments. Coupled segments activate multiple actuators that the segment covers. These, of course, reduce independence of the adjacent SMA wires to a certain degree, but on the other hand generates a coordinated movement among them. The shape and position of the coupled segments can be designed using the “similarity” of output trajectories of each actuator.

The basic principle of Segmented Binary Control will be first presented, followed by multi-axis segmentation theory and a design procedure. The method is applied to a five-fingered robotic hand capable of taking a variety of postures. A 10-axis SMA actuator array is built, and Segmented Binary Control is implemented using Peltier-effect thermoelectric devices for selective local heating and cooling. Experiments demonstrate the feasibility and effectiveness of the new method.

5757-33, Session 7

Shock absorption capability of woven-SMA skin

A. Masuda, A. Sone, T. Yamamura, Q. Ni, R. Zhang, Kyoto Institute of Technology (Japan)

Pseudoelastic shape memory alloys (SMAs) have great potential of shock absorption because of their large reversible strain and the “force-thresholding” characteristics, especially when used with geometric nonlinearity such as post-buckling deformation. Martensitic SMAs also have favorable shock absorption capacity with actuation capability. In this paper, we apply both pseudoelastic and martensitic SMAs to the design of the outer skins of structures to give them significant shock tolerance. Since it is difficult to fabricate a SMA plate with large area, we weave SMA wire to make thin skin with arbitrary dimensions using traditional techniques of “bamboo-weaving”. Some sample pieces of SMA woven skin are fabricated, and their basic mechanical properties are investigated to develop an appropriate model as well as a design framework.

5757-34, Session 7

Modeling of ferroelastic behavior of shape memory alloys

T. Ikeda, Nagoya Univ. (Japan)

A simple yet accurate model of shape memory alloys (SMAs) for analyses of ferroelastic behavior is derived based on the shift-skip model [Ikeda et al 2004 Smart Mater. Struct. 13 916-925: Ikeda et al 2004 Proc. SPIE 5383 112-121]. In this ferroelastic model, three martensite variants are considered, namely, the thermal induced (T), the tensile stress induced (TS), and the compressive stress induced (CS) martensite variants. Stress-strain hysteresis loops for a martensitic bar under tension-compression cyclic loading are simulated. Comparison of them with measured data shows that this model can quite well capture experimentally observed behavior. This result indicates that the proposed model is reasonable to describe the ferroelastic behavior of SMAs and will be a good tool to design a structural element with SMAs.

Ferroelastic behavior of SMAs is important as well as pseudoelastic behavior, especially when SMAs are used as damping or/and shock absorbing elements. In such a case not only tensile behavior but also compressive behavior must be taken into account. According to the observation of tension-compression behavior of martensitic SMA by Liu et al [1998 Acta Metar. 46 4325-4338: 1997 J. de Phys. IV 7 C5-519-524], stress-strain curves for tension and compression are different from each other, and strain rate has slight influence on stress-strain behavior although it has significant influence on temperature change. Some theoretical studies for the ferroelastic behavior are performed, but no theoretical model can be found to describe such interesting behavior of SMAs. Therefore, in this paper a new simple yet accurate model is derived, which can describe such interesting ferroelastic behavior. The new model is derived from the shift-skip phase transformation model. In the shift-ship model, the martensite and reverse transformation orders are assumed the same and the required transformation energy is approximated by a sum of two exponential functions in terms of martensite volume fraction. These assumptions are obtained through discussion on experimental results using the micromechanical model [Nae et al 2003 Smart Mater. Struct. 12 6-17: Ikeda et al 2003 Proc. SPIE 5049 35-45]. Here T to TS, T to CS, CS to TS, and TS to CS reorientations are assumed to take place instead of martensite to austenite and austenite to martensite transformations. The result of numerical simulation of a SMA bar under tension-compression cyclic loading shows the asymmetry stress-strain loops for tension and compression and the strain rate effect on stress-strain-temperature relationship which are observed in the experiment. Moreover, it is shown that this model can also capture the difference between the first stress-strain loop and the other loops.

5757-35, Session 7

The nonlinear fully coupled thermodynamic model of martensitic micro-shells and their application to the design of a targeted drug delivery system

P. Kloucek, Rice Univ.; D. Reynolds, Lawrence Livermore National lab.

We present a thermodynamic model of martensitic micro-shells based on the thin film theory of martensitic materials obtained as the Gamma-limit of a bulk theory for the Helmholtz free energies of crystalline materials. Martensitic thin films have properties profoundly different from the bulk martensitic materials in that they can form equilibrium shapes suitable for various industrial applications. The presented computations show release of a substance contained in a martensitic hemi-sphere covered with a thin bio-degradable film to the blood stream upon non-damaging heat activation.

5757-74, Session 7

Testing of the thermomechanical response of shape memory alloy hybrid composite beams

B. A. Davis, North Carolina State Univ.; T. L. Turner, NASA Langley Research Ctr.; S. Seelecke, North Carolina State Univ.

Previous work at NASA Langley Research Center involved the fabrication, and testing of composite beams with embedded shape memory alloy (SMA) ribbons within the beam structures. That study also provided comparison of experimental results with a generated research code making use of a new thermomechanical model for shape memory alloy hybrid composite (SMAHC) structures. The previous work showed validation of the new thermomechanical model through a generated research code, but more definitive investigations were necessary. The goal of this work is to again conduct experimental investigations on the SMAHC beams, but to more accurately quantify the static buckling/post-buckling and dynamic response characteristics of the specimens with the addition of the precise measuring techniques such as an infrared thermal imaging camera, laser displacement transducer, and Projection Moire' Interferometry (PMI). Numerical results are generated in the commercial finite element code ABAQUS for comparison to experimental results, in contrast to the generated research code previously used. Static, thermal buckling, post-buckling, and dynamic inertial random excitation response experiments were conducted on the SMAHC beams under clamped boundary conditions. The experimental data demonstrates the ability of the embedded SMA actuators to adaptively stiffen the structure. Excellent aggreement is achieved between the predicted and measured results of the static, and dynamic thermomechanical response. As a result, the study shows an accurate measurement of the attractive functionality of SMAHC structures, and validates the use of a thermo-elastic constitutive model to accurately capture the behavior.

5757-36, Session 8

Application of Monte Carlo simulations to the prediction of the effective elastic moduli of hydrated Nafion

L. M. Weiland, Virginia Polytechnic Institute and State Univ.; E. K. Lada, Statistical and Applied Mathematical Sciences Institute; J. Mathews, R. C. Smith, North Carolina State Univ.; D. J. Leo, Virginia Polytechnic Institute and State Univ.

Application of Rotational Isomeric State (RIS) theory to the prediction of Young's modulus of a solvated ionomer is considered. RIS theory directly addresses polymer chain conformation as it relates to mechanical response trends. Successful adaptation of this methodology to the prediction of elastic moduli would thus provide a powerful tool for guiding ionomer fabrication. The Mark-Curro Monte Carlo methodology is applied to generate a statistically valid number of end-to-end chain lengths via RIS theory for four solvated Nafion cases. For each case, the distribution of chain lengths is then fitted to a Probability Density Function by multiple methods, including the classically applied cubic spline approach. It is found that the stiffness prediction is sensitive to the fitting methodology; the significance of each, as it relates to the physical structure of the polymer, is explored so that a method suitable for stiffness prediction may be identified.

5757-37, Session 8

Characterization of the solvent-induced nonlinear response of ionic polymer actuators

C. S. Kothera, D. J. Leo, Virginia Polytechnic Institute and State Univ.

Ionic polymer transducers exhibit coupling between the electrical, chemical, and mechanical domains, allowing their use as both sensors and actuators. Because of their compliance, light weight, and low voltage operation, ionic polymers have become an increasingly researched intelligent material, although their fundamental mechanisms are still open for debate. While most of the existing models provide linear, dynamic approximations of the response, nonlinear characteristics have been observed experimentally. Some of these include the introduction of permanent strain or remnant deformation in the step response, and distortion in the forced response to harmonic excitations. Recent experimental results have shown that the solvent plays a significant role in the dynamic response of ionic polymer actuators in the cantilever configuration. Given a single-frequency input voltage, the major difference from changing solvent materials was concluded to be a nonlinear distortion with varying influence, seen in both the actuation current and tip velocity measurements. These results compared the response of a water-based sample to a sample prepared with the ionic liquid EMITf, where it was found that the voltage-to-current relationship was much more nonlinear in the water sample, while it was predominantly linear with the ionic liquid sample. This research looks to further explore this nonlinear distortion by incorporating a larger set of candidate solvent materials and investigating the impact of how changing properties affect the overall response. System identification techniques using the Volterra series are employed to aid in the characterization of the harmonic distortion. The knowledge gained in this study will provide useful information about the nature of the nonlinearity and some of the factors that affect its relative influence, which will assist physical model development.

5757-68, Session 8

Implementation techniques for a ferromagnetic hysteresis model

R. C. Smith, T. R. Braun, North Carolina State Univ.

In this talk, we present energy-based modeling techniques to accommodate the hysteretic accommodation and after-effect phenomena inherent to magnetic compounds. These models are based on energy relations at the lattice level in

combination with stochastic homogenization techniques to obtain highly efficient macroscopic models. The performance of the models is illustrated through comparison with experimental data.

5757-39, Session 9

Hysteresis in a smart plate: identification and simulation

B. Fan, Univ. of Houston

One dimensional hysteresis has been extensively studied in the last two decades, whereas two dimensional hysteresis receives less attention. This paper studies hysteresis in a piezoelectrically actuated smart plate based on the elastic plate theory and Preisach model. In addition, an inverse Preisach hysteresis model is used to compute the necessary voltage input to actuate the plate in a desired fashion. With a Laser Doppler Vibrometer, the hysteresis of the piezoelectrically actuated plate is experimentally studied at low actuating frequencies. Experiments show that the developed model matches well with experimental results and show that such an approach may help to precise control of such smart plates for applications such as micro-pumps.

5757-40, Session 9

Modeling of acoustic reflection and radiation fields generated from elastic boundary using MHSV model reduction

W. Chang, National Univ. of Singapore (Singapore)

Numerical modeling of a three-dimensional acoustic field coupled with a piezoelectric-elastic structure demands significant computation load even on modern high speed computers. Especially when wavelength is much smaller than the field scale, the size of the coupled model and its computation time can be excessively large. In this paper, MHSV (Modal Hankel Singular Value) based model reduction technique is employed to minimize the size of the coupled model. This model reduction technique enables us to compare both the radiated waves and the reflected waves from a piezoelectric-elastic source in three dimensional spaces. Thus, it enables to verify whether it is possible to fully suppress reflected waves by radiating control waves in three dimensional spaces. In order to verify the simulation, the computation results, model size and computation time are compared with those from a commercial software.

5757-41, Session 9

Active damping of piezolaminated composite beams using combined extension and shear piezoelectric mechanisms

H. Abramovich, L. Edery-Azulay, Technion, I.I.T. (Israel)

The present study exhibits a comprehensive investigation performed to study the effects of piezoceramic materials on the active damping of vibrating piezo-composite beams. The active damping is obtained by using an actuator and a sensor made of piezoceramic layers, acting in 'closed-loop'. By transferring the accumulated voltage on the sensor layer to the piezoelectric actuator layer, causes the beam to actively damp-out its vibrations. The voltage transferred from the sensor to the actuator has to be amplified through a feedback gain.

An exact mathematical model, based on a first order shear deformation theory (FSDT), was developed and described. By splitting this general model into two sub-models, we could study the effect of all four piezoelectric 'closed loop' combinations; One, using only one piezoelectric mechanism, extension or shear, as both sensors and actuators, (Ext-Ext and Sh-Sh), and second, using both piezoelectric mechanisms, extension and shear, in a combined 'closed loop', as sensors or actuators (ES and SE).

Eight layers cross ply beam, containing the two piezoelectric mechanism layers (as active or structural layers), was used and enabled to do a correct comparison between the all four piezoelectric damping options that were calculated.

Using the present model, both natural and damped vibrations were calculated. The required feedback gain, G, of each piezoelectric combination was computed. In addition, the effect of piezoelectric materials on damping higher frequencies was investigated.

The present study shows that using extension and shear piezoelectric mechanisms can be used in order to achieve active damping. The two mechanisms may be configured separately or combined to achieve a continuous damping (x=10% ¸ 90%).

This damping scale was calculated for the first three natural frequencies that were tested. For a structure using only one piezoelectric mechanism, extension or shear as both sensor and actuator, it was found that, using Sh-Sh structure requires less feedback gain (G), while, no significant advantage as a rule was found when using combined piezoelectric mechanism. For the combined configuration, consideration of using one structure on other depends on the beam's boundary conditions.

To understand the ability of using piezoelectric material in active damping, the present study is restricted to beams with symmetric cross play, and continuous piezoelectric layers all over the beam. In order to complete this investigation, a serial of tests are planned to be performed, to confirm this theoretical research. The outcome will be reported in due time.

5757-42, Session 9

A fully thermoelectromechanicaly coupled FE analysis for the dynamic behavior of smart plates using discrete-layer kinematics

G. Giannopoulos, J. Vantomme, Royal Military Academy (Belgium)

In last years composite structures with embedded piezoelectric elements have been used in many applications, especially in aeronautics. The potential of using the piezoelectric elements as both actuators and sensors leads to structures that can both sense and adapt their performance according to the loading or even according to their structural integrity. A number of different methods have been developed in order to study such structures and predict their performance under different conditions. Both analytical and numerical methods have been presented, with the later to become very popular during last years. The first attempts to predict the response of composite structures was to use the classical laminate theory and including the effect of piezoelectric elements through induced forces and moments. This analysis could give a preliminary idea of the performance of such a smart structure. In [1] and [2] one can see some representative examples of this type of work.

The next step was to use in the analysis an uncoupled electromechanical formulation for the piezoelectric elements combined with CLPT or with a higher order single layer theory (e.g. FSDT). This formulation solved some of the problems that were present in the previous type of analysis; however it is obvious that even this formulation could not provide the full electromechanical response of smart plates. In [3] and [4] one can see some representative examples of such analyses.

Further developments on the analysis of piezoelectric structures gave rise to the establishment of new type of formulations. In addition to the structural degrees of freedom, electrical degrees were added in the solution and furthermore in the equation of motion the charge equation was also included. This formulation in combination with single layer theories and later with discrete layer theories improved the prediction capabilities of the response of smart structures. In [5], [6] and [7] one can find some characteristic examples, while the number of works performed in this are is great and a few are mentioned here for brevity. In addition an excellent review work on all these theories can be found in [8].

As it is shown in previous works, discrete layer theories are gaining more and more attention for the analysis of smart structures. The inherent advantages of this type of formulation, like the accurate prediction of intralaminar stresses and interlaminar shear stresses and also the capability to monitor local effects inside the layered structure, makes them a very useful analysis tool.

In this work, the fully thermoelectromechanicaly coupled dynamic response of a smart plate is presented. In order to perform the analysis, a 4-node plate element has been developed. A linear through the thickness approximation was implemented. This approximation considered to be sufficient for the type of analysis presented here. The prediction of the overall performance of the structure as well as the intralaminar stresses can be predicted very accurately. Thermal forces are also considered in the analysis, a very important parameter considering the interaction of different layers of composite materials and piezoelectric layers with different thermal expansion coefficient. In order to be able to predict the full coupled response all three constitutive equations were introduced in the analysis. In the classical coupled electromechanical formulation of the structure the thermal terms are added and in addition the third constitutive equation, the equation of entropy is included in the analysis.

The dynamic response of the plate in different thermal, mechanical and electrical loads is considered. Parametric analyses are also presented for both thick and thin plates in order to investigate the range of applicability of this theory. Using such formulation it is possible to predict the behavior of a smart plate under combined loading conditions in an accurate way. Furthermore these results can be used in order to perform shape control or vibration control in a later stage. Finally comparison between the results of this work and similar works from other researchers is also presented in order to prove the validity of the present approach.

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5757-43, Session 9

Finite-element computation of dispersion in piezoelectric waveguides

P. W. Loveday, M. Shatalov, CSIR (South Africa)

Guided wave ultrasonics is an area of active research and offers the ability to inspect lengths of infrastructure, such as pipelines and railroad tracks, using stationary transducers. Knowledge of the wave propagation characteristics, including phase and group velocities, of the propagating waves is valuable in the design of such inspection systems. These characteristics can be computed analytically for simple geometries such as plates and cylinders but geometries that are more complex and waveguides comprising combinations of different materials require numerical analysis.

Efficient computation can be achieved by formulating 2-D finite elements using wave functions to describe the displacement variation along the waveguide and conventional interpolation functions over the cross-section of the waveguide. Formulation of these elements for waveguides including piezoelectric properties will be presented. The waveguide elements are verified by comparison with models using conventional 3-D finite elements and appropriate boundary conditions.

In the analytical solutions, it is simple to separate one mode from the others and compute group velocities. In the finite element method the frequency is set and an eigensolution yields a set of wavenumbers or the wavenumber is set and an eigensolution yields a set of frequencies. It is necessary to track each mode from one step to the next to be able to compute group velocities. A method of automatically achieving this is proposed and verified against analytical results for an infinite piezoelectric cylinder. The method is applied to compute phase velocities, group velocities and piezoelectric coupling factors of waves propagating in piezoelectric waveguides of non-simple geometry. This approach can be used to study various topics in smart structures.

5757-44, Session 10

Vibration confinement of flexible structures using piezoceramic actuators

A. Punhani, H. Yoon, G. Washington, The Ohio State Univ.

The vibration of systems with vibration sensitive components creates problems for the longevity of those sensitive system components. Vibration confinement is the act of restricting the vibration to a certain region of the system. Confinement or restriction of vibrations to relatively unimportant areas helps in isolating sensitive components from vibratory disturbances and mitigating the propagation of acoustic noise.

Passive methods for vibration confinement have been suggested by Vakakis (1994) by altering the design of the structure and isolating the critical part from the vibration. Keane (1995) used a genetic algorithm optimization to incorporate noise filtration feature in the structure. These passive methods are inexpensive to employ but have limitations and are not always feasible from a practical point of view. Recently, much effort has been put into active vibration confinement. Yigit and Choura (1995) suggested that a proper selection of distributed feedback forces could convert the original mode shapes into exponentially decaying functions. Shelley and Clark (2000) suggested scaling the eigenvectors such that the amplitude of vibrations is much smaller in the critical areas of importance, thus confining the vibration to the unimportant areas. To overcome the difficulty of coupling between the equations of motion they also suggested the Singular Value Decomposition method of eigenvector shaping. Tang and Wang (2004) used Rayleigh's principle for the optimal selection of eigenvectors, which would generate optimal achievable sets of eigenvectors to minimize the amplitude of vibration in the area of concern.

In this research, the eigenstructure assignment algorithm based on the Singular Value Decomposition and optimal selection of achievable eigenvectors using Rayleigh's Principle is revisited and extended for flexible structures controlled by piezoceramic patch actuators. First, we use a full-state observer using a PVDF sensor to get the real-time state information. Then, using this estimated information, a certain number of modes (eigenvectors) are shaped and the others are left to the same as the open-loop eigenvectors. This number of shaped modes is determined by the number and the position of the actuators. Using the full-state observer, this selective mode shaping can be done exactly by inversion of a full-ranked matrix without approximating the control gain using projection. To demonstrate the proposed approach, a pin-pin beam is selected. The beam is modeled and discretized using the finite element method and the piezoelectric control actuation is modeled as a moment couple along the edge of the patch.

The length of the PZT patches is taken to be the same as the length of the beam elements. Each beam element consists of two nodes and each node has two degrees of freedom (except the end nodes, which has one DOF each), deflection and slope. Increasing the number of elements (number of nodes in a structure) thus increases the degree of freedom of the structure. The actuation moment by the piezoelectric patches are taken as positive in the counter clockwise direction.

In addition to the simulation, an experiment is conducted and the result is compared with the simulation result.

5757-45, Session 10

Applications of neuro-PID adaptive controller based on RBF

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In recent times, there have been several devastating earthquakes around the world which have underscored the tremendous importance of structural vibration control. The protection of civil structures has continued to attract attention, which has resulted in the increasing research activities in the field of structural control. Since the introduction of the concept of structural control which was first proposed to the civil engineering community in 1972, much progress has been made towards exploiting the considerable and potential benefits offered by control for protection of structures against environmental loads such as strong earthquakes and high winds.

Many researchers have made significant contributions toward the development of structural control; these contributions include theoretical and experimental approaches for the active and hybrid control of civil engineering structures. As for control methods, many advanced control technologies, including , , , sliding mode control, and neural networks control, have been investigated for applications to civil structures. In the control of civil engineering structures, most research effort has been focused on the development of systems that are more reliable and on the development of implementable control strategy.

Neural networks are now generally recognized as effective tools in control problems. In this paper, a PID adaptive controller, which is based on RBF Neural Networks Identifier, is developed for structural control. The combined controller includes a PID neural network controller and an identifier based on RBF neural networks. The input of the controller is velocity of the system, which can be easily measured. This controller uses the simplicity of PID control, so that it is readily implementable for engineering applications. Moreover, because of the introduction of the identifier, the controller does not need the exact model of the system.

This combined approach was implemented on linear and nonlinear single and multiple degree of freedom systems subjected to external disturbances based on the El Centro (1940) earthquake loadings. The response of the building structure represented by the SDOF and MDOF systems are stimulated using appropriate equations of motion. An RBF network is used to identify the systems from the response data while a neuro PID controller is used to control the response of the structures. It is demonstrated that the neuro PID adaptive control method can effectively suppress the vibration of structures.

5757-46, Session 10

MIMO adaptive control of thruster-firing-induced aibration of satellites using multifunctional platforms

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This paper presents the concept, control strategy, and simulations for suppressing the thruster-firing-induced vibration of satellites. First, a satellite vibration reduction concept of utilizing the UHM multifunctional platform is discussed, and the structural configurations of the platform and the combination of the platform and a satellite are described. A satellite-like frame with the platform is analyzed, and the predominant modes of the frame are determined. A MIMO adaptive control scheme, including on-line identification of the controlled frame and control scheme, is then developed to suppress the frame vibration. The identification process can update the dynamics of the frame timely and assure an accurate model for the controller while the platform makes any manipulation such as the misalignment correction of the satellite thrust vector. This controller is adjusted based on the vibration information of the frame and drives the platform to isolate the vibration transmission from the firing thruster to the satellite structure. The entire system has seven actuators, four of them are piezo-stack actuator and three are piezo-patch actuators. Eleven vibration components are controlled. Finally, simulations are performed to suppress the vibration of the frame for different disturbances and platform manipulations. The results demonstrate that the entire frame vibration at its dominant frequency can decrease to 7-10% of its uncontrolled value in various platform manipulations.

5757-47, Session 10

Damage detection and gain-scheduled control of CFRP smart board mounting the metal core assisted piezoelectric fiber

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This paper deals with damage detection and vibration control of a new smart board designed by mounting the piezoelectric fibers with metal core on the surface of the CFRP composite. The damage of the board is identified on the assumption that the piezoelectric fibers using a sensor and actuators are broken at the damaged location simultaneously. When piezoelectric fibers are broken by the damage, piezoelectric fibers expand and contract between the root and the damaged position of the cantilever beam. Damaged positions are detected by focusing attention on this property. Furthermore, the gain-scheduled controller considering the deterioration of sensors and actuators caused by break of piezoelectric fiber is designed. First, the finite element method (FEM) model of the cantilever beam with considering length of piezoelectric fibers is derived. If the length of fibers shortens caused by break, not only the actuator performance but also the sensor output decrease. Thus, peak gain of the FEM model is calculated for the every length of piezoelectric fiber. The relation between peak gain and the damage position is computed for the damage detection. Furthermore, the reduced-order model for the controller design where the first mode is only considered is derived and transformed into a linear fractional transformation (LFT) representation for the gain-scheduled controller design. The parameter contributing to the variation is the position of the damage. Next, the gain-scheduled controller using LFT representation is designed. Finally, the simulation and experimental result of the damage detection and the gain-scheduled control is shown. From the results, it is shown that the gain-scheduled controller can improve the control performance in the case that piezoelectric fiber is broken caused by the damage.

5757-48, Session 10

Tracking control of a piezo-actuated stage based on frictional model

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The tracking control accuracy of (PEA) is limited due to their inherent hysteresis nonlinearity. Besides the dynamic behavior of a motion stage with friction force causes some control problems such as static errors, limit cycles and stick-slip in mechanical system. An approximated piezoelectric-actuator model is synthesized based on linear transfer function and time delay system with two tuned parameters. The frictional model for stage both in the presliding and sliding regime is considered. The H-infinite tracking controller is designed for compensating the hysteresis delay and static force in PEA actuated stage during linear positioning. The Iterative Learning Control (ILC) is designed for the Stribeck effect of the frictional characteristics. Numerical simulations and experimental tests consolidate that the RMS tracking error can be close to the hardware reproducibility and accuracy level. Experimental results show the piezo-stage control system can be potentially used for nano technology applications for precision engineering in industrial systems.

5757-49, Session 11

The development of variably compliant haptic systems using magnetorheological fluids

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A telerobotic system consists of a pair of manipulators in which an operator handling one manipulator (the master) directly controls the second manipulator (the slave), which acts on an external object. The performance of telerobotic systems can be greatly improved if some form of kinesthetic (or force) feedback is employed. The systems are called “transparent” when the operator controlling the master has the feeling of direct interaction with the remote object without any distortions in forces or geometry caused by the slave. Transparency is greatly limited in state of the art systems because most systems have slave inertias that are in general considerably higher than their corresponding master inertias, leading to the feedback of large signals emanating from impacts between the slave and its external object. These abrupt signals must be significantly attenuated to prevent instability, but this attenuation produces nontransparent systems that have a characteristically “mushy” feel, requiring excessive amounts of operator training for safe operation.

The inertia of the slave system can be significantly reduced if the motorized system used for classical haptic feedback is replaced by a Magnetorheological (MR) fluid based system. The MR based haptic system works as follows: the master joystick which includes a rotary MR damper in parallel with a spring controls the movement of the slave end-effector. Force and displacement sensors in the slave sense the environment conditions along which the end effector moves. This information is then used to control the MR damper to provide appropriate force feedback to the user. For example if the slave encounters soft tissue (low force, small to no deceleration) a relatively small current signal will be sent to the MR damper which will give the user the slight resistance associated with soft tissue. Likewise if the slave encounters bone (high force, large deceleration) a large signal will be sent to the MR damper, which will give the user a larger resistance.

There are a number of simple models used to describe MR fluid operation such as Bingham model [1] and Herschel-Bulkley viscoplasticity model [2]. While present rheological based modeling techniques of MR fluids work well for modeling dampers, clutches, and brakes, there are some advanced applications (e.g. tactile and force feedback systems) that require higher fidelity models, force feedback, and variable compliance.

In this study the authors develop haptic systems for telerobotic surgery. The research outlined in this document is subdivided into two parts: microstructural, kinetic theory based modeling and actuator design. A microstructural, kinetic theory-based model of MR fluids has been developed [3]. For modeling these composite systems, dumbbell models in which two beads joined by an elastic connector were investigated. The iron particles are modeled as elastic dumbbells suspended in a carrier fluid. Microscale constitutive equations relating flow, stress, and particle orientation are produced. All coefficients in the constitutive equations are specified not by a fit to macroscale experimental flow measurement but rather in terms of primitive measurements of particle microstructure, carrier fluid viscosity and density, and temperature. These new models for MR fluids are three dimensional and applicable to any flow geometry. The model developed in this study is fully vectorial and relationships between the stress tensor and the applied magnetic field vector are fully exploited. The higher accuracy of the model in this regard gives better force representations of highly compliant objects.

The advantages of using MR fluids in haptic devices stems from the increase in transparency gained from the lightweight semiactive system and controller implementation. The most notable negative is the “sticky wall” phenomena (an inability to create reaction forces when moving away from a depressed object). The work in this study overcomes these limitations by the addition of variable compliance to the system and nonlinear controls. Singular perturbation analysis has been used to show that by adjusting the magnetic field to vary the amount of damping, the transmission can be varied between compliant and effectively rigid modes [4]. Variable compliance is incorporated by the addition of a spring in parallel with the damper. In order to accommodate systems with significant nonlinearities and unmodeled dynamics a nonlinear, sliding mode technique is used to control the stiffness emanating from the actuator. Because of the large range of forces necessary a number of different MR fluids are employed: Carbonyl iron powder with two different particle size ranges (2-

5 and 4-7) mixed with silicone oils with five different viscosities (=0.00935, 0.1906, 0.34055, 0.974, and 12.1875 Pa.s) as well as mineral oil are used to make twelve different samples of MR fluids. These MR fluid samples are used in the designed MR sponge damper [5] and tested in a MTS machine commonly used for tensile tests. The resulting force-velocity graphs of the damper for twelve varieties of MR fluids are used to determine the damper with the greatest range (in terms of force). In the second stage, MR fluids are used in the design of a rotary MR sponge damper based joystick [6] and a ball socket MR joystick for controlling a single degree of freedom (SDOF) and multiple degree of freedom (MDOF) systems respectively.

SDOF system: the end effector for the force feedback system is shown in figure 1. The rotation of the probe (robotic arm), which is held at the center by two springs, is controlled by the joystick. When the probe contacts a solid object or barrier, the probe will pivot and the angular change is sensed by an encoder. As the angular change increases, the current sent to the MR joystick increases and the user feels the force from MR joystick proportional to the force encountered by the springs.

MDOF system: the ball and socket joystick device shown in figure 2 will be used for force feedback controlling of a two degree of freedom system in which a probe moving in x-y plane will be controlled. The ball and socket joystick cannot be effectively modeled using the rheological based models because the flow and its corresponding magnetic field are spatially varying vector quantities.

5757-50, Session 11

Orthotropic deflection model for corner-supported plates with segmented in-plane actuators

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The shape control of thin, flexible structures has been studied primarily for edge-supported thin-plates. For applications such as optical reflectors and radio transmitters, corner-supported configurations prove more applicable. Corner-supported adaptive structures allow for parabolic geometries, greater flexibility, and larger achievable deflections when compared to edge-supported geometries under similar actuation conditions. Initial models have been developed for corner-supported thin plates actuated by isotropic piezoelectric actuators. However, typical piezoelectric materials are known to be orthotropic. This paper extends a previously-developed isotropic model for a corner-supported thin, rectangular bimorph to a more general orthotropic model for a bimorph actuated by a two-dimensional array of segmented PVDF laminates. First, a model determining the deflected shape of an orthotropic laminate for a given distribution of voltages over the actuator array is derived. Second, the results of the model are shown to agree well with a layered-shell finite element simulation of the structure. Finally, actuation of a sample laminate employing orthotropic PVDF film is investigated.

5757-52, Session 11

Mechanical modeling of failure in surface coatings

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Films and surface coatings provide protection for the surfaces which they cover. In the past few years, a number of methods have been proposed for the self-healing of materials used in coatings and films. [1, 2] The first step in modeling macroscopic properties of self-healing coatings is to model their initial failure.

We use a quasi-static three-dimensional Lattice Spring Model coupled with the Born Model to simulate fracture, elastic response, and shrinking of surface coatings. The results provide a framework upon which investigation of “self-healing” properties of surface coatings can be investigated.

The Lattice Spring Model (LSM) has been shown to simulate the micromechanical model of highly heterogeneous films.[3] It allows for the simulation of polymeric systems through a representation of nodes connected by harmonic elements (also called springs or bonds). LSM accounts for the nearest and next-nearest neighbor interactions between nodes, and allows for the use of static and quasi-static modeling methods based on the Born Model for balancing node positions and bond forces [4].

When a crack is formed, a surface is created which is normal to the direction of the bond which experiences failure. A statistical bond selection process favors bonds with high stress. By creating a bounded surface which breaks all bonds passing through it, rather than breaking a single bond, it is possible to introduce a region around the location of the stress which cannot bear any applied load [5].

To simulate shrinking, we exponentially decrease the natural length of the springs within the LSM at each time step.

The simulation procedure consists of three processes: initialization, time stepping, and solution/iteration. During initialization, the LSM array is established and configured; node positions are given a small offset to model heterogeneity; and bonds between each node, nearest and next-nearest neighbors are created using periodic boundary conditions. For each time step, a stress profile is obtained; bonds are broken to create fracture surfaces; springs are shrunk; and forces on all nodes are re-calculated; finally, the iterative solution of the Born Model brings the system to equilibrium.

We have shown how this model can be used to model the formation of a crack. The system simulated contains two substrate layers and three coating layers. Periodic boundary conditions are used for the lengthwise directions. The system is capable of modeling the deformation of a surface layer due to both elastic stress and bond breaking.

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5757-53, Session 11

SMARTSIM: an integrated design tool for smart structures

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From vibration suppression of complex composite structures to vibration damping of snowboards, smart structures and materials have found increased use in many applications. In many cases, the smart structure components have multiple roles beyond load bearing. Of relevance to this paper is the use of smart structures that incorporate sensors, actuators, and a control system that can improve the dynamic characteristics of the overall structure.Designing a smart structure involves the determination of many factors such as: (a) the optimal combination, composition, and shape of materials, (b) the optimal choice and placement of sensor and actuator types, and (c) the optimal design of the controller. Given the vast number of design parameters, extensive design iterations involving the evaluation of numerous prototypes may be necessary. Based on an initial set of requirements and assumptions, several variants may be generated and evaluated during a given iteration step. Promising variants may be refined into several variants for evaluation in the following iteration step. The iterative process may need to be performed numerous times until a single optimal design is obtained. Depending on the complexity and novelty of the design, such experimentation may be time and cost prohibitive.Relegating some of the experimental prototype design and evaluation to numerical simulation, especially those in the earlier stage of the design development, could significantly reduce the time and cost requirement. As the design gradually evolves, the dependence on experimental prototype design and evaluation can then be gradually increased.In addition to the vast number of design possibilities to evaluate, designing a smart structure requires the expertise of scientists and engineers specializing in different fields. Without a common tool to maintain a tight cooperation among groups with different expertise, an over-the-wall method could inadvertently be adopted. Such a method could significantly reduce the overall efficiency and effectiveness of the design process.Given the iterative and inter-disciplinary nature of smart structure design, the use of numerical methods that allow natural exchange of information from one process to another makes sense. Dedicated numerical design tools that usually do not allow seamless information exchange among one another can amplify the tendency to adopt an over-the-wall method.An integrated design tool based on relevant numerical methods from various fields could save development time and cost. SMARTSIM is a design tool developed for the design of smart structures in this capacity. While many existing numerical design tools approach various aspects of smart structure design from one or several specific fields, SMARTSIM attempts to approach the design problem by generating an integrated environment that allows for the various numerical design aspects to interact as seamlessly as possible. This paper provides a general overview of the current version of SMARTSIM, followed by a numerical design example.

5757-54, Session 11

Transient analysis of delaminated smart-composite structures by incorporating Fermi-Dirac distribution function

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In the analysis of integrated smart composite structures, it is important to take into consideration imperfections, such as delamination, that are often pre-existing or are generated by external impact forces during the service life. Although extensive research has been conducted in investigating delamination in laminated composites, a vast majority of the work in the field of delamination detection has concentrated on predicting delamination growth and the associated reduction in compressive strength of the structure. The effects of delamination on the dynamic response of a structure are subtler, compared to the large reductions in compressive strength, and there are fewer models for describing these effects.

In this paper, some new approaches in the modeling of delaminated smart composite structures as applicable to Structural Health monitoring and NDE application will be discussed. Normally, sub laminates technique or Heaviside unit step function is applied to model possible slip or jump at the delaminated interface of laminated composite structures. In these techniques, it is not easy to model smooth transition in the displacement and the strain field of the delaminated interfaces during the opening and closing of the delaminated layers under vibratory loads. In quantum mechanics, the Fermi-Dirac distribution applies to Fermions particles whose characteristics are half-integer spins. The present paper uses Fermi-Dirac distribution function to model a smooth transition in the displacement and the strain fields of the delaminated interfaces during "breathing" of delaminated layers. The improved layerwise laminate theory and a coupled piezoelectric-mechanical formulation will be incorporated into Fermi-Dirac distribution function to account transverse shear effects of anisotropic laminated composites and to develop the coupled constitutive equations between laminated composites and piezoelectric sensor/actuator, respectively. An adoptive implicit nonlinear transient algorithm will be used to generate the voltage time history, which is useful in characterizing the presence of delamination. It is expected that the Fermi-Dirac distribution function can be used to accurately model the dynamic effects of delamination in smart composite structures. It is also expected that optimizing the parameters in the Fermi-Dirac distribution function can lead to more accurate modeling of the dynamic and transient behavior of the delaminated zones in laminated composite structures.

5757-55, Session 11

Analytical study on the influence of the normalized Bouc-Wen model parameters on hysteresis loops

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Hysteresis is encountered in a wide variety of processes in which the input-output dynamic relations between variables involve memory effects. Examples are found in biology, optics, electronics, ferroelectricity, magnetism, mechanics, structures, among other areas. This paper is primarily concerned with hysteresis in mechanical and structural systems. In these systems, hysteresis appears as a natural mechanism of materials to supply restoring forces against movements and dissipate energy.

To describe the behavior of hysteretic processes several mathematical models have been proposed: the Duhem model uses the property that a hysteretic system's output changes its character when the input changes direction; the Ishlinskii hysteresis operator has been proposed as a model for plasticity—elasticity and the Preisach model has been used for the modelling of electromagnetic hysteresis.

The Bouc-Wen model for hysteresis is widely used in structural engineering. It consists of a first order nonlinear differential equation whose parameters shape the hysteresis loop. Since the model is nonlinear, the relationship between the parameters and the shape of the hysteretic loop has only been investigated using numerical simulations. Recently a new normalized form of the model has been derived by the authors which uses a different reduced set of parameters. This new form of the model has allowed the analytical description of the hysteresis loop. This paper uses this description to analyze the influence of the parameters on the hysteretic loop and draws physical interpretations of these new parameters.

5757-57, Poster Session

On the applications of orthogonal functions in pattern recognition

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In the applications of remote sensing at optical wavelengths to different surfaces from satellite borne and high-resolution instruments, an understanding of the various physical mechanisms that contribute to the measured data is important. Accordingly, numerical radiative transfer solutions in one and higher dimensions have been utilized in several applications such as pattern recognition, target information retrieval techniques, and the bidirectional reflectance model in the remote sensing. Some approximate, numerical and rigorous solution for radiative transfer equation (RTE), such as iterative, series expansion, variational, Pade approximation, and linear spline approximation have been reported.

The available sets of orthogonal functions can be divided into three classes. The first includes set of piecewise constant basis functions (e.g., Walsh, block-pulse, etc.). The second consists of set of orthogonal polynomials (e.g., Laguerre, Legendre, Chebyshev, etc.). The third is the widely used set of sine-cosine functions in Fourier series.

While orthogonal polynomials and sine-cosine functions together form a class of continuous basis functions, piecewise constant basis functions have inherent discontinuities or jumps. It is worth mentioning that approximating a continuous function with piecewise constant basis functions results in an approximation that is piecewise constant. On the other hand if a discontinuous function is approximated by continuous basis functions, othe discontinuities are not properly modeled.

In pattern recognition and remote sensing, images often have properties that vary continuously in some regions and discontinuously in others. Thus, in order to properly approximate these spatially varying properties it is necessary to use approximating functions that can accurately model both continuous and discontinuous phenomena. Therefore, neither continuous basis functions nor piecewise constant basis functions taken alone can accurately model these spatially varying properties. For these situations, hybrid functions, which are combinations of piecewise constant basis functions and orthogonal polynomials, will be more effective. In this talk we present a new approach to the solution of RTE by using hybrid functions. The application of hybrid functions to the discretization of selected problems has generated excellent results [1-4]. Numerical examples are included to demonstrate the applicability and the accuracy of the proposed method and a comparison is made with the with existing results.

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5757-58, Poster Session

Sensor calibration using density estimation-based error model

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Calibration in wireless ad-hoc sensor networks is a canonical task that impacts the effectiveness of many other tasks such as sensor fusion and data aggregation. It has been mainly addressed as a step of sensor fusion. Almost inevitably it is assumed that the error model follows the Gaussian distribution. Therefore, the least linear squares norm is used in order to minimize measurement discrepancy. However, a number of recent experiments indicate that errors in sensor systems do not follow the Gaussian distribution. They often have complex structure that cannot be captured using the standard distributions and parametric statistical methods.

Our goal is to first study the error behavior using nonparametric statistical techniques where no assumption on error distribution is required. As we demonstrate with the distance (acoustic signal strength) measurements and the light intensity measurements, error behaviors can only be accurately captured by

non-parametric statistical techniques. We construct the error model using the density kernel estimation technique, which is represented in terms of 3-dimensional probability density functions (PDF). Specifically, we used a novel approach that maps the kernel density estimation problem into an instance of graph theoretic problem. The approach is generic in that the error model can depend on an arbitrary number of measured parameters. In addition, we evaluate the predictability and the consistency of the error model. Predictability measures how accurately the error model estimates the correct values that are not in the training data used to construct the error model. In our study of the relationship between the percentage of the training data and the modeling accuracy, even with only 30% of the training data, the error model still achieves only a prediction error of 8.27% when compared to the correct values. Consistency provides a measure of how often the error model is within a certain bound of accuracy. It is done using the resubstitution method, where a percentage of the original data is randomly selected to construct the error model while the remaining data is used to evaluate the model. This process is repeated a large number of times to construct the interval of confidence for one specific value or for the overall consistency.

Once the error model is available, we demonstrate that the calibration function used to map the recorded values to the correct values in order to compensate for sensor bias can be defined in several different ways depends different objectives and applications. More specifically, we propose four ways to select the corresponding calibration values based on the error model in order to construct the calibration model, which is represented by fitting the selected values with piece-wise polynomial functions. The piece-wise polynomial functions are compact, easily transmittable, and prevent over-fitting.

Finally, we demonstrate the broad range of applications of statistical error models by investigating how incorporating statistically constructed error model as the optimization objective impacts the accuracy of the location discovery task in sensor netowrks. Our results indicate an average of 47.2% improvement in terms of location accuracy when compared with the traditional optimization targets.

5757-59, Poster Session

Sensor calibration based on external stimulus actuation

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Sensor calibration is an inevitable requirement due to the natural process of device decadence and imperfection. On-line in-field sensor calibration is particularly important in wireless distributed sensor network since manual calibration is difficult also infeasible at times. Calibration is a technically challenging task mainly due to the existence of random noise and the absence of suitable error models. In addition, in many applications there are constraints in terms of latency.

We have developed an on-line sensor calibration scheme that employes a additional single source as the external stimulus that creats differential sensor readings used for calibration. We distinguish between the time-invariant systematic bias and the random noise component of the measurement error, and focus on identifying and correcting the bias.

The key idea of our approach is to use an actuator to produce differential simultaneous excitement of all sensors over a number of time frames while the environment the sensors are deployed in is relatively inactive. The sensor calibration functions are derived in such a way that all sensors (or a group of sensors) agree on the effect of the actuator in the most consistent way. More specifically, we utilizes the maximal likelihood principle and a nonlinear system optimization solver to derive the calibration functions of arbitrary complexity and accuracy. The approach has the following novel properties: 1) It is maximally localized in that each sensor only needs to communicate with one other sensor in order to be calibrated; 2) The number of time steps that are required for calibration is very low. Therefore, the approach is both communication and time efficitent. We present two variants of the approach: 1) One where only two neighboring sensors have to communicate in order to conduct calibration; 2) One that utilizes an integer linear programming (ILP) formulation to provably minimize the required number of packets that must be sent for calibration.

The on-line calibration techniques have many benefits including suitability for robust enhancement using either consistency checking or sensor fusion. In addition to the maximal likelihood, the technique can also provide other types of calibration, including one where the maximal error is minimized or the sum of weighted expected error is minimized in order to properly address the random noise.

We evaluate the two variants using traces from light sensors recorded by deployed sensors and statistical evaluations are conducted in order to obtain the interval of confidence to support all the results. Our experimental results show that the first variant achieves calibration error of 7.3%±0.5% with 92% of confidence. The calibration error is defined by normalizing the difference between the calibrated value and the measured value against the difference between the correct and the measured values. The second variant achieves calibration error of 7.5%±0.5% with 82% of confidence.

5757-61, Poster Session

Finite element analysis of a ring-type ultrasonic motor

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The ultrasonic motor (USM) is undergoing rapid development since its invention more than two decades ago and has been prototype by commercial firms such as Canon, Panasonic and Shinsei. Industrial interest in USM arises because of its unique characteristics such as its high output power per unit volume, high stationary limiting torque, high maximum operating torque, simple design, silence, and high precision controllability. Despite this, many aspects of USM are still not well understood and have not been successfully modeled. In this paper, a finite element model to simulate the steady-state operation of an USM is proposed.

Firstly, the governing equations for the dynamics of stator and the contact of stator and rotor are derived. The interaction between contact stress and piezoelectric effect is included which is often ignored. The equations are simplified by ignoring the impact of stator on the rotor because the velocity of particles on stator is low. Next, an algorithm to solve the equations is presented, where in one iteration, the dynamics of stator actuated by piezoelectric force and updated contact force are first solved, from which the static contact between deformed stator and rotor can be estimated. The convergence criterion used is that the maximum change in any component of contact stress, as a fraction of the maximum absolute contact stress, is less than a specific tolerance, say 1.e-5.

The iterative routine is performed using commercial FEM software ABAQUS version 6.4. For the dynamics of stator, three dimensional solid elements are adopted and the direct integration method is used because the modal-based procedures do not adequately transform the electric loads into modal loads. Rayleigh damping is adopted and the damping ratio is set to 0.5%. For the contact between stator and rotor, the Lagrange multiplier and penalty function method are used to simulate the normal and tangential interaction between stator and rotor respectively. Based on the proposed routine, given the applied torque, applied axial loading, and piezoelectric drive voltages as inputs, the general motor performance measures are obtained, namely speed, input power, output power, and efficiency.

A prototype ultrasonic motor is fabricated and tested for its natural frequencies, structural damping, and also the aforementioned parameters. The correlation of the measured and predicted results by FEM model shows that the model is valid in most instances.

The approach presented here provides more accurate and moderate computational cost framework for modeling USM as well as a design tool for optimizing prototypes.

5757-62, Poster Session

Designing a smart damping system to mitigate structure vibration part 1: experimental approval of unified Lyapunov control algorithm

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This paper proposes an effective vibration control algorithm using a smart damping system for vibration mitigation. The proposed algorithm, which is extended into a unified system from Lyapunov stability theory, enables to correct the errors in quantization by its increased stability. The validity of this design method was proved in the experiment on a control model of three-storied building structure. Smart damper was used for shear mode MR damper in the experiment, and its control effectiveness was evaluated. In order to make a more accurate control model experimentally, model updating was performed on the basis of the analysis of dynamic characteristics of structure and of the mathematical analysis of a lumped mass model, and then it employed a state space model redefined by structural property matrix. In this vibration control experiment, control effect under the influence of each different earthquake magnitude was evaluated to various performance index, and thus the algorithm presented here is proved to be valid.

5757-63, Poster Session

Magnetorheologial material-based sandwich beams with various sealant and boundary conditions

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The semi-active vibration control capabilities of Magnetorheological (MR) material based adaptive beams are investigated in this paper. The host structure of the adaptive beam is composed of two elastic face layer, and the sealant material are used for sealing the MR suspension between the face layer and holding the integrity of the specimen. With the frequency dependent viscoelastic properties of the MR suspension in pre-yield region, a discrete dynamic model of the sandwich beam structure is developed and the dynamic characteristic of the adaptive beam in response to varying applied magnetic field levels are discussed firstly. Then the variances in the boundary conditions and sealant materials are considered, respectively. The boundary conditions adopted in this study include clamped-free, clamped-clamped, clamped-simply supported and simply supported, while three kinds of rubber are employed as the sealant at the same time. The influences of these changes on the natural frequencies, modal damping and transverse vibration response of the sandwich beam are analyzed and compared. Additionally, effects of variations of the MR layer thickness of the specimen on the structural damping are studied. As a result, the semi-active control capabilities of MR material based adaptive beams are theoretically illustrated.

5757-65, Poster Session

Lead niobium stibium zirconate titanate piezoelectic ceramics having tetragonal and rhombohedral coexistent phases

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The relationship between composition and the electric mechanical properties for Lead niobium stibium zirconate piezoelectric ceramics (PNSZT),in which there are tetragonal and rhombohedral coexistent phase ,has been studied .A series of piezoelectric ceramics with good properties has been obtained ,having dielectric constants(ε) is 1500-2500,plane electromechanical coupling factor(Kp) is 0.45-0.65 ,mechanical quality factor(Qm) is 500-1600 .These materials are used for making ultrasonic sensor and filter,and marine acoustic launching and receiving device ,and so on. It has been explored that the influence of composition on the lattice constant and phase composition of PNSZT piezoelectric ceramics by XRD . The character of dielectric constant changing of PNSZT before polarization and after polarization .Analyzing and discussing the affecting mechanism about composition on the electric machine properties of phase coexistent PNSZT.

5757-69, Poster Session

Virtual and flexible digital signal processing system based on software PnP and component works

T. He, Hubei Polytechnic Univ. (China)

An idea about software PnP is put forward according to the hardware PnP(Plug & Play).Referring to IC design (data bus, address bus and control bus), making full use of the speciality of multi-task of Windows operation system, a virtual flexible Digital Signal Processing system(FVDSPS) is realized. FVDSPS is composed of a main control center, many sub-function modules and other hardware I/O modules. The main control center is programmed with Visual C++. It sends out command to the sub-function modules, and manages the running order, parameters and results of the sub-functions. The software kernel of FVDSPS is DSP module, which is realized through programming with Lab Windows/CVI and used to process digital signal. These DSP modules communicate with the main control center through some protocol, accepting commands or sending requirements. The data sharing and exchanging between the main control center and the DSP modules are realized and managed by the files system of the Windows operation system through the effective communication. FVDSPS is real oriented object, oriented engineer, oriented engineering problem. Through FVDSPS, user can freely plug and play, fast regroup a signal process system according to the engineering problem without programming. What you see is what you get. Thus, an engineer can orient to engineering problem directly, pay more attention to the engineering problems, and promote the flexibility, reliability and veracity of FVDSPS. Because of FVDSPS is oriented TCP/IP protocol, through Internet, the measurement engineers, technology experts and measurement field can be connected freely without space. The engineering problems can be resolved fast and effectively. VFMS can be used in many fields such as instruments and meter, fault diagnosis, device maintenance and quality control and so on.

5757-71, Poster Session

Verified models of multi-agent systems for vehicle health management

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We are concerned with how computational resources may coordinate with each other and with the platform hierarchy to achieve timely, reliable diagnostics and prognostics. Our approach involves multiagent systems. We focus particularly on coordination achieved by negotiation, and we consider the characteristics of vehicle health management systems that make multiagent systems attractive. We note the vulnerability of these systems to concurrency problems, which we rigorously attack at the design phase with model checking.

We use the special notion of an agent that has evolved in computer science, especially in the field of distributed AI. An agent in this sense is a computer system capable of autonomous action meeting its design goals and situated in a given environment. An intelligent agent in particular is capable of flexible autonomous action, which involves being both reactive and pro-active. A multiagent environment provides an infrastructure specifying communication and interaction protocols, and it is open (no “central designer”), so agents may be added to a multiagent system as it matures. A multiagent system provides fault tolerance through redundancy (agents with overlapping capabilities).

Coordination is critical and can be achieved with negotiation, which maintains the autonomy of the individual agents and allows collaboration that is not hardwired into the system. We use the contract net protocol (CNP), which is the original and perhaps the most fundamental negotiation protocol. It is generally desirable to have several agents that can solve a given task since an agent with unique capabilities is a potential bottleneck. Given a sub-task, then, we need some way to select a particular agent for that sub-task. In the CNP, an agent with a task decomposes it into sub-tasks and announces them. Agents bid on the sub-tasks they choose, and the original agent—the manager—evaluates the bids to determine how the sub-tasks are assigned to agents as contractors. When the contractors finish their sub-tasks, they return final reports, which the manager assembles into the overall result for the task. Unlike a procedure or method call, assigning a contractor is a mutual selection of the “caller” and the respondent. Also, sub-tasks themselves may have sub-tasks, so a given agent may be both contractor (of one task) and manager (of another), resulting in a control hierarchy. A control hierarchy does not preclude static hierarchies of agents, but it is not hardwired into the system. Finally, besides a final report, a contractor can send interim reports to the manager. This gives two complementary ways to use the CNP: (1) for initialization, selecting agents for subtasks in an ongoing task, and (2) during operation, where agents performing ongoing tasks handle problems or tasks on the fly with control hierarchies of limited duration.

There are several characteristics common in more sophisticated health management systems that lend themselves to multiagent systems in this sense. The availability of multiple diagnostic and prognostic techniques directly presents the selection problem addressed by the CNP. When an entire component hierarchy is monitored, one can bind agents to the components in a way that reflects that hierarchy, but there is generally also considerable room for flexible control hierarchies among agents, some of which may not be statically allocated to portions of the component hierarchy. Again, when there are multiple operation regions of various components, interpretation of one aspect can enhance the interpretations of others, and these relations must be established on the fly. As the number of such relations increases, the role of negotiation becomes more critical. Finally, flexibility allows one to focus resources on critical features of critical data, thus accommodating large amounts of data. Garga and his collaborators have noted that multiagent systems allow us to capture different hierarchical, temporal, and mission contexts relevant to rotorcraft systems.

Coordination, however, involves concurrency, in which deadlock, failure of mutual exclusion, and many other pathological states can arise. It is critical that diagnostic and prognostic software avoid these problems, but the limited observability and controllability of such systems limit a tester’s ability to exercise their behavior. We therefore rigorously validate a design for system of agents against its specification. For this we use the SPIN model checker, whose design language essentially describes finite state automata and whose specification language is linear time temporal logic (LTL). LTL has temporal operators (capturing such notions as “always”, “eventually”, and “until”) that allow us to express abstract requirements on the execution sequences of multiple agents. SPIN flags runs derived from the automata descriptions that violate the LTL specifications.

We currently have a prototype implementation of the contract net protocol in Java, prototype design descriptions in SPIN's design language, and prototype specifications in LTL. We have several agents that are bound to sensor groups and essentially perform feature extraction. We are working on agents that interpret these features, respond to critical events, adjust the behavior of the feature extractors, supply historical data, and interact with human users. The goal is an effective, efficient, open, and flexible system whose coordination behavior has been rigorously verified to avoid the major concurrency problems.

5757-72, Poster Session

FE analysis for the residual stress in diamond turning

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In order to investigate the depth of cut and cutting velocity influencing on the residual stresses in diamond turning, a coupled thermo-mechanical plane-strain large deformation orthogonal cutting finite element (FE) model is proposed on the basis of updated Lagrangian formulation to simulate the cutting experiment and predict the residual stress firstly. Also, the two factors quadratic regression design and analysis are utilized in experiments planning. In this FE based model, rezoning technology is used as chip separation criterion for the sake of considering the cutting edge radius effects of diamond cutting tool. The flow stress of workpiece is considered as a function of strain, strain rate and temperature to reflect the dynamic changes of physical properties, and both the conduction and convection are included in the heat analysis. Secondly, the cutting experiments are carried out in ultraprecision machine tool and the residual stresses are measured in X-ray stress analyzer. Based on these two sets data, two regression equations are deduced, one is determined from FE model and the other is obtained from experiments. At last, according to these two regression equations, the regression curves can be plotted and compared with each other. The comparison results show that the FE predicted curve is consistent with the experimental curve well. This indicates that the proposed FE model is reasonable and can be used to analyze the residual stress.

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5758-01, Session 1

Transverse strain sensitivity of fiber Bragg grating sensors

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Fiber Bragg gratings (FBG) written into polarization-maintaining (PM) optical fibers have been shown to act as excellent multi-axis strain sensors. Therefore it is important to predict the sensitivity of the reflected peak or peaks to strain applied to the fiber in each of the orthogonal strain directions. A large collection of experimental data has appeared in the literature for calibration of this sensitivity. In addition to the experimental data, several approaches to predict the transverse strain sensitivity have been applied. Generally, the strain components (or principle strain components) at the center of the optical fiber due to the applied loading are calculated. From these strain values the index of refraction changes are calculated along two orthogonal axes to determine the peak shifts in the FBG reflected spectrum. The fundamental assumption is made that since the LP01 mode propagates primarily in the core, the center strain values can be used to calculate the effective index of refraction for the fiber. However, complete matching of the experimental data to the predictions has not been achieved.

This paper presents the calculation of the transverse strain sensitivity of a FBG through the appropriate calculation of the change in effective index (or indices) of refraction of the fiber cross-section due to the applied strain field. It is shown that the inclusion of the change in index of refraction throughout the cross-section yields close agreement with the experimental data. For the calculation of the fiber propagation constants, a two-step finite element (FE) formulation is used modeling the optical, geometric and material properties of the cross-section. Similar to previous analyses, the FE model is used to calculate the strain field throughout the fiber cross-section due to the applied loading. In contrast to the previous models, however, the local change in indices of refraction of each element (the material is optically orthotropic due to the applied strain) is calculated. Using this modified index of refraction distribution and the same element mesh, the wave propagation equations are then solved perpendicular to the cross-section and the propagation constants are calculated.

For this paper, three diametrical compression cases cited most often in the literature are considered: a circular fiber, a PM fiber loaded parallel to its pre-existing polarization axes, and a PM fiber loaded at an arbitrary angle. Comparison of the FE results to the experimental data demonstrates: (a) excellent correlation of the FE and experimental results; (b) for the circular fiber case, the wavelength shift of the primary Bragg reflection peak is initially not very sensitive to the transverse strain (for a small load range), then demonstrates a relatively linear sensitivity over a significant load region and then becomes non-linear; (c) there is a significant difference in the results of the current FE and previous center strain component calculations, particularly since for a linear-elastic silica material, the strain component (or principle strain component) calculations can only predict a linear behavior for the first two cases considered.

5758-02, Session 1

Tuneable laser-based carbon composite strain sensing system using wavelength division multiplexed fiber Bragg grating sensors

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The development of the Fibre Bragg Grating (FBG) has been one of the most significant in the area of fibre-optic sensing in the last decade. This development together with advances in composite material technology has opened up the new field of fibre optic smart structures. FBG technology offers engineers the possibility of integrating non-destructive fibre optic nervous systems into their designs, allowing in situ process monitoring and continuous structural health checks. FBGs can be used to monitor strain and temperature.

FBGs can be multiplexed, allowing the possibility of quasi-distributed strain measurement. In this paper we present an FBG sensor system, which utilises a tuneable laser (1550 nm region with 80 nm tuning range) to interrogate an array of FBGs embedded in a carbon composite panel. The laser is used to interrogate each FBG in turn. An optical power meter detects the reflected laser light from the grating array. The tuneable laser and optical power meter are controlled using custom designed LabView drivers operating over a GPIB. A LabView program was also written that can measure and display the effective reflection spectrum from the FBG array.

The measured reflection spectrum can then be automatically compared to the unstrained FBG array spectrum stored in memory. The wavelength shifts between the unstrained and strained FBG spectral peaks can then be used, via the appropriate equation, to determine the strain experienced by each of the embedded FBGs. The system can also accept inputs from conventional resistive strain gauges for comparison. Consistent strain measurements were achieved using a scan resolution of 0.02 nm, which corresponds to a strain resolution of approximately 15 me.

The system was tested using a composite panel consisting of 28 plies of carbon fibre with the structure [2 x 90°, 2 x 0°, 2 x –30°, 2 x 60°, 2 x 30°, 2 x –60°, 1 x 0°, 1 x 90°]: symmetric. The angle refers to the relative alignment between the fibres of two adjacent plies. An array of four FBGs, supplied by Blue Road Research, were embedded at various locations in the panel parallel to the adjacent reinforcing fibres between the first two 90° plies. The FBGs had centre wavelengths of 1540 nm, 1545 nm, 1550 nm and 1555 nm with a bandwidth of 0.2 nm. The FBGs were coated with Polymide, which enables efficient transduction of the panel strain to the FBG. The panel was mounted in a specially constructed metal frame. A large screw was then used to apply a force to the centre of the panel. The resulting strain was then measured by the interrogation system. Simulations of the panel were carried out using the Marc/Mentat finite element program for advanced engineering analysis. The experimental results compared well to those obtained from the simulations. A full set of results will be presented in the full paper together with a more detailed look at the FBG sensor system itself.

5758-03, Session 1

Adaptive multiplexed two-wave mixing array demodulator to monitor dynamic strains using fiber Bragg grating sensors

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An adaptive Fiber-Optic Sensor (FOS) network to monitor dynamic strains using a novel array demodulation scheme is discussed. Unlike scanned-demodulation approaches where each sensor is probed sequentially, the proposed approach will enable all the fiber sensors to be active at all times. The sensor network will also automatically adapt to low-frequency sensor drift such as those induced by slow structural deformation or temperature changes, while retaining sensitivity to dynamic strains. The adaptive fiber-optic sensor network can therefore be used to monitor structural vibration, impact damage, acoustic emissions, or intentionally-induced ultrasonic signals. At the heart of the adaptive FOS network is an array demodulator based on two-wave mixing (TWM) using InP:Fe in the C-band wavelength at 1550nm. A wavelength demodulation scheme will be presented for use with Fiber Bragg-Grating (FBG) ultrasound sensors. In this configuration, the FBG is illuminated with a broadband source, and any strain in the FBG is encoded as a wavelength change of the light reflected by the FBG. The reflected light from the FBG is spilt into two beams (pump and signal) that travel unbalanced paths prior to being mixed in the TWM demodulator. A small wavelength change in the FBG reflected light results in an equivalent phase change between the pump and signal beams as they travel unbalanced path lengths. The advantages of the FBG demodulation using TWM come from the adaptive nature of the photorefractive crystal used in the TWM interferometer. By taking advantage of the photorefractive response time, it is possible to compensate for any slow changes that occur in the mixing beams, and only changes that occur faster than the response time will be monitored. Therefore FBG sensor system using TWM demodulation is immune to quasi-static strains or temperature drift. Furthermore, since TWM interferometers can be readily multiplexed, a single TWM demodulator can be used to demodulate signals from a network of fiber-optic sensors for use in structural health monitoring.

5758-04, Session 1

Etched in-fiber Bragg gratings for temperature sensing at high temperatures

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In submitting this extended abstract I am requesting consideration for the 2005 SPIE/ASME Best Student Paper Presentation Contest.

Many industrial and military applications require sensors able to withstand extreme temperatures. Fiber Bragg gratings (FBGs) rely on a periodic photoinduced refractive index modulation to reflect light in a narrow wavelength band

centered on the Bragg wavelength. As the temperature of the fiber increases, it expands, and the period of the grating increases, shifting the Bragg wavelength and allowing for temperature sensing. However, FBGs aren't suitable for sensing at high temperatures because the photoinduced index modulation grating washes out above ~350 °C. Etching Bragg gratings into the flat surface of an elliptical-core D-shaped optical fiber provides an alternative method of fabricating in-fiber temperature sensors. Since these are surface relief gratings, they can be used at very high temperatures. The sensor is limited by the melting point of the glass and not by diffusion, as index modulation gratings are. These gratings can also have a very strong reflection coefficient because of the high index contrast between air and the cladding materials.

To understand the performance of etched gratings on D-fibers we performed simulations of their spectral and thermal characteristics. In order to simulate etched gratings, a solver was developed for the coupled-mode equations, which describe the interaction of different modes in a perturbed waveguide. In this case, the perturbation was the presence of the grating on the fiber. First, fiber modes are found using the mode solver in BeamPROP™ and these are used to compute the coupling between the forward and reverse traveling modes in the fiber. The coupled-mode equations are then solved using the Runge-Kutta method. The solver allows for arbitrary grating shapes as well as for chirp, apodization, and changes in temperature. Numerical simulations indicate that a 100 nm deep sinusoidal grating fabricated at the top of the core of the fiber should be ~5 mm long to back-reflect 99% of the input power. The 3 dB linewidth of the reflection spectrum of this type of Bragg grating should be ~0.4 nm. Deeper gratings are more efficient at retro-reflecting incident light, but also have a broader reflection linewidth. Simulations of the temperature sensitivity of this device show that the reflection peak shifts 9 pm for every 1 °C increase in temperature.

The fabrication of etched in-fiber Bragg gratings consists of two steps; the removal of the cladding above the core, and the creation of a surface relief grating on the fiber. The first step involves the use of buffered oxide etch (BOE) to etch the cladding of the D-fiber until the elliptical core is barely exposed. The proximity of the core of a D-fiber to the flat side of the D shape allows the core to be exposed while leaving the cladding largely intact. The core must be exposed so that the grating can interact strongly with the fields in the fiber core. While the fiber is being etched, laser light is transmitted through it and the output power is monitored using a detector and computer. When the etch reaches the core of the fiber, the output power decreases sharply and the fiber is removed from the etch, leaving the core exposed.

To put a surface relief grating onto the etched fiber, we first prepare the fiber for the application of photoresist by placing it in a reactive ion etcher (RIE) for 30 seconds and then applying SurPass™ to improve adhesion. We then spin thinned photoresist onto the fiber. We interfere light of wavelength 364 nm on the flat surface of the fiber to record a grating in the photoresist. To improve the stability of the interference pattern on the photoresist, a Lloyd's mirror configuration is used in which half of the exposing beam falls on a mirror and the other half on the fiber, which is mechanically secured to the mirror. The mirror reflects its half of the beam onto the fiber, where the two portions of the beam combine interferometrically. Developing the photoresist leaves a surface relief grating on the fiber. The fiber is then etched again in a RIE to transfer the grating from the photoresist down into the cladding and core of the fiber. The reason for using thinned photoresist is that the RIE tends to wash out gratings in etching through a thick layer of photoresist to get to the fiber. We designed the gratings so that the Bragg wavelength would be 1550 nm.

Using an atomic force microscope (AFM) we were able to examine experimentally produced gratings. The AFM indicated that these gratings were approximately sinusoidal and ~100 nm deep. To characterize the thermal response of the gratings we launched an amplified stimulated emission (ASE) source into the fiber and used an optical spectrum analyzer to monitor the output as a function of temperature as the fiber was heated on a hot plate. Experimentally realized Bragg gratings have shown similar temperature sensitivity to the simulated results, with a change in the Bragg wavelength of ~10 pm/°C.

5758-05, Session 1

Processing of signals from fiber Bragg gratings using unbalanced interferometers

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Fiber Bragg gratings (FBG) have become preferred sensory structures in fiber optic sensing system. High sensitivity, embedability, and multiplexing capabilities make the FBGs more superior to other sensor configurations. The main feature of the FBGs is that the gratings respond in the wavelength domain with the wavelength of the returned signal being the indicator of the measured parameter. The wavelength has then to be converted to optical intensity so the following photodetector could detect changes in the intensity and send appropriate electronic signals for further processing. This wavelength-to-intensity conversion is a crucial part in any FBG-based sensing system.

Among various types of wavelength-to-intensity converters unbalanced interferometers are especially attractive because of their small weight and volume, lack of moving parts, easy integration, and good stability.

Intensity of an interference pattern generated by an unbalanced interferometer is described by a well known expression which is a function of the intensity of the interfering beams, the optical path difference, and the incident wavelength. The bandwidth of the incident light also plays a role in determining the intensity of the resultant pattern. Analyses show that the intensity of the interferometric pattern has a cosine dependency on the optical path difference and quasi-cosine dependency on the wavelength.

In this paper we will discuss effects of parameters of unbalanced interferometers in view of their applicability to analyze signals reflected from Bragg gratings. Various configurations of unbalanced interferometers will also be presented. Furthermore, analytical and experimental data will be given.

5758-06, Session 2

Process for mounting and packaging of fiber Bragg grating strain sensors for use in harsh environment applications

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Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. Optical fiber sensor operation and instrumentation have become well understood and developed. However, one of the areas in need of further development and commercial maturity is that of sensor packaging and installation technique. In this regard, there is a need to develop appropriate fiber sensor protective coatings and housings; investigate the fundamental transfer of strains, stresses, pressure and temperature from the host specimen or matrix to the sensing fiber and the associated materials inter-play; as well as the development of field installation processes and deployment techniques suitable for the various application areas and expected environmental conditions. This is particularly attractive for harsh environment areas where conventional foil strain gauges cannot operate.

In this paper, we report the development of a new bonding agent and method for the surface mounting of optical fiber Bragg grating strain and temperature sensors for use in harsh environments—where there is a presence of water, moisture, dust, susceptibility to corrosion and/or elevated temperatures up to 500 °C. The compound is based on a combination of ceramic fillers with an epoxy binder that is applied with a brush technique. The mounting procedure will be discussed along with experimental results on the sensor's strain and temperature response under controlled environmental conditions.

5758-07, Session 2

Development of high-speed optical wavelength interrogation system for damage detection in composite materials

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We have been studying an optical sensing technologies using fiber Bragg gratings (FBGs) for health monitoring of aircraft structures made of composite materials. The sensing system is composed of a piezoelectric transducer (PZT) actuator that generates an elastic wave of several hundred kHz and a FBG sensor that receives the elastic wave. When any damages generates in the composite materials, the elastic wave that propagates in the composite materials changes. Therefore it is possible to detect the damages by analyzing the elastic wave that is received by the FBG sensor. For detecting this elastic wave, we have developed high-speed optical wavelength interrogation for FBG sensors and FBG sensor module that can be embedded in the composite materials. In this high-speed wavelength interrogation, we have developed an arrayed waveguide grating (AWG) to an optical filter that converts wavelength shift of the reflected light from the FBG into the output optical power change, and the part of signal processor that could convert the electrical signal into wavelength by 10 Mega samples per second (MSPS) after optical to electrical (O/E) conversion. In addition, we have applied an automated temperature adjustment function for AWG to adjust the FBG center wavelength to the middle of wavelength between the center wavelengths of the adjacent output ports of the AWG. In FBG sensor module, we

have developed a connector for a small-diameter optical fiber that can connect a normal diameter optical fiber. By using this interrogation and FBG sensor module, we found that this sensing system is very promising for damage detection in composite materials.

5758-08, Session 2

In situ simultaneous strain and temperature measurement of adaptive composite materials using a fiber Bragg grating based sensor

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Fiber Bragg gratings (FBGs) have shown a great potential for sensing applications, and are easily embedded in materials with a negligible impact on the mechanical properties of the host (1). In particular, incorporation of FBG sensors into fiber-reinforced composite materials permits their monitoring from the curing stage through their working life. A growing application is for monitoring the activation of adaptive composite materials, for example the strain response upon heating of materials containing shape memory alloys. However, the use of FBG sensors is limited by their simultaneous dependence to strain and temperature. To overcome this cross sensitivity, a number of techniques has been proposed (1,2).

In this work, a sensor design suitable for simultaneous measurement of strain and temperature has been tested on an adaptive composite material. The sensor is formed by two FBGs, which are written in optical fibers with different dopants and then spliced close to each other. A sensing element results with two Bragg gratings having peak wavelengths around 1550 nm of similar strain sensitivity but different response to temperature. This is due to the dependence of the fiber thermo-optic coefficient on the core dopants and dopants concentration. A 193 nm excimer laser and the phase-mask technique were used to inscribe 7 mm long Bragg gratings in a Cabloptic germano-silicate fiber with 22-mol% GeO2 and in a Fibercore PS1500 germanium-boron co-doped fiber, respectively. The global sensor length after splicing the two gratings was of 15 mm. Following a FBG thermal annealing process, the induced central wavelength shifts of the reflected peaks were monitored for a strain range of 0-2000 μ strain and a temperature range of 20-150 °C. Temperature and strain sensitivities were KT1 = 7.48Å~10-6 °C-1, KT2 = 6.00Å~10-6 °C-1, Ke1 = 0.75 and Ke2 = 0.77, respectively. These sensitivities lead to a well-conditioned matrix solution for temperature and strain discrimination (3).

Adaptive composite materials were then produced. The host was unidirectional Kevlar-epoxy prepreg material, in which several 150μm diameter NiTiCu shape memory alloy (SMA) wires were embedded, together with one FBG-based sensor in the center. The wires were pre-strained by 3 % and maintained in a frame, during processing in a vacuum bag, at 70°C for 12 hours, followed by a post-cure for 4 hours at 140°C (4,5). Strain and temperature during curing were obtained by the FBGs peak wavelength shifts. The temperature reading was validated using a thermocouple placed on the sample. Finally, activation tests were performed on the finished composites by placing them in an oven up to 100 °C, and monitoring the strain and temperature. The composite contracted upon heating due to the recovery of the SMA wires above the transformation temperature. The experimental strain-temperature curve compared well with an elastic force balance analysis, taking into account the hysteretic behavior of the wire.

In conclusion, the FBG-based sensor tested in this work is a suitable tool for simultaneous and in-situ strain and temperature monitoring in adaptive composites during their manufacturing, and in service.

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5758-09, Session 2

Demodulating interferometric and FBG sensors in the spectral domain

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Fiber optic sensing systems are increasingly recognized as a very attractive choice for structural health monitoring. Moving form demonstration project to industrial applications requires an integrated approach where the most appropriate technologies are combined to meet the user's requirements. In this context it is often necesssay and desirable to combine different sensing technologies in the same project. A bridge-monitoring project might for example require long-gauge interferometric sensors to monitor the concrete deck, interferometric inclinometers for the piles and fiber Bragg grating sensors for the monitoring of the strains in the steel beams and for measuring temperatures. Although fiber optic sensors relying on different technologies can easily be combined at the packaging and cable levels, they often require dedicated instruments to be demodulated. A unified demodulation system would therefore be very attractive.

This paper describes a technique relying on the analysis of reflected spectra and allowing the demodulation of interferometric (Michelson or Faby-Perot) sensors and fiber Bragg grating sensors with a single measurement system. It also compares the obtained performance in terms of resolution and dynamic range with the available dedicated systems.

5758-10, Session 2

Modeling of transverse loading effect on Bragg grating signals

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Fiber Bragg gratings (FBGs) can provide extremely

sensitive strain measurements for various materials and structures. The main functionality of the Bragg grating is along the fiber?s main axis, where changes in the grating?s spacing induced by applied strain

can be converted into a wavelength shift in the Bragg output. Previous work from a number of researchers has identified bifurcation and broadening of the Bragg signal under transverse loading. The work presented in this paper highlights efforts to relate transverse loading to changes in index of refraction in the fiber core cross section, and then ultimately to predicted changes in Bragg signals. The developed model provides a useful tool in predicting effects of transverse loading on FBGs, whether these effects are undesirable, or sought after. Analytical and numerical analyses are presented as well as a background of

interest in loading effects and birefringence with respect to Bragg grating applications.

5758-11, Session 3

Use of multidimensional fiber grating strain sensors for damage detection in composite pressure vessels

M. Kunzler, E. Udd, Blue Road Research

Arrays of multi-axis fiber grating strain sensors have been integrated into a composite pressure vessel test article, and are used to monitor changes in the transverse and axial strain fields during curing and pressure cycling near cut tow and Teflon tape defects. These changes in the multi-axis strain due to four pressure cycles and repeated impacts are measured and compared to ultrasonic and eddy current scans. Examples of the remote detection of damage using transverse strain and transverse strain gradients is given as well as data showing the ability of the system to distinguish broken tow and delamination defects.

5758-12, Session 3

Damage growth detection of composite laminate structure using embedded FBG sensor/PZT actuator hybrid system

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This paper present a part of research and development with respect to damage monitoring of the aircraft structure using the FBG optical fiber sensor/PZT actuator hybrid system, which is embedded to bonding interface.

In recent research about structural health monitoring, the detection of an elastic wave, which was launched to the host material has been attempted in several

condition. In this case, FBG sensor has been bonded to the surface of the CFRP composite laminate. As the results, it was confirmed that the elastic wave detection by the FBG sensor could be conducted and the detection of the delamination, which is generated to inside of the composite material by the acquisition of elastic wave was possible.

For the improvement in reliability of high efficient bonded structure that is expected the employment to the actual aircraft structure designed by composite material, the application of structural integrity diagnostic system is required. The installation to the host material of these monitoring systems is necessity. However, the property degradation of the host material is anxious about the installation of the system.

Therefore, the authors acquired material properties using coupon specimen, which was simulated bonding interface with embedded FBG sensor in order to verify the no degradation of material properties. Further, it was confirmed that the detection of delamination and debonding, which exist in the bonded structure, using hybrid sensor system was possible.

In this research, the configuration of damage monitoring system, the optimized location of sensor and actuator that the damage onset and growth is detectable and damage detection technique was proposed due to the application to the actual structure. Then, the overview of the damage growth monitoring technology also will be discussed based on the obtained data by this system.

5758-13, Session 3

Identification of impact damage in sandwich structures by application of high-speed MEMS-OSA to FBG sensors

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The authors have applied fiber Bragg grating (FBG) sensors to detection of damages in composite laminates by monitoring the deformation of the reflection spectrum from FBG sensors. However, conventional optical spectrum analyzers (OSA) can be used for only static measurements because of those slow scan speed. In recent years, Takahashi et al. in Anritsu Corporation developed a new high speed MEMS-OSA that can measure optical spectrum with the wavelength range of 40nm only in 1.0ms keeping the wavelength resolution of 0.15nm.When the reflection spectrum of FBG sensors can be measured at high speed using this device, more information on the damage progress can be obtained under dynamic loadings such as low-velocity impact. In this research, this MEMS-OSA was applied to the FBG sensor glued onto a surface of a sandwich panel in order to estimate the damage magnitude and the loading point due to a low-velocity impact in the sandwich structure.

The sandwich structure used in this research consists of carbon fiber reinforced plastic (CFRP) quasi-isotropic face-sheets and aluminum honeycomb core. When a low-velocity impact loading is applied to a surface of the sandwich plate, the core cells beneath the impact region are buckled and pull down the upper face-sheet. Due to the gentle indent of the face-sheet, the FBG sensor bonded to the surface has strain gradient and the reflection spectrum becomes broad.

In practice, however, there is a possibility that the strain distribution of the FBG sensor becomes the same between the following two cases: a small impact energy is applied in the vicinity of the FBG sensor and a large one is applied far from the sensor. In these cases, since the reflection spectra measured statically after the impact loadings agree, the magnitude of the impact damages might be misestimated. Hence, the deformation of the reflection spectrum during the impact loading was also monitored dynamically using the high-speed MEMS-OSA. The experiments were conducted using 10mm FBG sensors glued onto the sandwich panels under the following two conditions. (1) The impact energy of 0.5J was applied at the point 5mm away along the axial direction from one end of the FBG sensor. (2) 1.0J was applied 5mm away along the axial direction and 8mm away transversely from one end of the FBG. After the impact tests, the out-of-plane displacement measured by a laser displacement meter along the FBG sensor agreed between the two conditions and the reflection spectra had almost the same shape. However, during the impact loading, the spectrum in the case of 1.0J expanded to the shorter-wavelength side and the shift of the center wavelength was smaller. In order to confirm these results, the reflection spectra were simulated from the strain distributions measured by the array of five foil strain gauges during the impact loadings. As a result, the calculated spectra changed in the same way as the experimental results. These results indicate that the dynamic spectrum monitoring using the high speed MEMS-OSA has a potential to estimate both the damage magnitude and the loading point due to a low-velocity impact in sandwich structures.

5758-14, Session 3

On-line characterization of impacts on electrical train current collectors using integrated optical fiber grating sensor network

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In order to identify damages of the electrical infrastructure during train operation, a fiber Bragg grating based sensor system performs measurements of the distribution of temperature and contact forces between current collector and overhead contact line. The actual model calculations and the practical design of a 2-dimensionally arranged strain sensor network have been especially enhanced to the calculation of impact directions, additionally to the results for strength and position of quasi-stationary contact force.

The well-known advantages of fiber-optic sensors - embedding capability in the composite carbon/aluminum collector strip, multiplexing of distributed sensor networks, electrical isolation - are of particular importance for detection and characterization of fast impacts immediately at the position of incidence, at the high-voltage train/contact line interface.

Tests under every-days operation conditions with trains on high-speed tracks as well as under high load in mountain regions proved the application of this sensing technology. Problems and solutions for the sensor network embedment, the fast Bragg sensor interrogation algorithms, and actual test results with their application-orientated analysis will be presented.

5758-15, Session 3

Residual stress and debonding analyses using fiber Bragg grating in a model composite specimen

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Optical Fiber Bragg Grating (FBG) sensors are excellent tools for internal strain characterization of composite materials and structures. They can be embedded at selected locations during material preparation to provide accurate in-situ measurements.

In this study, the long-gauge-FBG acts as reinforcement and as sensor to characterize residual stress, cracking and interface debonding. They are introduced in cylindrical specimens of epoxy with an external radius and length of 12.5 mm and 40 mm, respectively. The adopted configuration is commonly used in the mechanics of composite materials to investigate, residual stresses on the reinforcing fiber and the surrounding matrix due to the polymerisation of the matrix and strain distribution when transverse crack or fiber-matrix debonding are present. Both experimental configurations introduce non-linear strain distribution along the FBG thus, modifying the intensity, phase and polarisation of the light-wave propagating along the fiber.

Because the matrix epoxy shrinks during the polymerisation process, the optical sensor undergoes substantial deformation as a consequence of the non-uniform strain distribution build-up along the fiber. The response of a FBG to a non-uniform strain distribution is investigated in the time domain using a new Optical Low-Coherence Reflectometry (OLCR) technique developed at EPFL. This method provides a direct reconstruction of the optical period and the corresponding strain distribution along the grating without any a priori assumption about the strain field.

Considering the non-uniform residual strains as a reference state, new Bragg wavelength distribution are obtained for two configurations.

First, a new Bragg wavelength distribution is measured as a function of the depth of circular cracks machined in radial direction. These measurements lead to the knowledge of (a) the zone of perturbation of the reinforcing fiber on the residual stresses and (b) the effect of the presence of the mechanically induced crack on the residual stress state in the specimen.

Second, the fiber is axially loaded in (tension-tension) fatigue and the interface crack between the epoxy and the fiber is monitored using optical microscopy. The induced variations in the grating response are measured when an interface crack (debonding) is generated and increased during progressive fiber loading. These measurements lead to the characterization of the interface properties between the fiber and the epoxy.

By measuring the FBG response with the OLCR technique, the non-uniform strain distributions are accurately retrieved. Using an equivalent thermo-elastic approach and fracture mechanics, the experimental data on the stress distribution in the entire two-phase cylinder are confronted with finite element simulations and theoretical models. Excellent agreement is demonstrated between the experimental and analytical results.

5758-16, Session 3

Lamb-wave sensing using fiber Bragg grating sensors for delamination detection in composite laminates

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The authors are constructing a damage detection system, taking advantage of the sensitivity of ultrasonic waves to internal damages. In this system, a piezo-ceramic actuator generates Lamb waves in a CFRP laminate. After the waves propagate in the laminate, the transmitted waves are received by a fiber Bragg grating (FBG) sensor attached on the laminate using a high-speed FBG demodulator developed in collaboration with Hitachi Cable Ltd. This demodulator uses an AWG filter for detection of Bragg wavelength. At first, the optimal gauge length of the FBG sensor to detect ultrasonic waves was investigated. Through the theoretical simulation of the reflection spectrum of the FBG sensor receiving an ultrasonic wave, it was found that the gauge length should be shorter than 1/7 of the ultrasonic wavelength. Then, the directional sensitivity of the FBG sensors to ultrasonic waves was evaluated experimentally using an isotropic aluminum plate. As a result, since the maximum amplitude of the received wave decreased in proportion to the increase in the propagation angle to the axial direction of the FBG, it was found that the sensitivity of the FBG sensors strongly depends on the propagation direction. On the basis of the above results, the FBG sensors were applied to the detection of Lamb waves propagated in carbon fiber reinforced plastic (CFRP) cross-ply laminates ([0-2/90-2]s, thickness: 1mm). Theoretical calculation showed that Ao mode and So mode of Lamb waves are excited in the laminate and the wavelengths at 300kHz are about 22mm and 4mm respectively. Thus, three FBG sensors whose gauge lengths were 5mm, 3mm, and 1mm were bonded on the surface of the CFRP laminate. A piezo-ceramic actuator was put on the laminate about 30mm away from the FBG sensor, and three-cycle sine waves of 300kHz with Hamming window were excited repeatedly. As a result, the amplitude of the received wave increased with a decrease in the gauge length, and the waveforms showed that So mode could be obtained by all the three FBG sensors, but Ao mode could be detected appropriately only by the 1mm FBG sensor. These results are consistent with the above theoretical expectation of the optimal gauge length. Using the 1mm FBG sensor, detection of delamination in the CFRP cross-ply laminate was attempted. An artificial delamination was made in the laminate by removing of a Teflon sheet embedded in the 0/90 interface after the manufacturing. When the Lamb waves passed through the delamination, the amplitude decreased and a new wave mode appeared. In order to confirm this phenomenon, the wave propagation was simulated using a finite element solver "PZFLEX". The simulation results also had the same phenomenon. The new mode was caused by the separation of the Ao mode into the pass of [0-2] and the pass of [90-4/0-2] in the delaminated area. From these results, it was found that the delamination in CFRP laminates could be detected by using FBG sensors as Lamb wave receivers. Furthermore, since the amplitude and the velocity of the new mode increase with an increase in the delamination length, this system has a potential to evaluate the interlaminar delamination length quantitatively.

5758-17, Session 4

Airplane structure health monitoring by the optical frequency modulation Brillouin distributed measuring method

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The necessity for Airplane structural health-monitoring technology has been increasing because of improvement of reliability and cost saving. Optical fiber sensor system is an attractive method for structural health monitoring, because of its lightweight, non-electromagnetic interference, and to be embeddable to composite structures. Especially the distributed optical fiber sensor fits the health monitoring for large-sized structures. However, the distributed optical fiber measurement system using the pulse light represented by BOTDR has low spatial resolution and long measurement interval. These performances have been the obstacle of application to airplane structure health monitoring system. Then, the authors have proposed the Brillouin optical frequency modulation method for improvement of the spatial resolution and shortening of measurement intervals.

In this work, we conducted basic approach in order to development Brillouin Optical Frequency Domain Analysis (BOFDA) measurement system, such as pump power property and frequency modulation property for Brillouin stimulated light. We confirmed ability to measure stimulated Brillouin Scattering light in 50mm section. In short sampling time measurement approach, we confirm that prove laser light modulation make it possible to measure 0.2Hz dynamic strain condition. Moreover, We considered the optical fiber sensor installation issue on the airplane structure. The issue is optical fiber sensor birefringence under asymmetric load and durability of installation method. We conducted two confirmatory tests for the issues. The proposed installation method has adequate performance. From these results, it was confirmed that BOFDA system has potential to be applied to an airplane structure health monitoring system.

5758-18, Session 4

Thermo-acoustic emission method of failure prediction of composites

E. G. Nesvijski, Univ. of Minnesota

This paper describes a novel nondestructive method for composite material and structures testing and failure prediction. This method are recovering all types of composites includeing cement based material, rocks, other earth substances and structures from them. under critical level of stresses or less. This new method can estimate current state of composites for failure prediction by thermal acoustic emission which called "Thermo-Acoustic Emission" (TAE) method and could be applied for evaluation of testing materials for stability state or cracking development under local, short term or low-cycle thermal loads. Thermal loads could be applied as heating, cooling or their combination. Registration and analysis of the TAE data, their signatures and patterns, as well as control data of thermal loads, allows predict failure of composites. The paper is describing an algorithm which uses heating-cooling device, acoustic emission sensor, acoustic emission data acquisition equipment and special evaluating parameters and analysis software for TAE pattern recognition and automatic decision making. Experimental results of TAE application is demonstrated and discussing their interpretation for composite analysis with smart sensors imbedding to structures in services and other future applications.

5758-19, Session 4

Mobile instrument for intelligent leak detection and location on underground water supply pipelines

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The paper discusses the instrumentation of adaptive leak detection and location on underground water supply pipelines. The equipment is designed to be self-contained and portably mobile with sensors, signal conditioning and data acquisition units and a laptop PC operating signal processing, information analysis and instrument control.

Where pinpointing a leak, sensors are positioned on either side of the suspected leak position to collect tubular vibrational acoustics. Obviously, sensor performances will be of great significance to final detection and location results. Considerations regarding the selection of sensors along with their installation (placement) in practice are addressed. For example, the choice of sensitivity has to relate the tubular vibrational acoustic and the ambient noise intensities and trade-offs. The effects of sensor placement on the vibrational acoustic features are explored by quantity of practical data acquisition and analysis. The preferable sensor placement positions are discussed on various engineering settings.

The signal conditioning and data acquisition units are connected through USB to the central control while receiving instrument commands and uploading data. However they operate on data acquisition simultaneously and independently. The strict acquisition synchronization among individual units is highly desirable as the synchronization error is a fatal one of sources to produce pinpointing deviation. In the paper, the relationship between the synchronization error and pinpointing deviation is characterized and schemes to suppress the synchronization error are proposed.

Piezoelectric accelerometers with an embedded IC, which transforms the high output impedance of accelerometers to a lower one for increasing resistance to electro-magnetic interference, are chosen to pick up tubular vibrational acoustics. Even so, programmable filters and amplifiers are developed in signal conditioning. This is because that signal features such as the spectral positions and intensities in both vibrational acoustics and ambient noises may have substantial variations in various engineering sites. The programmable filtering and amplification based on in situ detection of signal features can make data acquisition achieving optimal signal-to-noise ratio. This in turn will highly improve the detection.

Signal processing is the core of instrumentation. An adaptive detection and estimation strategy is proposed based on LMS adaptive filtering and modified Wavelet denoising. The availability for leak detection and pinpointing estimation is automatically analyzed by the signal processing procedure without any prerequisite on signals and the procedure may adaptively find the way to get better estimate. Even the collected signals are heavily blurred by bursting

interferences and present non-stationary, the adaptive detection may also carry on. The LMS time delay estimation itself is mature. However, the developed evaluation on the estimator is based on the assumption that the noise powers in independent signal channels are equal. This assumption, to any extend, is not realistic in pipeline leak pinpointing engineering. The paper gives a full analysis on the estimator error under the practical engineering settings. It is of great importance to fulfill the instrumentation.

5758-20, Session 5

Damage evaluation and analysis of composite pressure vessels using fiber Bragg gratings to determine structural health

M. Kunzler, E. Udd, Blue Road Research

With the increased use of high performance composites in critical infrastructure technology, it has become increasingly important to be able to use 'smart systems' to monitor such materials and provide rapid NDE. Using fiber Bragg gratings embedded into the weave structure of carbon fiber epoxy composite pressure vessels, Blue Road Research (BRR) is able to monitor cross-linking during cure, monitor damage over time, and use information collected to verify models. This paper emphasizes the results of recent work in which multiple arrays of Bragg gratings were wound into a composite pressure vessel and monitored while the part was cured, proof-tested, and damaged. Based on the response of these sensors, predictions were made via algorithms that identified the location of these impacts. Results were then verified using traditional NDE methods.

5758-21, Session 5

Optical technique for examining materials' elastic properties

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Structural health monitoring (SHM) and damage detection involves the use of in-situ, non-destructive sensing and analysis of structural characteristics for the purpose of detecting changes that may indicate damage or degradation.

In many important SHM applications, where the structure is under extreme temperature and/or stress conditions or for very small (micro or nano) systems, structurally embedded, contact sensors are not possible.

In this paper we present a complete non-contact, all-optical inspection tool for the extraction of the elastic properties on a mechanical structure.

In this inspection tool a Q-switch Nd:YAG short pulse high power laser heats the surface of the material under inspection generating stress and strain waves (Lamb waves for plate-like structures). These waves will propagate along the plate providing principal material elastic properties and information about structural loading or defects presence through the structure's entire thickness.

The inspection tool detects these stress and strain waves by means of a Michelson modified surface displacement optical fibre interferometer.

The material's elastic properties information stored in the detected waves has been extracted using different signal processing techniques. First we have obtained the dispersion information of the Lamb waves by two different ways: two-dimensional Fourier Transform technique and time-frequency technique.

Once we have represented the material's dispersion curves, an inversion technique has been developed and applied for each of the previous two different techniques obtaining the Young's modulus and Poisson's ratio of the material. We have also compared and discuss these two different techniques of obtaining the elastic properties.

The paper is finished showing the results obtained after applying the previous system for strain and fatigue loading sensitivity and detectability, for temperature change sensitivity as well as for damage detection.

5758-22, Session 6

An innovative method for monitoring impact events on complicated structures using system identification technique

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This paper presents a new method for monitoring impact events on complicated structures using built-in diagnostic technique. For this study, the SMART layer developed previously at Stanford was used as a sensor network.

In most cases, real structures are not simple structures like beams or flat plates, but rather they are complicated structures which have stiffeners, multiple layers or 3-D curvature. Also sometimes, boundary conditions cannot be simplified as free-free, simply supported, or clamped boundary conditions. In the case of complicated structures, it is not easy to have a mathematical model, such as FEM, which is able to describe the dynamic behavior of the structure covering stress wave propagation. The proposed technique does not rely on a mathematical model of the structure, but System Transfer Functions are obtained from input and output signals. For this objective, system identification technique was used to establish System Transfer Functions capable of reproducing the system's physical behavior. After the system model was determined through one set of test, it was examined with different set of tests including different types of impactors. This technique makes the whole monitoring procedure much simpler not only because there is no need of a complex structure model, but also there is no need of the calibration procedure for sensors to get accurate strain/stress value.

For the impact location, it was estimated by examining power distribution over a structure. The power was calculated from sensors signals due to external impact loading. This distributed power level on the structure shows impact events clearly including source location and can be obtained simply without using structure model.

This paper summarizes the monitoring technique and presents examples of the results from several impact tests on complicated structures including a stiffened panel, a 3-D curvature structure.

5758-24, Session 7

Camera-based digital real-time static and dynamic testing of deployable/inflatable structures

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Because the cargo space of a launch vehicle is limited, large spacecraft structures must be designed to be stowed during launch and deployed once on orbit. Moreover, since the launch expenditure of a NASA space mission always constitutes a significant fraction of the total cost, inexpensive launch vehicles with small payload masses are always desirable. Hence, instead of using previous electro-mechanical types of deployment systems, recent efforts of NASA concentrate on the use of deployable/inflatable structures for space applications. Deployable/inflatable structures have been used in space as parabolic antennas, radiators, solar concentrators, sun shields, habitats, radio-frequency structures, optical communication systems, radars, lightweight radiometers, etc. These highly flexible structures (HFSs) are designed to undergo large displacements and rotations without plastic deformation and are designed to satisfy space limitations, provide special mechanisms, and/or reduce structural weight. However, current HFS systems are usually designed by trial and error. We have developed a new modeling technique using Jaumann strains and stresses and new concepts of local displacements and orthogonal virtual rotations to derive geometrically exact structural theories for one- and two-dimensional structures. Moreover, a total-Lagrangian finite element code GESA (Geometrically Exact Structural Analysis) is being developed by implementing these new structural theories for the modeling, analysis, and fast prototyping of HFSs.

To experimentally verify numerical solutions from GESA this paper will demonstrate the use of an 8-camera EAGLE-500 real-time motion analysis system for measuring HFSs undergoing large static and dynamic deformations. The motion analysis system uses 8 high-resolution CMOS (complementary metal-oxide-semiconductor) cameras to capture pictures of a structure when 8 visible red LED strobes light up retro-reflective markers on the structure. The cameras and strobes are synchronized to work at a speed between 0.1 to 2000 FPS (frames per second). For a frame rate between 0.1 and 480 FPS, a full resolution of 1280x1024 pixels is used. For a frame rate between 480 and 2000 FPS, a reduced resolution is used. Using triangulation techniques and the known focal lengths (after calibrations using an L-frame with 4 markers and a T-wand with 3 markers) of the cameras and the known coordinates of the bright points (caused by the retro-reflective markers) on the 2D pictures inside the cameras, the EAGLE real-time software EVaRT 4.2 automatically computes and records the instant 3D coordinates of the center of each retro-reflective marker that is seen by at least two cameras. Hence, 3D time traces of all makers are available for performing dynamic animation using stick figures and showing pop-up graphs of displacements, velocities, and accelerations, and they can be output to other programs for further signal processing. The recording time length is effectively infinite and up to 600 markers can be simultaneously traced due to the use of large computer memory and a 100 Mbit data upload rate. Because the 3D coordinates of each marker are checked and calibrated when more than two cameras see the marker, the measurement accuracy is high. For example, the measurement error is far less than 1.0mm when the measurement volume is 2x2x2 m^3.

The principle of triangulation measurement using two or more cameras, the distortion model for correcting perspective and optical distortion to obtain correct image plane coordinates, the calibration procedure, and the measurement procedure will be shown. Moreover, experimental results obtained from several highly flexible deployable/inflatable structures (including a string, a cantilevered beam, a triangular frame, a circular frame, a rectangular membrane, an initially curved composite panel, and spinning rotor blades) will be used to show the capabilities of this system in characterizing buckling, nonlinear dynamics (such as nonlinear modal coupling and chaotic vibrations), and flutter of HFSs. The measurement accuracy, constraints, and limitations of this static and dynamic measurement technique will be addressed.

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5758-25, Session 7

Design of a distributive load sensor using PZT

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When measuring a force at a point on a body, the problem is a straight forward one. However, when a dynamic distributive load is to be measured, the problem is not as trivial. The number of sensors and signal conditioners or amplifiers needed could make the whole exercise impractical and/or very expensive to undertake. But there are many instances when it is desirable to measure the spatial distribution of the load transmitted by a device, component or structure. The traditional way for such measurements is the use of an array of discrete load sensors.

The work presented relates to the design and construction of an inexpensive distributive load sensor. It is to be used for impact tests on samples which are in the form of flexible or deformable beams of a considerable length. The sensor compromises of forty fingers made of steel arranged next to each other and covering a total length of about a meter. Both ends of each finger are clamped. A PZT ceramic patch, which is bonded to the bottom surface of each finger, is used to translate the impact response into an electrical signal. An appropriate amplifier and filter is designed for each finger. The frequency range over which each finger operates is extended by the use of an appropriate filter. Each finger was calibrated separately, and an amplifier box was built containing the charge amplifier circuitry and filter of each of the forty fingers comprising the distributive sensor.

Tests are performed on the distributive sensor in order to show that this simple and inexpensive distributive sensor is effective. For the tests, deformable beams are used. These are tubes containing a mixture of elastomeric beads and a matrix viscous liquid. The impact force exerted on the tube raises the pressure of the matrix liquid inside the tube. The matrix liquid transfers the impact energy not only to the beads which are directly below the impact point, but to all the beads along the length of the tube. The distributive load sensor is used in order to measure the magnitude of the force transmitted from the impact on both sides of the impact point, and to monitor the travelling shock wave inside the tube. The effectiveness of the distributed load sensor is demonstrated.

5758-26, Session 7

Digital phase modulation and demodulation techniques based on low-coherence fiber-optic interferometry and phase-measurement interferometry

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Phase modulated fiber-optic sensors based on Fabry-Perot interferometers have been widely used in many applications. However, direct modulation and demodulation techniques can not be applied when Fabry-Perot sensors have small cavity length due to insufficient depths of modulation. In this paper, a novel digital phase-stepping modulation and demodulation technique is developed to overcome this limitation. This technique is based on combining the principle of low coherence fiber-optic interferometry (LCFOI) and phase-measurement interferometry (PMI). An integrated optical circuit (IOC) phase modulator that enables a high frequency modulation is used to acquire multi-step phase shifts added to the sensor phase output signal. Phase retrieval algorithm along with phase unwrapping technique is detailed and phase error associated with this technique is discussed. Analysis has shown that this technique is especially useful for fiber optic sensors with sensor cavity length in micrometer range and sensor bandwidth requirements in kHz to MHz range. In addition, it enables the realization of multiplexed sensor systems based on Spatial Division Multiplexing (SDM).

5758-27, Session 8

Fiber pressure sensors based on periodical mode coupling effects

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Fiber-optic sensor technology offers the possibility of implementing low weight, high performance and cost effective health and damage assessment for infrastructure elements. With the technical developments in the optoelectronic and fiber optic communication, highly sophisticated components are available at modest price. Common fiber sensors are based on the effect of external action on the spectral response of a Fabry-Perot or a Bragg grating section, or on the modal dynamic in multi-mode (MM) fiber. We were interested in the later type of sensors because of their cost advantage. In this paper, we report some observations of fiber-optic pressure sensors based on modal coupling induced by pressure. One of the techniques uses modal selector to split the LP01 and LP11 modes, where the output intensity ratio of these modes is susceptible to the pressure change on the fiber. Our modal selector is an asymmetric mode coupler (AMC), where one fiber was pre-tapered to induce a preference for a given mode. This AMC device is based on phase-matched evanescent coupling between two dissimilar fibers. Our preliminary data shows a 20% variation on the output ratio for a 200 gr loading on the fiber. The second technique uses an offset-splice device, where a MM fiber is collinearly spliced to a single-mode (SM) fiber with a small radial misalignment. The offsetting degree can be precisely controlled by monitoring the splice transmission. This MM-SM offset-splice (MSOS) device acts as a rugged modal filter, where the pressure-induced modal coupling on the MM fiber causes the power to change after the offset-splice owing to the difference in the extent of their evanescent fields between LP01 and LP11 modes. By translating the pressing point along the sensing MM fiber with a constant speed, a sinusoidal intensity modulation was observed. The amplitude of the sinusoidal waveform is linearly proportional to the load imposed on the MM fiber up to 100 gr load with maximum intensity modulation of about 25%. This intensity sinusoidal behavior during load translation can be explained by the known theory of mode-coupling due to microbending periodical perturbation. In the microbending case, the most effective microbending period is Λ = 2π/∆β, where ∆β is the z-component wavevector difference between the two-coupled modes. Our observed intensity modulation period, which coincides with the period of microbending perturbation above, is about 0.43 mm for a 980 nm laser in a typical communication SMF-28 fiber. Due to the β dependence on wavelength, this sinusoidal waveform period is expected to show wavelength dependent too.

This was tested by launching two lasers (at 980 and 850 nm) into the MSOS device, and observing a sinusoidal waveform, with a clear 12.2 mm beat period envelope. In an attempt to demonstrate a sensor sub-system, we tested two MSOS devices in series using a 3dB coupler to allow for intensity modulation from individual MSOS device to be detected. With the MSOS as a basic sensing unit, a fiber pressure sensor-array with the potential of detecting the strength and location of the pressure on the infrastructure elements can be constructed.

5758-28, Session 8

Geotechnical pressure cell using a long-term reliable high-precision fiber optic sensor head

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The paper will describe a fiber optic sensor head, which can be used for long-term high-precision measurements of very small deflections of mechanical diaphragms. In order to measure deflections in the range of a few micrometer, an absolute fiber Fabry-Pérot interferometer is positioned in front of the diaphragm inside the housing. This sensor head has been developed in a research cooperation between the Federal Institute for Materials Research and Testing in Berlin and the German Gloetzl Company in Rheinstetten - a geotechnical instrumentation supplier. The sensor head is going to be used in geotechnical measuring systems and other applications.

There were a number of requirements for the sensor head that had to be fulfilled. Most important requirement concerns reliable information about the long-term zero-point position of the sensing element because there is no opportunity to re-calibrate an embedded sensor head after years of service (lost installation). Additionally, the zero-point value of the sensor head must not be lost even if the probe was disconnected for a long period. Another requirements concern a stable characteristic curve of the sensor head to enable the reproducibility of static measurement values over years, to control drift and relating hysteresis

problems. Together with the data processing unit, the specially designed absolute interferometer sensor allows to measure unambiguously static deformations with high precision.

The paper describes the sensor head, which meets the requirements and will present results from the validation carried out to evaluate possible drift effects, and to identify mechanical and thermal hysteresis. The validation revealed that the stability of the sensor is very well; a long-term standard deviation of < 2 % for the diaphragm deflection could be confirmed.

5758-30, Session 9

Demonstration of an intelligent hydrogel-based diffraction grating

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We report the fabrication of a diffraction grating cast into a responsive hydrogel using a silicon rubber intermediate cast from an engraved glass master grating. The aim to investigate if changes in the swelling of this gel in response to changes in the concentration of a specific analyte led to changes in the line spacing, and hence diffraction pattern, of the grating.

The protocol for casting gratings was initially developed using a composite carboxymethyl dextran/bovine serum albumin gel produced using carbodiimide chemistry to assess the optimum gel properties required. Examination under a light microscope showed that, formed under appropriate synthesis conditions, CM-dextran-BSA hydrogels retained the grating structure and appeared to have similar optical properties to the silicon rubber sub-master.

For a facile initial evaluation of the detection principle a number of similar gels were produced using cross-linked alginic acid. In this case excess carboxylic groups remaining after cross-linking were able to form additional ionic cross-links in the presence of divalent cations (Ca2+). Test experiment with these gels showed that both the size and position of the reflected and refracted spots obtained from illumination with a Helium-Neon laser changed as gel swelling changed with calcium ion concentration i.e. the size of both diffraction and reflection spots increased as the alginate hydrogel shrank in response to changes in environmental Ca 2+.

The utility of the alginate based gels for the detection of cations, together with evidence that dextran protein gels can retain grating structures, suggest that this assay procedure should applicable to any hydrogel where the response is based on protein-ligand interactions. The key requirement is that the cross-linking interactions constraining gel swelling can be quantitatively displaced by the analyte acting as a specific competitor.

5758-31, Session 9

ORB: an airborne microsensor observing platform

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ENSCO, Inc has identified a need for airborne in-situ measurements of various quantities such as meteorological parameters (temperature, humidity, pressure), as well as biological and chemical agents. In this paper, we present one approach for the development of such a probe using advances in smart materials, microelectromechanical systems, and bio-nanoengineering.

The Observational Roving Body (ORB) is a self-contained constant altitude vessel (balloon/bubble) that incorporates an electronic payload as part of its shell. The inside of the ORB would be filled with lighter-than-air gas such as helium to make the vessel buoyant. The vessel could take any form, but would most likely be spherical, cylindrical or saucer shaped. The vessel shell would consist of a polymer composite laminate and would contain a thin-film photovoltaic array, printed circuits for the communication and processing electronics, a patch antenna for communications, and functionalized sensing areas.

The size of the vessel can be minimized by decreasing the shell thickness. The primary tradeoff for ORB miniaturization relates the surface area of the ORB shell to the efficiency of the thin-film photovoltaic collection. The shell cannot be made smaller than the area necessary to generate enough power to run the other electronics, especially the transceiver. Common thin-film solar cells generate approximately 1 mA cm-2 with a conversion efficiency of 10%. Thus the surface area of ORB must be large enough to supply the necessary energy for the other embedded electronics.

One application that is critical to both the Department of Defense and the Department of Homeland Security is chemical and biological detection. The ORB can be used for this application by incorporating the appropriate sensor suite. The shell could be functionalized to perform various chemical sensing as well as biological immunoassay. The ORB would allow for in-situ measurements of chemical/biological clouds in both urban areas as well as on the battlefield. The ORB could be equipped with a multitude of different sensor types to provide high probability of detection and low false positives.

ORB will require further advances in the fields of flexible electronics so that the processing capabilities can be embedded into the shell. These advances could come in the form of thin-film based semiconductors, organic electronics, or nanoelectronics. Thin-film based semiconductors typically suffer from poor electronic performance due to the amorphous or polycrystalline nature of the material. Organic electronics are already used in the thin-film display market and are showing rapid gains in terms of functionality but are still orders of magnitude slower than standard semiconductor electronics. Nanoelectronics have shown great potential in the research laboratory and could become commercially available within the next five to ten years. Most likely the solution will come from a mixture of these technologies.

We will present the technology roadmap for creating an ORB as well as discuss the different characteristics such as power generation / storage, communications, networking, sensing, and aerodynamic design associated with development of airborne probes for in-situ measurements.

5758-32, Session 9

Gas sensor with starburst dendrimers: molecular recognition and molecular structure

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An idealized model for the dendrimer polyamidoamine is used as a gas-chemical sensor. The system considered is a solution of this dendrimer in a binary fluid mixture of two solvents: one being the analyte molecules and the other the placebo molecules. The analyte species possesses special affinity to the corona (the surface) of the dendrimer, or to the end groups; while the other fluid being neutral. Both Monte Carlo simulation and integral equation studies have been carried out to determine the excess adsorption of analyte population on the surfaces of dendrimers.

In the simulation studies, we explicitly account for the presence of the solvent molecules (solvent-explicit). As a consequence, we find that at low gas permeation, the dendrimers exhibit dense core behavior. However, at high gas contents, the dendrimers transit to the dense shell configuration. This behavior is clearly shown in the values of Rg (radius of gyration) at difference gas densities. By functionalizing the end groups, we observe pronounced analyte aggregation around the corona. We quantitatively show the variations of the "molecular recognition" as function of the temperature, affinity strength, and gas density and composition conditions. These effects shall aid in the design and function of dendrimer-made sensors.

5758-33, Session 9

Fiber optic pH sensor for early detection of danger of corrosion in steel-reinforced concrete structures

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The lifetime of a steel-reinforced concrete structure depends strongly on its pH stage as embedded steels in concrete structures are only passivated at pH-values higher than 9. Hence, monitoring of pH-values is very important for early detection of corrosion damage. Fiber optic sensors are gaining in importance as inexpensive, flexible and non-destructive measurement systems for health monitoring of large steel-reinforced structures.

In order to create a concrete-embeddable pH Optode, we first developed a fiber optic sensor based on the measurement of the energy transfer from a luminescent metal-ligand complex to a pH-sensitive dye. Different combinations of materials and methods for the co-immobilization into a solid polymeric support were applied to prepare sensing membranes suitable for the pH-range 9 to 13. Luminescence lifetime measurements exhibited, however, only a short-term-stability of the resulting films due to the effect of the molecular oxygen (acting both as a quenching and a bleaching agent) and the leaching of the indicator molecules from the support. The optimization of that kind of pH sensor was considered to be too difficult with regard to the long-term-stability requirements for monitoring of the pH-value in concrete structures.

Therefore, another method was chosen. It bases on the absorption measurement of a pH-sensitive dye at different wavelengths (e.g. absorption maximum or isobestic point) and the comparison of intensity changes between two absorption intensities (ratiometric method). A number of pH indicators were investigated with regard to the pH range 9 to 13 and the long-term stability. Only few of those indicators fulfilled the requirements. Another task concerned the

immobilization of the suitable dyes into a polymeric matrix to obtain pH-sensitive films. Different methods, e.g. adsorption, entrapment and covalent binding were applied for immobilization. Absorption measurements showed that most of the sensor membranes were not appropriate due to the decrease in the concentration of the pH indicator (leaching or photobleaching) or the unexpected change of the pH-properties of the dyes after immobilization.

At present can be stated that only a strong hydrophobic polymeric support is suitable for preparation of stable sensing membranes. First experiments with pH sensor heads embedded in concrete samples have demonstrated their long-term-stability.

The presentation will explain the necessary steps to develop a long-term stable pH sensor. Critical points to be considered will be discussed and experimental results from applications on-site will be shown.

5758-34, Session 9

Cable-free wearable systems using conductive fabrics transmitting signals and power

E. R. Wade, H. Asada, Massachusetts Institute of Technology

In this paper, we present a novel design of a wearable network for health monitoring, fitness, and rehabilitation. This wearable network consists of three components; the transmission medium, the smart sensor nodes, and the command node.

First, the authors developed a method for combining signals and power onto a single conductor using DC powerline communication (PLC) techniques. By using DC-PLC, we need only a ground line and a single supply line to provide power and a data transmission medium for multiple nodes. The DC-PLC innovation is incorporated into a wearable network through the use of woven conductive fabrics. Whereas other wearable networks rely on bulky sensors and cables, we use two separately insulated layers of conductive fabric with no metal wires woven into them. Using silver-coated nylon, and suitable flexible insulators, we have created a garment that is perfectly capable of being used to transmit data and power, but physically indiscernible from normal clothing.

In addition to the conductive fabric medium, the network consists of smart sensor nodes, which are composed of a sensor, microprocessor, modem, and a local amplifier. The sensor nodes are quite versatile, and can include sensors for measuring biological signals (such as temperature, posture, respiratory, and pulmonary sensors), actuators for rehabilitation, wireless communication devices, or other device aids. The strength of the smart sensor design is that the authors focused on a modem design that allows for the use of sensors with varying power requirements and data transmission rates. The modem, which is included at each smart sensor, acts as the interface between the actual sensor and the wearable network. It handles all the necessary signal processing, modulation, and data conversion required to send the sensor output signals over the wearable medium to the centralized command node.

The 'command' node oversees both the communication and power delivery among the sensor nodes. The command node contains the system battery that is used to power the nodes, and also a central processor that communicates with the sensor nodes. The command node maintains a wireless link with a local station (such as a PC or laptop), that can in turn be used to communicate the user's biological information to a health professional over the internet. This provides the user with much greater freedom of movement.

This design has a few salient features not yet seen in wearable networks: robustness to sensor location, durability, comfortability, washability, and no metal wiring. Soldiers in combat situations, athletes undergoing health fitness training, and elderly outpatients with serious health problems are all prime candidates for a smart system of this type. In this paper, we discuss the design considerations for such a system, present a system prototype, and present preliminary results.

5758-35, Session 9

Self-sensing structures for control of micro and nano-cantilevers

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A sensing approach based on resonance frequency shifts of oscillating micro- or nano- cantilever can potentially provide ultimate sensitivity for detection of a single molecule. However, implementation of this sensing technology on micro-scale has intrinsic limitations: The quality, Q, of an oscillating microcantilever vibrating in air is approximately in the 30-100 range and this value dramatically drops in a liquid environment. Feed-back control of the oscillations can improve the quality of the system but it meets multiple challenges with the sensing and actuation. Traditional data acquisition approaches, which includes optical, piezoresistance, piezoelectric and capacitance methods, have very limited application in signal transduction from micro- or nano- cantilever beams. Electrostatic and thermal actuations are not appropriate for liquid environments.

A novel approach utilizing the self-sensing and self actuation response of electroactive materials is proposed for control of the cantilever beams vibration. Any dielectric material exhibits dielectrostriction effect which is defined as variation of dielectric properties of the material with deformation. Similarly, electrostriction response can be used for actuations. In this work we will present theoretical background and experimental data for dielectrostriction and electrostriction study of various materials. Control challenges and approaches for such non-linear systems with self-sensing and self-actuation capabilities will be discussed.

5758-36, Session 10

Musca domestica inspired machine vision system with hyperacuity

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Musca domestica, the common house fly, has a simple yet powerful and accessible vision system. Cajal indicated in 1885 the fly's vision system is the same as in the human retina. The house fly has some intriguing vision system features such as fast, analog, parallel operation. Furthermore, it has the ability to detect movement and objects at far better resolution than predicted by photoreceptor spacing – termed hyperacuity. We are investigating the mechanisms behind these features and incorporating them into next generation vision systems. We have developed a prototype sensor that employs a fly inspired arrangement of photodetectors sharing a common lens. The Gaussian shaped acceptance profile of each sensor coupled with overlapped sensor field of views provide the necessary configuration for obtaining hyperacuity data. The sensor is able to detect object movement with far greater resolution than that predicted by photoreceptor spacing. We have exhaustively tested and characterized the sensor to determine its practical resolution limit. Our tests coupled with theory from Bucklew and Saleh (1985) indicate that the limit to the hyperacuity response may only be related to target contrast. We have also implemented an array of these prototype sensors which allow for two-dimensional position location. These high resolution, low contrast capable sensors are being developed for use as a vision system for an autonomous robot and the next generation of smart wheel chairs. However, they are easily adapted for biological endoscopy as well downhole monitoring.

5758-37, Session 10

Methodology for image-based tracking of seismic-induced motions

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Previous experiences during earthquake events emphasize the need for new technologies for real-time monitoring and assessment of facilities with high value nonstructural elements such as equipment or other contents. Moreover, there is substantial limitation in our ability to rapidly evaluation and identify potential hazard zones within a structure, exposing rescue workers, society and the environment to unnecessary risks. A real-time monitoring system, integrated with critical warning systems, would allow for improved channeling of resources. The optimal system would allow for non-intrusive, high-speed data, which is rapidly collected via a fast network and analyzed in a central repository for building owners and rescue workers to make informed decisions. In recognition of these issues, in this paper, we describe a methodology for image-based tracking of seismically induced motions. The methodology includes the calibration, acquisition, processing, and analysis tools for seismic assessment. We present sample waveforms extracted considering edge and contour-type algorithms applied to images collected from an array of high speed, high-resolution charged-couple-device (CCD) cameras. This work includes use of a unique hardware and software design involving a multi-threaded process, which bypasses conventional hardware image frame grabbers and internally (within the software) acquires, synchronizes and time stamps images.

5758-39, Session 11

Metal RubberTM sensors

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This paper discusses mechanical sensors based on Metal RubberTM, a new free-standing nanocomposite material that combines the properties of metals and

rubber. Like metals, Metal RubberTM has high electrical and thermal conductivities. Like elastomers such as rubber, it has low modulus and can be repeatedly elongated to several hundred percent strain yet relax elastically back to its original shape, all while remaining conductive. Metal RubberTM is formed by a modified electrostatic self-assembly approach that allows the formation of thick, large surface area nanocomposites to be formed with multiple controlled constitutive properties. In specific formulations, the electrical conductivity can be made to vary as a function of elongation, and as a result, the material may be used as a sensor of strain, vibration or acceleration, as well as pressure in special configurations. This paper presents a first-order physical model of the material as a strain sensor and gives experimental results for the repeated measurement of large strains of many tens of percent, beyond the limits of conventional strain gages. Other sensor applications are suggested based on this demonstrated behavior.

5758-40, Session 11

Nondestrtuctive damage sensitity of functionalized carbon nanotube and nanofiber/epoxy composites using electrical resistance measurement

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Electro-micromechanical techniques were applied for functionalized carbon nanotube (CNT) or nanofiber (CNF)/epoxy composites with their adding contents using four-point probe method. Carbon black (CB) was used only for the comparison with CNT and CNF. The fracture of carbon fiber was detected by acoustic emission (AE) correlating to the change in electrical resistance, R under double-matrix composites (DMC) test. Stress sensing on nanocomposites was performed by electro-pullout test under uniform cyclic loading. At the same volume fraction, the damage sensitivity of fiber fracture, matrix deformation and stress sensing was highest for CNT/epoxy composite, whereas CB/epoxy composite was lower compared with CNT or CNF cases. According to mechanical properties and apparent modulus, the reinforcing effect by CNT was highest among three CNMs. Damage sensing was correlated consistently with the morphological observation of nano-structure. Homogeneous dispersion and interfacial interaction among CNMs could be keying parameters for better damage monitoring as well as mechanical performance. Thermal treatment and temperature effect on apparent modulus and electrical resistance were compared to each other. Damage sensing and reinforcing effect of carbon nanocomposites could be evaluated well nondestructively by the electrical resistance measurement with AE.Acknowledgement: This research was supported by a grant (Code #: 04K1501-00611) from 'Center for Nanostructured Materials Technology' under '21st Century Frontier R&D programs' of the Ministry of Science and Technology, Korea.

5758-41, Session 11

Polarization plane's weak rotation amplifiers and polarization azimuth stabiliziers

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Optical activity (rotation of the polarization plane) and circular dichroism (differential absorption of left and right circularly polarized light) are used for a long time to study the gyrotropy of the media. In this way information on internal molecular structure and gross molecular arrangement has been obtained. And this method is one of the main one in chemistry and biology. Recently a significant progress in this field was achieved for polarimetric and spectropolarimetric measurements [1-7]. This achievement allows increasing the sensibility of measurements of polarization plane's weak rotations by several degree [1-7] (see also the references in them). Such measurements help to construct exact material equations for Maxwell's equations or can be used for wave-guide propagation of supper high frequency radiation in the lower layers of the atmosphere.

There are many methods were designed to increase polarimetric measurement's sensibility [1-7]. Kobayashi et al. [6-7] developed a high-accuracy universal polarimeter (HAUP), which enables one to measure simultaneously optical activity, birefringence, and the rotation angles of the indicatrix of crystals with any symmetry. The amplification of polarization plane rotation in [2] was offered to increase polarimetric measurement's sensibility. The amplification of polarization plane rotation was achieved due to the decrease of the signal intensity. An amplification method for the reflection from a half-space isotropic medium was also considered [3].

However, in these approaches the signal intensities are limited within the validity region of the linear optics, which decreases the application range of the above-mentioned methods. On the other hand, the large incident light intensities (power) decrease significantly the sensibility of the polarimetric measurements. In certain problems there is a strong limitation in obtaining of high power signal. These all make the search of the new mechanisms of amplification of polarization plane's weak rotations and corresponding resolving power very actual.

We offer a simple and effective method, viz. the use of an amplifying medium as polarization plane's rotation amplifier. This amplifier allows us to solve the problems, which are connected with the intensity of signals, and also with the signals polarization ellipticity. An important particular of considered amplifiers is the practical absence of ellipticity at the maximum amplification azimuth (a linear polarized signal remains linearly polarized) and we solved also the problems connected with the enhancement of noises when the amplification of polarization plane takes place, and when amplification of light intensity takes place.

The offered sensible method to detect light polarization states can also be applied for detecting weak changes of parameters of a medium, which is under various influences.

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5758-42, Session 11

Ferroelectric-based multiple radiations source for in situ multifunctional analytical instruments

Y. Bar-Cohen, S. Lih, X. Q. Bao, S. Sherrit, Jet Propulsion Lab.

A ferro-electric based multiple source radiation device was developed and tested at JPL. This device was shown feasibility to emit five radiation types is enabling a new generation of compact, low power, low mass in-situ analysis instruments. These radiation types include visible light, ultraviolet, X-ray, as well as electron and ion beams. These types of emitted radiation can support multiple instruments that can potentially be used in future NASA missions to detect water, perform mineralogical/ chemistry analysis and identify biological signatures. A prototype multiple radiations source vacuum tube containing a ferro-electric wafer with a continuous ground electrode on one side and a grid-shaped electrode on the other side was used to generate plasma by a switching high voltage pulse. The generated plasma was used to create the multiple radiation sources. A series of experiments were performed to evaluate the characteristics of the generated sources. Preliminary experimental results of this study demonstrated the proposed multiple radiation devices could be a valuable tool for future space applications.

5758-43, Session 11

Electrode shape design for multi-mode sensors using genetic algorithm

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This paper presents a new shape design method for the multi-mode sensor that can detect selected multiple modes for the active vibration control of mechanical structures. The structure used for this study is an isotropic cantilever beam type with a PVDF (polyvinylidene fluoride) which is bonded onto the structure as a sensor. Characteristic behaviors of the sensor are related with the electrode shapes of PVDF. The shape optimization problem is solved by defining a new multi-objective function and using the genetic algorithm. Resulting electrode shape functions have good performances to detect the multiple vibration modes. The results of analytical simulations are compared with those of experiment works. The results agree well with each other. Therefore, the obtained experimental results give evidence for the validity of the presented theoretical analysis of the electrode shape design problem.

5758-44, Session 12

Efficient electromechanical network model for wireless acoustic-electric feed-throughs

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There are numerous engineering design problems where the use of wires to transfer power and communicate data thru the walls of a structure is prohibitive or significantly difficult that it may require a complex design. Using physical feedthroughs such systems may make them susceptible to leakage of chemicals or gasses, loss of pressure or vacuum, as well as difficulties in providing adequate thermal or electrical insulation. Moreover, feeding wires thru a wall of a structure reduces the strength of the structure and makes the structure prone to cracking due to fatigue that can result from cyclic loading and stress concentrations. One area that has already been identified to require a wireless alternative to electrical feedthroughs is the container of the Mars Sample Return Mission which will need wireless sensors to sense pressure leak and to avoid potential contamination. The idea of using elastic or acoustic waves as to transfer power was suggested recently by [Y. Hu, et al., July 2003]. However, the model was developed directly from the wave equation and the linear equations of piezoelectricity. This model suffers from an inability to incorporate head and tail mass and account for loss in all the mechanisms. In addition there is no mechanism for connecting the model to actual power processing circuitry (diode bridge, capacitors, rectifiers etc.). An alternative approach which is to be presented is a network equivalent circuit that can easily be modified to account for additional acoustic elements and connected directly to other networks or circuits. All the possible loss mechanisms of the disclosed solution can be accounted for and introduced into the model. The circuit model allows for both power and data transmission in the forward and reverse directions through acoustic signals at the harmonic and higher order resonances. This system allows or the avoidance of cabling or wiring. The technology is applicable to the transfer of power for actuation, sensing and other tasks inside sealed containers and vacuum/pressure vessels.

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5758-45, Session 12

Identifying dynamic characteristics of structures to estimate the performance of a smart wireless MA system

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In this paper, a smart wireless MEMS-based accelerometers(MA) system for smart monitoring system of civil structures has been designed and implemented. And dynamic characteristics of model structure have been identified to estimate the performance of a smart wireless MA system(SWMAS). This system employs a high-performance AVR micro-controller, a wireless modem, and MA for multiplex communication capability and real time duplex communication. Various performance and experimental tests have been carried out to evaluate whether this system is suitable for monitoring system of civil structures. First, we examined the sensitivity, resolution, and noise of the system specifically to evaluate the performance of the smart wireless MA system. The results of experiments enable us to estimate performance of the MA in SWMAS in comparison to the value of data sheet from MA. Second, characteristics of model structure are analyzed by ambient vibration test based on the NExT combined with ERA. Finally, this analysis is compared to the one which is made by FE results, and the comparison proves that a smart wireless MA system is fitted in smart monitoring system effectively.

5758-47, Session 12

An improved fiber optic strain sensor with RF interferometric and I & Q demodulation techniques

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RF sub-carrier phase measurements of RF intensity modulated light are long established as a method to measure length changes in an optical fiber sensor. RF amplitude modulated light is launched into an optical fiber and detected at its output by a photodiode receiver. The electrical signal obtained is then input into an electrical mixer together with a reference signal obtained from the signal generator producing the RF modulation. The output from the mixer is then low pass filtered to produce a dc signal whose magnitude depends on the phase difference between the receiver and reference signals. Since the phase of the reference signal remains constant any change in the phase of the optically derived signal will produce a change in the dc output. This change may be produced by straining the fiber to change its physical length or by altering its temperature and thereby changing its effective refractive index. A limitation for long term static measurements is, however, the possibility of dc drift from the mixer that could produce spurious signal. For a practical RF sub-carrier fiber optic strain monitoring system this long term static dc drift could result from the optical power fluctuation of the laser source or the mixer itself due to the characterisation of its frequency-dependence and temperature-dependence. This is a problem whether we measure changes in dc output or if we measure the change in RF frequency.

To develop an on-line fiber optic strain monitoring system for commercialised composite high-pressure storage tanks, the fiber sensor should be reliably capable of detecting any deviation of the strain experienced by a composite tank during pressurisation from those that would be expected for a healthy vessel. Therefore it is very necessary to eliminate or at least minimise this long term dc drift. In this paper we will report an improved RF sub-carrier fiber optic strain sensor for monitoring a gas storage carbon composite tank by introduction of an in & quadrature phase (I & Q) demodulation technique. With an I & Q demodulator the output from the mixer is split into two nearly equal parts with quadrature phase difference. These two parts are proportional to ASARsin(phi)(in phase) and ASARcos(phi) (quadrature phase), respectively. Here AS and AR are the voltage amplitudes of the sensor and reference input signals to the mixer.  is the phase change to be measured. If we let I= ASARsin(phi)and Q= ASARcos(phi), we can then easily get the phase change phi=atan(I/Q). Any changes in the amplitudes of the mixer input signals will appear in both the I and Q components but will be in principle eliminated by their ratio. In practice the mixer and the I & Q demodulator are never perfectly balanced in gain or dc offset, therefore the effect of amplitude fluctuation of the mixer two input signals can only be minimised but can never be completely removed. In conclusion the performance of the RF sub-carrier fiber optic strain sensor by employing an I & Q demodulator has been moderately improved.

5758-48, Session 12

Spatial resolution enhancement of a Brillouin scattering-based fiber optic distributed sensor using a pulse base

J. J. Lee, Korea Advanced Institute of Science and Technology (South Korea)

Spatial resolution enhancement of a Brillouin scattering-based fiber optic distributed sensor using a pulse base

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Stimulated Brillouin scattering (SBS) refers to the scattering of a light caused by an acoustic phonon, and Brillouin optical time domain analysis (BOTDA) system is a well known fiber optic sensor which can measure the strain or temperature distribution along an optical fiber by using the SBS. The spatial resolution of BOTDA is determined by the width of the launched pulse and is inversely proportional to the width of the pulse. Therefore, a short pulse must be used for high spatial resolution. However, as the pulse width is reduced there is a decrease in the detected signal power, and the Brillouin linewidth is broadened, causing a penalty in resolving the Brillouin frequency. In BOTDA, a steady state gain of SBS is required for the reliable measurement of strain or temperature distribution along an optical fiber, and it is generally known that more than ~ 10 ns pulse is required for the steady state gain of SBS. Therefore, it was commonly known that the limit of spatial resolution of BOTDA was ~1 m.

In this paper, the characteristics of the BGS for the width of the launched pulse light were demonstrated based on the experimental works. Experimental results showed that the Brillouin gain decrease and the linewidth broadening became larger as the pulse width is reduced, and also showed that it was very difficult for short pulse less than 10 ns, in a conventional pump-probe system of BOTDA, to get a high-gain-Brillouin spectrum sufficient to measure the Brillouin frequency distribution along an optical fiber. The pulse width determines two significances, such as the Brillouin interaction length and the excitation time of a medium, in the Brillouin interaction between pump and probe lights. It was experimentally shown that the excitation time of a medium is more important in the Brillouin amplification than the Brillouin interaction length. We proposed a new technique that uses a CW component of a pulsed pump light, that is pulse-base, to get a sufficient high-gain-Brillouin spectrum, from which the Brillouin frequency

distribution of a fiber could be measured, even for the short pulse less than 10 ns, and the proposed technique was experimentally verified. The strain distribution of a steel beam was measured through the injection of 5 and 10 ns pulses, and the measured strain distribution was highly consistent with the actual strain distribution of the beam.

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5758-49, Session 13

Fiber optic sensor reliability and survivability issues in structural health monitoring

F. Ansari, Univ. of Illinois/Chicago

No abstract available

5758-50, Session 13

Long-term reliability testing of packaged strain sensors

D. Inaudi, SMARTEC SA (Switzerland)

Establishing and testing the performance of a monitoring system designed for long-term applications presents some challenges that do not always apply to other measurement instruments. The evolution of the main measurement parameters must be evaluated over long periods of time and the reliability and failure rate must be estimated in a statistically sound procedure. When establishing testing procedures for any system it is important to achieve three goal: the procedures must be based on traceable international standards, the procedures must be reproducible by the system users or third-parties testing authorities and the procedure should be applicable to different measurement systems to allow a fair comparison of the respective performances. This contribution describes the main testing procedures used to test the compliance of SMARTEC's SOFO system components to the published specifications. It also offers a general overview of some issues related to the testing of long-term performances.

5758-51, Session 13

Failure mechanisms of fiber optic sensors placed in composite materials

E. Udd, Blue Road Research

This paper will overview methods that have been used to place fiber optic sensors into composite materials. Emphasis will be placed on failure mechanisms that have been encountered over a 20 year period and means to avoid them.

5758-52, Session 13

Reliability of components for fiber optic sensors

F. Berghmans, SCK•CEN (Belgium)

Optical fiber sensors have been deployed for many years in a wide variety of applications. Each of these applications comes with its own specific demands and optical engineers have always been very resourceful in finding the appropriate answers. As a result a multitude of sensing methods have been developed and many different fiber sensors have been designed, manufactured and applied, some of them very successfully. These sensors are built using diverse kinds of optical fibers having different types of coatings. The fibers are sometimes modified in a dedicated way, for example by the inscription of Bragg gratings or by the removal of parts of the coating/cladding. In the case of extrinsic optical fiber sensors, the fiber needs to be interfaced and packaged with an external sensing body, for example a Fabry-Perot cavity. This calls for the use of reflective end face coatings, epoxies, connectors, lenses, capillaries, chemical reagents, etc. Generally speaking, a fiber sensor has to be considered as a complex system consisting of individual parts/components between an optical source and an optical detector. However, in the case of a distributed fiber sensor, it can be as "uncomplicated" as a single fiber cable between source and detector.

The issue of the reliability of optical fiber sensors becomes increasingly important as they are more and more frequently used in critical applications where a failure of the sensor might have dramatic consequences on cost and/or safety. However, assessing the reliability of a fiber sensor remains a complicated issue as this reliability can be defined on different levels. First the reliability of the modulation that might require, for example, an optical source with very stable spectral and intensity characteristics. Second the reliability of the interaction between the measurand and the sensor probe, for example the strain transfer between the structure of interest and the sensor element. Third the reliability of the demodulation and signal processing, for example the accuracy and stability of wavelength measurements on fiber Bragg gratings. Fourth the reliability of the calibration or recalibration and finally the reliability on the component level.

In this paper, we intend to deal with the latter, starting from a general definition of reliability stating that : "The reliability of a product (device, module or system) can be defined as the probability that this product will perform a certain function within a set of pre-defined specifications for a given period in time". The discussion is inspired from the activities conducted within the former COST 246 and present COST 270 actions on "Reliability of Optical Fibers and Components" and includes thoughts on aging and degradation of optical fibers, fiber cables, fiber Bragg gratings and connectors. Finally, we also illustrate the importance of the knowledge of the service environment as the conditions in which fiber sensors are used are often incomparable to the relatively benign environments for which standard off-the-shelf optical communication devices are designed.

5758-53, Session 13

Validation of space flight fiber components

M. N. Ott, NASA Goddard Space Flight Ctr.

Full qualification for commercial photonic parts as defined by the Military specification system in the past, is not feasible. Due to changes in the photonic components industry and the Military specification system that NASA had relied upon so heavily in the past, an approach to technology validation of commercial off the shelf parts had to be devised.

This approach involves knowledge of system requirements, environmental requirements and failure modes of the particular components under consideration. Synthesizing the criteria together with the major known failure modes to formulate a test plan is an effective way of establishing knowledge based "qualification". Although this does not provide the type of reliability assurance that the Military specification system did in the past, it is an approach that allows for increased risk mitigation.

The information presented will introduce the audience to the technology validation approach that is currently applied at NASA for the usage of commercial-off-the-shelf (COTS) fiber optic components for space flight environments. The focus will be on how to establish technology validation criteria for commercial fiber products such that continued reliable performance is assured under the harsh environmental conditions of typical missions. The goal of this presentation is to provide the audience with an approach to formulating a COTS qualification test plan for these devices. Examples from past NASA missions will be discussed.

5758-54, Session 13

Radiation and cladding modes as independent measurements of Bragg grating sensor integrity

M. Prabhugoud, J. Pearson, K. J. Peters, M. Zikry, North Carolina State Univ.

As with any choice of sensor, the reliability of fiber-optic sensors in the long term is a key issue for monitoring of structures. In particular, the development of an independent measure of the sensor integrity for sensors embedded in composite material systems would provide a manner to separate sensor failure from failure in the surrounding host material. Without such an independent measure, the two effects cannot be separated, potentially leading to erroneous indications of the response of the structure. This paper demonstrates the appearance of cladding and or radiation modes as such an independent feedback on the integrity of short period Bragg gratings, one of the most commonly used fiber-optic sensors. These modes can be detected without additional instrumentation required other than that used to measure the sensor response.

In addition to the classical Bragg reflection due to a forward propagating fundamental core mode coupling to a backward propagating core mode, additional couplings can occur in short period Bragg gratings. For example, core mode to cladding mode or core mode to radiation mode coupling can be temporarily or permanently induced in an optical fiber through mechanical or thermal perturbations along the fiber. Although, theoretically, the cladding and radiation modes should be apparent in short period Bragg gratings prior to any damage occurring, it has been demonstrated for most fabricated gratings, these resonances are weak and therefore not usually resolved from the transmission spectrum.

Experimental results from three separate studies are presented in this paper. The first two experiments, tensile tests on an epoxy specimen with an embedded Bragg grating sensor (one with a weak glass / epoxy interface condition and one with a strong interface condition) provide a controlled measurement of the progression of cladding or radiation modes at the onset of failure in the grating. In each experiment, the grating was loaded beyond the point at which no light was propagated through the fiber, however not to the point of breakage in the optical fiber. The transmission and reflection spectra were continuously monitored throughout the loading cycle. Once unloaded, each grating showed a slightly modified reflected spectrum with the appearance of cladding modes in the transmission spectrum. Post-mortem investigation of the gratings, performed by propagating visible light through the fibers, demonstrated that each grating had sustained microcracking along the grating, resulting in a small amount of light radiated along the length of the grating. These phenomena were correlated with the appearance of cladding modes in the transmitted spectrum in the IR wavelength range. The appearance of identical cladding modes in both specimens indicates that the modes are not due to a change in interface conditions at the exterior boundary of the fiber. In the third experimental study, a Bragg grating sensor was surface mounted on a woven composite specimen subjected to multiple low velocity impacts. The resulting measured spectra, although strictly in reflection, demonstrate evidence of cladding modes due to microcracking near the location of a breakage in the grating.

5758-46, Poster Session

Real-time highway vehicle pullover monitoring using fiber microbending-loss reflectometry

K. Wang, B. Chen, H. Cui, Stevens Institute of Technology

Highway overtime pullover vehicles present a potential hazard to traffic and other vehicles, especially in conditions of poor visibility. Thus, a real-time, accurate, low-cost, long-lifetime sensing system is necessary for monitoring the overtime pullover vehicles and sending alert(s) to the highway administration/ patrol.

This paper introduced a microbending-based fiber optic sensing system for monitoring highway overtime pullover vehicles. The system contains a single-mode optical fiber cable, a pulse laser, a photoreceiver and a data processing unit. The optical fiber is buried directly under the highway shoulder. The roughness of the earth and the weight of the pullover vehicle will cause microbending in the fiber, so that the fiber loss at the spot of the pullover vehicle will be larger than usual. Short laser pulses are injected into the fiber, and the reflections from different locations of the fiber are collected by a photoreceiver. The photoreceiver collects the reflected signals as a function of time, and then the locations of the weight-induced microbending losses can be calculated. Both losses and locations are recorded. The system will scan the whole length of fiber at a designed frequency (e.g. every minute), depending on the total monitoring length. By comparing the loss at different time, the vehicle pullover duration can be monitored, and an alert will be sent to highway administration/patrol according to the defined vehicle pullover duration, e.g., 5 minutes.

In our experiment, a 700-meter single-mode fiber cable (Corning SMF-28e) was used. Two zigzag-shaped plates were used to induce microbending. A Tektronix TFP2 Fibermaster optical time domain reflectometer (OTDR) was used to give the laser pulses (1550nm, 10ns) and to detect the reflections. A PC-running LabView program was employed to automate the whole system. The alert time was set to 5 minutes. The microbending was created by hydraulic press with weight up to 5 tons. The two plates were put on the press with fiber cable sandwiched inside. The timing started with a 5dB loss compared with the no-pullover case. During the experiment, 5 locations were selected for pullover vehicles and they were all detected and given alerts by the system. Thus the highway administration officers can make their decision to deal with the vehicle pullover issues based on the sensing system alerts. The sensing system was also tested on site. The fiber was buried into a concrete/earth tray and pushed down by vehicles with different weights. The system showed good responses with locations, with very low false-alarm rates.

It should be pointed out that the microbending loss at one spot will affect the loss some distance after it. With the technology described in this paper, the accuracy of locating a pullover vehicle is in the order of 10 meters, which will be adequate for the application of monitoring highway overtime pullover vehicles.

5758-55, Poster Session

An application of data fusion technology in structural health monitoring and damage identification

X. Chun, Wuhan Univ. of Technology (China)

All man-made structures have finite lifespan and begin to degrade as soon as they are put into service. Processes such as corrosion, fatigue, erosion, wear and overloads degrade them until they are no longer fit for their intended use. It would be very dangerous to people's life and possession if we could not estimate the magnitude of the damage of the civil infrastructure timely, and decided whether to remedy the structure, or replace it, or throw it away. This danger can be avoided or controlled by the structural health monitoring and damage identification technology. With the development of modernized construction industry, constructions are more and more fine and enormous, and need more sensors to obtain the structural message, so traditional health and diagnosis technology can not take on the task of damage identification. Multi-sensor data fusion is a new and developing technology whose research was started in 1980's, based on signal process, control theory, pattern recognition, artificial intelligence etc. It is the outcome of many frontal studies (such as statistical analysis, wavelet analysis theory, neural network, fuzzy logic and expert systems etc.) combined with pop applications (such as image classification, target detection, target identification and fault diagnosis etc.). Firstly, this paper simply reviews the necessity of the appearance and development of the structural health monitoring and damage identification and multi-sensor data fusion. Secondly, the framework of structural health monitoring and damage identification system is introduced. Thirdly, the three levels of multi-sensor data fusion, which are pixels-level, feature-level and decision-level fusion, are analyzed in detailed, and the fusion methods and their applications of each data fusion level are also discussed. Lastly, the relative merits of different data fusion methods, which are wavelet analysis method, neural network method and expert systems method, are analyzed systematically. As each method is doomed to have its own disadvantages, the method of data fusion has been raised based on the requirements of the structural health monitoring and damage identification. On the basis of the previous statement, a data fusion method of neural network combined with wavelet analysis is provided and analyzed, and its realization and application in structural health monitoring and damage identification are researched. The analysis result indicates that the data fusion method of neural network with wavelet analysis evidently enhances the accuracy of structural damage identification.

5758-56, Poster Session

A resonant coding passive wireless SAW sensor array system

P. Li, Y. Wen, Chongqing Univ. (China)

In many special applications of micro-sensor array, the sensor system often is embedded in the structure, with no power supply and physical connection to the outside world. The conventional solution is to use passive wireless sensors based on either SAW resonator or SAW delay line, they could be used in the fields of non-contact remote sensing and object recognition. Both sensors have themselves advantages. Because the delay-line sensor can be encoded by using delay time, it can be used in large-scale array sensor. On the contrary, the resonant sensor has a low loss and can be used in a longer detection distance. However, neither of them is suitable for long-distance multiple sensor access application.

This paper presented a new passive wireless sensor array system based on SAW resonator and delay line. The new sensor element structure combines advantages of SAW resonator and delay line. In the experimental system, temperature sensor array, antenna and transceiver system are setup. The input signal received from antenna is sinusoidal bursts and its response of every sensor element is a delaying damping oscillating signal. The central frequency of the response signal is related to temperature; the delay time of the response signal in each element of sensor array is related to its coding. Thus the coding of every sensor element is implemented to map the array. Therefore detecting the delay time and resonant frequency of sensor element can reflect its coding and value of sensing parameter, respectively. In the passive wireless system, the energy of the receiving signal is reciprocal to the fourth power of measurement distance between the sensor and the transceiver. With the increase of the measurement distance, the amplitude of the reflecting signal will decrease rapidly and the duration time will shorten suddenly. In order to improve the signal-to-noise ratio, the measurement speed and the sensing distance, revised maximum likelihood estimation is applied to estimate the resonant frequency. By detecting the signal energy and estimating the resonant frequency, the transceiver can automatically track and quickly detect the resonant frequency and delay time. This paper introduces the measuring principle and the setup of the passive wireless array

sensor system. It also analyses roles and impact of major components in the transceiver and sensor elements. In the temperature experiment, SAW resonators with frequency of 89.6MHz and SAW delay lines with different delay time of 0-35.6us are used to construct different passive wireless sensor elements. Each tracking and detecting process in different distances can be gotten by using only 2-4 detecting numbers. When the sensing distance is 2 meter, the variation of resonant frequecy with temperature in each unit of the array can also be shown. Thus the experiment justifies the design. Because the multiple reflecting waves are superimposed within the resonant cavity, the amplitude of the output signal of the resonant coding sensor is larger than that of conventional once-reflected delay line SAW sensor, the new sensor can be used in long-distance distributed measurement. The SAW array sensors not only percept change of temperature, but also measure multiple parameters of stress, strain, acceleration and displacement by using rational designs.

5758-57, Poster Session

Simulation of micro-cooling system with measuring and controlling function

X. Liu, R. Chuai, G. Zhang, X. Wang, H. Ni, Harbin Institute of Technology (China)

With the development of device miniaturization and the increase of the power density of Very Large Scale Integration (VLSI), especially the development of Multi-chip Mounting (MCM) technology, the demand for heat dispersion is more than beforetime. To attain higher heat dispersion rate, a new type micro-fluidic cooling system with measuring and controlling function is presented in this paper. Based on the technique of microeletromechanical systems (MEMS), the cooling system has been fabricated.

The cooling system is composed of controlling circuits and a silicon-base chip on which microchannels, micropump, temperature sensors, and flow sensor are formed. The microchannels are distributed densely on the left and the right parts of the silicon-base chip; the two parts are connected through a microchannel with a flow sensor and another microchannel with micropump respectively at middle part of the chip. So that the whole microchannels buildup a close-circulating system of micro-fluidics, after the chip is bonded with a proper glass piece. Heating wafer and radiator are placed respectively at the left and the right part corresponding to the dense microchannels, and contact with the silicon chip intimately. When the water sealed in the micro-fluidic system is driven by the micropump, the water circumfluence could transfer quantity of heat from the left part of the silicon-base chip to the right part. Meanwhile, using the signals collected from the temperature sensors and the flow sensor, the transmission of heat can be controlled intelligently through the controlling circuits.

To design the system optimally, the cooling base chip, including its whole components, has been simulated and analyzed through finite element method (FEM) by means of ANSYS FLOTRAN. Based on the analysis, the relations have been found between the three aspects that are the mainstream velocity of the fluid, the temperature distribution of the base chip, and the pressure drop from the inlet of the high temperature section to the outlet of the low temperature section respectively. When the mainstream velocity increases, the even temperature of the base chip decreases, and the temperature distribution tends to uniform. The highest temperature of the chip relates nonlinearly with the velocity; if the velocity approaches 2 m/s, the temperature could lower very slowly with the velocity expediting. But the relation between the velocity and the pressure drop is almost linear. This is not only a basis of micropump design, also a foundation of system controlling. After the velocity exceeds 3 m/s, the temperature difference could be under 3℃ of the straight channel which connected the high and low temperature section. The result could lead to the precision of the flow sensors is degraded. On all accounts, the optimal velocity selected is about 2 m/s.

Because the cooling system is provided with more effective heat transfer, it could be applied to many fields, such as the future device encapsulation, the temperature distribution control in micro-satellite, semiconductor chip cooling system, micro-chemical analysis, and liquid dosing system etc.

5758-59, Poster Session

Pavement deflection vehicle weighing method with embedded piezoelectric sensor

L. Guo, C. R. Liu, Univ. of Houston

In weigh-in-motion system (WIM), the gross weight or the axle weight of the passing vehicle can be measured dynamically by the sensors installed in or on the pavement. Although pavement embedded piezoelectric sensor has limited measurement accuracy, it is widely deployed for the low cost and easy installation. To use the piezoelectric sensor, several factors have to be considered for the WIM site itself to ensure the vehicle passing over the sensor with a relative stable state. In addition, the piezoelectric sensor is seldom used for low speed measurement because of the piezoelectric material's performance. Traditional measurement method just uses the interactions between the sensor and the vehicle's tires that make the measurement inaccurate because the sensor cannot cover the whole tire patch along the driving direction. In this paper, the pavement deflection by the vehicle under measurement is introduced based on which a new weighing method is developed for the embedded piezoelectric sensor. The corresponding field tests are made and the measurement errors are calculated based on the static weights measured from static scale. Comparing to the traditional method, the said method is proved to have a higher accuracy and require less from installation site and vehicles under measurement. Furthermore, the method shows a better performance under low speed.

5758-61, Poster Session

Distributed sensing of composite over-wrapped pressure vessel using fiber Bragg gratings at ambient and cryogenic temperatures

J. Grant, NASA Marshall Space Flight Ctr.

Fiber Bragg gratings are use to monitor the structural properties of composite pressure vessels. These gratings optically inscribed into the core of a single mode fiber are used as a tool to monitor the stress strain relation in laminate structure. The fiber Bragg sensors are both embedded within the composite laminates and bonded to the surface of the vessel with varying orientations with respect to the carbon fiber in the epoxy matrix. The response of these fiber-optic sensors is investigated by pressurizing the cylinder up to its burst pressure of around 2800 psi. This is done at both ambient and cryogenic temperatures using water and liquid nitrogen. The recorded response is compared with the response from conventional strain gauge also present on the vessel. Additionally, several vessels were tested that had been damaged to simulate different type of events, such as cut tow, delimitation and impact damage.

Conference 5759: Electroactive Polymer Actuators and Devices (EAPAD)

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5759-01, Session 1

Artificial support and replacement of human organs

P. Bonde, Johns Hopkins Univ. School of Medicine

Fascination with replacing the human organs with a functioning artificial substitute has existed for centuries. Till the start of 20th century, this was primarily restricted to the use of limb prosthesis to replace the function of a lost limb due to trauma or disease. Earlier studies on organ preservation and perfusion led to the latter development of artificial organs and support systems. The modern era of artificial organs and support systems was ushered in with the development of an artificial kidney by Kolff. This was followed by the development of Gibbon blood oxygenator capable of supporting the human heart and lungs temporarily to allow cardiac surgical procedures. That revolutionary device opened up the field of cardiac surgery and was one of the major medical advances of the last century. Soon after the widespread use of cardiopulmonary bypass became commonplace, failure to wean from cardiopulmonary bypass became recognized as a problem whose solution required temporary cardiac support to enable post cardiotomy cardiac recovery. This led to the development of various artificial substitutes and support systems for the heart, lungs and recently the liver.

One of the common denominator for these devices is the capability to perfuse and maintain the blood flow and substituting the functioning of individual organs outside or inside the body. These devices have changed the lives of many patients to date and have revolutionized the medical management of certain diseases which would have had a grim prognosis. However, the current systems are far from perfect. Here we review these interesting developments and analyze the advantages and limitations offered by the current devices available from a clinical perspective, with a special emphasis on artificial assist devices and artificial heart. The technological advances in the 20th century is rapidly changing medical care in general and will have a lasting impact on the future devices and organ replacement systems. Here we take a glimpse in to future to see what promises and challenges lay ahead.

5759-02, Session 1

Biomimetics: the mimicking and inspiration of biology

Y. Bar-Cohen, Jet Propulsion Lab.

After billions of years of evolution, nature has learned what works, what is appropriate and what would last. The evolution of nature led to the introduction of highly effective and power efficient biological mechanisms. Imitating these mechanisms offers enormous potentials for the improvement of our life and the tools we use. Humans have always made efforts to imitated nature and we are increasingly reaching levels of advancement that it becomes significantly easier to imitate, copy, and adapt biological methods, processes and systems. Advances in science and technology are leading to knowledge and capabilities that are multiplying every year. This brought us to capabilities that allow us to act beyond the simple mimicking of nature. Having better tools to understand and to implement nature's principles we are now equipped like never before to be inspired by nature and to employ our tools in far superior ways. Effectively, by bio-inspiration we can have a better view and value of nature capability while studying its models to learn what can be extracted, copied or adapted. EAP as artificial muscles are adding an important element in the development of biologically inspired technologies. This paper will review the various aspects of the field of biomimetics and the role that EAP play and the outlook for its evolution.

5759-03, Session 1

Web-based actuator selection tool

J. D. W. Madden, Univ. of British Columbia (Canada)

Device designers are continually confronted with the challenge of selecting the best actuator for a task. A web-based interface is presented that enables designers to input basic needs (force, displacement, frequency, cycle life, dimensions, cost, power available etc.) and retrieve an initial evaluation of the suitability of the various actuator technologies in the database. The prototype contains data for only two actuators technologies - conducting polymers and dielectric elastomers. The ultimate aim is to expand this database to include a very broad range of actuators. The system is very early in the development process, and it is hoped that feedback from the EAP community will help guide the growth of and establish the need for this tool.

5759-49, Session 1

Eyeball pseudo-muscular actuators for an android face

D. De Rossi, F. Carpi, A. Migliore, Univ. degli Studi di Pisa (Italy)

Within the social nonverbal communication, the human attention system is based on the capability of the eye of focusing and tracking. These actions are performed by the eyeball muscle system, as a consequence of visual stimuli. The F.A.C.E. (Facial Automaton for Conveying Emotions) project at our lab concerns the development of an android face endowed with dynamic expressiveness and artificial vision. Aimed to realise an artificial attention system for such an automaton, we present here a study for the development of pseudo-muscular polymer actuators to be connected to its eyeballs. The system is based on the muscular architecture of the human eye and intends to emulate biomechanical movements of the eyeball. In particular, linear actuators made of dielectric elastomers have been designed to replicate actions exerted by the main ocular muscles.

5759-05, Session 2

Ionic polymer-metal composites: recent advances

K. J. Kim, Univ. of Nevada/Reno

Potential applications of EAPs are enormous in number and accordingly there are many EAP forms. One promising EAP of interest is the Ionic Polymer-Metal Composite (IPMC). IPMCs are an electroactive polymer capable of soft actuation under low driving voltages as well as sensing/transduction. The IPMC operation mechanism is somewhat complex in terms of its full operation and capabilities; however significant progress has been made leading to the belief that IPMC will be capable for use in advanced actuation and sensing applications. In this invited paper, recent advances in IPMC including electrochemistry, advanced manufacturing processes, and industrial applications are discussed.

5759-06, Session 2

Operation of ionic polymer-metal composites in water

J. W. Paquette, K. J. Kim, S. Heo, Univ. of Nevada/Reno; W. Yim, Univ. of Nevada/Las Vegas

Ionic Polymer-Metal Composites (IPMCs) offer a solution for unique propulsor applications such as biomimetics. IPMCs have preferential operation within an aqueous environment and offer a completely silent actuator mechanism with no moving parts for propulsion. The large bending motion inherent to the polymer actuator provides the thrust for a small propulsor. In this paper, we investigate the feasibility of the IPMC actuator as a means of low Reynold's number propulsion. Measurements are made in terms of thrust and velocity for various shaped IPMC actuators and the results are compared with theoretical equations and numeric analysis for justification of results. Overall, it would appear that IPMC are capable actuators for smaller scale propulsors with low Reynold's number flow.

5759-07, Session 2

Self-oscillatory behavior of ionic polymer-metal composite (IPMC): a new finding

D. Kim, K. J. Kim, J. Paquette, Univ. of Nevada/Reno

The use of Ionic Polymer-Metal Composite (IPMC) based materials is attractive since they are operational in aqueous environment producing good forces/useful nominal strains under low voltages. Moreover, they can be operated in self-oscillatory manners so as to simplify the necessary electronics needed in conventional modes of operation. These features allow us to make a chemical design and to develop useful IPMC materials possessing desired properties for various engineering applications including underwater propulsor blades. The self-oscillation of IPMCs can be achieved electrochemically via active surface electro-chemical reactions. Truly, the surface electrochemical reactions can lead to the current oscillation in requisite concentrations of additives during

voltammetry. Generally, the hidden negative differential resistance and Hopf bifurcation in front of current oscillation are noticeable. In this paper we discuss the fundamental principles that describe such self-oscillatory phenomena of IPMC. The measured data including in situ displacement, voltammetry, and AC impedance are presented for a various additives including methanol, formic acid, formaldehyde, and their mixtures. The measured voltammograms and impedance data indicate that the hidden negative differential resistance and Hopf bifurcation in front of oscillation are noticeable.

5759-08, Session 2

Frequency response analysis of IPMC actuators by an IR system

C. Bonomo, L. Fortuna, P. Giannone, S. Graziani, Univ. degli Studi di Catania (Italy)

Ionic Polymer Metal Composites or IPMCs are emerging materials belonging to EAP class. They are of increasing interest in innovative applications due to several advantages respect to competitive technologies (SMA, piezoelectric, etc.), such as the possibility to be used both as moving actuators and sensors, their lightness and the low voltage they need to bend. On the other hand their behaviour is not fully known and it is still subjected to deeper studies.

In this perspective the development of a complete model, able to fully describe the electromechanical properties of the IPMC materials, is the aim of many research group involved in their study. To that purpose this work focuses on designing and realising a system to determinate the bandwidth of an IPMC strip as actuator in order to collect information useful to model it in analytical way. In literature it is possible to find a certain number of works dealing with the topic of this paper, but the proposed solutions are very expensive especially for the instruments they make use of to detect the IPMC deformation. Indeed it is usually measured by a laser vibrometer or by a CCD camera in order to analyse also the high frequency response not detectable by a common digital camera where the frame rate is low.

Here the IPMC deformation, caused by applying a voltage input signal across its thickness, is detected by using an infrared transmitter and receiver couple. This methodology is largely diffused and it is based on the measure of the intensity of the emitted ray after being reflected by the moving target, moreover it constitutes a low cost solution. For the specific application a conditioning circuitry and the software for the signal processing has been designed, realised and it will be described in details in the extended paper.

The tested IPMC is a strip, 25x6 mm2 sized, pinned in a cantilever configuration and excited by a frequency sweep signal in the range where the caused deformation doesn't exceed few millimetres, it means down to 5 Hz Under this hypothesis the infrared characteristics is linear with the distance.

Both the voltage input signal and the output signal from the IR conditioning circuitry, are acquired with a sample rate of 10 kHz by using LabVIEW®.

A post elaboration of the corresponding IR output signal allows to estimate the frequency response. Preliminary results show a typical two order system behaviour, characterized by the presence of a flat band and a resonance peak.

A virtual instrument has been developed to process the acquired data in order to give the resonance frequency and the 3dB bandwidth.

5759-09, Session 2

Recent advances in ionic-polymer conductor composite materials as distributed nanosensors, nanoactuators, and artificial muscles

M. Shahinpoor, Environmental Robots Inc. and Univ. of New Mexico and Artificial Muscle Research Institute

In this presentation first a summary of the fundamental properties and characteristics of Ionic Polymeric-Conductor (Metal) Composites (IPCC's and IPMC's) as distributed biomimetic nanosensors, nanoactuators and artificial muscles is first presented. This summary will include descriptions of the basic materials' molecular structure, sulfonyl fluoride vinyl ether (SFVE) copolymerization with tetrafluoroethylene (TFE) to form the basic material resin and subsequent hydrolysis to manufacture the basic material for chemical plating and electroactivation. Further described are some recent advances in connection with chemical molecular plating technologies to make IPCC's and IPMC's, nanotechnologies of manufacturing and trapping of nanoparticles, SEM, TEM, SPM and AFM characterization of IPCC's and IPMC's, biomimetic distributed nanosensing and nanoactuation characterization techniques, electrical characterization and equivalent circuit modeling of IPCC's as electronic materials, and manufacturing of 3-D artificial muscles from IPCC's and IPMC's. Recent results on a comprehensive phenomenological model of the underlying sensing and actuation mechanisms in IPMC's are also discussed. A simple version of this modeling is based on linear irreversible thermodynamics with two driving forces, an electric field and a solvent pressure gradient and two fluxes, electric current density and the solvent flux. However, a more sophisticated model based on micro mechanical consideration is also presented and a rigorous formula for the bending deformation of cantilever samples of IPCC's is also presented. It is concluded that IPCC's and IPMC's are quite versatile materials for distributed nanosensing with outputs in the range of 10's of millivolts and high band width to kiloHz, and for distributed nanoactuation creating large displacement, large force under high band width low electric fields of 10 V/mm. Furthermore, IPCC's and IPMC's can be cut arbitrarily small or large for applications in MEMS, NEMS, BioMEMS and BioNEMS or industrial applications requiring soft sensors, actuators and micro or nano robotic applications.

Finally, a number of potential industrial, aerospace and medical applications of ionic polymeric-metal composites (IPMC's) as distributed biomimetic nanosensors, nanoactuators and artificial muscles is presented and followed by a number of live demos of artificial muscles in action, after the presentation. These applications include but are not limited to:

- Soft small sensors and actuators for ophthalmological problems and diseases.
- Combined capacitive and resistive sensors (replacing the piezoelectric and piezoresistive sensors with one)
- Micro and nano-robotic grippers & systems
- Numerous other medical, industrial and entertainment (Toy) applications, creating soft facial expressions.
- Data suit, attire, gloves, shoes equipped with soft IPMC sensors for military, industrial and medical applications.
- Biologically-Inspired Engineering Devices and Systems (BIRDS)
- Electronics Braille alphabet for the blind (active dots)
- Artificial eyelids (Ptosis, eyelid droop syndrome)
- Artificial epiglottis (Artificial Larynx)
- Heart assist devices & systems
- Artificial vocal cords, artificial tongue
- Soft flow meter, peristaltic pumps, microfluidic devices
- Diving suit and wristband for Navy Seals
- Artificial diaphragm for respiratory systems
- MEMS and NEMS (nanoelectromechanical systems) Biomedical Applications, Micro-Surgical Applications
- Muscle Atrophy or Dystrophy Devices, Ptosis
- Continuous Passive Motion Devices (CPM)
- Biomimetic devices - artificial fish, artificial insects, Crawling Robots, Flying Robots, Artificial Snakes
- Virtual Reality and Human-Computer Interfacing Devices, Haptic Interfaces

5759-10, Session 4

A new contractile linear actuator made of dielectric elastomers

F. Carpi, A. Migliore, D. De Rossi, Univ. degli Studi di Pisa (Italy)

Electromechanical devices made of dielectric elastomers represent today one of the most attractive and performing technologies within the field of electromechanical polymer actuation. We describe here a new configuration designed for monolithic dielectric elastomer actuators capable to show electrically activated linear contractions. Two helical electrodes integrated within the wall of an elastomeric hollow cylinder represent the core of the device, enabling the generation of active axial contractions and radial expansions. Detailed architecture, principle of operation and preliminary data on the performances of the new device are presented.

5759-11, Session 4

Actuation performance of cellulose-based electroactive papers

J. Kim, C. Song, Inha Univ. (South Korea); W. Craft, North Carolina A&T State Univ.

Electro-Active Paper (EAPap) is attractive as an EAP actuator material due to its merits in terms of lightweight, dry condition, large displacement output, low actuation voltage and low power consumption. EAPap material has been made using cellulose materials. Cellulose fiber is dissolved into solution using NaOH and made into a sheet by using spin coater. Thin electrodes are deposited on the cellulose paper to comprise a EAPap with different orientation of the paper fiber. The EAPap is clamped in an environmental chamber and the tip displacement of

EAPap is measured with laser sensor. Also blocking force of EAPap is measured using a force transducer. These measurements will be performed by changing the frequency, voltage, temperature and humidity. Characteristics of EAPap in terms of fibrous nature, their crystallinity, and mechanical, physical and electrochemical characteristics will be shown.

5759-12, Session 4

Viscoelastic model of axisymmetric dielectric elastomer membranes

E. Yang, M. I. Frecker, E. M. Mockensturm, The Pennsylvania State Univ.

Non-linear viscoelastic constitutive equations for axisymmetric circular and annular dielectric elastomer membranes using Christensen's theory of viscoelasticity are developed. For a time efficient numerical solution, the constitutive integral equations with a time dependent kernel are reformulated into a set of ordinary differential equations containing only terms evaluated at current and previous time steps using Feng's recurrence formula. Solutions for the principal stretch ratios and principal stresses for both configurations are presented for various pre-stretches and electric fields. Pressure-volume variations for the circular membrane at various electric fields are presented. The results of the model are compared to experimental data presented in a concurrent paper. Solutions obtained using the Mooney-Rivlin and Ogden material models are also presented for comparison.

5759-13, Session 4

A modified electroactive polymer-ceramic hybrid actuation system (HYBAS) for aerodynamic control applications

J. Su, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace

As previously reported, a NASA Langley-developed electroactive polymer-ceramic hybrid system (HYBAS) demonstrates significant enhancement in the actuating displacement. The displacement of the system is derived from both the electrostrictive polymer and single crystal elements. The electroactive elements are driven by a single power source. Recently, a modification of HYBAS has been made to increase the capability of air driving for synthetic jet devices (SJ) used in aerodynamic control technologies. The dependence of the air driving capability of the modified HYBAS on the configuration of actuating devices has been investigated. For this particular application, the modified HYBAS demonstrated a 50% increase in the volume change in the synthetic jet air chamber, as compared with that of the HYBAS without the modification/.

5759-14, Session 4

Enhanced thickness-mode electroactive polymer actuators and their applications

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Many different actuator configurations based on SRI's Dielectric Elastomer (DE) type of electroactive polymer (EAP) have been previously studied for a variety of applications [1]. These actuators have shown excellent actuation properties including maximum actuation strains of up to 380% and energy densities of up to 3.4 J/g, using the planar mode of actuation [2].

Recently, SRI has invented different embodiments of DE actuators that allow complex changes in surface deformations and thus the creation of active surface texture. In one embodiment, the active polymer film is bonded or coated with a thicker passive layer, such that changes in the polymer thickness during the actuation of elastomer are transferred to the passive layer. Therefore, changes in thickness in the passive layer can be used to amplify, in absolute terms, the displacement produced by the change in thickness of the active elastomer layer. The entire structure can be attached to a rigid frame, or can be laminated to a flexible foam or gel backing. In this way, a thin, flexible skin can be made that can cover large or small areas and contains finely patterned electrodes. This skin can be quite rugged because it is made entirely of rubbery materials. Although the device gives out-of-plane motion, it can be fabricated with only two-dimensional patterning.

A schematic diagram of this type of device and the results of thickness-mode actuation is shown in Figure 1. A piece of DE undergoing thickness-mode actuation is shown in Figure 2. This figure demonstrates that one can create virtually any desired pattern of bumps and troughs on a single substrate simply by using enhanced thickness mode EAP with electrodes patterned on one of the surfaces of the DE.

Applications of such surface textures are numerous. A thin, compliant pad made from these actuators can have a massaging or sensory augmentation function. The bumps and troughs could act as valves or pumping elements in a fluidic or microfluidic system. Such a device could also be the basis of a smart skin that controls boundary-layer flow properties in a boat or airplane so as to reduce overall drag. The DE elements of the pad can also be used as sensors to make a touch-sensitive skin for recording human interaction with the environment. By driving a thin, compliant vibrating layer at resonant frequencies, one can also configure these devices as solid or fluidic conveyors that transport material on a macroscopic or microscopic scale.

5759-15, Session 4

Novel forms for electroactive polymer actuators

A. J. Snyder, A. M. Tews, E. Eaton, The Pennsylvania State Univ.

To date, investigators have focused upon simple forms for EAP actuators, especially tubes and rolls for linear actuators and diaphragms for volumetric, linear or reflective applications. While the forms studied to date are useful and appealing for their simplicity, use of high proportion of active material, and amenability to integration with conventional machines, we are beginning to study other actuator forms, with a particular interest in devices composed mainly of compliant materials, designs inspired by nature, and designs that take advantage of secondary EAP characteristics such as elastic instability. We discuss our investigations to date and share our thoughts on particular challenges and opportunities.

5759-16, Session 4

Stacked liquid crystalline elastomer films as artificial muscles

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Supramolecular ordered assemblies such as liquid crystals in the nematic phase provide a framework for incorporating anisotropy as well as functionality in materials that respond to external stimuli, thereby emulating the properties of a biological muscle. We have developed liquid crystal elastomer (LCEs) films capable of uniaxial contraction when stimulated by heat to undergo a transition through the nematic to isotropic phases of the material. The LCE films exhibit an actuation strain and elastic modulus comparable to biological muscles. We have evaluated their mechanical properties and now demonstrate the ability to stack LCE films to create a thermally actuated muscle unit. Stacks of LCE films also contain thermal conducting paste and small heating units to maximize the efficiency of actuating the stack. The stacks have been mounted in an apparatus that is capable of monitoring the force production as a function of both time and the preload of the stack. In addition, we have tested the speed of contraction as a function of actuation. We seek to optimize the performance of the LCE film stacks in order to minimize the response time and maximize the force generated upon actuation.

5759-17, Session 5

Novel multilayer electrostatic solid state actuators with elastic dielectric

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Electrostatic solid-state actuators consist of elastic dielectric layers between compliant electrodes. Applying electric fields of up to 100 V/μm at the electrodes the dielectric contracts due to electrostatic forces and expands in orthogonal direction. We use high elastic silicone elastomers with thin graphite powder electrodes.

In order to increase the absolute strain values at limited voltage, we have developed a novel multilayer process technology to fabricate elastomer stack actuators with up to 200 layers. The two components of an addition curing silicone elastomer are pressed through a static mixer and a thin film of 25 μm thickness is realised by spin coating. After thermal curing of the spun-on silicone film the electrodes are applied by spraying graphite powder through a shadow mask. This procedure is repeated automatically.

The electromechanical properties of the actuators have been evaluated theoretically and characterised experimentally. The mechanical stress versus strain characteristic shows a strong nonlinearity for strains \› 30 %. The strain in vertical direction versus driving voltage shows a hysteresis due to viscous friction in the elastomer layers. Maximum strain values up to 20 % for pre-

stressed multilayer films have been achieved. These measurements correspond to a visco-elastic theoretical model. The dynamic characteristic has been evaluated by measuring the mechanical impedance in the frequency range of 10 to 1000 Hz. The long term stability and the influence of temperature on the actuation have been evaluated.

The novel multilayer fabrication technology provides multilayer stack actuators with various electrode patterns like universal linear actuators or matrix arrays for a wide range of applications as tactile displays for telemanipulation or Braille displays.

5759-18, Session 5

The strain response of silicone dielectric elastomer actuators

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Dielectric elastomers are known to produce large transverse strains in response to electrically induced Maxwell stresses and thus provide a useful form of electromechanical actuation. A ZYGO Doppler interferometer has been used to study the transverse strain response of silicone (Dow Corning HS III RTV) based Maxwell stress actuators as a function of driving electric field, frequency and pre-load. Experimental results show that a static pre-load initially causes an increase in the dynamic strain amplitude. However, this increase appears to be a function of the relative geometries of the electroded area and of the specimen itself. The dynamic transverse strains in these materials decrease when larger values of pre-load are applied. This cannot be understood on the basis of linear elastic theories, but models of hyperelasticity that are capable of describing the large deformation of polymeric materials can be used to interpret our results. These effects can be taken into account in numerical simulations of the material's behaviour in order to provide an accurate prediction of actuator performance.

Funding support from Defence Research and Development Canada is gratefully acknowledged.

5759-19, Session 5

A new type of carbon-nanotube yarn for artificial muscle and other multifunctional material applications

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No abstract available

5759-21, Session 6

Electroactive polymer hydrogels for bio-inspired actuators

S. J. Kim, S. I. Kim, I. Y. Kim, Hanyang Univ. (South Korea)

Interpenetrating polymer networks (IPN), as polymer hydrogels, exhibiting high electrical sensitivity were prepared. The swelling behavior of the IPN was studied by immersing the gel in various concentrations of aqueous NaCl solutions and various pH buffer solutions. The response of the IPN to electric fields was investigated. When a swollen IPN was placed between a pair of electrodes and an external DC electric field applied, the IPN exhibited a bending behavior. The IPN also displayed a step-wise bending behavior, that depended on the magnitude of the applied electric field, In addition, some IPN hydrogels underwent a change in volume on application of electrical stimulus. Switching the electrical stimulus led to a reversible volume change in the hydrogels. One electrode induced a contractile response, while the other electrode induced an expansion in the IPN. The behavior of the hydrogels aries from the movement of counterions in the solution, which is induced by the applied voltage. This movement allowed for a rapid contraction and expansion behavior with repeated voltage changes. The rate of change of the volume of the hydrogels was related to the magnitude of the applied voltage. This behavior suggests that the hydrogels studied are suitable candidates for a wide range of applications, including drug delivery systems, in robotics, as soft linear actuators, as sensors, and as biomimetic energy transducers.

5759-22, Session 6

Ionic electroactive hybrid transducers

B. J. Akle, M. D. Bennett, D. J. Leo, Virginia Polytechnic Institute and State Univ.

Ionic electroactive actuators have received considerable attention in the past ten years. Electroactive polymers, commonly referred to as artificial muscles, have the ability to generate large bending strain and moderate stress at low applied voltages. These transducers include ionic polymers, conducting polymers, carbon nanotubes and ionic liquids. Preliminary works that have appeared in the literature combining multiple types of materials have proved to enhance certain transduction properties. Ionomer– ionic liquids hybrids transducers proved to operate in air and showed potential to reduce or eliminate the back-relaxation issue associated with ionomeric polymers and they have higher electrical stability window than those operated with water as the solvent. The use ionomer-conducting polymer hybrids can be employed to increase the force generation, low frequency response and natural frequency of these actuators. Carbon nanotubes as an electrode material increase the conductivity through the electrode enhancing the high frequency response. Moreover, carbon nanotubes have large modulus leading to an increase in the force output of the actuator.

In this work, a new plating technique developed for metal particulates in ionomeric materials is applied to the development of hybrid transducers. The hybrid transducers considered in this work consist of an ionomeric substrate plated with carbon nanotubes and conductive polymers. The new plating technique consists of mixing a conducting powder with an ionomer solution. This technique has demonstrated improved response time and strain output as compared to previous methods. Furthermore, these methods are less costly to implement. Electrodes applied using this new technique of mixing RuO2 (surface area 45~65m2/g) particles and NafionTM dispersion provided 5x the displacement and 10x the force compared to a transducer made with conventional methods. Carbon powders with larger surface area (500 m2/g) performed worse than the RuO2 electrodes due to the high resistance through the electrode. This powder mix painting technique allows the use of any conducting powder including metal particles, metal oxide particles, conducting polymer powders, and carbon nanotubes.

5759-23, Session 6

Experimental study of Nafion-based ionic polymer-metal composites (IPMCs) with glycerol as solvent

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Ionic polymer-metal composites (IPMCs) consist of a perfluorinated ionomer membrane (usually Nafion® or Flemion®) plated on both faces with a noble metal such as gold or platinum and neutralized with a certain amount of counterions that balance the electrical charge of anions covalently fixed to the membrane backbone. IPMCs are electroactive materials that can be used as actuators and sensors. Their electrical-chemical-mechanical response is highly dependent on the cations used, the solvent, the amount of solvent uptake, the morphology of the electrodes, and other factors. With water as the solvent, the applied electric potential must be limited to less than 1.3V at room temperature, to avoid electrolysis. Moreover, water evaporation in open air presents additional problems. These and related factors limit the application of IPMCs with water as the solvent. Glycerol has a viscosity of about 1000 times that of water at room temperature, and has a greater molecular weight. Like water, it consists of polar molecules and thus can serve as a solvent for IPMCs. We present the results of a series of tests on both Nafion-based IPMCs with glycerol as the solvent, and compare these with the results obtained using water. We also present the response of Nafion-based IPMCs with various cation forms treated with glycerol stimulated with suddenly applied and then sustained (DC) electric potentials in open air. IPMCs with glycerol as their solvent have greater solvent uptake, and can be subjected to relatively high voltages without electrolysis. They can be actuated in open air for rather long time periods. They may be good actuators when high-speed actuation is not necessary.

5759-24, Session 6

Computational model of ion transport and electromechanical transduction in ionomeric polymer materials

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Ionomeric polymers material transducers (also known as IPMCs) exhibit electromechanical coupling due to ion transport within the polymer matrix. Recent work in our group has shown that the accumulation of charge at the polymer-metal interface is strongly correlated to the bending strain induced upon actuation. Normalizing the bending strain to the charge motion induced upon application of an electric field illustrates that the strain per unit charge is approximately constant (between 5 and 20 microstrain / C / m^2) over a wide range of mobile ions, solvent viscosities, and polymer compositions.

This work has resulted in the development of a computational approach to model the ion transport and electromechanical coupling in ionomeric materials. Numerical methods previously developed by Wallmersperger for hydrogels are applied to the modeling of ion transport for ionomeric materials. The model

incorporates the full nonlinear transport equations associated with ion flux across the semi-permeable membrane and an ion-blocking electrodes as the boundary conditions. The charge density as a function of space and time is solved using a discretization technique.. This technique is used to predict the electrical impedance of the polymer as a function of frequency and amplitude to determine the effect of asymmetric charge density profiles on the voltage-to-current response of the polymer.

Electromechanical coupling is computed from the charge density profile by assuming three mechanisms for induced bending. An electrostrictive term is incorporated to account for 'fast' bending induced by mobile ion migration. Results demonstrate that an electrostrictive term that is proportional to the square of the charge density can account for the bending towards the anode upon application of an electric field. Mass transport is considered to account of ion-size effects in the mechanical response of the polymer. Finally, we are currently incorporating an osmotic pressure term due to free diffusion of water due to charge imbalance to account for relaxation of the polymer under step voltage changes.

The final paper will include a comparison of analytical and experimental results using a charge-controlled amplifier for actuation.

5759-25, Session 6

Circular prestrained dielectric elastomer actuator: modeling, simulation, and experimental verification

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Mathematical models are required for the design and optimization of dielectric elastomer actuators. Thereby the constitutive behavior of the elastomer is of crucial importance. In this work a pre-strained circular actuator made of a dielectric elastomer is investigated under several pre-strain levels: constitutive models based on uniaxial data are verified by comparing calculation results with experimental observations. An analytical model is derived for the instantaneous response to an activation voltage in the pre-strained circular actuator and a finite element model is used to simulate the time dependent behavior. Hyperelastic models are used and three strain energy formulations (Yeoh, Ogden and Mooney-Rivlin) are compared in their predictive capabilities. The results of the calculations with the three strain energy forms differ significantly, although all forms were successfully fitted to the same uniaxial data set. Predictions of the actuator behavior with the Yeoh form agree to a great extent with the measurements.

5759-26, Session 7

Multiwalled carbon nanotube/IPMC nanocomposite

K. J. Kim, Univ. of Nevada/Reno; D. Y. Lee, Daelim College of Engineering (South Korea); S. Heo, Univ. of Nevada/Reno; M. Lee, Korea Institute of Ceramic Engineering and Technology (South Korea)

The key to the success of modern advanced materials is the tailored material behavior. In this paper, we present an effective way to obtain desirable macroscopic properties of IPMC based upon nano-level materials processing. The IPMC actuators, in the form of a cantilever, have shown remarkable displacement under low voltage and very low input power. However, one drawback at present is the limited capability of varying the actuators' intrinsic properties, in particular, their electromechanical coupling, modulus and conductivity of the base-materials. In this paper, our effort to develop the Multiwalled Carbon nanotube (M-CNT)/IPMC nanocomposite is described. Our intended use of such a nanocomposite is to tailor the intrinsic properties of the base polymeric material with only a small amount of M-CNT loading (1-5 wt%). The obtained electromechanical performance of such a nanocomposite and voltagrams indicate that the M-CNTs are uniformly dispersed in a continuous polymer matrix such that they can be effectively used as the starting material of IPMC's. We observed that the effect of incorporating M-CNTs in IPMC materials is so drastic in improved electromechanical coupling arising from enhanced electric capacitance, increased electric conductance, and increased modulus. One remaining challenge is to simplify the debundling processes of the M-CNTs in the base polymer, Nafion.

5759-27, Session 7

Multi-walled carbon-nanotubes-sheet actuators: theoretical and experimental investigations

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In this paper we present experimental measurements as well as a theoretical model for the chemo-electro-mechanical behavior of both multi walled (MWNT) and single walled (SWNT) carbon nanotubes sheet actuators. Considerations on the preparation of MWNT paper and investigations on its actuation characteristics are special features of the presented work. In this work, a comparison of MWNT materials as actuators with respect to SWNT materials is presented. Parameters influencing the actuation behavior such as diameter and thickness of sheet materials, electrolyte concentration, and geometry of the porous ceramic as intermediate layer have been investigated. We report the specific actuation characteristic (per unit area of the active surface of the sheet material) by measuring the active displacement as well as the generated force. Finally, a correlation between the active displacement and force for the considered materials was found.

In the theoretical part, we present a macroscopic actuation model for the global displacement behavior of SWNT and MWNT materials; furthermore, a microscopic/ mesoscopic model for the chemo-electrical interactions is proposed. Numerical simulations for both the static and the time-dependent behavior have been performed. With these models, an optimization of the actuator could be attained.

5759-28, Session 7

Carbon nanotube-polymer composites as electroactive sensors/ actuators

O. Zoubeida, P. Ricardo, Virginia Commonwealth Univ.; C. Park, J. S. Harrison, NASA Langley Research Ctr.

This work seeks to enhance the electroactive response of piezoelectric polymers through additions of single wall carbon nanotubes (SWNT). The goals are to take advantage of the benefits that electroactive polymers offer, while reducing or eliminating their shortcomings to generate new multifunctional sensors and actuators. The excellent mechanical, thermal and electrical properties of SWNTs along with their low density have motivated their use in these polymer composites. The challenges with SWNT composites are uniform dispersion within the matrix, nanotube/material wetting and adhesion, and alignment. In this study, some of these issues are addressed in order to expand our understanding of SWNT-polymer interaction, and to assess the role of SWNT in improving or tailoring the electroactive response of the resulting composite.

An aromatic piezoelectric polyimide, b-CN APB/ODPA, is selected as the polymer matrix. The SWNT-polyimide composites are prepared by in situ polymerization under sonication. Electrical, dielectric and mechanical properties of the SWNT-reinforced polyimide composites are investigated as a function of SWNT concentration. The electric conductivity, dielectric constant, and mechanical modulus exhibit a sharp increase between 0.0 and 0.1vol% SWNT. This behavior is indicative of a percolation transition. Percolation theory predicts that there is a critical concentration at which a conductive path is formed in the composite, causing the material to convert electrically from a capacitor to a conductor. The experimental dielectric constant was found to obey a percolation-like power law with a relatively low percolation threshold of 0.06vol%. The low value of the percolation threshold is indicative of good dispersion.

The effect of SWNT on the electroactive behavior of the polyimide is assessed for SWNT concentrations below and above percolation. It is observed that the presence of the SWNT increases the value of the dielectric relaxation strength Deps. The increase in Deps translates in an increase in the remanent polarization Pr, and subsequently an increase in the piezoelectric behavior. Above percolation, the SWNT-polyimide composites display out-of-plane as well as bending strains. Electric field values of the order of 0.1 MV/m and lower result in bending displacements in the range of 0.1-1 cm. Likewise, the same levels of electric fields yield out-of-plane strains that are of the order of 0.1%. Both the bending and the out-of-plane strains are proportional to the square of the electric field, indicating either electrostriction or Maxwell stress effects. Preliminary analytical calculations indicate that electrostriction is responsible for the majority of the resulting strains. By studying the percolative behavior of a SWNT-polyimide composite system, regions below percolation are identified where the SWNTs enhance the piezoelectric behavior of the composite system. Above percolation, the composite becomes conductive, and an electrostricitve behavior relating strain to electric field is observed. The presence of the SWNT seems to increase

the response of the dipoles, perhaps by stabilizing them further through some electrostatic interactions.

These SWNT-polyimide composites are attractive as ElectroActive Polymers (EAPs) due to their lightweight, low actuation voltage, and the fact that they are solid-state, dry actuators, that also display sensing capabilities. Future work will further probe the mechanism of alignment of SWNT in the polyimide and its effect on the electroactive response of the SWNT-polyimide composites. A comparison to the randomly dispersed cases will be accomplished.

5759-29, Session 7

Conducting polymer as smart interfaces for cultured neurons

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This work is part of a research project aimed at realising conducting polymer matrices for interfacing with cultured neurons. The polymer matrix has a dual function, one as a medium for recording electrical activity, the other is chemical stimulation through the release of some bioactive molecules.

In this work we use poly-3-hexylthiophene as polymeric matrix and test its stability with different oxidant agents and with different preparations.

The polymer for recording must be stable and possess high conductivity, thus we used as high molecular weight dopant (polystyrene sulfonate).

To test molecular release we worked with glutamic acid which is a very important neurotransmitter for the central nervous system.

Conducting polymer samples were tested with neuroblastoma cell line SH-SY5Y.

5759-30, Session 7

Porous polypyrrole films for better performance of artificial muscles

K. Kaneto, Kyushu Institute of Technology (Japan)

In electrochemical devices the rate of reactions is determined by the surface and bulk morphology as well the conductivity of active materials. Among various kinds of conducting polymers, polypyrrole (PPy) can be polymerized electrochemically as a tough film with relatively high electrical conductivity. In the electrochemical deposition, however, the morphology of the films can not be easily controlled. In this report, methods for electrochemical preparation of porous PPy films will be presented. The films are also characterized in terms of electrochemomechanical contraction ratios (strain) and contraction forces (stress).

One of porous polypyrrole film was electrochemically polymerized using an aqueous electrolyte solution of pyrrole, p-phenol sulfonic acid (PPS) as the supporting electrolyte. Ethyl acetate solution consisting of anionic surfactant of sodium bis(2-ethylhexyl) sulfosuccinate was used as the source of micelle emulsion. The film was porous with the diameter of approximately 1m, resulting from the effect of micelle emulsion. The film immobilized anionic micelles and was able to be doped with large cation like tetramethyl ammonium (TMA), showing large strain of 4.5%. Another porous PPy films was prepared using the organic electrolyte solution of pyrrole and tetrabutyl ammonium (TBA) bis(trifluoromethanesulfonyl)imid (TFSI) in methyl benzoate. The film surface at the electrode side shows beautiful porosity with the diameter of 0.1- 1 m. The film showed ca.20 % strain and stress of 6.7 MPa in the operation of aqueous electrolyte of LiTFSI solution at scan rate of 2 mV/s. The results will be discussed in detail with some of interesting results recently obtained.

5759-31, Session 7

Conducting polymer actuator utilizing novel planar patterned flexible supporting electrode

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A number of architectures have been employed to realize the linear contraction desired of a large scale conducting polymer artificial muscle, with each having merits and problems. Bulk polymer actuators with no supporting electrode structure, coil- or spring-type designs, and thin linear actuators with pliant metal or semi-metallic surface electrodes have all found moderate success. For the purpose of scalable, highly reactive artificial muscles, it is proposed that a design of several thin, well coupled and highly conductive linear actuators will allow more rapid charging, ion transport, and actuation than bulk actuators of a similar volume. Here we present a novel electrode design utilizing conducting polymers, incorporating recent work on electrode materials, solvents, and electrolyte. The soft supporting electrode is a highly flexible design made from metal foil patterned by lithographic techniques to allow a wide range of deformations and no hindrance to linear motion by the supporting metal electrode. The design is such that the electrode metal maintains excellent electrical coupling with the actuator material throughout the range of motions. The actuator is based on the well characterized conducting polymer polypyrrole. Other merits of this actuator lie in the inexpensive material design, ease of manufacture, and modular potential to create multi-actuator devices for high stress applications.

The electrode materials chosen for low cost and patterning ease were not ideal for polymer growth and adhesion. In order to overcome adhesion and conduction problems exhibited by these materials, several surface treatments were evaluated. In the course of development, stainless steel samples coated with a number of chemically stable metals and their oxides were evaluated with an adhesion tape test and for general film quality. In an attempt to improve overall actuator performance, films were grown from organic and ionic liquid solvents, doped with various ions, and actuated in organic and ionic liquid based solutions. Initial results suggest that a narrow selection of coatings offer superior performance, particularly when coupled with the proper growth and actuation media for the desired performance.

5759-32, Session 7

Integrating conjugated polymer microactuators with CMOS sensing circuitry for studying living cells

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We report a conjugated polymer actuator based microsystem that integrates structures for culturing living cells together with electronics for in-situ measurement and characterization. In prior work [1,2], cell-holding vials were fabricated on “passive” substrates. Since then, efforts have been made toward developing a biolab-on-a-chip with integrated sensors for long-term monitoring of cells [3]. The microelectromechanical systems (MEMS) are surface micromachined directly over CMOS circuitry. Arrays of vials (100 X 100 X 100 micrometer3, L X W X H) have been realized on a custom IC (3 X 3 mm2) fabricated in a commercially available 0.5 μm technology. Inside each vial, electrodes connected to a VLSI bio-amplifier record voltages from electrically active cells. Polypyrrole/gold bilayer hinges rotate lids that close the vials, encaging the cells to keep them in place over the electrodes. When the lids are closed, cells within one vial are electrically isolated from other cells inside adjacent vials.

The microsystem is being tested and refined for better performance and additional functionality. Long-term biocompatibility has been demonstrated by culturing bovine aortic smooth muscle cells on the actuators and structures. Currently, the actuation voltage is provided by an off-chip potentiostat. An on-chip potentiostat has been designed and will be added into the next-generation CMOS chip for system-level integration. The microsystem, with cells inside each vial, is placed into an incubator for real-time, long-term measurements. We are also developing methods, such as optical tweezing and dielectrophoresis, to load cells into the vials.

The microsystem will benefit possible applications in life sciences, pharmaceutical development, and environmental monitoring. For example, a cell-based electronic nose is envisioned that records signals from olfactory neurons cultured in the microsystem. The neurons directly transduce chemical signals into an electrical output, which enables detection of odorants with high sensitivity and specificity.

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5759-33, Session 7

Bi-layer polypyrrole artificial muscle valves for drug delivery systems

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Swallowing pills or receiving injections are the most common methods for the drug delivery. However, formulations that control the rate and period of drug delivery (i.e., time-release medications) and target specific areas of the body for treatment are complex. Implantable drug delivery devices which include batteries, sensors, telemetry, valves, and drug storage reservoirs will give patients an alternative method to use medicine. There exists a need to develop a "responsive drug delivery system," in which a sensor measures a marker in the patient's body and releases medication the patient requires at any given moment. In this way, we can tightly control the drug concentration in the patient's body to enhance drug efficiency and lessen side effects. In order to achieve responsive drug delivery, a reliable release device (e.g., a valve) has to be developed. The main requirements for such a release method are biocompatibility, low energy consumption, and minimal or no leakage.

In our previous work, we have developed drug reservoirs covered by polymeric valves which can open and close reversibly by applying a small voltage. The valves feature a bi-layer structure where one layer is a thin metal film, functioning as a structural layer and a working electrode, and the other layer is an electrochemically deposited polypyrrole film. The latter shrinks and swells under applied voltages. The actuation mechanism of the polypyrrole film is based on ion flux in and out of the polymer upon oxidizing and reducing the film . The volume change of the polypyrrole film forces the bi-layer to bend resulting in the opening and closing of the valve. We call this flap an "artificial muscle." This type of actuator only operates in electrolytic solutions, such as body fluids. Polypyrrole has been demonstrated to be biocompatible and unlikely to cause side effects in the body .

To decrease the power consumption and control the amount of drug released from the chamber, the size of the valve has been minimized from millimeter to micrometer in this work. The counter electrode and working electrode have been integrated on the same chip. By doing this, the applied power will actuate the valve more efficiently. Using MEMS processes, the distance between the two electrodes can be further decreased so that lower voltages can be applied to actuate the valves. The voltage applied for actuation was less than 1 V and the current was lower than 1 mA for an actuator with an area of 0.04mm2. By cycling the voltage between negative and positive values, the bi-layer valve were opened and closed repeatedly.

5759-34, Session 8

Metal RubberTM electrodes for active polymer devices

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This paper discusses progress in the development of flexible conducting electrode materials based on Metal RubberTM, a new free-standing nanocomposite material that combines the properties of metals and rubber. Like metals, Metal RubberTM has high electrical and thermal conductivities. Like elastomers such as rubber, it has low modulus and can be repeatedly elongated to several hundred percent strain yet relax elastically back to its original shape, all while remaining conductive. Metal RubberTM is formed by a modified electrostatic self-assembly approach that allows the formation of thick, large surface area nanocomposites to be formed with multiple controlled constitutive properties. Recent progress in the use of this material as an electrode for polymer-based actuators and sensors has been in the development of materials with a broader range of combined electrical conductivity and modulus than obtained previously. Conductivity may be made to vary between approximately one order of magnitude less than that of bulk noble metals to insulating, and modulus may be varied from approximately 1 MPa to 100 MPa. The resulting design space allows specific materials to be tailored to uses in EAP and other polymer-based sensor and actuator devices, as well as in other electronic applications as robust replacements for flex-circuit interconnect materials. An experimental demonstration of improved Metal RubberTM materials as part of active devices is planned for the accompanying EAP-IN-ACTION session.

5759-35, Session 8

Interfacial layer: a new mechanism for electromechanical response

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Polymers have many attractive characteristics: lightweight, inexpensive, fracture tolerant, and easy to process. New polymers – electroactive polymer (EAP) – have emerged that respond to electric stimulation with a significant shape or size change. The progress of developing EAPs has added an important capability to the smart materials. The EAPs are attracting the attention of engineers and scientists from many different disciplines. Since they behavior very similar to biological muscles, EAPs have acquired the moniker "artificial muscles". From materials science point of view, it is very interesting to study the mechanism responding for the high strain response obtained in EAP. Electric field induced phase transition was used to explain the high strain response in some PVDF-based EAP. However, it is hard to understand some features (such as the relationship between the strain and preload) of elastomer – an important type of EAP.

In this presentation, we first report the recrystallization study of high-energy-electron irradiated P(VDF-TrFE) copolymer. The morphology and structure as well as the structure transformation in the recrystallized copolymers were studied by means of x-ray diffraction, DSC, FTIR, dielectric and polarization properties. The effect of crosslinking induced by the irradiation is discussed based on the results. Based on the results, a new interface layer, which is partially ordered, is induced. The partially ordered interfacial layer is a novel micro-origin of high polarization obtained in EAP. Based on the concept, the effect of preload on the electromechanical performance of the elastomers can be well explained. A new method to develop high performance electroactive polymer is outlined by using the interface state.

5759-36, Session 8

High-contrast ratio and long-lifetime polymer electrochromic devices (ECDs)

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Electrochromic windows (ECDs) have attracted much of the recent interest of electrochromism. ECDs that exhibit high contrast ratios (%T) between their bleached and colored states are of special fascinating for use in dialed-tint windows, large area displays and automatic dimming mirrors. Such windows promise actively controlled, continuously tunable light transmittance. In this field, utilizing conjugated polymers as electroactive layers have received increased attention owing to their ease-of –color –tuning properties, fast switching times, and high contrast ratios. Our laboratory has developed several new electrochromic coloring EC films and EC windows. In this study, a preparing and characterization of ECD which was based a cathodic EC polymer film, Poly[3,3-dimethyle-3,4-dihydro-2H-thieno[3,4-b][1,4]dioxepine] (PProDOT-(CH3)2) is reported. The device was constructed by sandwiching a gel electrolyte between PProDOT-(CH3)2 EC film deposited on an Indium Tin oxide (ITO) glass and counter electrode which is an ITO glass coated by Vanadium oxide thin film. Device contrast ratios, measured as %T, ranged from 2% to 62%. A lifetime of over 40,000 cycles between the fully oxidized and fully reduced states has been achieved and is expected to be improved upon. The switching speed could be reached 1 second between the bleached state and colored state. The device also has a long open circuit memory. It could keep colored state without electric charge for 30 days, and transmittance was lost less than 6%. This property is huge benefit to window application and economizing on energy. This study also focused on optimizing characteristics of PProDOT-(CH3)2 EC film, gel electrolyte and device assembly.

The EC film was electrochemically deposited onto the ITO glass through Chronoamperometry method. The thickness of the EC film has been controlled by electropolymerization time from 300 nm to 400nm. The electrolyte is a transparent, ionic conductive, semi-solid state gel electrolyte, which is prepared by combining propylene carbonate (PC), ethylene carbonate (EC), polymethylmethacrylate (PMMA) and lithium perchlorate ($LiCLO_4$). The volume ratio between EC and PC is 1:1. The concentration of lithium perchlorate ($LiCLO_4$) and polymethylmethacrylate (PMMA) was optimized. Solvents and salts had been dried before mixing. For the sake of life time of the device, moisture level in the gel electrolyte was critically requested. Cyclic voltammetry method was used to detect the moisture content in the gel electrolyte. Less than 10-5 A of current under applied -1.4~0.8V voltage was found to satisfy the device. Vanadium oxide as an ion storage layer of counterelectrode was electrophoretically deposited onto an ITO glass from a sol-gel water solution. The counter electrode with an ion storage layer has certain electric conductivity, ion capacity, transmittance,

durability and EC matching rate. The thickness of the gel electrolyte between the counter electrode and the working electrode is less than 100μm. The device assembly was done in the gloves box. UV curing epoxy is in charge of sealing.

5759-37, Session 8

Co-fabrication techniques in the development of an artificial pectoral fish fin from conducting polymers

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Fish possess a greater degree of agility, maneuverability, and energy efficiency over current man-made devices. Kinematics studies show that a high degree of 3D control of multiple active surfaces distributed around an undersea vehicle's center of mass is critical to achieve fish-like superior performance. This paper presents techniques in co-fabrication using integration of rapid prototyping and molding to develop a pectoral fin which incorporates conducting polymers as force sensors (analogous to the Golgi organs in tendons), strain sensors (like muscle spindles), structural elements (such as bones, joints, and webbing), and actuators (akin to muscle). Conducting polymer actuators provide the necessary structural flexibility while exceeding the 800 N/m^2 force requirements typical of fish muscle by 40 fold. Maximum speed requirements of 2-3Hz for swimming speeds up to 6 TL/s (total body length/s) are attainable at the strains required for metrics of the current artificial fin design.

5759-38, Session 8

Fabrication of polypyrrole nanoactuators

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Conducting polymer actuators contract and expand due to the ion flux into and out of the polymer matrix under applied voltage. Therefore, the time response of such actuators is diffusion limited and has a strong dependence on the dimensions and geometry of the actuator. At microscale, the time response is on the order of seconds, while a 3-D nanoactuator can be several orders of magnitude faster. This would compare favorably to biological muscle. In this work, polypyrrole nanofibers doped with dodecylbenzenesulfonate (DBS) are fabricated using template synthesis. Furthermore, template synthesis is also used to fabricate nanofibers directly on semiconductor substrates. This technology can be used to improve the performance of artificial muscles, particularly time response. In addition, the nanoactuators could be used for biomedical applications, microrobotics, and MEMS/NEMS.

Template synthesis of nanowires or nanofibers involves electroplating or electropolymerizing the target material in the nano-sized pores of a variety of membranes, many available commercially. In this work, an alumina membrane with the pore size of 0.2 μm (Anodisc, Fisher Scientific) was coated with thermally evaporated layer of gold on one side to provide a conducting seed layer. More gold was then electroplated onto the seed layer to close the pores and provide support for polypyrrole nanofiber growth. Polypyrrole was then electropolymerized from an aqueous solution of NaDBS and pyrrole monomer (Aldrich) at 0.55V versus Ag/AgCl reference electrode. The alumina membrane was then completely dissolved by immersing in a NaOH solution, leaving standing polypyrrole nanotubes on gold substrate. The structure was evaluated under SEM, and it was found that 15 min polymerization time results in a growth of a polypyrrole nanotubes 200 nm in diameter and approximately 4 μm long. Deposition time of 2 hours gave nanotubes approximately 20 μm long.

In order to synthesize nanotubes on a semiconductor substrate to allow integration with microelectronics and other microdevices, alumina film needs to be fabricated in situ on a semiconductor wafer or chip. A thermally oxidized silicon wafer was coated with a thin titanium adhesion layer and a layer of 1μm thick aluminum film. The aluminum was then completely anodized in an aqueous phosphoric acid solution with voltage of 170 V. This produces a porous alumina (Al2O3) film ~ 1.7 μm thick with pore spacing of 220 nm. Pore size can be adjusted using etching in phosphoric acid. A byproduct of this anodization process was the production of a barrier layer of alumina at the bottom of the pores; the barrier was approximately 200 nm thick between pore bottoms and the titanium layer. The barrier layer was removed after reactive ion etching in an inductively-coupled plasma (ICP) reactor with a mixture of boron trichloride and argon gases. This left the titanium layer exposed at the bottom of the pores, providing a conducting seed layer. Polypyrrole electropolymerization was then carried out using same conditions as above, the alumina membrane was dissolved, and the resulting structure evaluated using SEM.

5759-40, Session 9

The construction and characterization of a fish-like conducting polymer actuator for microAUVs

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In this paper I describe the design, construction and characterisation of a biomimetic actuator based on the ventral fin of the black ghost knifefish, Apteronotus albifrons. The black ghost is a weakly electric eel found in the Amazon River system. Nearly blind, it navigates and finds its prey using an electric field generated by modified muscle cells near its tail. Objects near the fish cause the field to distort. The fish uses electrosensory cells spread out along its body, densest near the head and lateral line, to detect these distortions. The fish modulates the electric field at the source, but also bends its body to modulate its perception of the field, much as sighted animals move their eyes side to side to scan the visual field.

The knifefish has evolved a propulsion system which elegantly complements its electrosensory system. The animal swims without bending its body, using a single ventral fin which runs the full length of its body. Rays in the fin are oscillated laterally and phased such that a wave runs along the fin in one direction or the other, with oscillation amplitude increasing in the direction of thrust. Water is captured through the lateral oscillation and conveyed forwards or back to create thrust. In this way, the knifefish is the only fish which can swim forwards or backwards with equal ease.

While a generalist fish is limited by its thick body to sinusoidal oscillations, the knifefish can adjust the waveform to maximise thrust delivery. The phasing of the lateral movements of the rays is adjusted such that the waveform along the outboard edge of the fin is nearly square in order to increase the amount of water captured by the lateral oscillations. This results in a larger mass of water being accelerated away from the animal.

In this paper I describe two prototype knifefish-like actuators. The first uses pairs of SMA wires set in an elastomeric sheet. The second uses conducting polymer (polypyrolle) trilayer bender actuators in place of the SMA wires. Early prototypes simply created a sinusoidal wave, but later prototypes have begun to recreate the nearly square wave used by the knifefish. In this paper, I describe the comparative electromechanical efficiency and thrust generation ability of the actuators, discuss encapsulation and interconnect issues, and describe the actuators' potential applications in underwater robotics.

5759-41, Session 9

Toward standarization of EAP actuators test procedures

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Since the field of Electroactive Polymers (EAP) actuators is fairly new there are no standard testing processes for these actuating/sensing materials. This drawback can seriously limit the scope of application of EAP materials, since the targeted industrial sectors (aerospace, biomedical...) demand high reliability and product assurance. As a first iteration two elements are required to define a test standard for an EAP actuator: a Unit Tester, and a Component Specification. In this paper a EAP Unit Tester architecture is presented along with the required measurements to be included in the EAP actuator Component Specification. The developed EAP Unit Tester allows on-line monitoring and recording of the following properties of the specimen under test: deformation, small tip displacement, temperature at the electrodes, weight of the specimen, voltage and current driven into the EAP, force of the EAP actuator, output voltage of the EAP in sensing operation and mode of operation (sensor / actuator / structure). The measurements are taken simultaneously since a novel force transducer has been designed and included in the Unit Tester.

Force developed by a skeletal muscle is strain dependent and velocity of the contraction dependent. The strain-force curve is generated by maximally stimulating a skeletal muscle at a variety of discrete lengths and measuring the tension generated at each length (isometric force). During force-velocity measurements a muscle is stimulated maximally and allowed to shorten against a constant load. Muscle velocity during shortening is measured and then plotted against the resistive force. This type of measurements are fairly common albeit the force-length and force-velocity relationships obtained differ from natural locomotion. This is because during movements muscle constantly act with varying length and velocity. For this reason, current techniques tend to measure tendon force and muscle length In vivo. Based on this experience a novel methodology of measuring the properties of the EAP specimen against a variable load was studied. A digital load generator in the range of mN was developed. The device is based on a DC mini-motor. It generates an opposing force to the

movement of the EAP actuator. Since the device constantly opposes the EAP actuator movement it has been named Precision Analog Break (PAB). The PAB design allows simultaneous length and velocity measuring versus different load signals. By including such a device in the EAP Unit Tester the most suitable application for the specimen under test can be easily identified (vibration damper, large deformation actuator, large force actuator, fast actuator...). The EAP Unit Tester includes a friendly Graphical User Interface. It uses embedded Excel tools to visualize data. Real-time connectivity with MATLAB allows an easy testing of the control algorithms for the specimen.

Based on the proposed EAP Unit Tester and classical mechanical tests of elastic materials an EAP actuator component specification is suggested. The Component Specification describes the performance and reliability of the device.

Finally, IPMC samples were developed according to literature and characterized using the introduced methodology.

5759-42, Session 9

Mechanical characterization and implementation of antagonistically

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Although various types of polymer actuators have been introduced for a decade, most of them still remain in a conceptual stage. Examples of successful industrial application of polymer actuators are very limited despite their potential for high efficiency and great flexibility. Especially the morphological freedom of the polymer insures production of small scale complex mechanisms or human-like actuators. Dielectric elastomers have been proven to be successfully used for industrial applications provided controllability and reasonable amount of actuator output displacement are guaranteed.

This article presents a construction of antagonistically driven dielectric elastomer actuator and a study on mechanical characterization of the actuator. Detailed topics to be covered are as follows,
1. Most of currently available driving concepts of dielectric elastomers are dependent on prestretching of the elastomer in order to maximize output displacement. A systematic study on the dependency of prestretching the material and the corresponding actuator output in terms of input power and principle actuation mode is to be presented. An attempt for determining an optimal morphology of the actuator design based on the study is also mentioned.

2. A single-directional dielectric elastomer actuator that produces fairly "reasonable" amount of displacement and guarantees controllability is introduced and tested.

3. Introduction of antagonistically driven architecture greatly benefits both stability and performance of the dielectric elastomer actuator. An antagonistically organized actuator that enables to produce bi-directional motion is presented and its functionality is thoroughly evaluated.

4. The present work demonstrates a feasibility that the proposed concept can be implemented in some of industrial applications as a substitute of the conventional actuator.

5759-43, Session 9

Characterization of conducting polymer actuators in room-temperature ionic liquids

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Our recent progress shows that polypyrrole actuators activated in room temperature ionic liquids generate large contractions (14.5 % recoverable strain at 2.5 MPa, 21 % max) at slow speeds (0.4 %/s). In addition, cycle life can be extended to a million cycles without significant polymer degradation as discovered by Wallace and Colleagues. Mammalian skeletal muscle on the other hand generates about 20 % strain in contraction (at 0.35 MPa load), but at much faster rates (100 %/s). These results move conducting polymer actuator technology closer to matching mammalian muscle performance in all key figures of merit. In this paper we present an in depth characterization of the behavior of polypyrrole actuators in 1-butyl-3-methyl imidazolium tetrafluoroborate room temperature liquid salt electrolyte. The characterization includes the assessment of passive and electroactive mechanical properties, electrical properties as well as the use of in-situ electrochemical quartz crystal microbalance (EQCM) analysis to determine the relation between the activation potential and the resulting electrochemomechanical response. Strategies to increase the contraction speed of this conducting polymer actuator system are also discussed.

5759-44, Session 9

Polypyrrole/gold bilayer characterization

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Devices using polypyrrole/gold (PPy/Au) bilayer microactuators are being developed in our laboratory for several biomedical applications, including microvalves and cell clinics [1]. To fully open and close the valves and microvials, the bilayer hinges must be able to rotate between 0° and 180° against known fluid and other forces, and within certain time constraints. Simple models predict that there is a ratio of PPy to Au thicknesses at which bending angle is maximum [2], whereas force simply increases with PPy thickness. The layer thicknesses and hinge length must therefore be properly designed: the minimum PPy thickness is determined by the required force, with greater thickness negatively impacting speed; the gold thickness is then set by the PPy:Au ratio that gives the smallest radius of curvature; and the length is set by the requirement for 180° bending. However, existing models [3] fail to predict the correct behavior of microactuators, in part because 1) there is a strain gradient in the PPy arising from the electrodeposition process [4]; 2) during actuation, the Young's modulus of the polymer varies [5]; 3) the modulus of PPy has only been measured for thicker films [5]; 4) the morphology of the PPy changes with thickness [6]; 5) the radius of curvature is small; and 6) the properties of the PPy may be affected by the micro-fabrication process. Therefore, experimental data are needed to develop a model that correctly forecasts the performance of these PPy/Au bilayers.

Starting with predictions from existing models, ranges of PPy and Au thicknesses and hinge lengths were chosen to be investigated, and samples were fabricated that varied these parameters independently. Bending angles were recorded through a stereomicroscope that viewed the samples edge-on, or at an angle, so that the shape of the hinges could be determined as well as their total rotation. The isometric forces exerted by the hinges were measured with a force transducer (Aurora Scientific 406A, maximum force 0.5 mN, sensitivity 0.01 mN). The output of the force transducer was read by the potentiostat (EcoChemie pgstat30), and thereby correlated with the applied potentials. Based on the data, a model that takes into account the strain gradient and thickness dependence of strain was developed.

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5759-45, Session 9

Quasi-static and dynamic inflation of a dielectric elastomer membrane for an artificial heart pump

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A dielectric elastomer membrane is to be used as the pumping element in an artificial heart pump. In its conceived mode of operation the initially flat circular membrane is constrained along the edges such that it is inflated by an external pressure and an applied voltage; removal of the voltage results in elastic recoil of the membrane which drives fluid out of the pump. In this paper, analytical solutions are presented for multilayer dielectric elastomer membranes. Due to the scalability of the presented mathematical formulation, solutions are also obtained for dielectric elastomer micromembrane pumps. Further, the analytical method is incorporated into an optimization routine to determine the best fit parameters for operation of the diaphragm subject to various physiological constraints. Three different objective functions are investigated: the Ejection Stroke Kinetic Energy, the Ejection Fraction and the Total Energy Density per Unit Volume. A single composite objective function is then formulated for optimization based on observations of the three independent functions. Additionally, to address mechanical concerns about potential failure at areas of high stress concentrations, an optimization routine is also used to determine the initial thickness configuration of the membrane such that relative thinning along the deformed profile of the membrane is significantly reduced.

In previous work, inertial effects have been neglected and a quasi-static approach employed. The analytical method is presently expanded to include the dynamic response of the dielectric elastomer membrane. The proposed incorporation of an electroactive membrane in the artificial heart will render a variable-displacement volume pump unlike currently available artificial pumps which are all fixed-displacement volume pumps. In this case inertial effects become increasingly important as different equilibria modes are obtained during dynamic operation. The material and geometrical nonlinearities of the membrane configuration result in a system of nonlinear partial differential equations to be solved for the membrane response. For initial considerations we simplify the problem by employing the ideal gas law to model external pressure effects. The dielectric elastomer membrane's dynamic response is examined under two conditions: (1) a constant pressure, (2) a physiologically plausible gas flow rate.

5759-46, Session 10

In pursuit of high-force/high-stroke conducting polymer actuators

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Practical devices for electromechanical actuators will only be realised when the actuator materials can generate sufficient movement (stroke) and forces within a suitable time frame. Low voltage actuators based on conducting polymers such as polypyrrole (PPy) appear attractive choices because of the relatively large strains (up to 26%) and stresses (to 5-10 MPa) that have been previously reported. However, the small size of the actuator materials used mean that the actual stroke (few mm) and forces (‹1 N) are quite small. Many more applications become feasible if low voltage actuators could produce \›10mm stroke and \›1 N force- preferably within one second.

We have previously shown that the actuator performance is enhanced by incorporating a flexible metal interconnect into a hollow tube geometry. We have also shown that the overall performance is greatly affected by changes in the Young's modulus of the polymer during electrochemical stimulation. We present in this paper some recent observations of the effects of different actuator geometries and the influence of modulus shift on the actuator behaviour. The latter is particularly influenced by the incorporation of carbon nanotubes as a reinforcing agent.

In our recent work the effect of helix wire pitch and the effect of bundling the helix wires have been studied. It was found that by increasing the pitch of the helix wires that the strain generated increased by a factor of 5. Similarly, the strain under load was increased by bundling fibres. The strain increased roughly in proportion to the number of fibres in the bundle since the applied stress per fibre decreased at a fixed applied load. The force generated by bundles was also investigated and was found to decrease with increasing pre-load tension as a result of modulus changes during stimulation.

The influence of modulus changes on actuator performance has been more closely examined by utilising simultaneous dynamic oscillations along with electrochemical cycling. Preliminary results show surprising time-dependency of the modulus when electrochemically cycled. In addition, composites of carbon nanotubes and polyaniline have shown a much reduced "modulus-shift" effect due to the reinforcing effect of the nanotubes.

5759-47, Session 10

Reversible work by electrochemical intercalation of graphitic materials

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The intrinsic behavior of graphite intercalation compound (GIC) formation offers a potential route towards structural, high-force, high-strain and high-temperature solid-state actuation for aerospace applications. Graphite and other layered materials are known to undergo substantial, reversible volume changes during electrochemical ion insertion (\›150% depending on structure and intercalated ion species). Although extensively studied for energy storage applications, the potential for harnessing this reversible compound formation and the associated volume changes to perform reversible work has only recently received serious consideration. We have examined constant-current electrochemical GIC formation under static compressive loading conditions up to 8 MPa for several "model" systems: single-crystal highly-oriented pyrolytic graphite (HOPG), nanocrystalline HOPG, and highly porous graphitic paper; all three cases employed HSO_4^+ as the intercalated ion. For the HOPG systems, energy densities of about 500 kJ/m3 and strains greater than 30% were observed between 2 and 6 MPa. The graphitic paper samples exhibited reduced performance (15% at .85 MPa), but with better stability at higher currents. Single-crystal samples exhibit the most robust behavior, but are significantly more kinetically constrained than the other cases. We discuss the potential and limits of GIC formation to form the basis for high-performance actuation.

5759-48, Session 10

IPMC actuator array for a 3D haptic display

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Imagine sitting in front of your computer with the goal to design a vase in 3D space. But instead of using your mouse or space-ball and an active stereo screen you are using a freely shapable object, "virtual clay", that you can manipulate and transform to desired shape. The changing shape is of course instantly appearing in the computer, the "vitual clay" is an input device. Imagine doing some corrections on the digital counterpart of the vase that was just generated by the clay and these corrections simultaneously being physically displayed again. "Virtual clay" is also output device. Just fantasy?

A lot of research is being done in this field of so called tangible user interfaces and a few interesting and very promising concepts have been proposed. Mazzone et al. propose a novel digital clay mechanism capable to deform at will in order to imitate arbitrary objects. The mechanism is based on a grid of nodes and linkages. Similar to CAD triangular meshes, the mechanism imitates an object by altering the lengths of the linkages with the use of linear actuators. However, the successful implementation of the concept with more than several tenths of nodes remains difficult, due to the low power to weight ratio and the discrete manufacturing and interconnection of conventional actuation technology.

We propose here IPMC (Ionic Polymer-Metal Composites) as actuation technology for a virtual clay device. Its main features are shape flexibility, low driving voltage, long life time and especially the possibility of batch fabrication. Furthermore, we propose to use the IPMC not only as an actuator but also as structural element of the complete device. Hence, the weight can be drastically minimized. Multiple actuators, joints and connections can be created in a single fabrication processes by patterning electrodes on the membrane.

Experimental work has been started with a simple linear 4-actuator strip, more elaborate shapes can easily be realized according to exactly the same principles. In order to calculate the deformation, a simplified model describing one actuator as a combination of three layers, swelling, shrinking and natural layer, is proposed. The deformations are due to strain caused by water migration inside the IPMC when low voltage is applied to the electrodes. Experimental results agree well with numerical and analytical preliminary studies. At the heart of the fabrication procedure is the patterning of electrodes in a specially developed platinum chemical plating technology. Connections of the electrodes are realized by flexible PCBs, a method easily extendable to a large number of discrete actuators. The experimental results demonstrate the feasibility of this concept.

Current work now aims at a 2x2 mesh shaped device with 12 actuators. By increasing the number of nodes and by decreasing the size of the actuators, resolution can be increased. Along with the fabrication technology, numerical modeling of the device is also refined and will be presented.

5759-50, Session 10

Progress in design of EAP pumps

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With the goal of building simple and effective pumps using EAPs, we have previously reported measurement of pressure-volume characteristics of dielectric elastomer diphragms and construction and testing of multilaminate diaphragms. We have continued stepwise development of practical pumps. In this paper, we describe fabrication and testing of an EAP pump having dual diaphragms so that the majority of the pump chamber surface is composed of active material.

We discuss pump performance and its relationship to EAP properties and fabrication methods, and prospects for improvement based upon continued development of materials, fabrication methods and shape optimization.

5759-51, Session 10

A bio-inspired EAP actuator design methodology

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Current EAP actuator sheets or fibers perform reasonable well in the centimeter and mN range, but are not practical for larger force and deformation requirements. In order to make EAP actuators technology scalable a design methodology for polymer actuators is required. Design variables, optimization formulas and a general architecture are required as it is usual in electromagnetic or hydraulic actuators design. This will allow the development of large EAP actuators specifically designed for a particular application. It will also help to enhance the EAP material final performance. This approach is not new, since it is found in Nature. Skeletal muscle architecture has a profound influence on muscle force-generating properties and functionality. Based on existing literature on skeletal muscle biomechanics, the Nature design philosophy is inferred. Formulas and curves employed by Nature in the design of muscles are presented. Design units such as fiber, tendon, aponeurosis, and motor unit are compared with the equivalent design units to be taken into account in the design of EAP actuators. Finally a complete design methodology for the design of actuators based on multiple EAP fiber/sheets is proposed. In addition, the procedure gives an idea of the required parameters that must be clearly modeled and characterized at EAP material level.

5759-52, Session 10

Wirelessly controllable inflated electroactive polymer (EAP) reflectors

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Inflatable membrane reflectors are attractive for deployable, large aperture, lightweight optical and microwave systems in micro-gravity space environment. However, any fabrication flaw or temperature variation may results in significant aberration of the surface. Even for a perfectly fabricated inflatable membrane mirror with uniform thickness, theory shows it will form a Hencky curve surface but a desired parabolic or spherical surface. Precision control of the surface shape of extremely flexible membrane structures is a critical challenge for the success of this technology. Wirelessly controllable inflated reflectors made of electroactive polymers (EAP) are proposed in this paper. A numerical model was developed to predict the behavior of the inflatable EAP membranes under a distributed electric charge on the surface. The controllability of the reflectors made of available EAP materials was explored and will be covered in this presentation.

5759-68, Session 10

Biomimetic actuator

V. Bouda, Czech Technical Univ. (Czech Republic)

The universal actuator in the animal kingdom is the muscle. Its efficiency is very high and the length change is very large when compared with other piezo-ceramic, magneto-strictive actuators or electro active conducting polymers. According to the classical contractile mechanisms, adenosin triphosphate hydrolysis inside the myosin heads induces their swing. Swinging of the globular myosin heads drives the actin filaments toward the center of the sarcomere, thereby shortening the muscle cell. New theories of the muscle cell function appear [1].

We believe in the paradigm of the significant role of the phase transition of the system of myosin heads [2]. Interactions between the two heads are estimated by DLVO approximation for thin double layers [3]. The interaction energy is a sum of energy of electrostatic repulsion and of energy of van der Waals attraction.

There are two states of the system of the myosin heads: the relaxation and the contraction one [4]. The relaxation state at low Ca2+ ions concentration demonstrates two important features of the relaxation state. First, the actin filaments are free in movement typical for the relaxation state of the muscle because the diameter of actin filament is less than the equilibrium distance between the myosin heads. Second, the myosin heads are regularly arranged and can control the process of evolution of self-assembly of the internal structure of the muscle cell.

At the transition to the contraction state, the cations Ca2+ released by action potential increase their total concentration. The induced decrease of the interaction energy and the increase of attractive force between the myosin heads with decrease of distance would render the coagulation of the myosin heads. However, the coagulation is prevented because of the presence of the actin filaments between the heads. The myosin heads firmly grip the actin filaments and shift them to the center of the sarcomere. The computed sum of the forces of all the myosin heads in a specific muscle transmitted to the direction parallel to actin filaments approaches the force measured on the muscle in experiments.

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5759-53, Session 11

Electro-driven polypyrrole actuators working in air

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The combination of electrical and hygroscopic nature of conducting polymers provides an insight into the development of a new class of electro-driven actuators or artificial muscle systems that work in ambient air. We have previously reported that electrochemically synthesized polypyrrole films undergo quick and intensive bending in air as a result of a dimensional change due to the sorption of water vapor from one side of the film. Furthermore, we have found that an application of electric field causes contraction of this film in air. Polypyrrole (PPy) films were electrochemically synthesized by anodic oxidation of pyrrole in the presence of tetraethylammonium tetrafluoroborate.

Upon applying dc 3V under 50% RH at 25 °C, the electric current of 27 mA passes through the film and the temperature at the film surface rises from 25 °C to 33 °C due to the Joule heating. It is noted that RH in the vicinity of the film surface abruptly increases by the electric field, which reveals that water vapor sorbed in the film desorbs and scatters into ambient air. The gradual decrease of RH with elapse of time will be due to the temperature rise near the film, while a drop of the RH when the electric field is turned off, can be explained as the resorption of water vapor from the air surrounding the film. It is also found that the dehydration brings about contraction of the film: the length of the film, in the direction parallel to the electric field, decreases by 1.3%, which is comparable to that caused by electrochemical doping and dedoping of conducting polymers in an electrolyte solution. It is noted that the width of the film, in the direction perpendicular to the electric field, significantly decreases by 3.1%, which is more than twice that in length. The fact demonstrates the PPy film undergoes anisotropic contraction under the electric field.

Under isometric conditions, the film generates contractile stress in response to the RH change and/or electric field. When dc 2V is applied to the film under the thermostatic conditions (25°C, 50% RH), the film generates contractile stress repeatedly in response to the applied voltage. The stress reaches 6.1 MPa, corresponding to an equivalent contractile force of 93 gf, which is 4 orders of magnitude larger than its own weight (7.6 mg) and is nearly 20 times that of skeletal muscle in animals (0.3 MPa). The mechanism can be explained in terms of the electrically induced dehydration of the conducting polymer film caused by the electric field.

Unlike in the conducting polymers based on the electrochemical doping, this system can serve as a new type of electrically driven muscle that works in air without using an electrolyte solution or counter and reference electrodes, where the electric field is capable of controlling the sorption equilibrium to desorb water vapor from the film. Furthermore, various conducting polymers that undergo dimensional changes due to the sorption of water vapor can be employed on the same principle.

5759-54, Session 11

Bending response of an artificial muscle in high-pressure water environments

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Ionic Polymer-Metal Composites (IPMCs) are soft actuators, generally referred to as “artificial muscles” which are made out of high polymer gel films of perfluorosulfonic acid chemically plated with gold. These composites bend by applying a low voltage between electrodes on both sides.

The actuator is soft and works in water. It bends silently, responds quickly and has a long life. In our previous work, snake-like swimming robots and a 3DOF 2-D manipulator have been developed.

In this research we have investigated the bending response of an IPMC artificial muscle in high-pressure water environments, with future applications in deep-sea actuators and robots. The artificial muscles have an advantage over electric motors because they do not need sealing from water, which is difficult in high-pressure water environments.

Bending responses of artificial muscles were measured at three different pressure levels, 30MPa, 70MPa and 100MPa. The maximum pressure, 100MPa is the same pressure as the deepest ocean on earth, (10,000m.)

From experiments, there was found to be almost no difference with that at normal water pressure of 1Pa. We present detailed results of responses of these artificial muscles including current responses and videos of bending motion with respect to combinations of several different input voltages, frequencies and wave patterns.

5759-57, Session 11

Understanding ion transport in conjugated polymers

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The transport of charged species, including both polarons/bipolarons and charge-compensating ions, must occur when conjugated polymers switch between oxidized and reduced states. This movement determines the performance of many conjugated polymer devices, such as smart windows, capacitors, and actuators. However, good physics-based models of the charge transport process, and how it depends on material and cycling conditions, have not yet been developed.

Last year, we presented a device geometry that made the path for ions much longer than that for electrons, ensuring that ion transport was the rate-limiting step during redox, and that displayed the location of the ions through the film's electrochromism. A 1-D model that included drift and diffusion of ions was presented that accounted qualitatively for the results.

In this presentation, a more realistic 2-D model is introduced that includes interactions between polarons and ions, includes doping level dependent mobility and diffusion, and makes quantitative predictions. Experimentally, the effects of electrolyte concentration, electrolyte temperature, and film thickness on the phase front velocity and front broadening are explored. We also report the correlation between the phase front and volume change. Finally, a polymer structure that results in increased switching speed is demonstrated.

5759-58, Session 11

Application of polypyrrole(PPy) as the media material for the release and the detection of a neurotransmitter

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Conducting polymers are widely studied for the replacement of traditional conducting material, i.e. metal, in many biomedical applications where metal is inappropriate. The use of polypyrrole(PPy) has been investigated by many researchers because it is simply polymerized electrochemically on metal surfaces of an arbitrary shape and hence it can be formed as micro structures, which is very useful for various micro sensors and actuators development. The ion exchange property of conducting polymers is also useful in releasing and detecting ionic material such as some neurotransmitters or ionic drug. This paper presents the use of PPy as a media material for releasing and detecting a neurotransmitter, in particular epinephrine, and some of experimental results.

Neuron, as a basic unit of the nervous system, carries information by transmitting electrical impulse signals along the axon. These signals are transmitted between neurons by releasing neurotransmitters at one end of the axon terminal and collecting these released neurotransmitters at the other end (dendrites). Conducting polymers can hold ionic neurotransmitters and release them when a proper biased voltage is applied. Also, the electrochemical redox current varies depending on the concentration of the ionic neurotransmitters in the solution and hence it may sense the released neurotransmitter amount. Epinephrine, as an important hormone secreted by the medulla of the adrenal glands, serves as a chemical mediator for conveying neuron signals. When PPy is polymerized with this material as a dopant, the controlled releasing is possible by varying the level of the applied voltage. The released epinephrine amount was detected by using ultraviolet spectrometry and its value was compared with that obtained from electrochemical detection. The electrochemical detection of the epinephrine was performed with the overoxidized PPy/Au electrode which lost electrical conductivity but still had ionic conductivity due to the quite permeable film structure. The electrostatic binding of the overoxidized PPy film and cations results in good cation permselectivity for the detection of epinephrine.

PPy was electrochemically polymerized on Au electrode and its thickness was controlled to 0.4㎛ by controlling the charges flown during PPy polymerization. The theoretical relationship between the flown charges and the thickness of the electropolymerized PPy was reported by S. Holdcroft et al.[1] and the measured thickness showed a little higher value than the theoretical value. PPy was polymerized in 0.2M pyrrole solution with dopants at the potential of 0.6V.

Based on ion transporting mechanism of a conducting polymer at the polymer/solution interface, epinephrine can be doped by voltammetric method. In other to find the better method, doping step was performed with two different doping methods, which are mixing method and substitutional method. PPy could be polymerized and doped with epinephrine at the same time by the mixing method which resulted thinner thickness of the PPy compared with that of the PPy polymerized without epinephrine. This was because most potential was consumed to the oxidation of the epinephrine. In the substitutional method, PPy was polymerized with KCl as dopants and then dedoping step was added to remove the residual negative ions before doping the epinephrine, so that the epinephrine could be doped more easily without the interruption of the residual ions. Cyclicvoltammetry(CV) with the voltage range of -0.6V~0.8V was used for the doping process. Epinephrine is very unstable material and it transforms into various oxidized products such as leucoadlenochrome or adrenochrome. The chemical transformation is pH dependent because the deprotonation step is involved. So, the doping process was performed in a low pH solution, H_2SO_4 at pH 1, to avoid the generation of by-products. Furthermore, the solubility was better in a lower pH solution.

Epinephrine was released by applying -0.7V vs. Ag/AgCl reference electrode so that the PPy could be reduced as releasing the doped epinephrine. This process was performed in the 10㎖ potassium phosphate buffer solution of pH 6 for 30 minutes for both of the doping methods. The detection of the released epinephrine and the analyses were done with a UV spectrometer. Before releasing, epinephrine was dipped in a potassium phosphate buffer solution of pH 6 for an hour to evaluate how much the spontaneous epinephrine release was. The amount of the released epinephrine could be estimated from the comparison to the measured absorbance according to the various concentrations of epinephrine. The PPy doped by mixing method released 124.1㎍ of epinephrine and the PPy doped by substitutional method released 30.0㎍ of epinephrine on the average and no spontaneous diffusion was observed from the former.

For the electrochemical detection electrode, the PPy was electropolymerized with NaDBS as dopants on the Au electrode and was overoxidized in a high pH solution of 0.1M KCl + 0.5M NaOH for 20minutes by applying positive bias of 1V vs. Ag/AgCl reference electrode. The detecting electrode was tested by CV both in a potassium phosphate buffer solution of pH 6 and in the identical solution with added epinephrine to find the detection voltage, which is the oxidation voltage of the epinephrine. The overoxidized PPy/Au electrode which had the size of 50mm2 and the film thickness of 0.4㎛ was tested in the various concentrations of epinephrine to find the minimum possible detecting concentration. The minimum possible detecting concentration was 100μM with the detecting voltage of 0.4V which was acquired from the CV test. This result was compared with that obtained with bare Au electrode of same size and of same film thickness.

The results show that the doped epinephrine can be successfully released from the PPy by controlling the applied voltage. The detection of the released epinephrine was done with a UV spectrometer and the PPy doped by mixing method released larger amount of epinephrine than the PPy doped by substitutional method. Electrochemical detection of epinephrine was possible with overoxidized PPy/Au electrode and the minimum possible detecting concentration was 100μM. This presents the possibility of replacing the nervous system in the body with the bio-compatible PPy as a media material.

5759-64, Session 11

A robotic architecture composed entirely of EAP components

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Electro active polymers (EAP) hold great promise for robotic applications, coming closer than any of the metal/glass/silicon based technologies to biological tissue as an organ substrate. EAP based components may be used as actuators, sensors, energy transducers, energy storage devices, and computational elements. We will describe in this presentation a robotic architecture, composed

entirely of EAP based components. We will present our architecture modeling and dynamic simulation methods and results, and discuss the architecture's utility in selected applications. We will introduce a new generic architecture incorporating EAP elements that will permit the construction and control of low cost, low density, light weight, highly flexible and compliant robots across a wide range of physical size and form.

5759-75, Session 11

Improving adhesion of polypyrrole on Au for long-term actuation

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Improving the structural stability of conjugated polymer based devices and systems under long-term, cyclic electrical stimulation is important for commercialization. In general, conjugated polymers are contacted by metal electrodes; electrical signals flow through the electrodes to control electrochemical oxidation-reduction (redox) reactions. The reactions cause changes in the physical and chemical properties of the polymers, making them promising for a variety of applications. However, strain from volume change can cause the polymers to delaminate, which slowly deteriorates performance or results in sudden device failure. In this paper, we used polypyrrole (PPy) on gold (Au) to investigate methods for improving adhesion.

Possible solutions to PPy delamination can be categorized into mechanical and chemical means. Pyo [1] reported improving the adhesion of as-deposited PPy by increasing mechanical interlocking: a rough layer of Au was electroplated on top of a smooth layer of evaporated Au; PPy was then deposited on the rough surface. The morphology of the plated Au (e.g. the crystal size and shape) played an important role. Chemical means that have been reported to improve adhesion include oxide surface silanization and deposition of PPy with cyclic potentials.

In prior work, adhesion improvements have not been tested upon extended cycling, nor have the various methods been compared. We report results from systematically investigating the effects of Au electroplating conditions (solution concentration, plated Au thickness, and plating temperature) on the Au surface morphology. In addition, we roughened the Au surface by wet chemical etching for different times and at various etchant concentrations. PPy deposited on these surfaces was electrochemically cycled until driven to failure. Adhesion was determined with an ASTM tape test at regular cycling intervals. We found both plated Au and etched Au surfaces with specific morphologies effectively improved the adhesion: only minor delamination was observed after PPy was cycled 60,000 times between 0 V and –1 V vs. Ag/AgCl, at which point the polymer had degraded so that it was not longer electroactive. We also investigated the effect of PPy thickness on the adhesion.

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5759-85, Session 11

Electromechanical response of P(VDF-TrFE)-P(VDF-CTFE) blends

Y. Wang, Z. Li, Z. Cheng, Auburn Univ.

PVDF-based electroactive polymers exhibit high electromechanical performance that is attractive for developing high performance actuators and sensors. In en effort to develop very inexpensive electroactive polymers, P(VDF-TrFE)/P(VDF-CTFE) copolymer blends are studied. The structure and morphology of the blend system were investigated and are presented in this presentation. It is found that the addition of P(VDF-CTFE) has a strong influence on the ferro-to-paraelectric phase transition behavior of P(VDF-TrFE). It is also found that the phase transition behavior of the blends can be significantly modified using thermal and mechanical treating conditions. The electric filed induced strain response can reach more than 4% in the copolymer blends with certain thermal treatment. Considering the high Young's modulus, the results indicate that the copolymer blends have a high electromechanical coupling factor, an important parameter for electromechanical application.

5759-60, Session 12

Proposal of new actuators using ion gels driven at low-voltage under atmospheric conditions

M. Watanabe, S. Nanjo, Yokohama National Univ. (Japan)

Electroactive polymers (EAPs) that respond to external electrical stimulation with a significant shape or size change have been of great interest for use in a variety of actuator applications [1]. However most of the current EAP actuators [2] can be driven only at high voltage or in aqueous media, therefore they have safety defects or long-term stability problems that impose some restrictions on the operating conditions.

In this research, aiming at solving the drawbacks, new EAP actuators that can be driven at low voltage under atmospheric conditions have been successfully made. We have proposed and realized the application of electric double layer capacitors (EDLCs) using ion gels as the polymer electrolytes, prepared by incorporating ionic liquids in network polymers [3], to the new EAP actuators. They have an advantage to be driven at low voltage, and the presence of non-volatile ionic liquids in the ion gels allows them to be operated under atmospheric conditions for a long term.

From the specific bending displacement that the actuators show to the external applied voltage, we have investigated the principle of the applicability of the EDLCs to the new EAP actuators, and have approached to the elucidation of the operating mechanism.

The ion gels were prepared by in situ radical polymerization of methyl methacrylate (MMA) in an hydrophobic ionic liquid, 1-ethyl-3-methylimidazolium bis(trifluoromethane sulfone)imide ([emim][N(SO2CF3)2]; EMITFSI). Then, the EDLCs were made by adhering carbon powder as compliant electrodes to the both sides of the ion gels. The EDLCs were supported by clamping the one ends and displacement of the free ends of them were measured by a laser displacement meter. The displacement responses under atmospheric conditions were stimulated by applying rectangular waveform voltage (±1.5 V) at a cycle of 20s or 120s, and triangular waveform voltage (±1.5 V) at a scan rate of 0.01V s-1 to 9 Vs-1.

The displacement responses of the EDLCs to the applied voltage are always bends to the anodic side, and the applicability to new actuators driven at ±1.5 V under atmospheric conditions can be found. Firstly, on applying rectangular waveform voltage, the displacement increases with increasing the charging of the electric double layer. Secondly, on applying triangular waveform voltage, the displacement responses reversibly follow the forwarded and backwarded volatege change. The displacement trends can be seen over a wide range of capacitance caluculated from cyclic voltammograms scanned at each rate, and the displacement increases with increasing the capacitance caluculated from cyclic voltammograms scanned at each rate.

According to these responses, it is considered that the actuators can convert a part of the electric energy stored at the electric double layers into the mechanical energy used for the deformation, and the charging and discharging are associated with the reversible deformation.

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5759-61, Session 12

Development of a tactile array with the utilization of dielectric electroactive polymers

G. Chakrabarti, Dalient; R. Chakraborty, Thermefficient

We propose a novel tactile display unit built on dielectric electroactive polymers. Restriction buckling of an electroded area was used as a means of vertical actuation. A 6x6 array of planar dielectric electroactive polymers was used to actuate an array of pins .5mm in diameter with an interspacing of 2mm. An electrically insulative coating was deposited on the electrodes, protecting the user from the applied electric field. Tactile patterns refreshed at a rate of 800 Hz with a maximum indentation of 2mm. The density of the display is one actuator per square millimeter. A qualitative analysis showed that a sufficient tactile sensation was created. In addition to shape and pressure distributions, the tactile apparatus emulates dynamic thermal sensations through thermoelectric generators. The research presents an inexpensive yet efficient means of creating tactile sensations.

5759-62, Session 12

Actuation behavioral studies on polyaniline-cellophane based electroactive paper actuator

S. D. Deshpande, C. Song, Q. Li, J. Kim, Inha Univ. (South Korea)

In the present investigations, we have fabricated the electromechanical actuators using conducting Polyaniline and Cellophane paper. This was achieved by electrochemical synthesis of polyaniline onto cellophane paper. The electro

generation of polyaniline was carried out in propylene carbonate medium in the presence of dichloro acetic acid (DCA) and trichloro acetic acid (TCA) at different reaction conditions. The comparative results of the two types of paper actuators namely bi-layer and tri-layer are presented here. The displacement in tri-layer devices, are more than that of bi-layer counter parts. The explanation towards this type of actuation behavior is given. Actuation behavioral studies were mainly focused on the effect of various dopant ions namely Cl-, ClO4-, BF4- and PF6-. The effect of varying film thickness and change in relative humidity are also addressed in this communication. The possible working mechanism has been discussed.

5759-63, Session 12

Low-voltage driven dry soft actuators using carbon-anotube gels with ionic liquids

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This paper firstly reports soft actuators which can be operated in perfectly dry conditons driven by low voltage such as several volts using carbon nanotube. It is well-known that carbon nanotube paper can show extension/contraction upon low voltage application in electrolyte solutions. Recently, Fukushima et al found that single walled carbon nanotube formed gels when being ground with ionic liquids (IL), which are known to be room temperature molten salts. We constructed a base polymer-supported bimorph actuator with internal IL polymer gel electrolyte layer, sandwiched by carbon nanotube gel electrodes layers. The bimorph actuator shows quick (30Hz) and long-lived (more than 9000 cycles) motions in air driven by low voltage (less than 3.5V). The actuators were fabricated very easily by layer-by-layer casting, which can be molded in any shape easily.

5759-65, Session 12

Design and performance analysis of a novel IPMC-driven micropump

S. K. Lee, K. Kim, S. Heo, K. Choe, Univ. of Nevada/Reno; H. C. Park, Konkuk Univ. (South Korea)

This paper presents the design and analysis of an IPMC(Ionic Polymer-Metal Composite)-driven micropump. It should be noted that IPMC is a promising material candidate for micropump applications since it can be operated with low voltage inputs and can produce large stoke volumes along with controllable flow rates. Moreover, the micropump manufacturing process with IPMC is convenient. It is anticipated that the manufacturing cost of the IPMC micropumps is competitive to other competing technologies. In order to design an effective IPMC diaphragm that functions as an actuating motor for a micropump, a finite element analysis was utilized to optimize the shape of IPMC diaphragm through several parametric studies. Appropriate inlet and outlet diffusers for the micropump were also chosen. Based on the selected geometry, the stroke volume and flow rate of the IPMC micropump is numerically estimated and effect of the pump chamber's pressure on the stroke volume was investigated.

5759-67, Session 12

Smart actuators based on electromechanically active conjugated polymer diodes

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The discovery of the conducting and semiconducting properties of conjugated polymers led to their application in opto-electronic devices. Today, semiconducting, conjugated polymers are widely investigated and technologically implemented as electroluminescent light emitters in Organic Light Emitting Diodes (OLED), and as active semiconductors in high-rectification ratio diodes, photodiodes, solar cells, organic polymeric transistors, and organic nonvolatile memories.

Nevertheless, up to now, only a limited number of studies have been performed on the actuation properties of this class of materials for applications in nano- and micro-electro-mechanical systems (MEMS). In the early nineties, conjugated, conducting polymers such as polypyrrole (PPy) and polyaniline (PANI) were recognized as electroactive polymers (EAP). Indeed, they were shown to undergo large dimensional changes during oxidation or reduction in an electrochemical bimorph electrode configuration. Besides, very recently PANI was used to improve the capabilities of two different EAP types, namely relaxor ferroelectrics and dielectric elastomers. In both cases, the strategy consists in increasing the input electric energy density by increasing the dielectric constant (ε) of the active material. Upon adding PANI into elastomers like polyurethane with low ε and low elastic modulus, electrostrictive material with very high ε has been achieved. The amount of PANI in the host elastomer matrix was always kept below the percolation value, to maintain the electrically insulating properties and the high breakdown voltage.

We report here a new approach to electromechanical actuation in conjugated polymers. We observed that beyond their interesting electronic properties, organic polymeric semiconductor diodes based on poly (para phenylenevinylene) (PPV) exhibit unusual mechanical strain upon driving the device at reverse as well as forward bias voltage. In forward bias, once the diode is open, the high electrical current flowing in the device results in a strong electro-thermal actuation. The power dissipated in the resistance of the device induces Joule heating of the surface of the substrate. The local heating of the substrate creates an "in situ bimorph" through the temperature gradient across the cross section of the substrate. This bimorph structure causes a strong deflection and bending of the substrate in the μm/mA range (electro-thermo-mechanical actuation). Under reverse bias, the diode can be considered as an insulator sandwiched between two electrodes. Strains induced by Maxwell forces appear (in the 0.1pm/V range): when a voltage is applied, the opposite charges on the electrodes attract each other, leading to a compressive stress and a corresponding compressing strain (electrostrictive actuation). The latter was observed to be constant up to frequencies as high as 10 000 Hz.

Thus, thin conjugated polymer diodes show two types of actuation depending on their driving voltage opening up the possibility for electrically controlled nano-electromechanical sensors and nano-actuators based on organic electronics. Therefore, conjugated polymer diodes may add a new class of electromechanically active materials.

5759-39, Poster Session

Electrical response characterization of interpenetrating polymer network hydrogels as an actuator

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An interpenetrating polymer network (IPN) hydrogel composed of polyacrylic acid-co-poly(vinyl sulfonic acid) and polyaniline was prepared. The volume behavior of the hydrogel was studied by immersion of the gel in aqueous NaCl solution. The stimuli response of the hydrogel was also investigated in electric stimui. The volume change of the hydrogel was measured with respect to the applied voltages, then the hydrogel exhibited a volume change with the applied voltages. The volume behavior of the hydrogels induced by electric voltage showed increasing variation (contraction and expansion) with time. As of increasing voltage have been increased the variation velocity of the volume change of the hydrogel. The hydrogel's behavior is very sensitive to the applied electric stimuli, also showed possibility for application as a sensor, switches and actuator.

5759-55, Poster Session

Characterization of Nafion and Flemion with several new ionic liquids

J. Andexler, M. O. LeGuilly, C. Xu, L. Liu, M. Taya, Univ. of Washington

A characterization of two ionic polymers, Nafion and flemion, with several Ionic Liquids is reported. Air actuation with Ionic Polymer Metal Composites (IPMC) requires development of polymer/solvent pairs that does not suffer from excessive drying in air while maintaining reasonable actuation. Most current designs of IPMCs use ions, such as Na+, dissolved in water as the solvent. This limits actuation to water environments because actuation of the IPMC in air will suffer from rapid evaporation of the water and loss of function. To overcome this problem, Ionic Liquids have been suggested as a replacement as the solvent due to their negligible vapor pressures in air at room temperature. Results have already been published showing 250,000 cycles in air with only 25% loss in actuation. Another possible benefit of using Ionic Liquids instead of water-based solvents is that the voltage used with water-based solvents must be kept below the decomposition potential (~1.3 Volts) in situations where bubble formation is undesirable. Since many applications of IPMC technology, such as biomedical or microfluidics, cannot allow gases to be formed during operation, this limits the effectiveness of water-based solvents, which must be run below water's decomposition potential. Ionic Liquids on the other hand, can have much higher decomposition voltages. More research is needed in the use of IPMC devices with Ionic Liquids as the solvent before the promise of air actuation can be

realized. The IPMC structure is created by chemical plating of Au by successive swelling with a gold complex followed by reduction of the complex into Au metal. The plating process is repeated to increase the surface conductivity generally two to four times. Research on more polymer/solvent pairs will be completed to find an optimal combination. Characterization parameters include: blocking force, tip deflection, actuation speed and lifetime with air operation. All samples tested are cantilever beams and each series of tests are run from one parent membrane to allow better comparison of the results. Each series contains a baseline measurement conducted with Na+ ions for comparison to previously reported data and as a way to normalize measurements between different series. Four Ionic Liquids are combined with the two ionic polymers to produce eight separate solvent/polymer pairs.

5759-59, Poster Session

Electromechanical behavior of IPMC based on chitosan/ polyaniline

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The internal structure of the chitosan/polyaniline (CP) ion exchange membrane are important roles in the electromechanical property of ionic polymer-metal composite (IPMC) based on CP interpenetrating polymer network (IPN). The freeze-drying was identified to be an effective method in improving the IPMC electromechanical behaviors. Scanning electron microscopy (SEM) observations can be obtained that the ion exchange membranes became more porous after freeze-drying. From swelling ratio and differential scanning calorimetry (DSC) measurements, the freeze-dried membranes exhibited a higher swelling ratio and increased free water content. Electron beam lithography (EBL) which was applied the fabrication of electrical device was used to manufacture the IPMC metal electrodes. Tests on the bending of IPMC samples in a direct current electric field showed that the freeze-dried samples had a faster response and larger scale bending motion than non-freeze-dried samples.

5759-69, Poster Session

Electrochemistry of ionic polymer-metal composite

D. Kim, K. J. Kim, Univ. of Nevada/Reno

The use of platinum as effective electrodes for IPMCs is popular. This is primarily due to the convenience of using platinum-salts for ion exchange and subsequent reduction of platinum during the manufacturing processes of IPMCs. However, the use of platinum electrodes for IPMCs introduces the complex electrochemical phenomena on the platinum/electrolyte interface under imposed electrical potentials. This study clearly points out that the electrochemistry of platinum is important to help understand the fundamental actuation mechanism of IPMCs. Further, the proper understanding of electrochemistry of IPMCs can adequately describe the relaxation behavior of IPMCs which many investigators have attempted to understand. The conventional electrochemical analysis including voltammetry, AC impedance, and capacitance measurements on IPMC samples was carried out in aqueous solutions. The experimental results reveal much complex electrochemical behaviors of IPMCs including inductive nature in high frequencies. Also, the Mott-Schottky experiment was performed to study the charge transfer and possible adsorption mechanism associated with IPMCs.

5759-70, Poster Session

PEDOT-electroded PVDF

J. T. Polasik, H. V. Schmidt, Montana State Univ.

The standard metallic electrodes supplied with the piezoelectric polymer poly(vinylidene fluoride) (PVDF) stiffen the sheet significantly and reduce performance in sensor and actuator applications. Conducting PEDOT polymer electroded PVDF has shown much promise. The PEDOT electrode is much more flexible than metal electrodes and depositing it using an inkjet printer allows the PEDOT to adhere to the PVDF very well. The printing method also deposits the PEDOT in uniform coatings that increase conductivity and allows the creation of any desired pattern on the surface of the PVDF. Three products will be tested; single sheets of PVDF, cantilever bimorphs, and actuators. The testing will be done in both vacuum and air at room temperature and above. Measurements for the sheet will include current vs. voltage at various frequencies, and DC strain measurements. The cantilever bimorphs and actuators will be tested for durability vs. frequency, displacement vs. force, and displacement vs. the applied electric field. The bimorphs and actuators have already provided great results, showing good displacement and frequency response. The PEDOT electrode has proven effective and extremely flexible, and a bimorph has already been put to use in another lab as an artificial bee wing.

5759-71, Poster Session

Modeling PVDF actuators with conducting polymer electrodes

L. M. Lediaev, H. Schmidt, Montana State Univ.

Piezoelectric polymer sheets are presently supplied with metallic electrodes that have thickness comparable to the polymer sheet, so the electrode stiffness substantially degrades the performance of actuators or sensors made of such sheets. Our goal is to determine whether use of polymer electrodes is feasible for some actuator and sensor applications. Our lab has developed a method for applying PEDOT/PSS conducting polymer electrodes to poly(vinylidene fluoride) (PVDF) sheets. The flexibility of such electrodes should enhance the piezoelectric response of devices made from such sheets. However, the lower conductivity of polymer electrodes will limit the high-frequency response of such devices. Our lab is constructing bimorphs and actuators, and will test their response at various temperatures over a wide frequency range. To guide actuator design, it is necessary to model electroded polymer sheets, bimorphs, and actuators. Mathematical models become increasingly intractable as bimorph geometry and electrode patterns become more complicated. As such we are developing a finite element model that can calculate expected electrical and mechanical responses to a large range of frequencies for arbitrarily specified bimorph geometries. By comparing the calculations with test results, we can refine our models for bimorph and actuator performance, and improve actuator design.

5759-72, Poster Session

Mechanical and electrical properties of electroactive papers and its potential application

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This paper focuses on mechanical and electrical characteristics of electro-active paper (EAPap) as bio-inspired actuators and the potential of these actuators for some applications. EAPap can produce a large bending displacement with low voltage, low power consumption, dry condition, moderate response time and stable output. EAPap is made with chemically treated cellulose papers with electrodes on both outer surfaces. When electrical field is applied to the electrodes, bending displacement is produced. Since the EAPap material is ultra lightweight and has many advantages, the use of this material can impact in many technology fields. However, for further investigation of the EAPap material is necessary for developing application devices.

Mechanical properties of EAPap materials will be addressed in this paper. Stress and strain relation and ultimate strength of EAPap are investigated. EAPap material exhibits two elastic constants through bifurcation point. The Young's modulus range of EAPap is in the range of 5-8GPa, which is quite high compared to other polymer materials. Thermo-mechanical analysis of EAPap is investigated for the understating of thermo-mechanical behavior. Dynamic mechanical analysis will be analyzed under different temperature, frequency and force. These series of analysis will give a better understanding of the EAPap material in mechanical aspect. Electrical impedance analysis with frequency will allow us to understand the behavior of EAPap in electrical viewpoint. By measuring instantaneous current and power, the power consumption can be estimated and a proper design of the device will be possible for a specific application. The electrical analysis can give a clue of actuation mechanism of EAPap material.

5759-73, Poster Session

Limited-angle motor using ionic polymer metal composite

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It is known that beam-shaped Ionic Polymer Metal Composites (IPMCs) bend in water by the applied electric fields. It is considered that bending moment of the IPMC comes from the pressure of the water flow caused by the ion flux. The motion of IPMC beam is mainly bending, therefore some mechanisms to transform the bending to the desired motion are required for robotic applications.

For example, Nakabo et al. have proposed flexible link manipulator which has multi degrees of freedom with the patterned electrodes. Yamakita et al. have proposed muscle actuator which can transform the bending motion to the linear motion.

Based on the observations, no rotary actuators have not been developed yet although it is useful for robotic applications.

In this study, we propose rotary actuator using IPMC. The proposed rotary actuator consists of three main elements; the spiral polymer strip(s), the output shaft and the actuator case. Motivated by the mechanics of spiral spring, we have discovered that the bending motion of the IPMC beam can be transformed to the limited angle rotary motion. The bending motion of the polymer causes the rotary motion of the output shaft even without the polymer contraction. The spiral polymer strip(s) as the element of the actuator can be made of two antagonistic polymer strips or one pre-shaped polymer strip. One end of the spiral polymer strip(s) is connected to the output shaft and the other end is fixed on the wall of the actuator case. The actuator case can be filled with water or a solution and therefore can act as the water reservoir. In order to develop the model based control law in the future, we introduce the approximated linear model which consists of the electromechanical system and the mechanical compliance.

For simplicity, the model does not include high frequency phenomena such as the mechanical vibrations of the polymer itself. The electromechanical system model is a transfer function from the applied voltage (or current) to the bending moment. The electromechanical transformation phenomenon is complicated and is still under investigation. We then identify the transfer function experimentally assuming a linear system. The mechanical compliance model is a linear function from the bending moment to the output shaft angle derived based on the theory of elasticity.

On the design of the actuator, we discuss the material properties and the geometries of the polymer. As the result of the analysis, the mechanical compliance is proportional to the length of the polymer, and is inversely proportional to the bending rigidity. In the experiment, the actual rotary motion is demonstrated. Nafion with gold electrode is used as the IPMC. The response from the input voltage (or current) to the output angle and the output torque are measured. The model is validated by the experimental results.

Furthermore, frequency response of the actuator is also measured.

5759-74, Poster Session

The effect of ionic-membrane properties on the performance of ionic polymer-metal composite (IPMC) actuator

J. Y. Jho, Seoul National Univ. (South Korea)

Ionic polymer metal composite (IPMC) is a kind of electroacive polymer (EAP) which has attracted the attention because it has many advantages such as large bending deformation, light weight, and low driving voltage. IPMC is composed of ion-exchange membrane and metal electrodes. The ion-exchange membrane is neutralized with an amount of metal ions, balancing the charge of anions covalently fixed to the membrane. When a small potential is applied to an IPMC in the hydrated state, the mobile metal cations are subject to diffuse toward one of the cathode. As a result, the composite undergoes bending deformation toward the anode. Ion-exchange membrane is the most important part in the IPMC which maintains its shape and functions as a pathway of hydrated cations. So the performance of IPMC actuator can be largely affected by the properties of ion-exchange membranes. But all IPMC materials known to us have been restricted to some commercially available perfluorinated ionic polymer membranes for reasons of synthetic convenience. Besides, the thickness of IPMC is limited to the established commercial membrane thickness. Up to date, most studies for IPMCs have been focused on the manufacturing methods, electroplating techniques and replacing various mobile cations. Our research is aimed at studying the relation between the ionic membrane properties and the IPMC actuation performances. For this studies, various ion-exchange membranes were prepared by the modification of partially fluorinated or perfluorinated polymers. Fluoropolymers were irradiated with γ-rays and grafted with styrene and sulfonated. Polyvinylidene fluoride (PVDF), polyvinylidienfluoride-co-hexafluoropropylene (PVDF-co-HFP), polytetrafluoroethylene-co-hexafluoropropylene (FEP) and polyethylene-alt-tetrafluoroethylene (ETFE) were used for initial matrix for the ion-exchanged membranes. Controlling sulfonation levels by grafting conditions, ion conductivities of the membranes were varied from low to high levels. Using these membranes, IPMCs were manufactured by chemical reduction process to form platinum electrode layer on the membrane surface. The actuation performances of IPMCs were analyzed by laser displacement meter and the bending tip forces were measured by load cell. As the ion conductivities were increased, the maximum displacement and the bending speed were increased. And it was possible to increase IPMC's thickness by controlling the initial film thickness. As increased IPMC thickness, the bending tip force of IPMC were increased. Having more anionic sulfonate group compared with Nafion, the PSSA-grafted fluoropolymer membrane showed high ion conductivity and large bending strain. And there were differences in the actuation performance and the membrane properties according to the initial matrix polymer type.

5759-76, Poster Session

Morphological characterization of ionic liquid/Nafion polymer composites

M. D. Bennett, D. J. Leo, Virginia Polytechnic Institute and State Univ.

Electromechanical transducers based on Nafion polymer membranes have large commercial potential due to their inherent robustness, low actuation potential, and high charge sensitivity. These materials have several key limitations that have prevented their widespread use, however. The most notable of these is the reliance of this technology on water as a suitable solvent. Previous work by the authors has demonstrated that ionic liquids can be used to replace the water and that transducers made using the ionic liquids possess superior stability when operated in air. Tests have demonstrated that ionic liquid solvents enable stable operation in air for over 105 cycles compared to only 103 cycles with water as the solvent. Ionic liquids are salts that exist as liquids at low temperatures and have a high thermal and electrochemical stability as well as a high ionic conductivity. They also have immeasurably low vapor pressures and therefore are attractive alternatives to water as solvents for Nafion polymer transducers as the primary limitations of water are its rapid evaporation in air and low electrochemical stability.

The use of the ionic liquids has the important added benefit that it overcomes the problem of back relaxation that is common in the water-swollen actuators. The mechanism for transduction in these ionic liquid swollen materials remains unclear, however. This paper presents a characterization of the internal morphology of Nafion polymers swollen with different ionic liquids and in different counterion forms. Results demonstrate that the ionic species and solvent within the polymer exist in clustered regions and that this clustering is a key element of the transduction. A structured characterization of the active and passive elements of electromechanical transduction in these materials is also presented, including generated strain and stress, electrical impedance, strain and stress sensitivity, and elastic modulus. The characterization of the transduction is combined with the results of the morphological study to support reasonable theories of the mechanism of transduction. The results indicate that the ionic liquid may be playing the dominant role in the transduction and that the electromechanical response is strongly affected by the viscosity of the ionic liquid and the degree of swelling of the membrane. These effects are explained in the context of the clustered morphology of the ionic liquid / Nafion polymer composite.

5759-77, Poster Session

Electro-deposited vanadium oxide as a counter-electrode for PProDOT-Me2 based electrochromic devices (ECDs)

C. Kaneko, C. Xu, L. Liu, D. Ning, M. Taya, Univ. of Washington

The choice of ion storage materials is more critical for transparent devices than for reflecting devices. Most studies of transparent electrochromic devices (ECDs) have been focused on thin solid metal-oxide films as ion storage materials. Vanadium oxides have been thoroughly investigated for their ionic storage properties as a counter-electrode in batteries and, more recently, their suitability as a counter-electrode for inorganic ECDs. Properties of Vanadium oxide thin films deposited under RF and DC sputtering and evaporation are well characterized and work has been done investigating the properties of sol-gel based thin-films.

In this study, a preparation and characterization of thin film vanadium oxide for use as an ion storage layer/counter-electrode in organic ECDs is reported. A cathodic polymer film, Poly[3,3-dimethyle-3,4-dihydro-2H-thieno[3,4-b][1,4]dioxepine] (PProDOT-Me2) was used as the electrochromic material. Counter-electrodes were prepared using a sol-gel method and deposited using electrophoresis. Indium Tin oxide (ITO) coated glass was used as an electrically conductive and transparent substrate. The transmittance, ionic capacitance, stability and electrochromic matching diffusion rate of the counter electrode are vitally important parameters for successful smart window applications. Following on the extensive research on vanadium oxide thin films and their application in electrochromic smart windows, this paper focuses on optimized characteristics complimentary to a PProDOT- Me2 based electrochromic thin film, particularly ionic diffusion rate.

Gels of thin film vanadium oxide were created from 99.8% pure V_2O_5 powder and dissolved into a deionized water solution having a pH of 2.7. Thin films were deposited onto an ITO substrate submerged in the solution and subjected to cyclic voltammetry (CH Instruments, Electrochemical Analyzer). Parameters varied during deposition include deposition speed, applied voltage, deposition cycles, substrate angle and solution temperature, pH and concentration. The effect on CE characteristics was investigated. Surface morphology, elemental

composition and crystalline structure of the thin films were observed and analyzed through Scanning Electron Microscopy (SEM), X-ray Photoelectron Spectroscopy (XPS) or Electron Spectroscopy for Chemical Analysis (ESCA) and X-ray Diffraction (XRD) analysis. Transmittance and lifetime were measured and optimized to 65-85 % in the 400-700nm wavelength and 70,000 cycles, respectively.

The capacity of the thin films could reach 7.0-9.0 mC within 2 second with a diffusion curve shape very similar to that of the electrochromic film. Results show that a vanadium oxide thin film having an ionic capacitance and diffusion rate complimentary to an electrochromic thin film could be achieved. The ensuing 1" x 1" smart window exhibits a change in transmittance of over 50% and a lifetime of over 40,000 cycles at a switching speed of 1 second. In conclusion, electro-deposited Vanadium Oxide appears a suitable counter-electrode for PProDOT-Me2 based electrochromic devices.

5759-78, Poster Session

Photo-active self-assembled PD interlayer polymer films

J. Su, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace; G. A. Miner, D. M. Stoakley, NASA Langley Research Ctr.; M. M. Caruso, Elon Univ.

Recently, a series of self-assembled, metallic interlayer polymer films has been developed at NASA Langley Research Center. These films consist of four distinct layers; a metallized surface layer, a polyimide layer with dispersed 2-5 nm metal particles, a conductive, metallized interlayer and a bulk polyimide layer with dispersed 12-15 nm metal particles. This paper presents results based on palladium (Pd) metallized polyimide films. The photo-mechanical characterization showed that the tip deflection of these films was a function of the intensity and positioning of the applied light beam. Preliminary results indicate the films have promising photo-mechanical properties useful for photo-driven bending actuators.

5759-79, Poster Session

Ferroelectric characterization of polymer blends with sensing and actuating dual functionality

J. W. Paquette, Univ. of Nevada/Reno; J. Su, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace; K. J. Kim, Univ. of Nevada/Reno

Recently, an electrostrictive-piezoelectric polymer blend system was developed at NASA Langley Research Center. The blends exhibit promising sensing-actuating dual functionality. For this paper, the ferroelectric characterization of the blends as a function of the composition of the constituents, an electrostrictive graft elastomer and a piezoelectric vinylidene fluoride-trifluoroethylene copolymer (50/50 mol %) [P(VDF-TrFE)], was investigated. The investigation provides results that are helpful in understanding the mechanisms for the sensing-actuating dual functionality; therefore, they provide a guidance to further improve and optimize the electroactive polymer blend system for the desired performance required in a variety of applications.

5759-80, Poster Session

Experimental characterization of non-linear viscoelastic dielectric elastomer membranes

E. Yang, M. I. Frecker, E. M. Mockensturm, The Pennsylvania State Univ.

A dielectric elastomer widely used for electroactive polymer actuators is 3M's VHB 4910 acrylic foam polymer. Motivation for this study is the need for detailed experimental characterization of the non-linear viscoelastic dielectric elastomer membranes. Axisymmetric configurations of circular and annular membranes were radially pre-stretched in the range of 125% to 200%, constrained at the outer radius boundary, and subjected to various electric fields across the thickness. Experimental results showed non-linear viscoelastic responses for both configurations. Viscoelastic response of the height at the pole of

an inflated membrane at constant inflation pressures and electric fields are also presented. Creep and relaxation time constants for both configurations

are determined and the change in the inner radius for the annular membrane for various electric fields is also presented. Experimental data are compared with hyperelastic and non-linear viscoelastic theoretical models presented in a concurrent paper.

5759-81, Poster Session

Study on bending behavior of ionic polymer metal composites with various organic solvents and cationic species

Y. Yoo, B. Nam, Konkuk Univ. (South Korea)

Ion exchange polymer metal composites (IPMC) are active actuators that show large deformation in the presence of low applied voltage. Perfluorosulfonic acid membrane, Nafion, is one of the most widely studied materials for this purpose. Experimental studies were carried out on the bending behavior of Nafion-based IPMCs containing various solvents and cation species. Various counter cations of sulfonate groups in the membrane were obtained by soaking the composite membrane in aqueous salt solutions. The salts used in ion exchange process include LiOH, NaOH, $Pb(NO_3)_2$, $Zn(NO_3)_2$, $Cu(NO_3)_2$, $Cd(NO_3)_2$, $Co(NO_3)_2$. $Mn(NO_3)_2$. Ion-exchange capacity of the IPMC were measured by ICP. It was also prepared the composites using different solvents in the membranes and investigated their bending behaviors. The solutions used were NMP, DMF, DMAc, DMSO, PEG 200 and H_2O.

5759-83, Poster Session

Novel solid polymer electrolyte systems for PEDOT conducting polymer actuators

M. S. Cho, Sung Kyun Kwan Univ. (South Korea)

Abstract: Using novel solid polymer electrolyte systems, the conducting polymer actuators were investigated. The solid electrolyte systems were composed of ionic liquids and synthetic rubbers, and poly(3,4-ethylenedioxythiophene)(PEDOT) was synthesized on the surface of the polyelectrolyte films. The ionic conductivity of the polyelectrolytes was examined as a function of the immersion time of the ionic liquid, and the cyclic voltammetry responses and the redox switching dynamics of PEDOT in the polyelectrolyte matrix were studied. The solid electrolyte system was also applied to the nano-sized fiber actuator of conducting polymers providing a great potential for the application of artificial muscles.

5759-84, Poster Session

pH sensors based on polyelectrolytic hydrogels

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The purpose of chemical sensors consists in converting chemical input data into output signals suitable for electronic measuring processes. The sensors are characterized by a material-recognizing element and a transducer. The transducer converts the non-electric measuring value into an electrical signal. Hydrogels are crosslinked polymers which swell in solvents to appreciable extent. The amount of solvent uptake depends on the polymer structure, and can be made responsive to environmental factors, such as solvent composition, pH value, temperature, electrical voltage etc. Hydrogels are capable to convert reversibly chemical into mechanical energy and therefore they can be used as sensitive material for appropriate sensors.

In the present work, in order to realize pH sensors, poly(vinyl alcohol)/poly(acrylic acid) (PVA/PAA) blend hydrogels with a pH value dependant swelling behavior were used as chemo-mechanical transducers. Commercially available pressure sensor chips (Aktiv Sensor GmbH, Stahnsdorf, Germany) with a distortable thin silicon membrane were used as mechano-electrical transducers for the transformation of membrane deflections caused by the hydrogel swelling into an appropriate electrical output signal. The hydrogel itself was brought into a cavity at the backside of the silicon chip and closed with a cover. This cavity on the backside of the chip was wet etched, with a silicon nitride mask used as etch resist. Therefore, only the backside of the chip came in contact with the measuring species, whereas the frontside with the electronic components was strictly protected from it. Since the sensor chips showed excellent stable properties, the long-term stability of the sensor was solely determined by the stability of the hydrogel characteristics.

Because the gel response is typically diffusion driven, the time response of the volume change approximately follows the square of the sample dimension. Scaling to micro-dimensions enhances the time response. Consequently, a reduction of the sample size improves the sensor performance.

Time constants down to a few ten seconds could be found for thin hydrogel films directly deposited on the membrane backside. The influence of the gel swelling/deswelling kinetics on the response time and long-term signal stability of proposed pH sensors was investigated. It was found that the time dependence of the swelling process consists of three parts. The first of them is a rapid swelling

with a time of 1.2 s for the 6μm thick hydrogel layer caused by the diffusion of water into the gel due to the osmotic pressure. The second retarded part of the swelling process with a time constant of 1.5 min is governed by the polymer chain mobility. The third part is the long-time drift in the swelling/deswelling hydrogel kinetics. The drift of the sensor signal influences the signal value in the next measurements of solutions with other pH values and complicates the calibration procedure for the pH sensor. It was found that the observed signal drift depends on the pH value of the ambient solution and is caused by the slow continuous change of the electrical potential at the gel-solution interface in consequence of the motion of mobile ions which influences the dissociation state of the fixed charge inside the hydrogel. In the pH1 solution a maximal negative drift rate of 10 μV/min was found for the 6μm thick hydrogel layer.

The set of experiments was performed to determine the measurement conditions necessary for high signal reproducibility. The influence of previous gel swelling states can be minimized by a prolonged rinsing in de-ionized water after every measurement at high pH values. Measurements in solutions with pH<3 and large pH changes should be avoided in order to maintain a sufficient sensor sensitivity for a long time. In order to achieve high signal reproducibility of pH sensors, a compensation of previous output signal values should be used.

5759-86, Poster Session

Structural investigation of PF6-doped polypyrrole as a function of oxidation state

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No abstract available

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5760-01, Session 1

Switched-state control of a vibration isolation mount using ionomeric materials

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Ionomeric materials are a class of polymers that exhibit large changes in their elastic and viscoelastic properties as a function of their chemical state. It has been shown in the literature that the modulus of an ionomeric material can be varied by as much as twenty times – from approximately 1 GPa to less than 50 MPa – by changing either the hydration state of the material or the ion that is incorporated into the polymer matrix. This compares favorably with other types of active materials such as piezoelectric materials or shape memory alloys, which can only produce 2X changes in modulus for typical alloys, ceramics, or polymers.

In this paper we will explore the use of this property as a method for switched-state control of mechanical systems. Several researchers have shown that real-time variations in modulus and damping properties is an effective means of energy dissipation in structures. Our preliminary results demonstrate that we can achieve 3X reversible changes in modulus of an ionomeric polymer film by simply changing the hydration state of the polymer. Under load this produces a controllable elongation on the order of 10%. The viscoelastic properties of the material also change; initial results demonstrate that the loss factor of the material changes approximately 3X under variations in hydration state.

Our goal is to use these changes in modulus for switched-state control of a vibration isolation mount. A text fixture consisting of a mass on a plate will be built. Simulations using our preliminary data indicate that the variation in modulus in the ionomeric material can produce controllable vibration isolation in the mount. The major limitation of this approach is that the time constant required to vary the hydration state is currently on the order of seconds. In the next three months we will study methods of reducing this time constant to a value on the order of 1 second for the purpose of increasing the utility of this approach for switched-state vibration control.

5760-02, Session 1

Damping control of micromachined lowpass mechanical vibration isolation filters using electrostatic actuation with electronic signal processing

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Some harsh environments, such as those encountered by missiles, rockets and various types of industrial machinery, contain high frequency/amplitude mechanical vibrations. Unfortunately, some very useful components are sensitive to these high frequency mechanical vibrations. Examples include MEMS gyroscopes and resonators, oscillators and some micro optics. Exposure of these components to high frequency mechanical vibrations present in the operating environment can result in problems ranging from an increased noise floor to component failure. Passive micromachined silicon lowpass filter structures (spring-mass-damper) have been demonstrated in recent years. However, the performance of these filter structures is typically limited by low damping (especially if operated in near-vacuum environments) and a lack of tunability after fabrication. Active filter topologies, such as piezoelectric, electrostrictive-polymer-film and SMA have also been investigated in recent years.

Electrostatic actuators are utilized in many micromachined silicon devices to generate mechanical motion. They offer a number of advantages, including low power, fast response time, compatibility with silicon micromachining, capacitive position measurement and relative simplicity of fabrication. This paper presents an approach for realizing active micromachined mechanical lowpass vibration isolation filters by integrating an electrostatic actuator with the micromachined passive filter structure to realize an active mechanical lowpass filter. The electrostatic actuator is used both as the control loop actuator and the proof mass position sensor. Electronic signal processing is used to generate the appropriate actuator control voltage to obtain the desired filter characteristics. Although the electrostatic actuator can be used to adjust the filter resonant frequency, the primary application is for increasing the damping to an acceptable level. The physical size of these active filters is suitable for use in or as packaging for sensitive electronic and MEMS devices, such as MEMS vibratory gyroscope chips. The resulting electromechanical system-in-a-package allows for optimum system performance through allowing the use of state of the art components in mechanically harsh environments.

5760-03, Session 1

Modeling and parameter identification of an active anti-vibration system

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In the field of high-resolution measurement and manufacturing, effective anti-vibration measures are required to obtain precise and repeatable results. This is particularly true for experiments or processes where the typical amplitudes of the ambient vibration and the dimensions of the investigated or manufactured structures fall in the same range, e.g. submicron semiconductor production, holographic interferometry, confocal optical imaging, and scanning probe microscopy.

In the active anti-vibration system examined, signals are acquired by extremely sensitive vibration detectors, and the vibration is reduced using a feedback c ontroller to drive electro-dynamic actuators.

This papers deals with the modelling and parameter identification of such an anti-vibration system. First the model of the system is based on rigid multi body systems. Then the parameters of the system such as the nonlinear spring stiffness, the mass, moment of inertias and the actuator as well as sensor behavior are identified. The model is then updated using measured transfer functions. The transmissibility curve of the system is then measured and compared with the transmissibility curve of the updated model. The comparison reveals the complete absence of resonance in the active damping treatment. Furthermore, the isolation of the active system is better at all frequencies than the transmissibility of the passive unit. Finally, different control concepts of the active anti-vibration system are discussed.

5760-04, Session 1

Launch vehicle payload adapter design with vibration isolation features

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Payloads, such as satellites or spacecraft, which are mounted on launch vehicles, are subject to severe vibrations during flight. These vibrations are induced by multiple sources that occur between liftoff and the instant of final separation from the launch vehicle. A direct result of the severe vibrations is that fatigue damage and failure can be incurred by sensitive payload components. For this reason a payload adapter has been designed with special emphasis on its vibration isolation characteristics.

The design consists of an annular plate that has top and bottom face sheets separated by radial ribs and close-out rings. These components are manufactured from graphite epoxy composites to ensure a high stiffness-to-weight ratio. The design is tuned to keep the frequency of the axial mode of vibration of the payload on the flexibility of the adapter to a low value. This is the main strategy adopted for isolating the payload from damaging vibrations in the intermediate to higher frequency range (45Hz-200Hz). A design challenge for this type of adapter is to keep the payload's pitch frequency above a critical value in order to avoid dynamic interactions with the launch vehicle control system. This high frequency requirement conflicts with the low axial mode frequency requirement and this problem is overcome by innovative tuning of the directional stiffnesses of the composite parts. A second design strategy that is utilized to achieve good isolation characteristics is the use of constrained layer damping. This feature is particularly effective at keeping the responses to a minimum for one of the most important dynamic loading mechanisms. This mechanism consists of the almost tonal vibratory load associated with the resonant burn condition present in any stage powered by a solid rocket motor. The frequency of such a load typically falls in the 45-75Hz range and this phenomenon drives the low frequency design of the adapter. Detailed finite element analysis is used throughout to qualify the design for vibration isolation performance as well as confirm its static and dynamic strength.

5760-06, Session 1

The reduced order optimum method for the placement and control law design of control devices between two adjacent structures

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To economically enhance the performance of active/passive control devices for the seismic response reduction of tall buildings, this paper investigates the optimal placement and optimal parameters of control devices using the linear quadratic performance index as an objective function. The linear relation between the increment of the performance index and the change of the position matrix of control devices is first established based on the assumption that the control gain remains unchanged. The optimal placement of control devices is then determined in terms of the sequence of the calculated performance index increments and the number of control devices to be used. With the control devices at their optimal places, the seismic response of the building is finally computed using the suboptimal control gain derived using the minimum error principle, from which the equivalent optimal parameters of passive devices can be also determined. The applicability of the proposed approach and its limitation are carefully examined through numerical examples. The results from the numerical examples show that the suggested approach is quite accurate and effective in determining the optimal placement and optimal parameters of control devices if the number of removed control devices is limited to a certain range.

5760-07, Session 2

A study on MR fluids subjected to high-shear rates and high velocities

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The objective of this work is to characterize the performance of MR fluid at high shear rates and high velocities. A capillary rheometer has been built which allows for high speed testing of MR fluid under varying field strengths. The gap size of the rheometer was chosen to achieve high fluid velocity and high shear rates. Two gap sizes are considered (0.5 mm and 1 mm). Fluid velocities range from 1e3 mm/s to 35e3 mm/s with resulting shear rates ranging from 0.14e5 s-1 to 2.4e5 s-1. In order to evaluate the performance of the fluid, the force required to drive the fluid through the capillary is measured and force-velocity characteristics are generated. From the force-velocity curves, the zero-field viscosity is found. Results indicate that shear thinning is still prevalent even at high shear. Two magnetic field strengths were considered for the field testing (50 kA/m and 100 kA/m). Results indicate that, even at high velocities and high shear rates, a yield stress is still developed in fluid in the presence of a magnetic field. Specifically, with a pole length of 25.4 mm and a mean fluid velocity of 35e3 mm/s, the dwell time is less than 1 ms, confirming that the response time of the MR fluid is less than 1 ms.

5760-08, Session 2

Pressurized magnetorheological dampers for train suspension

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A semi-active train suspension system using magnetorheological (MR) dampers can improve the ride comfort of the passenger in the railway vehicle. To achieve this, the objective of this paper is to develop and fabricate a custom-made MR damper, which is suitable for railway vehicle suspension. The behaviors of the MR damper are understood through the design, experiments, and mathematical modeling of the MR damper. The double-ended type MR damper is considered, and then the MR damper geometry and basic magnetic circuit have been studied. After design parameters have been determined, the custom-made MR damper is fabricated. Additional considerations of MR damper design including modification process, sealing and wire wrapping have been investigated. To eliminate the force-lag problem, special MR fluid filling is set up to increase the internal pressure of the MR damper. The MR damper is mathematically modeled with experimental validation and then integrated with the railway vehicle model. The passive, passive-on, passive-off and semi-active suspension systems are tested with different tracks. An on-off semi-active control strategy based on the measurement of the absolute lateral velocity of the car body is adopted for the semi-active suspension system. The performance of the semi-active train suspension system using MR dampers is evaluated by comparing with the passive, passive-on and passive-off suspension systems. The results indicate that the semi-active suspension with the developed MR dampers outperforms those passive suspension systems and it can improve the ride quality of the passenger substantially.

5760-09, Session 2

Semi-active controller dynamics in a magnetorheological tuned vibration absorber

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The main objective of this study is to experimentally implement semi-active control to a Magneto-Rheological Tuned Vibration Absorber (MRTVA) and evaluate the dynamic performance of the MRTVA. The MRTVA is a semi-active TVA that employs an MR damper as its damping element. A test apparatus was built to represent a two-degree-of-freedom system – a primary structure coupled with an MRTVA. Using this test setup, a series of tests were performed to assess the dynamics of the MRTVA and to compare them with those of a passive TVA. The TVA used displacement-based, on-off groundhook (on-off DBG) control to regulate the MR damper. Unlike a passive TVA, the MRTVA was able to effectively control the resonant vibrations without sacrificing the isolation valley at high damping (current). To interpret the dynamics of the passive and semi-active system, the damper lock-up dynamics were investigated. The lock-up analysis further explains the actual implementation of the on-off DBG control policy in the system. The results of the lock-up analysis indicated that the dynamics of the control logic prevented lock-up in the MRTVA. In summary, this paper demonstrated that the MRTVA with the on-off DBG semi-active control can offer the benefits of high damping at the resonant peaks while still maintaining good isolation around the natural frequency of the structure. In other words, the semi-active TVA that employed an MR damper was more effective than an equivalent passive system in reducing vibrations of the primary structure.

5760-10, Session 2

Design and performance optimization of magnetorheological oleopneumatic landing gear

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Aircraft landing gears are subjected to a wide range of impact conditions due to variations in sink speed, angle of attack and mass. Primarily, the landing gear must be able to absorb sufficient energy in severe impacts or crash landing scenarios in order to minimise structural damage. To accommodate this requirement, the performance for more common (i.e. less severe) impacts will be compromised and may serve to reduce structural fatigue life and increase levels of passenger discomfort. A novel solution to this problem, which remains largely unexplored [1], is to implement semi-active control using magnetorheological (MR) flow mode dampers. Such devices allow the continuous adjustment of damping force through the application of a magnetic field, which develops a yield stress within the fluid. Superior damping levels can then be achieved over a wide range of disturbance conditions. However, the feasibility of this approach will depend significantly on whether specific design and packaging requirements can be met since space and weight are vital design considerations for landing gear. The present study aims to develop effective device design and sizing procedures for MR landing gear subject to packaging constraints. Sizing constraints have not previously been considered in MR landing gear, where previous work has primarily focused on potential control strategies e.g. sliding mode control [1].

To aid the sizing analysis, accurate dynamic impact models of passive and MR oleopneumatic landing gear are developed. Performance optimisation is demonstrated by sizing an MR valve within the constraints of a commercial (passive) landing gear. Through benchmarking against experimental drop tests incorporating the passive device, it is demonstrated how a fail-safe, high performance MR valve can be achieved.

Few researchers have investigated high velocity MR valve flow as induced by impulsive loading [2, 3]. This area is still relatively unknown and the present study aims to give light on some important issues relating to it. For example, Reynolds number is considered with particular importance since turbulent values are known to reduce device performance [3]. Fluid compressibility is also investigated, which is likely to have a more significant effect on performance at high velocities. These may be critical factors when demonstrating the feasibility of MR landing gear.

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5760-11, Session 2

Experimental investigation on the effectiveness of of a magnetorheological fluid squeeze film damper

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The squeeze film damper (SFD) is one of most effective methods of applying external damping to the rotor system of high-speed rotating machinery, because of both its relative constructional simplicity and its effectiveness in attenuating rotor vibration and transmitted force in the properly designed cases. The characteristics of the conventional SFD is highly non-linear in the range of high journal eccentricity ratios and cannot be controlled easily on-line according with the different operating conditions of rotor, especially when the rotor passes through several critical speeds, the effectiveness of SFD in both attenuating rotor vibrations and transmitted force is, therefore, limited.

In order to improve the controllability of traditional SFD characteristics, we use magneto-rheological(MR) fluids with rapid, reversible and dramatic change in its apparent viscosity by an external magnetic field to develop a controllable MR fluid SFD. A rotor test rig with MR fluid SFD is built in order to demonstrate the effectiveness of the MR fluid SFD in attenuating the rotor vibrations. In this paper, we first describe the concept and structure of the controllable MR fluid SFD and the rotor test rig, then study the dynamic behaviour of the MR fluid SFD for attenuating rotor vibration and the effectiveness of the semi-active control on the rotor vibration by the MR fluid SFD. It is shown that the dynamic characteristics of the MR fluid SFD can be easily controlled and the MR fluid SFD is very effective for control of the rotor vibrations if the MR fluid with the relatively low initial viscosity and sensitivity to the low magnetic flux is used.

5760-12, Session 3

Experimental and finite element analysis of stand-off layer damping treatments for beams

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Passive stand-off layer (PSOL) and slotted stand-off layer (SSOL) damping treatments are presently being implemented in many commercial and defense designs. In a PSOL damping treatment, a stand-off or spacer layer is added to a conventional passive

constrained layer (PCL) damping treatment. In an SSOL damping treatment, slots are included in the stand-off layer. A series of experiments for PSOL and SSOL beams treated with polyurethane rigid foam stand-off layers was conducted to analyze the contribution of the stand-off layer to the overall system damping. In three sets of experiments, various material and geometric properties of the stand-off layer were varied. The first set of experiments measured the frequency response functions for a series of beams in which the total slotted area of the stand-off layer was held constant while the number of slots in the stand-off layer was increased for a constant stand-off layer material. The second set of experiments varied the stiffness and density of the stand-off layer while holding the geometry constant for slotted and solid stand-off layers. In the third set of experiments, the number of slots and the stand-off layer material were held constant while the total slotted area was increased from 0 to 46.7%.

Finite element analysis models were developed in ANSYS to compare the predicted frequency response functions with the experimentally measured frequency response functions for the 17 treated beams tested. Some significant findings from this study indicated that although the inclusion of slots in the stand-off layer may provide advantages such as reduced total treatment mass and increased conformability when applying these treatments to curved surfaces, the addition of these slots did not improve the damping performance. In addition, the bonding layers used to fabricate these treatments were found to be non-negligible in many configurations and these layers had a noticeable and significant effect on the frequency response of the structure. The experimental results further indicated that for beam structures, solid stand-off layer damping treatments made from lighter density rigid foams outperformed slotted stand-off layer damping treatments made from higher density rigid foams of greater total treatment mass.

5760-13, Session 3

Low-wave-speed media for damping at high-temperature

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The introduction of a granular material or foam into a structure orvmachine is a relatively simple and low-cost approach to attenuation of vibration. Many researchers have studied the use of granular materials for vibration suppression. Cremer and Heckl (1973) suggested that a granular material such as sand can be modeled as a continuum, and that damping in a structure

filled with such a granular material can be increased by adjusting dimensions so that standing waves occur in the granular material at the resonant frequencies of the structure.

Experiments by Fricke (2000) showed that a low-density granular fill can provide high damping of structural vibration over a broad range of frequencies. Varanasi and Nayfeh (2003) performed further experiments on beams with low-density granular fills and, by treating the fill as a compressible fluid in which dilatation waves can propagate, made quantitative predictions of the system response. They predicted that similar damping could be attained using any lossy medium (such as a foam) in which the speeds of wave propagation are low enough that waves can be set up in the medium at the frequencies of interest.

There are few techniques suitable for vibration suppression at high-temperatures, or in machines that undergo large variations in temperature. In this paper, we perform a study of low-wave-speed media, including glass and ceramic fibers abd hollow spheres, suitable for damping applications in high-temperature applications. We also study their durability and sensitivity to humidity.

5760-14, Session 3

On the damping behavior and stiffness of 8 wt% yttria-stabilized zirconia coatings deposited by APS and EB-PVD techniques

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Recent research into the use of thermal barrier ceramic coatings has shown that they can also provide sufficient additional damping, reducing vibration levels and significantly extending the life of the coated component.

Various deposition techniques may be employed to apply ceramic coatings: Air Plasma Spraying (APS) and Electron Beam - Physical Vapour Deposition (EB-PVD) are among the most common ones. However, one has to take into account that even when the starting ceramic material is the same, the microstructure of the resultant coatings depends strongly on the selected deposition technique.

The study of the differences in the damping behaviour and stiffness of an yttria-stabilised zirconia (YSZ with 8 wt% yttria) coating deposited by APS and EB-PVD is the objective of this paper. Both damping (internal friction) and stiffness of these two YSZ coatings were estimated from tests performed at room and high temperatures. Moreover, this paper presents the microstructural characterisation of these two YSZ coatings using scanning electron microscopy, and attempts a correlation of the differences in their properties to their microstructure.

5760-15, Session 3

A variational model of ionomeric polymer actuators and sensors

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Ionomeric polymers are a promising class of intelligent material which exhibit electromechanical coupling similar to that of piezoelectric bimorphs. Ionomeric polymers are much more compliant than piezoelectric ceramics or polymers and have been shown to produce actuation strain on the order of 1% at operating voltages between 1 V and 5 V. Their high compliance is also advantageous in low force sensing configurations because ionic polymers have a very little impact on the dynamics of the measured system.

This paper presents a variational approach to the dynamic modeling of ionic polymer actuators and sensors. The approach requires a priori knowledge of three empirically determined material properties: elastic modulus, dielectric permittivity, and effective strain coefficient. Previous work by Newbury and Leo has demonstrated that these three parameters are strongly frequency dependent in the range between less than 1 Hz to frequencies greater than 1 kHz. A model of a cantilevered beam incorporating this frequency dependence has been

developed. The variational method produces a second-order matrix representation of the structure. The frequency dependence of the material parameters is incorporated using a complex-modulus approach similar to the techniques for modeling viscoelastic materials.

Applications in sensing and actuating applications have been modeled and compared to experimental results. Because many potential applications of ionic polymer actuators and sensors require exposure to harsh environments these devices can be encapsulated in more durable passive materials for protection. The transducer models were extended to include this passive material encapsulation. These models were validated experimentally. Finally, this modeling method is expanded to include the two-dimensional problem. Out-of-plane actuation of a circular disk is modeled and simulations for several geometric boundary conditions are shown. The model predicts that only axis-symmetric actuation is possible if a single uniform electrode is used. Simulations and experiments are included for a multi-electrode configuration to demonstrate the utility of the variational approach for modeling systems that incorporate ionomeric materials.

5760-16, Session 3

Nonlinear finite element modeling of vibration control of composite piezolaminated composite plates and shells

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Nonlinear Finite Element Modelling of Vibration Control of Piezolaminated Composite Plates and Shells

Modeling and numerical simulation of the static and dynamic response of adaptive structures with integrated distributed control capabilities has attracted considerable research interest in recent years. While geometrically linear theories for structures with piezoelectric layers and associated numerical methods have been developed by many authors, geometrically nonlinear theories have been treated considerably less in literature, although these structurs are typically very thin and often the deflections are in the order of the thickness or even much bigger.

This paper deals with the geometrically nonlinear theory and analysis of layered beams, plates and shells consisting of a master structure with integrated piezoelectric layers. A theory and an associated Finite Element method for large deflection transient analysis are developed and applied to the numerical simulation of the dynamic response and control of structures with actuator and sensor layers or patches bonded to the surface.

More specifically, the geometrically nonlinear composite shell element with integrated piezoelectric layers developed in this paper is based on Reissner-Mindlin type shell theory, i.e. three translational and two rotational nodal degrees of freedom are used for the first order transverse shear approximation. Additional electrical degrees of freedom are introduced for each piezoelectric layer to account for the coupled electromechanical equations. The finite element has been tested on a number of problems using the piezoelectric layers as actuators as well as sensors. The numerical approximations to these problems are obtained using the Total Lagrangian formulation.

5760-17, Session 3

Study of damping capacities of nitinol shape-memory alloys in Martensite, Austenite, and Martensite-Austenite co-existence phases

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It is well known that both martensite and austenite (superelastic) Nitinol Shape Memory Alloys (SMAs) have damping capacities, benefiting from their hysteretic stress-strain relationships. In general, for SMA devices for passive vibration control, martensite SMA has a larger damping capacity, however, it requires external heat to cause a phase transformation to restore its original shape. On the other hand, superelastic SMA has less damping capacity, but it has a strong re-centering force to restore its initial shape and there is little residual strain of the superelastic SMAs. This paper researches the damping capacity of Nitinol in martensite and austenite co-existence phase. Nitinol with the co-existence of both martensite and austenite phases combines advantages of martensite SMAs and superelastic SMAs and has a large damping capacity with self-shape restoring ability. To quantitatively study the damping effect of Nitinol in martensite and austenite co-existence phase, a setup is designed and fabricated. This setup involves a cantilevered steel beam with pre-stressed SMA wires attached to each surface at the remote end of the beam. The SMA wires function as a damper to the cantilevered beam. A piezoceramic patch sensor attached to the beam near its cantilevered end is used to record the data of the vibration of beam and the data is then used to estimate the damping ratio of the system. The percentage of the martensite phase in the Nitinol SMA wires is controlled by electrically heating the wires via a closed-loop control system. Experimental results verify that the Nitinol wires with the co-existence of the both martensite and austenite have the best damping property for vibration suppression. For practical implementation, the transformation temperate of the SMA wire damper can be chosen as the room temperature so that both martensite and austenite co-exist.

5760-18, Session 3

Electrostatic tuning of the bending stiffness of simple slender multi-layer composite structures

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In addition to reliability considerations, one of the main distinguishing properties of ropes and cables is their flexibility. In more general terms, unbonded multi-layer structures exhibit similar tensile stiffness in directions parallel to the layers but much lower bending stiffness, compared to a bulk structure with the same cross-sectional area. The high flexibility is due to the near absence of shear stresses at the interface between layers under bending loads.

The bending vibrations of cables are of special interest in relation to wind-induced vibration and the resulting fatigue-induced lifetime reduction of the bridge stay cables and other similar elements. A vast community of scientists and engineers is working on vibration suppression devices and strategies, mainly using discrete dampers positioned in proximity of the anchor points of cables.

Recent work shows that even when under tensile load, the effect of bending stiffness of cables on their vibrational properties should not be considered negligible. Hence, methods to modify the bending stiffness of a cable should, to some extent, lead to a way to influence its vibrational behavior.

In the present work, an approach to the modulation of the bending stiffness of a simple, slender beam consisting of carbon fiber reinforced plastic (CFRP) bands is outlined and first results confirming the effectiveness of the approach are shown. In the present stage of advancement of the project, no tensile force is applied to the structure.

Four unidirectionally-oriented 150 mm x 12 mm CFRP bands, 0.15 mm thick, similar to the ones used for the stays that equip certain high performance racing yachts, were coated with a ceramic-loaded epoxy resin. The bands were stacked and clamped on one end, thus creating a simple cantilever beam. At the opposite, free end of the structure, a guide was applied to help maintain a constant distance between the layers while not restricting the relative motion in the longitudinal axis between them. Two small magnets were applied to the free end of the cantilever. The bands were individually connected to a high voltage power supply, so that poles were alternated.

The free end of the cantilever was placed in the center of a pair of Helmoltz coils. A force perpendicular to the face of CFRP bands can thus be applied by circulating a current through the coils. The vibrational behavior of the cantilever was observed under different potentials (up to 1.1kV) between CFRP bands. The normal electrostatic force between bands had a remarkably strong effect on the behavior of the system. As expected, the distributed normal force caused shear forces between contiguous CFRP bands to increase the effective bending stiffness of the system. A detailed study on the mechanisms influencing the system is currently being carried out.

The outlined approach to the reduction of transversal vibration in thin multi-layer structures is promising and can in principle be applied to parallel wire strands and multi-layer plates. An intermediate behavior between fully bonded and unbonded layers in terms of interlaminar shear stress can be achieved.

5760-19, Session 4

Characterization of carbon nanotube polycarbonate composites

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Singlewalled and multiwalled carbon nanotube fillers are uniformly dispersed in a polycarbonate matrix (weight fractions in the range of 1 to 5%). The nanocomposite samples as well as baseline polycarbonate samples are tested in tension using an MTS-858 servo-hydraulic test facility. The tests are performed over a wide range of strain amplitudes (0.01 to 1%), frequencies (1-20 Hz) and temperatures (30 to 170 deg C). The results indicate that the elastic modulus of the baseline (pristine) polycarbonate is enhanced by up to 75% by nanotube

fillers. The loss modulus also shows impressive increases (up to 100% for some of the test conditions). The high temperature tests indicate that the nanotube fillers enhance the loss modulus and damping capability of the polycarbonate system at elevated temperatures. Furthermore the glass transition temperature of the nanotube filled polymer system is higher compared to the baseline (or unfilled) polycarbonate. There are two possible mechanisms that could be responsible for the observed increase in loss modulus: (1) interfacial sliding of nanotubes in the polymer matrix and (2) morphology changes associated with the interface region between the bulk polymer and the nanotube fillers. Additional investigations are on-going to determine which of these mechanisms is responsible for the observed increase in energy dissipation.

The results shown in this paper indicate that carbon nanotube fillers provide an unprecedented opportunity to efficiently and reliably inject damping into structural components without sacrificing structural integrity or mechanical strength. These minimally-invasive nanoscale fillers can simply be co-cured with the host structure and may provide an unusually effective mechanism for damping augmentation, helping to reduce vibration levels, dynamic stresses and fatigue failure in a wide range of structural components and systems.

5760-20, Session 4

On the damping charateristics of polymeric composites with randomly oriented single-walled carbon nanorope fillers

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Carbon nanotubes (CNTs) based composites have recently attracted a lot of interest because of their exceptional mechanical properties. Due to their ultra small scale size and low density, the surface area to mass ratio of CNTs is extremely large. Therefore, high damping is anticipated in nanotube-based polymer composites if one can take advantage of the interfacial friction between CNTs and resin. Based on a “stick-slip” assumption, a micromechanical model was recently proposed by Zhou et al. (2003) to describe the single-walled nanotube (SWNT)/polymer interfacial debonding evolution. The results showed that significant increase of damping can be achieved for CNT-based polymers, even with very small amounts of SWNT (1% wt.) filler. Since realistically it is extremely difficult to achieve a complete dispersion of exfoliated SWNTs in the polymer, SWNTs are found mostly in parallel bundles or ropes referred to as “nanoropes.” In each bundled arrangement, the SWNTs are held together with relatively weak van der Waals forces. To model such configurations, Zhou et al. (2004) developed a constitutive model for the elastic and damping properties of composites with aligned nanoropes. In their study, a close-packed lattice consisting of seven nanotubes in hexagonal arrangement was used and the ‘stick-slip’ mechanism was assumed to apply to the interface between the nanorope and resin as well as that between nanotubes.

While the recent study presented by Zhou et al. (2004) is a necessary step toward modeling the damping characteristics of nanorope-filled-composites, it is still limited by the assumption that all the nanoropes are perfectly aligned. Since most CNT-based composites consist of nanoropes that are randomly oriented (unless special alignment processes are followed, such as that by Thostenson and Chou (2002)), this previous model needs to be improved. The objective of the research presented in the current paper is to address this issue and advance the state of art (Zhou, et al., 2004) in damping characterization of composites filled with nanoropes.

Based on the off-axis short-fiber composites theories (Chon, Sun, 1980; Sun, et al., 1985), a composite element consisting of a bundle of seven closed-packed SWNTs surrounded by a sheath of resin is developed. The sheath carries all the shear stress between nanoropes and resin while the remote material is assumed to exhibit average composite properties. Two types of load transfer are considered: one representing interactions between inner tube and six surrounding tubes, and the other representing interactions between surrounding tubes and resin. The ‘stick-slip’ motion is assumed to describe interfacial load transfer behavior and energy dissipation subjected to longitudinal normal stress and longitudinal shear stress. The Young’s moduli can be obtained by developing the Burgers vector (Mori et al. 1997; Onaka et al., 1998; Mori et al., 1998) for the interface of a three-dimensional material containing cylindrical inclusion. The energy dissipation and the corresponding loss factor can be calculated using the work done by the interfacial shear stress. Utilizing the new model, extensive parametric studies are performed. It is illustrated that the Young’s moduli and loss factors for composites with randomly oriented nanoropes are much lower than those of composites with aligned carbon nanoropes.

5760-21, Session 4

Optimization of carbon nanotube reinforced composite laminated structures for vibration damping

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Topology optimization has been successfully used for improving vibration damping in constrained layer damping structures with viscoelastic materials [1-3]. Reinforcing carbon nanotubes in a polymer matrix greatly influences the mechanical properties of the polymer. Such nanotube-reinforced polymers (NRP) can be used to further enhance the damping properties of the sandwich structures. The effects of nanotube inclusions on the damping properties of polymers and NRP for damping in structures have been studied previously [4,5]. The inclusion of nanotubes into a polymer matrix provides new design variables in the topology optimization studies on such structures. The aim of this research is to determine the optimal topology and the optimal constituent make-up of the constrained NRP layer, where the weight percentages and orientations of the nanotubes in the constrained layer are optimized to improve vibration damping.

The optimization objective is to maximize the system loss factor for the first resonance frequency of the structure. In the optimization process, the system loss factor is calculated using the Modal Strain Energy Method (revised for greater accuracy as in Xu, et al [6]). The composite material loss factor for the NRP is computed using the method outlined in Rios, et al [7], which uses a Standard Linear Solid model to derive an expression for the material loss factor in terms of the volume fractions of the inclusions, and the material constants are calculated using the rule of mixtures as the volume fractions of inclusions vary. The half-power bandwidth method (an exact method) is used to validate the loss factor calculated from the MSE Method (an approximate method). The ABAQUS finite element code is used to model the structure with two-dimensional plane stress continuum elements. A commercial code NLPQL [8] is used for the optimization, which uses an SQP (Sequential Quadratic Programming) algorithm. The design variables are:

1.The volume fractions of the nanotubes in the polymer matrix,

2.The orientations of the nanotubes in the polymer matrix,

3.The material fractions of NRP material and

4.The material fractions of the elastic material in each finite element.

Variables (1) and (2) are concerned with the microstructure and resulting properties of the NRP and design variables (3) and (4) are concerned with the topology of the NRP constraining layer.

This study is aimed at extending the results of previous studies [1-3], by including the effects of nanotube volume fractions and orientations on the optimal damping levels and the optimal topologies. A parameter study is carried out for each configuration of the cantilever beam. The parameters examined include the total elastic and NRP material fractions, and the base beam thickness to show the robustness of the topology optimization process.

The resulting configurations from the topology optimization studies are often extremely difficult to manufacture but manufacturable configurations can be interpreted from those ideal configurations. For this particular problem, the optimal solution allows an interpretation of a manufacturable topology for the constrained layer, which has been successfully obtained and verified for an isotropic viscoelastic layer in [3]. Even though these manufacturable configurations have lower damping factors than the optimal topologies, there is substantial improvement from the initial configuration. The results of [3] shows a prominent improvement in the loss factor of the beam and similar results are observed for the NRP case.

5760-22, Session 5

Physical therapy applications of MR fluids and intelligent control

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Resistance exercise has been widely reported to have positive rehabilitation effects for patients with neuromuscular and orthopaedic conditions. This paper presents an optimal design of magneto-rheological fluid dampers for variable resistance exercise device in the form of a knee brace. An intelligent supervisory control for regulating the resistive force or torque of the knee brace as well as the joint motion is presented. The device provides both isometric and isokinetic strength training for the knee. Extensions to other joints are also discussed.

5760-23, Session 5

An experimental analysis of suitability of various semiactive control methods for magnetorheological vehicle suspensions

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Semiactive suspensions have long been regarded as the most promising and effective choice for vehicle suspensions, as compared to fully active suspensions, due to their lower cost, higher reliability, ease of implementation, and other benefits. To this end various control strategies have been proposed in numerous past studies, with skyhook control and its derivatives among the most commonly-studied strategies. The vast majority of these studies have included a numerical evaluation of a quarter car model, bicycle model, or full vehicle model with a linear, adjustable damper. The linear damper is chosen because, in addition to being simper to model, it makes the results independent of the system input; therefore, broader conclusions can be reached from analyzing the output of the model. A linear model of the damper, however, does not include many of the subtle dynamics of the damper that are important to the suspension performance. For this reason a limited number of studies have resorted to experimental means for evaluating semiactive dampers for vehicle suspensions. The experimental studies have been fewer, because they require more facility and can be logistically more complex. The results of experimental studies, of course, are most often closer to the actual performance of the suspension in a vehicle. Among the experimental studies, the vast majority have been conducted with mechanically adjustable dampers, in which a bypass valve is frequently used to change the damping force from a small to large value, commonly in multiple steps. Although useful, the results of these studies do not directly transfer to suspensions that include magneto rheological (MR) dampers, because of the differences between the characteristics and performance of MR dampers and their mechanically-adjustable counterparts.

As such, the primary purpose of this study is to provide a comprehensive experimental analysis of how various popular semiactive control methods perform when used with magneto rheological dampers. Specifically, the performance of five different skyhook control methods is studied experimentally, using a single suspension test rig. The control methods that are analyzed include: skyhook control, groundhook control, hybrid control, displacement skyhook, and relative displacement skyhook. For an MR damper, this paper provides an in-depth analysis of how theses semiactive control methods perform at the sprung and unsprung mass natural frequencies, using the single suspension test rig.

Upon evaluating the performance of each control method in frequency domain for various conditions, they are compared with each other as well as with passive damping. The results indicate that no one control method outperforms others at both the sprung and unsprung mass natural frequencies. Each method can perform better than the other control methods in some respect. Hybrid control, however, comes close to providing the best compromise between different dynamic demands on a primary suspension. The results indicate that hybrid control can offer benefits to both the sprung and unsprung mass with control gain settings that provide equal contributions from skyhook control and groundhook control.

5760-24, Session 5

Viscoelastic behavior of a magnetorheological fluid-elastomer composite under oscillatory compression

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A magneto-rheological (MR)-elastomer composite sandwich is constructed by encapsulating a MR fluid in a polymer solid. The properties of the MR composite sandwich structure are controllable by an applied magnetic field. The dynamic behavior of the MR fluid-elastomer under various magnetic fields is investigated by means of oscillatory compression cycles over a frequency range of 0.1 to 10Hz for various deformations (less than 1 mm). The changes of the viscoelastic properties in a disc-type sample are investigated. Experimental results for storage modulus, and tan delta over a spectrum of time (or frequency) and strain amplitudes are presented. Significant changes of loss and storage moduli by applied magnetic fields at low frequency range (0.1~1.0Hz) are observed.

5760-25, Session 5

Dynamic property of magnetorheological elastomer-based sandwich beam

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The field-dependant dynamic property of MRE-based sandwich beam is addressed theoretically in this work through high order model. The sandwich beam with conductive skins and non-conductive skins are discussed in a detail. The non-dimensional model to reveal the role of the finite dimensions on the controllability of the sandwich beam is also presented. MRE is a kind of smart material due to its field-dependant dynamic shear modulus. MRE is stable since it is solid and its chain-like structure is formed during curing process. Thus, MRE is a more promising material in engineering. However, MRE is as soft as silicon rubber, whose shear modulus is less than 1MPa. This does prevent the application of MRE. Sandwich configuration is an alternative to apply MRE in engineering since the outer thin skins will strengthen the bulk stiffness of the structure and the transverse flexibility of the MRE core will affect the dynamic performance of the structure. The simulation on simply supported MRE-based sandwich beam indicates: the anti-resonant frequencies and resonant frequencies of the sandwich beam change with the applied magnetic field up to 30%; the field-dependant dynamic property of the sandwich beam with conductive skins are mainly induced by the change of the shear modulus of the MRE core; the change of the resonant frequencies is slightly when the Young's modulus of the skins is lower as several Giga Pascal. This work indicates that the sandwich structure can well utilize the controllable property of MRE to realize applicable semi-active devices with controllable stiffness.

5760-26, Session 5

Theoretical and experimental investigation into dynamics characteristics of a rotor supported on a disk-type magnetorheological fluid damper

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The rheological properties of magneto-rheological (MR) fluid can be dramatically and reversibly changed by the application of an external magnetic field, a disk-type MR fluid damper based on shear mode was developed and it was shown that the dynamic characteristics of the disk-type MR fluid damper are controlled by a low-voltage electromagnetic coil and that the disk-type MR fluid damper can effectively attenuate the rotor vibration. In this paper, the dynamic characteristics of the disk-type MR fluid damper are studied experimentally and theoretically in a flexible rotor with an over-hung disk. The effects of the applied currents, rotor imbalances and different fraction MR fluids on the rotor imbalance response are systemically studied. The experimental results are basic in agreement with theoretical ones obtained by the Bingham fluid model, but the differences are also analyzed. It is shown that the dynamic behavior of the disk-type MR fluid damper can vary with the applied current. There is a break-loose phenomenon in the unbalance response curve of the damper. The break-loose speed rotational speed of the damper, below which the damper does not move, depends on the rotor imbalance, applied current and property of the MR fluid. The higher the applied current, or the more the magnetizable particles in the MR fluid or the smaller the rotor imbalance, the higher the break-loose rotational speed of the damper will be. The dynamic characteristics of the disk-type MR fluid damper filled with a high weight percentage MR fluid or with higher applied current behave as a system with a softening force.

5760-27, Session 6

An automotive suspension strut using compressible magnetorheological fluids

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Current automotive suspensions use struts and shock absorbers to control vehicle ride comfort and handling with varying road inputs and driving conditions. Conventional strut devices rely on coil or leaf springs to support the vehicle's weight. These struts must be designed for a maximum loading of the vehicle and increase the vehicle weight and take up precious under the hood volume, especially in front wheel drive vehicles. Existing automotive struts and shock absorbers use pressure driven, mechanical valves to provide fixed or variable damping to the suspension system. These shock absorbers provide good suspension performance but require many small, integrated mechanical parts for the valve implementation. The goal of this investigation was to develop a prototypical design of an integrated automotive suspension strut with controllable damping and a liquid spring. The primary goal of this study was to

investigate the feasibility of combining a controllable MR damping component with a passive but dependent MR stiffness component. A laboratory prototype was fabricated and tested to assess the strut performance for different classes of inputs: (1) sinusoidal inputs over an appropriate range of frequency and amplitude, (2) ramp inputs to assess steady constant velocity performance of the MR strut. The controllable damping component of the suspension strut was implemented using a magnetorheological bypass valve on a conventional hydraulic cylinder. The liquid spring component was physically realized by exploiting the motion of the piston in the hydraulic cylinder to generate spring force via the bulk modulus of a compressible MR fluid. With these controllable stiffness and damping of the MR strut, these properties can be adjusted in response to changing load conditions, road inputs, and traction requirements via a feedback loop. In addition, these controlled variations in damper behavior can be accomplished electronically with no moving parts, in contrast to mechanical valve implementations of conventional struts that may (e.g. servovalves) or may not be (passive orifices and shim stacks) adjustable in real time. Thus, the MR strut would be more reliable because of the reduction in the number of moving parts.

Therefore, we developed an automotive suspension system using a Compressible Magneto-Rheological (CMR) fluid suspension strut. The CMR strut design uses a pressure driven flow mode bypass MR valve design. Two struts were built and tested to separately study controllable damping and variable stiffness behaviors. The first strut was a conventional hydraulic cylinder with an MR bypass valve or an MR strut, which was used to measure the controllable damping performance. The second strut was designed to have a liquid spring effect superposed on controllable MR damping effects, that is, a CMR strut. The MR strut was implemented as a bypass MR valve damper using a double rod hydraulic cylinder and a MR valve modified from the Lord commercial linear damper. A MTS-810 (5 kips) servo-hydraulic testing machine was used to measure the bypass damper forces under different displacement inputs and magnetic field conditions. For the MR strut, an increase in the output force of over 100% was achieved in the field on relative to the field off cases in the bypass damper as observed for damper responses under both sinusoidal and ramp displacement inputs. For the CMR strut, the compressible MR fluid effects were similar to that for the MR strut, but a designed hardening effect was observed in compression. We measured both spring and damping forces under ramp displacement inputs. In the MR strut results, as field increases, the damper exhibits the expected increase in dynamic Coulomb or yield force (intercept of the high speed velocity asymptote with the force axis). In the CMR strut results, it clearly demonstrates the designed spring hardening as the damper compresses. The CMR strut clearly demonstrated controllable MR damping and a dependent hardening effect. In the final paper, we will present a corresponding analytical model and validate it using our experimental data. We will also present additional design details of the MR and CMR struts, as well as provide a more extensive presentation of the test data.

5760-28, Session 6

Designing an adaptive semi-active magnetorheological seat suspension for heavy truck applications

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One of the challenges in using controllable suspensions, including those that employ magneto rheological (MR) dampers, is that the system parameters can vastly change from what was used in designing the suspension controller. For instance, in designing a primary suspension for a semi-truck, the designer must keep in mind the vastly different dynamic conditions resulting from the unloaded and loaded conditions. Ultimately, the control designer opts for using the loaded condition or a condition in between the loaded and empty condition as the nominal system for designing the controller, accepting the fact that the suspension may not perform optimally in other conditions. Similarly, in designing a seat suspension for heavy vehicle applications—semi-trucks, farm equipment, etc.—the designer must keep in mind the fact that the seat will be used by different individuals with varying weight and ride preferences. For the latter applications, the controller design challenges are great in the sense that the dynamics of the seat suspension is quite pronouncedly felt by the rider, due to the close proximity of the suspension to the rider's body. Another challenge that often arises in application of controllable suspensions is the nonlinearities and uncertainties that commonly arise in most practical applications. The nonlinearities can result from time-varying characteristics, displacement-dependent effects, and the hysteresis that may be present with systems. The uncertainties include mass and stiffness variations, similar to those mentioned earlier. Therefore, one of the main challenges in designing an MR suspension is to configure the system such that it can perform well under all varying, nonlinear dynamic conditions.

This study addresses the design of a nonlinear adaptive control system for reducing vibration transmission in applications with widely varying dynamic condition, such as those commonly arising in transportation systems. Specifically, a semi-truck seat with a scissor type suspension that incorporates a monotube magneto rheological (MR) damper is used in an experimental setup to evaluate the effectiveness of the suggested adaptive control methods. For the tests, the seat is excited along its principal axis of vibrations (i.e., the vertical axis) using various inputs at the base of the seats. The results are analyzed in both frequency and time domain. The input that is used for the tests predominantly include a sine sweep input in the range of 0.5 – 10.5 Hz and the ISO4 input that is commonly used for evaluating seat suspensions for off-road vehicles, such as farm tractors.

An adaptive semiactive control method is developed and applied to the seat suspension test rig that is mentioned above. The experimental evaluation of the suggested adaptive control method suggests that it is far more effective than other widely-used semiactive control methods, and it can cope well with the system nonlinearities and uncertainties.

5760-29, Session 6

Characterization of a commercial magnetorheological brake/damper in oscillatory motion

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A commercially available magnetorheological brake is modified to reduce the inherent backlash in the brake. The brake, which can then serve as a rotary damper, is tested under sinusoidal oscillation at various frequencies, activation voltages and angular displacements in a servomotor-driven test cell developed by engineering technology students. Torque (via a torque cell) and angular displacement (via a potentiometer) data at a given activation voltage are collected and the resulting time series manipulated to form an objective function for determination of lumped-element parameters to model the rotary damper. The optimization thus does not require numerical integration of equations of motion. The model chosen includes a Bouc-Wen hysteretic element, which has previously found successful application in modeling of linear magnetorheological dampers. The actual torque response for sinusoidal and quasi-random motion at a fixed activation voltage are favorably compared with the model torque response.

5760-30, Session 6

On the development of fuzzy skyhook control for semi-active magnetorheological systems

M. Ahmadian, Virginia Polytechnic Institute and State Univ.

Since the development of the vehicle suspension system, designers have been faced with the conflict of vehicle safety versus ride comfort. Originally, this trade-off was minimized by the single optimal adjustment of a passive damper. In more recent years, the development of computer-controlled suspension dampers and actuators has increased the investigation of the vehicle safety versus ride comfort trade-off, and has led to the development of numerous damper control policies. In this study, the vehicle safety versus ride comfort trade-off is studied for a certain class of suspensions with semiactive fuzzy control. The proposed semiactive fuzzy control is based on the control policies that are commonly known as "skyhook" and "groundhook." After describing the mathematical details of the proposed semiactive fuzzy control, it is applied to a roll-plane model of a heavy truck in order to compare its performance with conventional passive suspensions. The results of the study show that semiactive suspensions with fuzzy logic control can substantially reduce the likelihood of rollover in heavy trucks due to vehicle maneuvers. The results, however, show that for road inputs at the tire, the semiactive suspensions can cause larger body acceleration peaks, and a harsher ride.

5760-31, Session 6

Torsional vibration control with an MR fluid brake

S. Ye, K. A. Williams, Univ. of Alabama

Analytical and experimental work has been performed on the use of a magneto-rheological fluid brake for controlling torsional vibrations in rotating shafts. Three different control strategies were examined. First, implementation of the MR fluid brake as a passive friction damper with an on-line variable friction torque was investigated. In that application, actuation of the brake was only performed to modify the steady state friction in the device. The second approach was the use of the MR brake in a "stick-slip" fashion. Actuation of the brake was increased until a "locked" state was achieved, at which point the actuation was

removed to allow the system to slip again. The intent of that approach was to ride the stick-slip interface, such that the maximum torque could be achieved without completely locking the system. In that implementation, actuation of the brake occurred multiple times during each period of oscillation, such that the device was no longer acting as an adaptive-passive element. The final technique that was examined was the use of the MR fluid brake as a semi-active device that could apply a torque in the presence of relative motion between the brake inertia and the primary system. The work includes the results of system identification performed on the MR fluid brake, along with simulated and experimental performance results of the system under the different control strategies.

5760-32, Session 7

New semi-active damping concept using eddy currents

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Eddy currents are formed in a nonmagnetic conductive metal when it is subjected to a time varying magnetic field. These eddy currents circulate in the conductor such that a magnetic field of opposite polarity as the applied magnetic field is generated. However, due to the internal resistance of the conductor, the currents will dissipate into heat at the rate of I2R. If the conductor experiences a continuous change in magnetic flux then an electromotive force will be induced, allowing the eddy currents to regenerate and continue flowing. The density of the eddy currents generated is directly proportional to the velocity of the change in magnetic flux and the dissipation of the eddy currents allows energy to be removed from the system, thus, together functioning as a viscous damper. In the present study an eddy current damping system will be developed that consists of a permanent magnet and a cantilever beam. In the case of a vibrating beam, the motion relative to a fixed permanent magnet will cause eddy currents to be generated in the conductive beam and in turn damp the vibrations out. This system has been previously demonstrated and shown to be effective; however, this research will take the passive case a step father and utilize the idea that the velocity between the conductive beam and the magnet partially dictates the eddy currents generated and thus the damping force. To increase the velocity between the magnet and the conductor, the position of the magnet will no longer remain stationary, but will be displaced relative to the beam using an electro-magnetic shaker and a control law. Therefore, the damper will consist of the passive component from the beams motion relative to the magnet and an active component will be comprised of the motion of the permanent magnet relative to the beam.

This new damping system will be modeled, and simulations will be performed to demonstrate the effectiveness of the damper over its passive counterpart. Additionally, the effect on the damping of displacing the magnet with different waveforms will be identified. Following a thorough theoretical investigation of the system it will be constructed and experiments performed to validate the models accuracy. The study will demonstrate a new damping system and show its potential as a damping mechanism.

5760-33, Session 7

Viscoelastic behavior and the design of a delayed-resonator vibration absorber

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Delayed resonators (DRs) have proven to be effective vibration absorbers for tracking and canceling the effects of harmonic excitations on a structure. A DR uses time-delay feedback to make an auxilary damper appear to the host as an ideal, undamped vibration absorber. The poles due to an excitation lie on the imaginary axis, and the DR operates in a state of marginal stability in order to cancel them exactly. DR's operate in a state of marginal stability, and its stability limits are functions of its own stiffness and loss characteristics.

The energy loss from a physical structure results from a combination of many loss mechanisms. A simple modal test is often used to 'fit' an equivalent spring-mass-dashpot oscillator to each mode of a structure, whether or not the loss mechanisms are truely viscous.

It is hypothesized that a DR containing a viscoelastic loss mechanism modeled as a viscous dashpot may lead to unexpected limits on performance and stability. This is particulary important if the device is subject to wide temperature swings. Maxwell models are used to simulate the time-dependence in the DR, and temperature dependence is included via the time-temperature superposition principle. Results show a modest increase in performance. However, the assessment of stability of the system is greatly improved by the more accurate modeling of the loss mechanism.

5760-34, Session 7

Active vibration damping using an electrodynamic actuator with internal velocity sensor

C. K. Paulitsch, P. Gardonio, S. J. Elliott, Univ. of Southampton (United Kingdom)

Using self-sensing at an electrodynamic actuator for broadband active vibration damping requires compensation of the actuator resistance and of the self-inductance of the actuator by an appropriate shunted circuit. In order to reduce power consumption the actuator resistance should be small, but for robustness of self-sensing and a large bandwidth a large resistance is required. A high transducer coefficient is important for high sensitivity to sense the induced voltage proportional to the vibration velocity of an attached mechanical structure, but a large transducer coefficient implies a strong magnetic field that also increases the self-inductance so that the measurement bandwidth potentially is reduced. In this study in order to eliminate the first trade-off between power consumption and robustness an actuator with a primary driving coil and a secondary measurement coil is proposed. The primary coil is optimised for driving by choosing a small resistance, whereas the secondary coil is optimised for sensing by choosing a large resistance. It has been shown that the transformer coupling between the two coils could be reduced by decreasing the cross section of the secondary coil, but there is a geometric limit on the reduction of the cross section of the secondary coil. Therefore an analogue electronic compensation scheme is proposed to compensate for the transformer coupling between the primary and the secondary coil. Feedback of the sensed velocity in the secondary coil is implemented and experimental vibration damping results at a plate are presented. Results are compared to self-sensing vibration damping, active vibration damping using an explicit velocity sensor and passive means of the same weight as the actuator.

5760-35, Session 7

Vibration reduction and power flow using passive and active resonant devices

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One general class of devices for vibration suppression makes use of a mechanical resonance in the device to cause it to be particularly effective in a narrow frequency range. Passive devices including tuned vibration absorbers (TVAs) and tuned mass dampers (TMDs) have been in use for a century or more and employed in quantities of millions each year. Active devices that combine actuation with electrical inputs and outputs including sensing and control systems offer higher performance, with the required addition of external power.

This paper will treat passive and active resonant vibration control devices in a general framework, and will highlight the benefits and costs of each approach. In the simplest models, passive devices can be represented as a mass-spring-damper combination, and active devices typically add a force actuator and some type of control. The passive TVA, designed to greatly increase mechanical impedance at a specific frequency, has an analog in active devices that employ particular control algorithms for force cancellation. The passive TMD has an analog in active dampers. Each of these approaches will be considered with reference to low-order models of structural systems, including well-defined disturbance inputs and performance metrics.

Non-dimensional quantities extending the well-known tuning ratios for passive devices (Timoshenko, et al) will be developed. One of the emphases of the paper will be careful tracking of the differences in the behavior of the passive and active devices and an explicit tracking of where the vibrational energy goes in ach case.

Limitations of the idealized models will be addressed and specific hardware examples will be cited for each of the passive and active vibration suppression approaches.

5760-36, Session 7

Vibration damping of piezoactuated structures with electric circuits containing a negative capacitance: new developments

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Piezoelectric sensors and actuators are very suitable for vibration damping of thin and light structures. A passive damping device can be obtained by connecting a resistive-inductive circuit to the electrodes of a piezoelectric patch bonded on the vibrating structure. This control scheme is able to effectively damp only the vibrations along a single structural eigenmode. A different and very promising strategy employs semi-active electric circuits containing a negative capacitance. The negative capacitance can be obtained by

using a operational amplifier and is able to compensate the reactive impedance of the piezoelectric actuator, improving the achievable damping. Many authors considered circuits containing a negative capacitance in series or in parallel to a resistive or a resistive-inductive branch. As these circuits contain an active component, there exists a range of stability for the negative capacitance, limited by the value of the piezoelectric capacitance.

Both these typologies of circuits exhibit good performances either in single-mode and in multi-mode vibration damping only when the negative capacitance is chosen very close, in absolute value, to the piezoelectric capacitance, i.e. to the boundary of the stability range. As a matter of facts, in practical applications it is necessary to employ a value of negative capacitance sufficiently far from the stability limiting value, and thus far from its optimal value, in order to operate in safe conditions. As a result, only an amount of damping quite smaller than the optimal theoretical one can be obtained. In this paper new electric circuits containing negative capacitances are proposed and analytically optimized in the case of single-mode vibration damping. Closed form expressions of the optimal values of the electric components and the achieved exponential time decay rate of the free vibrations are found out, according to the pole placement technique, and the range of stability relevant to each control scheme is also determined.

Moreover, the application of the proposed circuits to multi mode damping is considered, and a numerical optimization of the electrical components relevant to each circuit is performed using a optimization tool of Matlab. The proposed circuits turn out to be very effective, both in single-mode and multi-mode damping applications, for values of negative capacitance contained in an unlimited range, thus avoiding the limitations exhibited by the previously mentioned circuits.

5760-37, Session 7

Vibration suppression of scale model of railway car body with piezoelectric elements: a new implementation method of shunt circuit considering large vibration amplitude and generated voltage

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Because of the reduced weight and less rigidity of car body shell, recent lightweight railway vehicles generally have an acceleration power spectral density (PSD) due to vertical elastic vibration larger than that of conventional heavy vehicles. Such bending vibration often occurs to adversely affect the riding comfort of passengers in the frequency range where humans are the most sensitive. Therefore, it is important to investigate methods to reduce bending vibration from the viewpoint of improving the riding comfort.

Several methods have already been proposed to suppress the bending vibration, for example, by attaching damping layers that consist of rubbers and carbon fiber reinforced plastics (CFRPs), optimize specifications of car body, trucks and their connecting elements, utilize a tuned mass damper, or apply active and semi-active vibration control systems. However, only a few of these are now being put into practical use because of the problems including high cost, heavy weight, low efficiency and/or low reliability. Therefore, it is needed to develop new techniques to reduce vibration more effectively with reasonable costs and weights.

The goal of this study is to apply a vibration suppression technique utilizing piezoelectric elements that are electrically shunted by an external circuit to reduction of bending vibration of railway vehicles. As the first step to realize the above goal, this paper describes a feasibility study by using a scale model of an actual Shinkansen car body with length about 5m and weight about 290 kg. The model is supported by air spring suspensions at four points, and an electrodynamic exciter that is attached on the bottom of the model excites it vertically. Small pieces of piezoceramics (PZT) are bonded to its floor structure and electrically connected to a shunt circuit.

Two types of shunt circuits are tested here, one is a serially connected resistor and inductor, and the other is a resistor and a negative capacitor in series. In actuality, the inductor or the negative capacitor constituting the shunt circuit is replaced by an active circuit including operational amplifiers and other passive components. The authors proposed a new method to implement such shunt circuits aiming at practical use. Both circuits are designed for use under conditions of large vibration amplitude that causes high voltage generated by the elements.

First, simulations are carried out in order to optimize parameters of the shunt circuit such as the values of resistor, inductor and negative capacitor, and estimate the performance of vibration suppression. Then, excitation tests are performed to verify the effectiveness of the proposed method. Results of excitation tests show that the circuits realized by the method successfully reduce the values of frequency response functions (FRFs) from excitation force to acceleration at some measured points around the natural frequency of vibration. Realized loss factors of the structure can be also increased at its natural frequency of the first mode bending vibration by using piezoelectric elements. Moreover, the circuit including the negative capacitor can also reduce vibration associated with higher eigen modes together with the first bending mode simultaneously.

5760-38, Session 7

Vibration control of a beam using linear magnetostrictive actuators

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Terfenol-D is one of magnetostrictive materials with the property of converting the energy in magnetic field into mechanical motion, and vice versa. We designed and fabricated a linear magnetostrictive actuator using Terfenol-D as a control device. It has 25mm diameter and 100mm long.

A series of experimental and numerical tests were performed to grasp the dynamic characteristics of the actuator. Induced-strain actuation displacements of the actuator measured by the test and predicted by magnetic analysis agreed well. And blocked forces according to the input currents were estimated from the testing results. Modeling method representing the exerting force of the actuator was confirmed through some testing results.

We also explored the effectiveness of the linear magnetostrictive actuator as a structural control device. A series of numerical and experimental tests was carried out with simple aluminum beam only supported at each end by the actuator. After the equation of motion of the controlled system was obtained by the finite element method, a model reduction was performed to reduce the numbers of degree of freedom. A linear quadratic feedback controller was realized on a real-time digital control system to damp the first four elastic modes of the beam. Through some tests, we confirmed the possibility of the actuator for controlling beam-like structures.

5760-39, Session 8

Optimization of constrained layer damping

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Conventionally, the viscoelastic cores of Constrained Layer Damping (CLD) treatments are made of materials that have uniform shear modulus. Under such conditions, it is well-recognized that these treatments are only effective near their edges where the shear strains attain their highest values. In order to enhance the damping characteristics of the CLD treatments, we propose to manufacture the viscoelastic cores from functionally graded materials (FGM) that have optimally selected gradient of the shear modulus over the length of the treatments. With such optimized distribution of the shear modulus, the shear strain can be enhanced, and the energy dissipation can be maximized.

The theory governing the dynamics of one-dimensional structures treated with CLD, that has functionally graded viscoelastic cores, is presented using a distributed-parameter approach. The distribution of the shear strain along the length of the CLD is determined and the equivalent loss factor of the treatment is computed for various shear modulus distributions. The optimal length of the treatment and gradient of the shear modulus are determined, in a rational manner, in an attempt to maximize the loss factor of the treatment.

Numerical examples are presented to demonstrate the effectiveness of the new class of CLD with functionally graded cores in enhancing the energy dissipation over the conventional CLD by orders of magnitudes.

Extension of the proposed one-dimensional FG/CLD to more complex structures is a natural extension to the present study.

5760-40, Session 8

Embedding viscoelastic damping materials in low-cost VRTM composite structures

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Abstract:

It has been well established that using viscoelastic damping materials in structural applications can greatly reduce the dynamic response and thus improve the structural fatigue life. Initially these materials have been used to solve vibration problems in metallic structures, where the damping material is attached to the structure and then a stiff outer layer is attached to promote shear deformation in the damping material. More recently, these materials have been

used successfully in expensive aerospace composite structures, where the damping material is embedded between plies of prepreg graphite/epoxy before the structure is cured in a high-temperature high-pressure autoclave. We have shown in previous studies that the damping materials must be coated before embedding them in the lay-up to protect them from epoxy infusion during the high temperature cure. Up to this point no one has successfully embedded these damping layers into low-cost composite structures which are typically fabricated using the Vacuum Resin Transfer Molding (VRTM) process. Examples of structures using this process include: general aviation aircraft, sport structures, boats, and civil applications. In this manufacturing process, the dry composite fabric is placed in a closed mold, then resin is drawn using vacuum to completely wet-out the part. Previous attempts to embed damping materials led to an incomplete wet-out (scrap parts). In the current study, the damped layers are perforated with a series of small holes to allow the resin to flow through the damping layer and completely wet-out the structure. Experimental fabrication and vibration test studies investigate the effect of hole diameter versus hole spacing so that low-cost composite damped structures can be easily fabricated without sacrificing structural integrity.

5760-41, Session 8

Chamber-core structures for fairing noise mitigation

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Extreme noise and vibration levels at lift-off and during ascent can damage sensitive components of launch vehicle payloads. Typically, acoustic blankets are attached to the inside of the fairing to reduce the acoustic loads acting on the payload. However, acoustic blankets are not very effective at low frequency where the blanket thickness is much less than one quarter of the acoustic wavelength.

Recently, the Air Force Research Laboratory, Space Vehicles Directorate has investigated a new composite structure fabrication approach, called chamber-core, for building payload fairings. Chamber-core offers a lightweight yet strong structure with inherent noise attenuation characteristics. Chamber-core uses many axial tubes that are sandwiched between inner and outer face-sheets to form the cylinder/fairing structure. These hollow tubes can be used as acoustic dampers to attenuate the amplitude response of low frequency acoustic resonances within the fairing's volume.

A cylindrical, graphite-epoxy chamber-core structure consisting of 180 tubes was built to study noise transmission characteristics and to quantify the achievable performance improvement. The cylinder was tested in a semi-reverberant acoustics laboratory using bandlimited random noise at sound pressure levels near 115 dB. The performance was measured using external and internal microphones. The noise reduction was computed as the ratio of the spatially averaged external response to the spatially averaged interior response. Frequency response functions were also measured to determine the important structural-acoustic dynamics in the transmission path and the effects of the chamber resonances on them.

The noise reduction provided by the chamber-core cylinder was measured over three bandwidths, 20 Hz to 500 Hz, 20 Hz to 2000 Hz, and 20 Hz to 5000 Hz. For the bare cylinder, with no acoustic resonators, the structure provided approximately 13 dB of attenuation over the 20 Hz to 5000 Hz bandwidth. Then, with the axial tubes coupled with the acoustic volume and acting as acoustic dampers at various frequencies over the bandwidth, the noise reduction provided by the cylinder increased to 19 dB, an overall increase of 6 dB over the bandwidth. Narrow-band reductions greater than 10 dB were observed at specific low frequency acoustic resonances. This was accomplished with virtually no added mass to the composite cylinder.

5760-42, Session 9

Modified LMS feed-forward control for active vibration with limited actuator authority

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The filtered LMS algorithm has been used effectively and practically for active vibration and noise cancellation [1,2]. However, in many cases the vibration or noise is so large and the control effort is out of the range of the actuator. For example, a PZT actuator in an active vibration isolator usually provides a limited displacement [3]. In this paper we propose a modified filtered-x LMS algorithm to achieve "best" performance taking into account limitations on actuator force or stroke. By employing an auxiliary cost, the algorithm maintains the control effort within a specified range. The convergence of the algorithm is discussed and its effectiveness is demonstrated in simulations and experiments.

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[3] Zuo and Nayfeh, Active-Passive Vibration Isolation and Position Control using a Post-Buckled Spring, Proceedings of the 7th International Conference on Motion and Vibration Control, 2004

5760-43, Session 9

Vibration disturbance rejection through left Eigen-vector assignment and piezoelectric circuits

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The objective of this research is to investigate the feasibility of utilizing left eigenvector assignment and piezoelectric circuits for vibration disturbance rejection. In previous studies [Wu and Wang, SPIE 2004], it has been shown that through right eigenvector assignment and mode confinement, one can enhance the performance of periodic vibration isolators. However, it was also recognized that since mode confinement is based on the concept of free modal response, it does not guarantee that vibration will always be attenuated under forced excitation scenarios.

In this research, the left eigenvector assignment technique and piezoelectric circuits are utilized to achieve vibration suppression throughout broadband frequencies. The left eigenvector assignment principle is to alter the left eigenvectors of the closed-loop system so that the system's forcing vector is as closely orthogonal to each left eigenvector as possible. With such an approach, one can directly attack the forced response problem.

Similar to the right eigenvector assignment concept, piezoelectric circuits connecting to the isolator structure increase the degrees of freedom of the integrated system, and enlarge the design space for achievable eigenvectors. A new formulation is developed so that the left eigenvectors of this integrated system are selected through solving a generalized eigenvalue problem, where the orthogonality indices between the forcing vector and the left eigenvectors are minimized. The integrated system with assigned left eigenvectors achieves to reject external disturbance of the complete electromechanical system.

Numerical simulations are performed to evaluate the effectiveness of the proposed method on disturbance rejection for an isolator design example. Frequency responses of the different generalized coordinates in the selected frequency range are illustrated. It is shown that with the piezoelectric circuits and left eigenvector assignment technique, the system's external disturbances are rejected and vibration amplitude of the structure can be effectively suppressed.

5760-44, Session 9

Hybrid multivariable controller architecture

M. A. Hopkins, Rochester Institute of Technology; D. A. Smith, P. Vallone, R. Sandor, ITT Industries, Inc.

This paper describes a multivariable controller architecture that is a combination of a classical controller and an observer-based controller. The hybrid-controller design process starts with a classical multivariable feedback controller, designed by any convenient method, such as sequential SISO loop closing. After designing the classical controller, an observer-based modern controller is designed to be stable in parallel combination with the classical controller.

In the final part of the design process, the hybrid configuration is realized by introducing an additional feedback path that subtracts the effects of the classical controller from the observer-state estimate. All of the controller gains are re-tuned to improve a variety of performance measures. The additional feedback path does not increase the total number of states in the controller but allows significantly higher gains to be used in the observer-based controller, resulting in better isolation.

A six-input, nine-output, large flexible structure provides a working example. The classical controller was implemented as six 21st-order SISO feedback controllers, at a sample rate of 20 kHz, closed in parallel around the six main mount struts, achieving very good isolation across the struts. A 300th-order observer-based modern controller, also at a 20 kHz sample rate, was designed to work with the classical closed loops and has been implemented in the hybrid configuration described. This non-square modern controller uses feedback signals from three non-collocated sensors, in addition to the six used by the classical SISO controllers, and improves isolation by about 5 dB across the controller bandwidth.

5760-45, Session 9

Tuning the switch timing of pulse-switched piezoelectric shunts for vibration control

J. Schoenly, W. W. Clark, Univ. of Pittsburgh

Various techniques have been studied for overcoming the shortcomings of passive piezoelectric shunts, including so-called “state-switching” (switching between short and open circuit conditions on the piezoelectric) and various forms of short-duration switching, called “pulse-switching” for the purposes of this paper. Pulse-switching can be done with a simple resistor shunt, but is more effective with an RL shunt. Previous research has shown that not only can the pulse-switched RL shunt provide very effective vibration control performance, but it eliminates much of the shunt parameter tuning required by the passive shunt approach, and can be done with a simple control circuit using very little power. In addition, it has been shown that a single switched shunt can simultaneously control multiple vibration modes. This paper will briefly describe the pulse-switching concept, and then will outline steps that can be taken to further improve the technique, which include the development of a technique and hardware for tuning the controller for optimal switching of a single vibration mode.

5760-46, Session 9

Averaging analysis of state-switched piezoelectric structural systems

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Switching strategies for vibration attenuation and damping enhancement using piezostructural systems have been studied more closely over the last several years. [1],[2],[4] Some approaches have been designed using intuitive notions such as maximizing energy dissipation during a typical cycle of a periodic response signal. Other methods have appealed to notion that a switching strategy should be stable if all the system configurations associated with each arrangement of switches are, when studied individually, stable themselves. While not rigorously true, this heuristic has produced excellent switching controls in practice. The authors of this paper have used the method of Multiple Lyapunov Functions to study the stability of switched, capacitively shunted piezoelectric vibration absorbers. But owing to the complexity of the analytical problem, the results obtained were limited in their scope of applicability. [3] A rigorous formulation of state switched piezoelectric structural systems in the framework of hybrid or switched system theory is indeed a complex analytical task. To be sure, useful tools from linear matrix inequality methods can be used for numerical analysis of these problems, but simple analytical tools remain lacking. This paper suggest an alternative approach to obtain quantitative analysis of state switched piezostructural systems. We employ averaging methods that have been used to great advantage in other contexts, such as nonlinear systems theory, to obtain the effective response of some state-switched piezostructural systems. While the approach is quite general, we focus on the class of switched, capacitively-shunted systems such as those studied in [Lesieutre]. In this reference the authors have demonstrated that the use of several physical relays that switch the effective shunt capacitance can yield a system well-suited to adaptive selection of a finite number of predetermined vibration absorption (notch) frequencies. In this paper, we illustrate that a fast-time-scale, pulse-modulated switching strategy may be an effective alternative. By applying a pulse modulated switching strategy in which the duty cycle determines the proportion time the shunted circuit is engaged, an “effectively continuous selection” of notch frequencies can be tuned. This conclusion follows from separating the fast time scales (associated with the PWM switching strategy) and the slow time scales (associated with the effective structural response) via the method of averaging. We note that while this technique is applied to a single configuration and problem, the approach is general. Similar approaches for deriving the effective response of switched power converters have defined an entire field of study. [5]

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5760-47, Session 9

Suboptimal bang-bang control of buildings using piezoelectric friction dampers

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Passive friction damper is widely used in the area of vibration suppression. It has the advantages of large energy-dissipating capacity, high efficiency and stability. Like other passive energy dissipation devices, it cannot alter its mechanical parameters in real time. Therefore it is impossible to achieve optimal structural vibration control using passive friction dampers. One of the invariable challenges in civil engineering is to find innovative and better means of reducing structural vibration due to earthquakes and wind gusts. The most promising means is to introduce smart structures in civil engineering. Piezoelectric material is one of most efficient smart materials. It has the ability to transform mechanical energy to electric energy and vice versa. Hence, the normal forces on the sliding plate of the friction damper can be actively altered using the piezoelectric effect and in turn frictional forces can be adjusted adaptively according to the vibration signal from structure or the status of the damper to achieve optimally dissipate structural energy through a passive manner. In this paper, a new piezoelectric friction damper is developed by combining the slotted bolted connection and piezoceramic actuators. It is composed of tube piezoceramic stack actuators, load cells, preload bolts, brass sheets, spring washers, an upper plate, a sliding plate and a lower plate. A semi-active control strategy using controllable friction dampers based on the sub-optimal Bang-Bang control law is presented. The controllable sliding frictional force and preload on the piezoceramic actuators are obtained by using the genetic algorithm. However, The Bang-Bang control strategy requests the normal forces switch fast between the preload and the maximal normal force. This may cause the stories chatter and the relative accelerations can’t be suppressed effectively. To avoid the highly speedy switches, the hyperbolic tangent function or the error function is used to make this transition smooth. In light of the above principles, a mathematical model of linear frame structures controlled by piezoelectric friction dampers subjected to earthquakes is established using Simulink and Stateflow nested in MATLAB© and this simulative program is capable of capturing the sticking and slipping phrases of the friction damper accurately. Numerical simulations clearly demonstrate the effectiveness of the proposed semi-active control strategy using controllable friction dampers based on the sub-optimal Bang-Bang control law. The maximal reduction ratios of the relative accelerations and the story drifts are 59.8% and 84.3%, respectively. The control efficacy for accelerations is improved evidently compared with those of Bang-Bang control laws without hyperbolic tangent functions or error functions, but the control efficacy of story drifts degrades. The adaptability of the above control law is tested through changing the peak value of the ground acceleration under the condition that the control parameters are fixed. Finally, this paper also suggests issues need further investigations.

5760-48, Session 10

Friction factor of magnetorheological fluid flow in channels with porous walls

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This work examines the friction factor of magneto-rheological (MR) fluids in channel flow, where the channel walls are porous surfaces impregnated with MR fluid. There is no flow through the porous walls. Several different porosity sizes and different impregnation techniques are utilized in this study. The results are compared to those of the smooth surface. From the experimental results it has been found that under an applied magnetic field, the impregnated porous wall surface would increase the friction factor of MR fluid flow significantly when compared to the smooth surface. It is also concluded that the impregnation technique affects the amount of iron particles trapped inside the porosities, therefore affect the friction factor. Based on the experimental results a power-law relation for friction factor of MR fluids is developed as a function of Mason number at the channel wall and porosity size. Using this relation the pressure loss of an MR fluid flowing through a channel with MR impregnated porous walls can be determined without using a constitutive model for MR fluids.

5760-49, Session 10

Effective design strategy of a magnetorheological damper using a nonlinear flow model

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With the high increasing interest in the application of various kinds of magnetorheological (MR) dampers, several theoretical models and analytical methods have been developed and discussed,1-3 which have been show to be very useful and adequate for most commercial controllable fluid device designs and characteristic analyses.4-5 However, most of these analyses are developed on the basis of linear (laminar) flow models in which the pressure drop down the Magnetorheological valve has a linear relationship with the flow rate. If the induced shear rate in the Magnetorheological valve is high, and under certain conditions, the linear flow model may not be acceptable. This paper presents an effective design strategy of a magnetorheological (MR) damper using a theoretical nonlinear flow model. The MR valve inside a flow mode MR damper is approximated by a parallel plate or rectangular duct and its governing equation of motion is derived based on a nonlinear flow model to describe a laminar or turbulent flow behavior. Useful nondimensional variables such as, Bingham number, Reynolds number, and dynamic (controllable) force range are theoretically constructed on the basis of the nonlinear model, so as to assess damping performance of the MR damper in a wide operating range. First, the overall damping characteristics of the MR damper are evaluated through computer simulation and, second, the effects of important design parameters on damping performance of the MR damper are investigated. Finally, the effective design procedure to meet a certain performance requirement is addressed. A high force-high velocity damper is fabricated and tested, and the resulting models and design procedure is experimentally validated.

5760-50, Session 10

Transient response of MR fluids subjected to magnetic fields under constant shear conditions

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MR fluids are known to response to the application of a magnetic field with an increase in its viscosity, which is due mainly to the creation of a yield stress in the material. The response time of MR fluids have been known to be around the order of microseconds. This paper presents the results of a set of experiments designed to study the transient response of MR fluids to a magnetic field. The MR fluid is subjected to a constant shear between two parallel discs, one of which is rotating at a fixed speed and the other grounded. The speed of the rotating disc is maintained constant by a controller that regulates the servo motor driving the disc. A step current is then applied to the electromagnet to create a magnetic field in the MR fluid. This causes the controller to increase the torque delivered to the rotating disc in order to maintain the speed of the disc. By examining the transient response of this delivered torque and the response of the torques exerted on the bottom disc, the response time and rise time for the MR fluid can be determined.

This paper presents the results of MR fluid mixtures made from three different magnetically active particles. The first type of particle is carbonyl iron powder (CIP) with a chemical purity of 97% iron content. The second type is CIP with more than 99.5% iron content, and the third also contains 99.5% iron but with silicon oxides on its surface. The response times of the three types of CIP are presented and compared. Possible reasons for the variations in the response times are also given. Results for the effect of particle concentrations on the rise time and response time are also presented – mixtures of 10%, 20%, 30% and 40% volumetric concentration were compared and examined. Furthermore, the effects of temperature variations on the transient response of the MR fluid are also presented - it was observed that as the temperature was reduced from +500C to -200C, the response time increased.

5760-52, Session 11

Particle impact damping

V. K. Kinra, R. R. Bijai, B. L. Witt, Texas A&M Univ.

Particle impact damping (PID) is a simple and ingenious means of achieving high structural damping by the use of a particle filled enclosure attached to a structure in a region of high displacements. In traditional methods of damping (e.g. viscoelastic damping), stored elastic strain energy is converted into heat. By contrast, in PID, damping is achieved by converting the kinetic energy of the structure to heat through inter-particle and particle-enclosure collisions. Accordingly, PID is defined as: Ψ = ∆T/T where Ψ is the specific damping capacity, ∆T is the kinetic energy converted into heat during one cycle, and T is the maximum kinetic energy during the cycle. An elementary mathematical model of PID has been developed based on the assumption that the particles move as a single mass. A dimensionless analysis of the problem reveals that the specific damping capacity (SDC): Ψ = f (μ, ∆, Γ, R) where μ is the mass ratio (= m/M), ∆ is the dimensionless clearance (= dω^2/g), Γ is the dimensionless acceleration amplitude (= Uω^2/g) and R is the effective coefficient of restitution; m is the mass of particles, M is the reduced mass of the beam (primary mass), d is clearance from the top of the particle bed to the ceiling of the enclosure, U is the displacement amplitude of the primary mass, ω is the undamped circular natural frequency and g is the acceleration due to gravity (=9.81m/s^2).

Experiments were conducted to measure PID for a steel cantilever beam with a particle filled enclosure attached to its free end. PID due to varying clearance (∆) between the particles and enclosure ceiling were studied. An interesting outcome reveals that there is a sudden reversal in the slope of Ψ(Γ) curve after the particles hit the ceiling. PID due to the effect of the mass ratio (0.02 ≤ μ ≤ 0.1), particle materials (lead, steel, glass, tungsten carbide, sand), number of particles (50 ≤ N ≤ 11000) and particle shape (spheres, dust)were studied.

5760-53, Session 11

Investigation of a model vertical motion liquid

C. Papadopoulos, H. Tabatabai, Univ. of Wisconsin/Milwaukee; C. Buechel, Univ. of Wisconsin/Milwaukee and Pierce Engineers, Inc.

Tuned Liquid Dampers are used to damp horizontal vibrations in structures, and offer practical alternatives to tuned mass dampers. However, to our knowledge, liquid damping systems have not been developed to lessen vertical vibrations. In this work, we develop a model for a vertical liquid column damper, idealized as a discrete, nonlinear, two degree of freedom dynamical system. One degree of freedom represents the 'target' structure that is to be damped, and the other represents the approximate, one-dimensional motion of a fluid in a U-shaped tube. The U-shaped tube has a flexible joint such that one vertical portion and the horizontal portion of the tube remain fixed, and the remaining vertical portion of the tube is affixed to the vibrating structure. The equations of motion are derived using Lagrange's Equations, and are integrated using Runge-Kutta algorithms that are available in Matlab. A physical model was built, consisting of a mass attached to the end of a cantilevered beam, and a U-tube made from PVC pipe. The various damping and stiffness parameters of the system were calibrated independently. Measured vibrations on the physical model show reasonable agreement with numerical simulations.

5760-54, Session 11

Modeling and motion control of inchworm considering nonlinearities

Y. Kim III, I. Kim, K. Kim, Kumoh National Univ. of Technology (South Korea)

This paper proposes a new modeling scheme to describe the hysteresis and the dynamic characteristics of piezoelectric actuators and to accommodate the preload to the inchworm. The paper also develops a control algorithm for the precision motion control. From the analysis of piezoelectric actuator behaviors, the hysteresis can be described by the curving fitting modeling method in which hysteresis loops are divided into a rising curve and a falling curve. Each curve is described by the second-order polynomial function of argument Vin (input voltage) and the coefficients of the polynomial are described by the function of argument Vmax (maximum input voltage). When loads applied to the inchworm, the characteristics of it are identified by experimental data and incorporated into the modeling scheme. The dynamic characteristics are also identified by the frequency domain modeling technique based on the experimental data. For the motion control, the hysteresis behavior is compensated by the inverse hysteresis model. The dynamic stiffness of an inchworm is generally low compared to its driving condition, so mechanical vibration may degenerate the motion accuracy of the inchworm. Therefore, the sliding mode control and the Kalman filter are developed for the precision motion control of the inchwarm. To demonstrate the effectiveness of the proposed modeling schemes and control algorithm, experiment validations are performed.

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5760-55, Session 11

Static electromechanical response of piezoelectric tubes

J. H. Huang, Y. Shiah, Feng Chia Univ. (Taiwan)

This article deals with the fully coupled electromechanical responses of an infinitely long piezoelectric tube as a sensor or an actuator. By adopting the variational approach for generalized loading conditions and utilizing Hamilton's principal, the governing differential equations of an infinitely long piezoelectric tube subjected to natural boundary conditions are derived. For studying the direct and converse effect of the piezoelectric tube, the obtained governing equations are solved to give the exact solutions corresponding to different boundary conditions prescribed for the tube functioning as a sensor or an actuator. For numerical illustrations of our analysis, polyvinylidene difluoride and lead zirconate titanate, which are widely used in industries nowadays, are chosen as the materials for our investigations. The piezoelectric tubes made of these materials are investigated with thorough discussions over their different electromechanical responses.

5760-56, Session 11

A novel tunable mass damper based on giant magnetostrictive composites

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A novel tunable mass damper (TMD) fabricated using giant magnetostrictive composites is developed for vibration control of a high-precision motion stage for semiconductor manufacturing. Magnetostrictive composites possess large strain-force capability with an increased operational bandwidth, reduced mechanical brittleness and cost as compared with their monolithic alloys. Magnetostrictive composite-based TMDs are capable of providing an improved semi-active vibration damping treatment to the motion stage. By adjusting the dynamic parameters of the damper, the damper's natural frequency can be tuned to a resonance frequency of the motion stage for effectively dissipating the vibrational energy from the targeted resonance. In this paper, the design, fabrication, and characterization of the magnetostrictive composite TMD are described. The tuning of the resonance frequency of the damper is achieved by controlling the actuation of the magnetostrictive composites to change both its stiffness and damping ratio. The controllability and stability of the stiffness and damping ratio of the damper are experimentally investigated. Tunability of resonance frequency as high as 20 % is achieved.

5760-57, Session 11

Application of LIPCA as smart actuator for active vibration control of dynamic structures

A. Suhariyono, N. S. Goo, H. C. Park, K. J. Yoon, Konkuk Univ. (South Korea)

This paper presents the use of Lightweight Piezo-composite Curved Actuator (LIPCA), recently-developed powerful smart actuator, for vibration suppression as actuator. LIPCA is composed of a piezoelectric ceramic layer, a carbon/epoxy layer and fiberglass/epoxy layers. When compared with the conventional piezoelectric ceramic (PZT) actuator LIPCA has advantages such as high performance, durability and reliability. In this study performances of LIPCA were showed in an active vibration control system. Experiment was performed simply on aluminum beam and conventional configuration. Accelerometer sensor, single LIPCA actuator and digital controller were used in the active vibration control configuration. In addition, attached LIPCA has been tested and analyzed to investigate delamination in adhesion between LIPCA and aluminum beam. Several adhesion methods have been tried to find the best one. Test results have indicated that LIPCA actuator could suppress the vibration of aluminum beam successfully with high performance, durability and reliability. It is possible to apply LIPCA as actuator to control vibration of complex dynamic structures.

5760-58, Session 11

Design of a novel magnetostrictive-viscous damper

X. Guan, J. Li, J. Ou, Harbin Institute of Technology (China)

During last 30 years, in order to mitigate damage to civil structure during earthquakes and winds, different kinds of energy absorption devices were designed and fixed on large quantity of structures. Especially, in the recently 10 years, new semi-active dampers, which designed based on special performance of smart materials, such as MR/ER fluid, piezoelectric ceramic and magnetostrictive material got rapid development. As possessing virtue of low power requirement, simple control and fast response, above semi-active dampers are potential to be main vibration control devices for civil engineering structures. In this paper, a novel adjustable viscosity damper, which designed based on character of traditional viscous damper and new magnetostrictive composite was introduced, the influence of structural parameters on performance of above damper was discussed. And one damper which can be used in civil engineering was theoretical designed.

5760-59, Session 12

Experimental analysis of wave propagation in periodic grid-like structures

M. Ruzzene, S. M. Jeong, Georgia Institute of Technology

This work presents the experimental investigations of wave propagation in two-dimensional periodic lattice structures. Periodic structures in general feature unique wave propagation characteristics, whereby waves are allowed to propagate only in specific frequency bands, while they are attenuated at frequencies belonging to the so-called "band-gaps". Two-dimensional periodic structures complement this feature with a low frequency directional behavior, which makes them attractive candidates for vibration isolation and confinement. The directionality and band-gap characteristics of a rectangular lattice are here investigated. An optimized configuration is found through a numerical model previously developed and presented. The specimen is manufactured via stereolithography techniques, and tested for validation and demonstration purposes. The wave field in the lattice is generated by a point harmonic excitation at various frequencies, and it is measured through a Scanning Laser Vibrometer. The objective of the tests is the validation of the numerical model and the demonstration of the unique filtering properties of the considered structural assembly.

5760-61, Session 12

Vibration isolation of automotive vehicle engine mounting systems

S. A. Asiri, King Abdulaziz Univ. (Saudi Arabia)

The automotive vehicle engine is the main source of mechanical vibrations of automobiles. The engine is vulnerable to the dynamic action caused by engine disturbance force in various speed ranges. The vibrations of the automotive vehicle engines may cause structural failure, discomfort to passengers because of high level noise and vibrations or malfunction of other parts.

Customer awareness and sensitivity to noise and vibration levels have been raised through increasing television advertisement, in which the vehicle noise and vibration performance is used as the main market differentiation. This awareness has caused the transportation industry to regard noise and vibration as important criteria for improving market shares. One industry that tends to be in the forefront of the technology to reduce the levels of noise and vibration is the automobile industry. Hence, it is of practical interest to reduce the vibrations induced structural responses.

The struts of the engines act as the transmission paths of the vibrations transmitted from the excitation sources to the body of the vehicle and passengers. Therefore, proper design and control of these struts are essential to the attenuation of the vibration of platform structures.

To improve vibration resistant capacities of engine mounting systems, vibration control techniques may be used. For instance, some passive and semi-active dissipation devices may be installed at struts to enhance vibration energy absorbing capacity.

In the proposed study, a radically different concept is presented whereby periodic struts are considered because these struts exhibit unique dynamic characteristics that make them act as mechanical filters for wave propagation. As a result, waves can propagate along the periodic struts only within specific frequency bands called the "Pass Bands" and wave propagation is completely blocked within other frequency bands called the "Stop Bands".

The experimental arrangements, including the design of mounting systems with plain and periodic struts will be studied first. The dynamic characteristics of such systems will be obtained experimentally in both cases. The tests will be then carried out to study the performance characteristics of periodic struts with geometrical and/or material periodicity. The effectiveness of the periodicity on the vibration levels of mounting systems will be demonstrated theoretically and experimentally. Finally, the experimental results will be compared with the theoretical predictions.

5760-62, Session 13

Damping of a composite drive shaft

H. A. Ghoneim, Rochester Institute of Technology

As in most engines, modern transmission drive shafts demand less weight and cost, as well as better performances, including operating at higher speed and transmitting more torque. Introducing drive shafts made up of composite materials may meet the higher torque and less weight requirements. The demand for higher speeds operation (near and post resonance) necessitates the implementation of a vibration suppression technique.

This paper proposes a technique for introducing the desired damping to a composite drive shaft. In principle, damping is introduced at the pivoted boundaries, where the couplings are located. The results of this proposed damping technique is compared with the recently introduced partial constrained cylindrical layer damping treatment [1].

A mathematical model, including the gyroscopic effects, based on the Timoshenko beam assumption, energy approach, and the extended Lagrange's equation, is adopted. The finite element technique is applied to derive the corresponding discrete dynamic equations of motion . The natural frequencies and damping ratios are determined from the mass [M], damping [C], and stiffness [K] matrices.

A simply-supported composite drive shaft made of a generic T300/5208 carbon epoxy with ±30 fiber angle orientation is the subject of investigation. The geometry of the drive shaft under investigation is 60 inch long, 6 inch average diameter, and 0.06 inch in thickness. Preliminary analyses investigate the variation of the fundamental bending frequency and corresponding damping ratio with the angular damping constant applied at both ends. The analysis is conducted for the stationary as well as for spinning drive shaft (12000 rpm).

The results capture the branching phenomenon and clearly demonstrate the merits of the proposed damping techniques. Not only does the technique stiffen up the flexure stiffness of the drive shaft, but it also can introduce considerable damping to the shaft. That is, this technique would successfully increase the operational speed of the drive shaft.

[1] H. Ghoneim, and D. J. Lawrie, "Analysis of flexural vibration of a composite drive shaft with a cylindrical constrained layer damping," SPIE Proceedings, Smart Structures and Materials, March 2004, 5386, pp 132-140.

5760-63, Session 13

Chiral hexagonal cellular sandwich structures: a vibro-acoustic assemssment

T. L. Lew, Univ. of Sheffield (United Kingdom); A. Spadoni, Georgia Institute of Technology; F. Scarpa, Univ. of Sheffield (United Kingdom); M. Ruzzene, Georgia Institute of Technology

In this work we describe the vibroacoustic behavior of a novel concept of core for sandwich structures featuring auxetic behaviour, enhanced shear stiffness and compressive strength compared to classical cellular cores in sandwich components for sandwich applications. The out-plane properties and density values are described in terms of geometric parameters of the honeycomb unit cells. Opposite to classical honeycomb cellular applications, the hexagonal chiral structure presents a noncentresymmetric configuration, i.e., a "mirror" symmetrical topology. The derived mechanical properties are used to assess the modal behaviour and modal densities of sandwich plate elements with chiral and standard cellular cores. The analytical findings are backed up by dynamic tests on chiral honeycomb plates and sandwich beams. The structural components, manufactured using Rapid Prototyping equipment, are tested using a Scanning Laser Vibrometer facility, while being subjected to random point excitation in the frequency range 10 Hz-1 KHz.

5760-64, Session 13

Impact response of flexible cylindrical tubes filled with a shock absorbing composite

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From 2005, a new EU legislation relating to pedestrian impacts with moving vehicles will come into force. This legislation poses considerable challenges for automobile design engineers, which cannot be met by existing technology. If the conventional impact absorbing materials are used, bumpers which are soft enough to satisfy the lower leg-to-bumper criteria will be too soft to provide adequate cushioning for bumper-to-bumper or other non-pedestrian impacts. This paper is an investigation of the impact response properties of flexible beams made from a blend of elastomeric capsules or beads in a matrix of a Newtonian fluid. For localised impacts that involve partial coverage, such as pedestrian leg impact, a hollow beam filled with this composite reacts with a relatively low stiffness. But for impacts that involve complete or almost complete coverage of the beam surface, such as bumper-to-bumper impacts, the beam reacts with a relatively high stiffness.

In this work, results are presented from impact tests on deformable cylindrical beams containing this shock absorbing composite. On impact the pressure of the matrix liquid increases and the beads compress absorbing the shock. The force is transmitted to the all the beads inside the beam via the matrix liquid. The container is cylindrical in shape, and has a diameter of 97 mm. The length depends on the volume of beads contained. The cylinder wall was made from layers of thin sheets of a polythene material. A drop mass of 15 kg with a semi-cylindrical impact head is used to impact the sample (cylindrical beam) at an angle of 900 degrees. The semi cylindrical impact head has a diameter of 100 mm and 150 mm length covering the width of the impacted sample beam. The method of preparation of the beams is described in detail and the different factors that affect the performance of the beams are outlined.

During impact, there are both compressive and viscous forces acting inside the beams. The first half of the characteristic curves obtained is more associated with the viscous forces acting in the composite beam. This is highly dependent on the shapes of the container and impact head as well as the impact velocity. The viscosity of the matrix liquid is also a factor, as at these initial stages of impact, the velocity of the drop mass is closest to impact velocity. It is also shown that as the number of layers of the polythene sheets used to fabricate the beam are increased, the deformable beam is able to withstand more pressure, and subsequently absorb more energy. These changes are more apparent in the second half of the characteristic curves obtained, where the drop mass velocities are smaller and the pressures are higher

5760-65, Session 13

Predicting the effectiveness of viscoelastic damping pockets in beams

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The high levels of response that can build up if a structure is excited at, or near, the natural frequency can only be reduced in a small number of ways. Firstly, the vibration levels can be reduced by changing the mass and stiffness characteristics so that the natural frequency is outside the operating frequency range. Another way is to isolate the structure from the excitation. The third approach is to introduce damping.

It is well know that Constrained Layer Dampers (CLD's) offer an effective means for suppressing structural vibration and for reducing levels of unwanted noise. The main way in which energy is dissipated in a traditional constrained layer damping system is through shear deformation in the viscoelastic core. But the application of CLD's generally requires smooth surfaces on which to apply the viscoelastic and the constraining metal layers. If the surface is rough or jagged, the application of CLD treatment becomes difficult or impossible. In such cases, the use of alternative methods for adding damping to the structure is useful.

The approach adopted in the present work is the use of 'damping pockets' in a structure. These are in the form of cavities filled with a viscoelastic material. These geometric features are designed-in or introduced into parts of the structure where there is significant strain such that the enclosed viscoelastic medium is subjected to significant levels of shear deformation.

To illustrate the benefits of using these designed-in damping treatments, the vibration response of viscoelastically-damped beams is predicted using the finite element method.

Firstly a beam with a traditional CLD treatment is considered. The levels of bonding between the viscoelastic layer and the beam surface is varied to represent beams with varying surface finishes and the effects this has on the levels of damping is recorded.

A series of beams are then considered, including bare undamped beams, beams with traditional CLD treatments applied at locations along the length of the beam, and beams with designed in viscoelastic pockets located at various locations along the length of the beam. Transmissibility analysis is carried out on FEA models of the different beams and the levels of damping, for each of the different treatments, at each of the locations are then compared.

It is shown that that the effectiveness of the damping pockets depends on their location and size with respect to the highly stressed regions of the beams. It is shown that there is a greater level of shear deformation in the damping pockets compared to the traditional CLD treatments and it is shown that the levels of

damping achieved is greater for the designed in dampers. The location and size of the designed in viscoelastic treatment must be considered carefully as the introduction of the damping pocket also changes the structural properties of the beam, and can lead to a reduction in stiffness.

5760-05, Poster Session

Vibration isolation of a ship's seat

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In the last century, mechanical vibration science was one of the most significant branches of science. Making huge structures, high-speed machines, rotary shafts with high rotational velocity, made designers study their vibration. Especially historical event of breaking Tacoma Bridge, defined the importance of vibration analysis more than before. Thus, mechanical engineers decided to put a safety margin in natural frequency for their machines. Moreover, civil engineers were searching for structures, which could sustain common earthquakes in so many modern cities such as San Francisco and Tokyo. Therefore, vibration isolation science was established. This science was completed with its complicated applications in chassis of motor vehicles, seats of planes and automobiles and the origination of the active control in decades of 1950 and 1960 was a newer and more modern start to it.

The purpose in this paper is to proceed to the theory of vibration isolation and then applying it to a ship's seat. According to this, the causes of vibration has considered first and then with mathematical modelling, the vibration over crew' seat is going to be minimized by using TMD method.

The principals of TMD method were used for the first time to reduce the ship's rolling like hull vibration. Later, Ormandroyd and Den Hartog presented a theory for TMD method in an article in 1928 following this; there was a partial discussion about optimum tuning of the damping parameters in the Den Hartog's book in mechanical vibration in 1940. The initial theory was used for an undamped SDOF system under sinusoidal excitation force. Numerical methods obtained the development of this theory to damped SDOF systems. Important activities have done by Lin and Tsai (1993), Warburton (1980, 1981, and 1982), Randall (et al. 1981).

There are examples of this method in damping unexpected vibration in common structures like John Hancock Tower (Engineering News Record, Oct. 1975), Citicorp Centre (Engineering News Record Aug. 1975, McNamara 1977, Petersen 1980), Canadian National Tower (Engineering News Record, 1976), Chiba Port Tower and Crystal Tower.

What is done in this paper is a successful reduction of system response around natural frequency of the structure by a passive method. Moreover using active control systems will be compared with passive systems

5760-67, Poster Session

Magnetic field analysis of disk-type magnetorheologic fluid dampers

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Magneto-rheological (MR) fluid is one of highly functional or smart fluids whose apparent viscosity can be dramatically varied by means of an external magnetic field. Such special characteristics of the MR fluid provide a possibility to control the dynamic characteristics of the traditional passive damper. In order to significantly change the MR fluid viscosity, the magnetic flux density in the working area filled with the MR fluid should be as high as possible and the magnetic field should be uniform in order to easily model the MR fluid damper. Therefore, the reasonable design the magnetic path and choose the size of the MR fluid damper are of importance. After analysis and comparison various designs of disk-type MR fluid damper based on the shear mode, a simple and effective disk-type MR fluid damper is presented in this paper. The magnetic field of the disk-type MR fluid damper with one moving disk and more moving disks is analysed by the finite element method, the effects of the magnetic path size and the design parameters of the damper, such as excitation current, air gap, axial width of the stator, on the magnetic flux density in the air gap are studied. The theoretical results are compared with the experimental results, and the results are well agreement. It is shown that the magnetic flux density of the designed disk-type MR fluid damper can significantly changed with the applied current in the coil, and the behavior of the MR fluid damper can be controlled by a simple magnetic coil with low voltages. The results obtained are helpful for designer to design this kind of damper.

5760-69, Poster Session

Sliding liquid surface in earthquake isolation bearing

F. Bartolozzi, Consultant

In absence of an earthquake, the building transmits a part of the vertical static load to the single bearing, where the internal liquid is stressed to centred compression, due to the presence of an hinge, located to the base of each pillar.The incompressibility of the liquid and the hermetic seal of the device, which contains the liquid, guarantee a reaction of the bearing in accordance with the conditions of equilibrium and stability. During an earthquake, the foundation-soil complex horizontally moves in any direction sliding without friction, due to the presence of the liquid, with respect to a central body, which leans on the liquid. This body, in turn, moves in opposed direction to the motion due to a system of pulleys and to an inextensible cable, sliding on the liquid surface with respect to the foundation-soil complex and involving in the motion the above building too, without so transmitting it earthquake energy, because the friction force between the building and the bearing, in correspondence of the liquid surface of sliding, is almost zero, in conformity with the equilibrium condition to the horizontal translation. The displacement of the foundation-soil complex in any direction occurs according to the vector sum of the components X and Y of the motion, thanks to the presence of the devices with ball bearings. The earthquake isolation system, which uses the above bearing, presents the following characteristics:1. the device, containing the liquid surface of sliding, must be with hermetic seal in the states of quiet and of the motion of the soil; 2.during an earthquake, the seismic energy in the building is practically zero, due to the almost total absence of internal friction in the liquid, which guarantees a very good possibility of the building sliding with respect to the foundation-soil complex;3. the system is independent from the earthquake frequency, due to the total absence of earthquake vibration natural frequency;4. the economical competitiveness with all systems with total or partial absorbition of earthquake energy is very high;5. the psycho-pysical discomfort in the inhabitants, due to the small horizontal translation of the buiding during an earthquake, is negligible.

5760-70, Poster Session

Predictive semi-active control of shock isolation system using magnetorheological damper

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Protection of sophisticated electronic devices mounted in military, air and marine vehicles used for maneuvering, guidance, reconnaissance, communication and control of weapon systems from shock loads is of extreme importance for the success of mission. For Shock isolation semi-active devices which operate in passive and active mode are important. Such devices combine the best features of passive and purely active isolation devices and have the ability to suppress shock loads even in case of actuator and sensor failures.

Objective of this paper is to use magnetorheological (MR) damper for shock isolation. MR fluids belong to the class of smart materials that its unique ability to change properties when magnetic field is applied and thereby, produce variable damping force. The MR damper shock isolation system considered in this paper consists of a target system (to be protected from shock) that is connected to the base by the MR damper and coil spring. The base is excited by the disturbance force causing the base acceleration that can be encountered in the typical military vehicles. We have designed an optimal control law based on the nonlinear predictive control theory for attenuating the acceleration of payload (target mass). The control law derivation includes the dynamics of the yield force that is modeled as a first order low pass filter with different time constants. The complete system is simulated and passive and semi-active modes of operation are examined. These results indicate that semi-active control of the MR damper system provides superior shock isolation performance compared to the passive (open-loop) control. Moreover the choice of performance which is a quadratic function of the acceleration of the target mass and the c1010ntrol input (voltage), provides flexibility in meeting the control magnitude and shock minimization (acceleration of the target) requirement.

Conference 5761: Active Materials: Behavior and Mechanics

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5761-01, Session 1

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No abstract available

5761-02, Session 1

Automatic measurement of resistance of carbon nanotubes sheet actuators and the influence of the resistance on its actuation behavior

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Recent advances in Technology have led to the development of nanostructured materials based on the assembly of carbon nanotubes with applications ranging from micromechanics to electronics and energy storage. An exciting property of carbon nanotubes is its electro-mechanical actuation behaviour. The actuation behaviour of the bucky paper is greatly influenced by its surface resistance. In this work we propose to find out the resistivity on the bucky paper, a porous meshwork of carbon nanotubes, automatically in a controlled and reproducible manner. The resistivity is measured by using four wire resistance measurement instruments. It has two pairs of identical poles, positive and negative. Opposite polarity poles are short circuited leading to two probes out of which one is taken as a reference and the other as varying probes. Considering a bucky paper of 20 mm diameter, the reference probe is kept fixed at a single point and the varying probe is moved in different directions of the bucky paper plane. When performed manually the obtained results are highly nonlinear having many disturbances. In order to avoid these disturbances, an automatic movable probe holder has been designed and tested which provides a reproducible condition for the measurement automated by LabVIEW® interfacing. A direct measurement of resistivity prior and later to the actuation testing is performed. Based on the results, the influence of resistivity on actuation performance has been analysed.

5761-03, Session 1

Electric field alignment of single-wall carbon nanotubes in polymers

S. Banda, Z. Ounaies, Virginia Commonwealth Univ.; J. Wilkinson, Virginia Polytech Institute and State Univ.; C. Park, National Institute of Aerospace; J. S. Harrison, NASA Langley Research Ctr.

Electric field alignment of single wall carbon nanotubes in polymers

Sumanth Banda, Zoubeida Ounaies, Cheol Park, John Wilkinson, and Joycelyn Harrison

Single wall carbon nanotubes (SWNTs) are long, slender fullerenes where the walls of the tubes are hexagonal carbon and are capped at both ends with C60 fullerene hemispheres. SWNT can be visualized as a graphene sheet that has been rolled into a tube. Due to their excellent electrical, thermal and mechanical properties, and their low density, SWNTs are attractive as inclusions in polymers, potentially resulting in composites that combine structural functions with sensing and actuation capabilities. SWNTs are highly anisotropic in nature because of their high aspect ratio; they can be aligned in polymers to produce controlled anisotropy in the composite. Dispersing and aligning SWNTs in polymers presents a challenge, as they tend to agglomerate and curl due to the strong van der Walls forces present. Different methods have been used to align the SWNTs, namely applying an electrical field, a magnetic field, or by mechanical stretching. In this work, electric field is used as a means to align SWNTs after dispersion in two different polymer matrices: a polar polyimide and a blend of (UDMA/HDDMA) polymer.

In the case of the SWNT-polyimide composite, alignment is accomplished by electrospinning. Electrospinning is a technique whereby the polymer solution is charged by a high voltage DC power supply, which is dispensed through a needle. A grounded target is kept at a distance from the needle. When the electric field overcomes the surface tension of the polymer droplet, a thin jet of the solution is ejected from the tip of the needle and is drawn towards the grounded target. As the jet travels towards the ground, the solvent evaporates, depositing a nonwoven fiber mat on the target. A DC voltage of 15 kV, 20 kV and 25 kV is used to produce well-oriented and aligned SWNT-polyimide fibers. In the case of the UDMA/HDDMA blend, AC electric field is used as a means to align the SWNTs. It is noted that the UDMA/HDDMA blend is selected for this study because it is photo-curable with the aid of a blue light gun. This allows the simultaneous application of an electric field while curing. An AC electric field of 43.5 V/mm is applied for 10 min at room temperature at frequencies that varied from 0.1 Hz to 100 KHz. Raman spectroscopy, electrical conductivity and dielectric measurements are done to assess the degree of alignment of the SWNTs in both polymeric systems. Figure 1 illustrates the measurement direction, namely parallel (z-axis) and perpendicular (x-axis and y-axis) to the electric field. The electrical conductivity (s) and the dielectric constant (e) are measured using a high precision LCR meter at frequencies of 20 Hz to 1 MHz at room temperature. Polarized Raman spectroscopy is performed using a Nicolet dispersive Raman spectrometer with a polarizer. Polarized Raman lines can often provide conclusive identification of the symmetry species of the vibrational mode responsible for the line. Applied here, the results can provide a qualitative assessment of the degree of orientation of the SWNTs in the polyimide fibers and in the (UDMA/HDDMA) polymer.

A few significant findings are noted when analyzing the conductivity and dielectric data of the aligned SWNT polyimide fibers and aligned SWNT/UDMA/HDDMA composites; 1) results indicate that the aligned samples exhibit a high anisotropy in conductivity and dielectric constant, namely, the values in the parallel direction are higher than those in the perpendicular direction (see Figure 2a, 2b for dielectric results); this anisotropy indicates a preferential alignment of the SWNTs; 2) the value of the dielectric constant in the parallel direction increases with increase in SWNT content in the polyimide matrix (Figure 2a); 3) the value of conductivity and dielectric constant increases with frequency of alignment in UDMA/HDDMA composite (Figure 2b).

The conductivity and dielectric constant is higher in the parallel direction due to the contribution of the aligned SWNTs. The parallel dielectric constant in the polyimide fibers increases with SWNT content as it is highly affected by the aligned SWNTs. The perpendicular dielectric constant in the polyimide fibers remains the same as it is dominated by the dielectric of the polymer matrix (Figure 2a). A similar trend is also observed in UDMA/HDDMA composite. There are different classical theories that describe the dielectric response of the composite medium with aligned inclusions; Bruggeman's theory is one that has been successfully used when analyzing carbon black polymer composites. The composites can be considered as aligned nano-cylinders (the SWNTs) dispersed in a continuous medium (the dielectric polymer host). The theory is used to find equivalent principal permittivities of the composite in x, y and z directions with the cylindrical inclusions aligned in the z direction. The equations of relative permittivities perpendicular (ex, ey) and parallel (ez) to the aligned inclusions are :

$$ex = ey = e1 + (C\,(e2-e1).2.e1)/(2.e1+(1-C).(e2 - e1)) \quad (1)$$

$$ez = e1 + C\,(e2-e1) \quad (2)$$

where ex, ey, and ez are the relative permittivities in x, y, and z directions respectively; C is the concentration of the inclusions in percent; e1 and e2 are the dielectric permittivities of the matrix and the inclusion respectively. The obtained equations allow us to evaluate the effects of the aligned inclusions on the dielectric behavior of the composite and compare them to experimental results. This analytical theory validates our experimental finding, in that the dielectric constant in the perpendicular directions (x and y) are isotropic, and mostly affected by the dielectric constant of the medium (e1); while that in the parallel direction is mostly dominated by that of the inclusion e2 (equation 2).

The Raman spectrum on SWNT polyimide fibers and SWNT/UDMA/HDDMA is recorded at several angles between the SWNT axis and the incident polarization ranging from 0° to 180°. The Raman peak in each spectrum corresponds to the tangential mode (1590 cm-1) of the SWNT in the composite. Inspection of the spectra reveals that the maximum intensity is obtained when the polarization of incident radiation is parallel to the SWNT axis, while the smallest intensity is obtained when the polarization of incident radiation is perpendicular to the SWNT axis. Difference in the intensities when the radiation is parallel and perpendicular to the SWNT axis indicates preferential alignment of SWNTs in both polyimide fibers and UDMA/HDDMA polymer.

Based on electrical conductivity, dielectric constant and Raman spectroscopy it can be concluded that SWNTs can be aligned in polyimide and (UDMA/HDDMA) polymer matrices both by electrospinning and by in-situ curing under AC electric field respectively.

Conference 5761: Active Materials: Behavior and Mechanics

5761-04, Session 1

Metal Rubber™ materials

R. O. Claus, Virginia Polytechnic Institute and State Univ.; J. H. Lalli, J. B. Mecham, B. A. Davis, R. M. Goff, A. Hill, S. Subramanayan, NanoSonic, Inc.

This paper discusses Metal RubberTM, a new free-standing nanocomposite material that combines the properties of metals and rubber. Like metals, Metal RubberTM has high electrical and thermal conductivities. Like elastomers such as rubber, it has low modulus and can be repeatedly elongated to several hundred percent strain yet relax elastically back to its original shape, all while remaining conductive. Metal RubberTM is formed by a modified electrostatic self-assembly approach that allows the formation of thick, large surface area nanocomposites to be formed with multiple controlled constitutive properties. The largest dimensions formed to date are approximately 0.6 meter square and 1 centimeter thick. The synthesis process uses an approach similar to conventional electrostatic self-assembly to rapidly form molecular level coatings on top of a chemical release layer applied to a substrate. After the desired thickness of material is achieved, the self-assembly process is stopped, and the chemical release layer etched away to free the nanocomposite from the sacrificial substrate. The presentation concerning this material will detail the current status of material development at the time of the conference, including the range of conductivities and moduli achieved. It will also describe the synthesis procedure which may be extended to other macroscale nanostructured materials with potentially useful properties, not obtainable through normal processing approaches.

5761-05, Session 2

Nano-coating with controllable reflectance spectrum

O. Aktsipetrov, T. Murzina, M. Murzina, J. P. Farrell, Brookhaven Technology Group, Inc.

We consider smart coverings based on nano-structured materials. The developed configuration allows one to dynamically modify the spectral position of the reflection coefficient of the material, e.g., dynamically change its color in the reflected light

The three major problems of nano-covering development are discussed.

1. Wafer. A principal problem of nano-covering development is building an adequate wafer, i.e. a matrix into which nano-particles are inserted. In this work, we suggest a unique design of multi-layered nano-porous wafer for 100% reflection control.

2. Active nano-material. A number of nano-particle materials are discussed as the candidates for insertion into the matrix for controllable nano-covering. Advantages and disadvantages of different materials are analyzed.

3. Controlling agent. In principle, the dynamical modification can be achieved by applying external electrical or magnetic fields, external illumination, or a temperature change. As the first implementation, we consider using electrical field as the controlling agent.

5761-06, Session 2

Dielectric constant measurements of nanoscale thickness polymeric films

R. Asmatulu, W. B. Spillman, Jr., R. O. Claus, Virginia Polytechnic Institute and State Univ.

Nanoscale polymeric films were fabricated on Al coated glass slides using a spin coater. The thicknesses of the films (anti-reflective coatings - ARC) were 350 nm, 240 nm and 195 nm obtained at 1500 rpm, 3000 rpm and 4500 rpm, respectively. Measurement electrodes were fabricated on the ARC films using silver epoxy. Capacitance tests conducted at 1 mV and 15% relative humidity were used to determine the dielectric constant of the films over various temperature and frequency ranges. Based on the test results, it is assumed that this is a very useful technique to accurately and easily measure the capacitance and dielectric constant values of nanothickness polymeric films.

5761-07, Session 2

Improving the lifespan of aircraft skins against corrosion attacks by using polymeric nanocomposites

R. Asmatulu, Virginia Polytechnic Institute and State Univ.

R. Asmatulu, R.O. Claus, J.B. Mecham and S.G. Corcoran

Corrosion is a phenomenon of functional and conditional decline of materials under the effect of environment influences including chemical, physical, electrochemical, and other physicochemical factors. The thin film coating is one of the important means to protect metals from corrosion attacks coming from the unwanted electrons, oxygen, water, and scattered ions, but in the long-term corrosion attacks can still take place and cause huge economical and environmental problems for many materials. As a result of these problems, it is estimated that approximately 5% of an industrialized nation's gross national product (GNP) is spent for the corrosion prevention, replacement of corroded parts, maintenance and environmental protections. This corresponds approximately $276 billion cost to the US economy per year at 1998 prices.

In the present studies, several nanoparticles (100 nm) were incorporated into epoxy polymers, and then the obtained polymeric nanocomposites were sprayed on the Al coupons (2024-T3) by a nozzle sprayer at different thickness. The main purpose of nanoparticles in coating materials is to absorb/block unwanted ions/molecules (i.e., Cl-, OH-, H2O, etc.). A urethane top layer (approximately 1 mil) was also coated on some of initially coated surfaces. Several corrosion tests including electrochemical impedance spectroscopy (EIS) and salt spray were conducted on the prepared samples using 0.5 M NaCl solution. The corrosion test results showed that the Al coupons coated by nanocomposites and urethane top coating gave the excellent corrosion resistances against the corrosion attacks. As a result, it is assumed that the novel coating materials will allow military, private companies and government agencies to effectively protect the aircraft surfaces against corrosions.

5761-08, Session 2

Characterization and release of surface tension energy in nanoparticles

O. Aktsipetrov, T. Murzina, J. P. Farrell, M. V. Murzina, Brookhaven Technology Group, Inc.

We develop a technology for characterization and release of Surface Tension Energy (STE) in nanoparticle structures. The technology is based on laser induced resonant plasmon and nonlinear optical effects in nanoparticles.

The direct relation between STE and nonlinear optical parameters of nanoparticles permits use of Second-order Harmonic Generation to measure STE. The method can be applied to characterize surface properties of a wide variety of nanoparticle materials, particularly active materials.

In terms of surface energy release, we concentrate on nanoparticle-dispersed materials in the form of arrays of metal nanoparticles. Second harmonic generation is considered to trigger local plasmon resonances to develop in the material. Local plasmons, in turn, lead to surface energy release.

Nanoparticle dispersed materials offer a very high potential to store energy in the form of Surface Tension. An important benefit of the project is the increased safety and control of energy storage compared to existing chemical systems.

5761-09, Session 2

Carbon nanotubes-coated electroactive paper (EAPap) as hybrid high-displacement actuator

S. Yun, J. Kim, Inha Univ. (South Korea); Z. Ounaies, T. St Clair, Virginia Commonwealth Univ.

Electro-Active Paper (EAPap) has been investigated as an attractive EAP material for artificial muscles due to its many advantages such as lightweight, availability, low cost, large displacement output, low actuation voltage and low power consumption. The EAPap is based on cellulose material, and is shown to involve primarily transport of ions in response to an external electric field. This mechanism is similar to that in ionic electroactive polymers (ionic EAPs), such as conductive polymer actuators, IPMCs, and ionic gels. Depending on the electrode material, EAPap has shown actuation displacement in the range of 2-10mm, at a few volts. Drawbacks of EAPap actuators include a low force output and a dependence on humidity. To address these, a hybrid EAPap actuator is developed based on single-wall carbon nanotubes (CNT)/Polyaniline (PANi)

electrodes, as a replacement to gold electrodes. It is expected that the use of CNT can enhance the stiffness of the tri-layered actuator, thus improving the force output. Furthermore, the presence of the CNT may increase the actuation performance of the EAPap material. CNT is dispersed in dimethyl acetamide (DMAc), and the resulting solution is used as a solvent for PANi. The entire reaction was carried out with stirring in a flask immersed in a 40 kHz ultrasonic bath until the solution viscosity increased and stabilized. The CNT/PANi/DMAc solution is then cast on the EAPap by spin coating. The coated EAPap is dried in an oven. The effect of the following processing parameters on the final performance of the CNT/PANi electrodes is assessed: sonication time, CNT content, spin coating parameters, curing time, and curing temperature. The final performance of the electrodes is quantified in terms of the electrical conductivity under dc and ac measurement conditions using an HP High Precision LCR meter and a High Resistance Keithley Electrometer. The actuation output of the CNT/PANi/EAPap samples is tested in an environmental chamber in terms of free displacement and blocked force. The performance of the hybrid actuators is also investigated in terms of frequency, voltage, humidity and temperature to help shed light on the mechanism responsible for actuation. Comparison of these results to that of the EAPap with PANi and gold electrodes is also accomplished.

5761-10, Session 3

Modeling the electrical impedance of ionic polymer transducers

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Ionic polymer transducers are a class of active material that exhibit interesting chemoelectromechanical coupling capabilities. Initially recognized for their chemoelectric properties, these materials have begun to receive notice as electromechanical transducers. This electromechanical coupling provides the fundamental mechanism for both actuator and sensor applications. Under relatively low electric stimuli (1-10kV) these materials are capable of achieving large bending strains (1-5%). Similarly these transducers provide effective sensing capabilities when subject to an applied external load or deformation. Recent studies indicate that the transducer's performance can be directly related to changes in the polymer's electrical impedance. An analytical model is proposed based upon these findings. The basic tenet of this model is that ion motion is induced as an electric field is applied across the polymer membrane. Transport theory is employed to model this ion motion through an electrostatics approach. This method yields a series of analytical expressions for charge density, electric field and electric potential across the polymer's thickness. The solution of the charge density profile is then used to calculate the isothermal transient ionic current (ITIC). Corresponding to the measured current, this ITIC expression related to the applied voltage to yield a relationship between the applied voltage and the ITIC. Considering the frequency domain representation of this relationship, a series of predictive curves are generated for comparison with experimental results. A series of experiments are also conducted to validate the proposed model. A series of experiments are conducted to examine the effects of excitation voltage on the ionic polymer's electrical impedance. In this manner an impedance map is constructed for the polymer sample, producing a V/I surface that characterizes the material's electrical impedance as a function of frequency and excitation voltage. A discussion of the impact of these findings is presented, along with a discussion of how these findings correlate with the predictive model that has been proposed.

5761-11, Session 3

Role of inherent polarization and ion transport in the actuation of cellulose-based EAP

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The application of electroactive polymer devices requires the availability of their properties at various operating conditions. This in turn necessitates a structure-property relationship based on an in-depth understanding of the underlying mechanism responsible for their strain-field response. Cellulose-based Electro-Active Paper (EAPap) has been studied as an attractive EAP material for artificial muscles due to its low cost, availability, lightweight, large displacement output, low actuation voltage and low power consumption. The understanding of the actuation mechanism of this material is important in order to improve the performance and also to better target the application. So far, based on the structure and processing of cellulose-based EAPap, it is believed that two actuation mechanisms are possible: ion transport and dipolar orientation. Cellulose paper is believed to be an ionic conductor, where ions can be injected in the paper fibers during processing. When an external electric field is applied, these ions become mobile. Based on the displacement results, we will show that the ion mobility is influenced by humidity, temperature, and frequency. Cellulose chains form hydrogen bonds leading to the formation of microfibrils with partially crystalline parts, making cellulose a semicrystalline polymer. Hydrogen bonding may contribute to the dipolar orientation, by stabilizing dipoles and leading to a permanent polarization, resulting in a piezoelectric behavior. Water, present as bound and free molecules, plays a significant role in strengthening the hydrogen bonding as well as in influencing the ion transport. Thermally stimulated current measurement (TSC) and dynamic dielectric spectroscopy (DDS) are used to characterize cellulose EAPap under electric field, temperature, humidity and frequency conditions. TSC and DDS are also used to assess the role of water molecules, hydrogen bonding, ion transport and permanent polarization on the actuation performance of EAPaps. TSC current shows a linear relationship with poling electric field, indicating dipolar orientation. DDS indicates a dependence of the dielectric constant on fiber direction, as well as on frequency, humidity and temperature.

5761-12, Session 3

Electrochemical-based solid state actuation mechanisms based on reversible Li compound formation

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Among the critical enabling factors for advanced reconfigurable or morphing systems are high energy-density active materials. For some of the more aggressive morphing applications, it would be highly desirable to achieve actuation with simultaneously high strain (\›100%) and high actuation stress (\›10 MPa) at elevated temperatures (\›350°C), with active materials that can be readily integrated into a highly multifunctional structure (i.e. all solid-state). In this talk we present theoretical and preliminary experimental demonstrations of the reversible work capability of solid-state electrochemical compound formation. Our experimental test case is the volume expansion incurred during the reversible electrochemical formation of thin-film lithium metal and LiSnx alloys from a standard ceramic lithium ion storage medium, LiCoO2. Reversible work is accomplished through the expansion or contraction of the pure Li or LiSnx film against an external load. Given typical electrochemical driving forces of ~1 eV/atom, the theoretical energy density of such configurations is quite high, exceeding 5 MJ/m3, being limited primarily by the mechanical stability of the individual elements in the system. We discuss the theoretical potential such reversible compound formation mechanisms to form the basis of a high-strain, high-force multifunctional actuator technology. We also discuss the inherent limitations of solid-state diffusion-based mechanisms for actuation, including rate and environmental stability issues.

5761-13, Session 3

Photoresponsive thin films containing Azobenzene

C. J. Barrett, McGill Univ. (Canada)

This paper will describe our recent physical and optical studies of multilayer thin films of novel polyelectrolytes which incorporate light-responsive azobenzene. These azo-polyelectrolytes are interesting as they have the capability to be both addressed with lasers as photo-responsive materials (useful for active surfaces, sensing, and signal processing devices for example), and can be self-assembled into structures on the molecular lengthscale in an aqueous environment, using the + and - ionic groups as building blocks. We report here our recent work with assembling a variety of polyelectrolytes, including nonlinear optical azobenzene polyanions, onto Si substrates. Up to 1000 alternating layers have been sequentially deposited, which exhibit good stability to temperature and solvents. We report a variety of deposition geometries explored for confined systems, and show how layer thickness can be controlled by bath pH over more than an order of magnitude on the nanometer lengthscale. A sample application as an optical sensor is presented.

We have prepared such materials as homopolymers, statistical copolymers, and block copolymers, each with a unique suite of photo-controlled properties. Optical, bulk, and surface properties can be interrelated in these materials, allowing studies both of how light can be used to gather new information about surfaces and self-assembled structures, and also how light can be used to influence surface and structural properties. Many interesting questions about the structure and behaviour of the layers remain unanswered however. We then describe our recent in situ methods to investigate some of these questions, using ellipsometry, surface plasmon resonance spectroscopy, electrophoresis, and solid state NMR spectroscopy.

Conference 5761: Active Materials: Behavior and Mechanics

5761-14, Session 4

Monte Carlo analysis of ionic polymers with cluster morphology

L. M. Weiland, D. J. Leo, Virginia Polytechnic Institute and State Univ.

A computational micromechanics model applying Monte Carlo methodology has been developed to predict the equilibrium state of a single cluster of an ionomeric polymer with cluster morphology. No assumptions are made regarding the distribution of charge or the shape of the cluster. Assuming a constant solvated state, the model tracks the position of individual ions within a given cluster in response to ion-ion interaction, mechanical stiffness of the pendant chain, cluster surface energy, and external electric field loading. Expressions are developed to directly account for forces imposed on ions due to ion-cluster surface interaction. Results suggest that ion pairing is rarely complete; this in turn suggests that the classic assumptions will tend to under-predict electromechanical actuation response.

5761-15, Session 4

Chemo-mechanical model of biological membranes for actuation mechanisms

V. B. Sundaresan, D. J. Leo, D. Hopkinson, H. Tan, Virginia Polytechnic Institute and State Univ.

Plants have the ability to develop large mechanical force from chemical energy available with bio-fuels. The energy released in hydrolysis of ATP assists the transport of ions and fluids to achieve the volumetric expansion through osmotic pressure variation in the cell membrane. Recent calculations for controlled actuation of an active material inspired by biological transport mechanisms demonstrated the feasibility of developing such a material and demonstrated the potential for actuation energy densities on the order of 100 kJ/m3 [1]. The present work focuses on the micromechanics of a representative actuation structure and describes our initial efforts in fabricating such a material. The equation for chemo-mechanical energy conversion is similar to the constitutive equation for a single capsule and is based on thermodynamics of membrane equilibria. Our previous studies demonstrate that the actuation performance is affected by several variables, including the osmotic pressure generated from chemical excitation [1], the mechanical properties of the vesicle membranes, and the matrix material where vesicles are embedded. Finite element analysis of a representative vesicle array demonstrated the utility of localized pressure control [1]. Although the finite element method can quantitatively simulate the actuator performance at a given parameter set, it is difficult to do parametric studies by this method and thus an analytical modeling is still favored in terms of system design and optimization. The micromechanics model developed in this work is applied to the analysis of controlled actuation using biological transport. The actuator material is considered as a composite material which consists of hollow spheres called vesicles and an isotropic linear elastic material matrix. The complex double-layer vesicle membrane is also simplified to be a uniform isotropic material and thus it enables us to focus on important parameters that affect the performance of actuation. Predictions on the actuation authority, time response, and energy density of a complete actuator will be obtained with this model.

This work will also describe our preliminary efforts in modifying biological membranes for actuation materials. We are currently synthesizing phospholipid vesicles formed by electroformation as synthetic alternatives to biological capsules. Micropipette aspiration is done to characterize the mechanical properties of vesicles from different phospholipids. The area compression/extension modulus of the biological capsules ranges from 0.24 N/m to 0.36 N/m, which is considered too compliant for use as an actuation mechanism. Methods for improving the mechanical properties of synthetic vesicles are being studied and reports will be included in this work.

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5761-16, Session 4

Three-dimensional atomistic computational model for electrostrictive graft elastomer

C. Zhang, Y. Wang, Kansas State Univ.; J. Su, NASA Langley Research Ctr.

The electrostrictive graft elastomer is a new type of electromechanically active polymer recently developed by NASA. The polymer contains flexible backbone chains and polarized crystal units. Upon application of an electric field to the polymer, a force is applied to each partial charge. These forces induce the rotation of crystal graft units, which further induces polymer deformation. In this paper, a three dimensional atomistic element approach is employed to predict the electromechanical properties of the polymer. Both crystal unit and backbone mechanical properties, such as modulus and strength, are first calculated. Unit cells of the polymer are identified; their mechanical properties then are analyzed. When mechanical loads are applied to the polymer, the polarized unit deforms and generates an electric field. The stress induced electric field is discussed. Finally, an electric field is applied to the unit cell that induces polarized crystal unit rotations. The polarized unit rotation in turn induces polymer deformation. Relations between applied electric field strength and induced polymer deformation are derived.

5761-17, Session 4

Variable stiffness materials for reconfigurable surface applications

G. P. McKnight, C. Henry, HRL Labs., LLC

Reconfigurable and morphing structures have attracted attention for potentially providing a range of new functionalities including system optimization over broad operational conditions and multi-mission capability. Previous efforts in morphing surfaces have generally focused on small deformation of high stiffness structural materials (e.g. aluminum) or large deformation of low stiffness non-structural materials (e.g. elastomers). This paper introduces a new approach to achieving large strains in materials with high elastic moduli (\>30GPa). The work centers on creating variable stiffness composite materials which exhibit a controllable change in elastic modulus (bending or axial) and reversible strains \>2%. We have examined composite structures composed of rigid elastic elements interleaved with a commercial shape memory polymer that exhibit a controllable change in stiffness as a function of temperature. Materials have been characterized experimentally under small strain bending as a function of temperature, and large strain at elevated temperatures. Simple rule of mixtures modeling and FEM analysis has been used to model expected elastic properties and give good agreement with experimental data. Composite materials with maximum bending stiffness in excess of 50 GPa and 10x stiffness decrease are reported. We discuss the potential use of these materials in large deformation surface reconfiguration applications.

5761-18, Session 5

Applications of magnetically active fiber reinforced composites

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As the application of fibre reinforced polymer composites (FRP) becomes more widespread there is a desire to add functionality beyond that of simple mechanical properties in order to facilitate the development of ‘smart’ materials. For example, the functionality being discussed in this paper is the imparting of significant magnetic properties to a FRP. This can take the form of soft magnetic performance for use in electrical machines or hard magnetic performance for novel forms of sensing or power generation.

It has been demonstrated that by using hollow glass fibres as a reinforcement, magnetic material can be introduced into these fibres without significant effects on the structural behaviour of the FRP. The current studies have included the assessment of such a magnetic FRP in a variety of applications. The addition of hard magnetic materials, e.g. magnetite and barium ferrite, has been achieved through the use of nanopowders and the resulting FRP has been assessed for a novel power generation application. Also, the inclusion of soft magnetic materials has been achieved and investigated for use in innovative electric machines. The magnitude of magnetic performance that can be currently achieved is controlled by the availability of suitable magnetic materials in fine powder form and the volume of magnetic material which can be incorporated within the fibres.

5761-19, Session 5

Characterization of quasi-static and dynamic properties of Terfenol-D composites

A. P. Mortensen, M. J. Dapino, The Ohio State Univ.

Materials with different properties are necessary to fulfill the

vast range of sensor and actuator applications which emerge as

technology advances. Terfenol-D provides large magnetic field-induced strain, or magnetostriction, but has limitations. The material is very brittle when not in compression and therefore cannot be easily machined. Monolithic Terfenol-D exhibits eddy current losses but this can be reduced with laminations, which are costly. Placing Terfenol-D powder in a matrix can help to overcome some of these limitations while maintaining high magnetostriction. The flexible geometry and impact resistance of the composite allows for a broader range of geometries in both cast and machined form. Inaddition, the composite insulates the metal particles and prevents eddy currents from forming thus reducing power losses in dynamic applications. The reduction in cost by using less Terfenol-D is another important advantage as it could enable the production of mass produced devices.

Magnetostriction is caused by domain wall motion and domain rotation within the material~\cite{jiles}. While the ‹111\› crystal direction provides the largest magnetostriction~\cite{knight}, current manufacturing methods only allow for the less active ‹112\› direction to be aligned along the rod axis. Particles in a matrix allow the alignment of the ‹111\› direction with the rod axis during the casting process which creates chains of Terfenol-D with the ideal alignment within the composite.

This paper will address the processing of particle-embedded Terfenol-D composites and present quasistatic and dynamic methods for their characterization. While composite concepts based on particles or fibers embedded in a nonmagnetic matrix have been discussed before~\cite{carman,knight}, this paper is novel in that (1) the specimen is a relatively large high aspect ratio rod, (2) quasistatic strain and magnetization measurements include extensive minor loop testing, and (3) dynamic measurements are performed in a hybrid piezoelectric/ magnetostictive transducer.

The desired specimen size for the testing equipment is a 2" (50.8 mm) long rod with a diameter of 1/4" (6.35 mm). The rod is magnetized along the cylinder axis and requires Terfenol-D particles to be oriented along the same axis. The particles should be aligned with a uniform magnetic field throughout the sample to provide ideal particle distribution. If the field is too low in the middle the particles will not align with the axis, while a high concentration of magnetic field at the rod ends may pull the particles to the poles. Finite element modeling was utilized to design a mold with a magnetic circuit that would achieve even distribution as seen in Figure 1. End magnets were not capable of achieving this, so a permanent magnet in the shape of a cylindrical tube was selected. A semi continuous circuit was designed to effectively balance the field throughout the specimen.

Magnetic testing is usually done with major loops that saturate a material in a positive and negative field. These tests are adequate for demonstrating the maximum strain, induction, and magnetization the material can achieve and for Characterization of certain material properties but do not provide information on material behavior at the smaller fields in which dynamic actuators and sensors are often operated. Minor loops cycle a magnetic field within a small range that allows characterization of behavior below or near saturation. Low frequency signals of 20 mHz or less were generated and zeroed with a DC bias circuit. This signal was amplified and used to power a research transducer which includes a water-cooling system for maintaining sample temperature constant. The induction was measured with a small sensing coil and an integrating flux meter and the magnetic field was calculated from the current supplied to the transducer which was previously calibrated~\cite{malla}. Major magnetization and strain loops were performed with sine waves and triangular waves of constant slope.

Minor loop signals were created for various amplitudes and locations along the hysteresis curve, as shown in the example measurements of Figure 2 for monolithic Terfenol-D. High frequency applications and broadband transducers can be implemented with the advantages of Terfenol-D composites. The composite reduces most of the hysteresis loss found in monolithic Terfenol-D by insulating the particles which prevents eddy current loops from forming inside the material. Dynamic tests were performed in a broadband transducer that is a double resonant system in which a piezoelectric stack and a Terfenol-D rod are mechanically connected in series. Broadband operation is obtained due to the inherent 90-degree phase shift between the piezoelectric and magnetostrictive materials. The former material controls the high frequencies while the latter controls the low frequencies~\cite{downey}. The composite rod is used in place of the monolithic rod with the goal of increasing the bandwidth of the transducer.

5761-20, Session 5

Degradation of Terfenol-D particle epoxy composites under low-frequency cyclic magneto-mechanical loading: comparisons of matrix polymer

W. D. Armstrong, Univ. of Wyoming

Particulate composites of magnetostrictive Terfenol-D were prepared with polyamine and anhydride cured epoxy polymer matrices with the presence or the absence of a strong magnetic field. These composites were studied to investigate (i) the influence of magnetic field that is applied during specimen preparation in strain output levels, (ii) performance loss at high temperatures, and (iii) the influence of matrix material in magnetostrictive strain performance. A six-way comparison is made of materials processed under magnetic field with materials processed under no magnetic field, and magnetostrictive strain performance at glass transition finish temperature with magnetostrictive strain performance at glass transition start temperature, and magnetostrictive strain performance in low modulus matrix systems with magnetostrictive strain performance in high modulus matrix systems. A four-way comparison is also made between the micrographs for strain-cycled and non-strain-cycled samples and relative damage incurred by samples prepared using high and low modulus matrix systems.

5761-21, Session 5

Magnetic sensor for high temperature using a laminate composite of magnetostrictive material and piezoelectric materials

T. Ueno, T. Higuchi, Univ. of Tokyo (Japan)

This paper describes a magnetic sensor using a laminate composite of magnetostrictive material and piezoelectric materials combined with a magnetic circuit. A voltage is induced on the piezoelectric materials by deformation of the magnetostrictive material when the distance of the sensor and a target yoke changes. The sensor does not only generate a sufficient voltage without any power supply, but also can be used in a high temperature because of high curie temperatures of both materials. We here constructed a sensor using a composite of Tb-Dy-Fe alloy and LiNbO3 and demonstrated its high heat resistivity up to 250 °C by experiments.

5761-22, Session 5

Genetic algorithms for rheological parameter identification of magnetorheological fluids

A. Chaudhuri, N. M. Wereley, Univ. of Maryland/College Park

Magnetorheological (MR) fluids are smart materials whose rheological properties may be varied by application of a magnetic field. While the overwhelming majority of existing MR fluids are composed of micron-scale particles of iron in a non-magnetic carrier liquid, the density of the iron particles makes them susceptible to settling in the absence of frequent remixing because of the predominance of gravity forces. Once sedimented, residual magnetic attraction between particles makes re-dispersion difficult. Nanometer sized iron particles (10nm to 100nm) have been introduced to reduce settling while maintaining useful levels of stresses. The mixture overcomes the settling problem but the shear stresses obtained at same shear rates are drastically reduced in comparison to fluids with micron-sized particles.

Both Herschel-Bulkley (HB) and Bingham-Plastic (BP) constitutive models are used to characterize the fluids. The BP model has two flow regimes: a rigid pre-yield behavior for shear stresses less than the field-dependant yield stress, and flow with constant viscosity in the post-yield region. The HB model is non-linear and has three parameters: the yield stress, the consistency parameter and the flow index. These fluids flow only if the local stress is greater than the yield stress.

Genetic Algorithms (GA) have been widely used in applications where a globally optimal solution is required. Usual estimation methods are susceptible to initial guesses and the obtained parameters may be only locally optimal. GA uses a probabilistically guided search procedure which simulates genetic evolution. Populations with stronger fitness are identified and retained, while those with weaker fitness are discarded. The algorithm cannot be trapped in local minima since it employs random mutation procedures. The overall search procedure is stable and robust and can identify globally optimal parameters of a system.

Rheological data is obtained from tests on MR fluids containing nanometer sized iron and cobalt particles. The iron particles have a mean diameter of 28nm while the cobalt particles are aspherical in shape and have an equivalent diameter of

100nm. Both the BP and HB models are fitted using a simple genetic algorithm to estimate the model parameters. Constraints are applied within the algorithm to ensure a monotonically increasing trend of the yield stress with increase in magnetizing current. The obtained parameters provide a good fit to the experimental data. The parameter variations with change in magnetizing current are smooth and offer greater physical insight into the phenomenon. Comparison of estimation errors shows that the Herschel-Bulkley model is a better choice as a constitutive equation for describing the behavior of nano particle based MR fluids. We also show that genetic algorithms can be efficiently applied to such rheological parameter estimation problems and it provides results comparable to those obtained from usual gradient-based schemes.

5761-23, Session 6

Elevated temperature aging of stress annealed of Fe-Ga transduction alloys

M. Wun-Fogle, J. B. Restorff, Naval Surface Warfare Ctr.; A. E. Clark, Clark Associates, Inc.; E. M. Summers, Etrema Products, Inc.

The addition of Ga to b.c.c. Fe greatly increases the magnetostriction of Fe in the ‹100\› directions (by a factor of 12 in Fe81Ga19).1 These Fe-based magnetostrictive materials are mechanically tough and thus can be used under both compressive and tensile loading. The object of this study is to examine the effects of temperature aging on FeGa alloys with built-in uniaxial stress anisotropies. A highly magnetostrictive material that can function under both tensile as well as compressive stress has been developed.2 To accomplish this a transverse anisotropy was built into these positive magnetostrictive Fe-Ga (Galfenol) alloys by heat-treatments under compressive stresses of 100 MPa and 150 MPa. To evaluate the performance of these materials before and after stress annealing, magnetostriction vs. applied field as a function of applied compressive and tensile stresses were made. For samples that have not been subjected to the heat treatments under compressive stress, the measured saturation magnetostriction decreases from the large value (~250 ppm) with decreasing applied compressive stress, falling rapidly near zero stress. Following a 6350C heat treatment for 20 minutes under a 150 MPa compressive load, the large saturation magnetostriction extends into the tensile region by approximately 27 MPa (~4 ksi). With this heat treatment it is now possible to obtain magnetostrictions greater than 250 ppm over a broad range of stresses extending from far into the compressive stress region, through the zero stress case, and into the tensile region. Here we examine the effect of long-term aging at elevated temperatures on the built-in uniaxial anisotropy in these stress-annealed alloys.

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5761-24, Session 6

Effect of cyclic stresses and magnetic fields on stress-annealed Galfenol alloys

J. C. Slaughter, J. Raim, Etrema Products, Inc.; M. Wun-Fogle, J. B. Restorff, Naval Surface Warfare Ctr.; A. E. Clark, Clark Associates

It has been shown that single crystal alloys of iron and gallium (Galfenol) have magnetostriction on the order of 400 microstrain.1 This amount of strain is significant in a material that can be machined, welded, and treated as a structural material. Research has also demonstrated that these materials can have a built-in uniaxial stress (stress annealing2) such that with no external stresses, the material appears to be under compressive stress of up to 27 MPa. This built-in stress creates the opportunity for Galfenol to be used under both tensile and compressive loads with full magnetostrictive capability. This research investigates the effect of cyclic stress loading and cyclic magnetic drive fields on the behavior of stress-annealed Galfenol 18.4 (Fe81.6Ga18.4) polycrystal samples. Testing includes cyclic stresses up to 27 MPa for as much as 106 cycles at low frequencies (‹10 Hz). Magnetic testing includes cyclic testing under no external loads with magnetic fields of amplitudes from 1 kA/m up to 16 kA/m. Cyclic magnetic fields are applied without a magnetic bias at low frequencies (‹10 Hz). Results of these tests determine aging effects of cyclic stresses and magnetic fields on stress-annealed Galfenol.

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5761-25, Session 6

Magnetostriction and surface-energy-induced selective grain growth in rolled Galfenol doped with sulfur

S. Na, A. B. Flatau, Univ. of Maryland/College Park

Textured polycrystalline Fe-Ga alloys have the possibility of being useful in magnetostrictive actuators and sensors due to their large saturation magnetostriction potential (~400 ppm) in low applied fields (~200 Oe). It was recently reported that textured polycrystalline Fe83Ga17 exhibits magnetostrictive strain of ~170 ppm as a consequence of rolling and annealing [1]. This value is 55% of saturation magnetostriction along to the [001] direction in single crystal with the same composition. In order to achieve maximum performance in polycrystalline form, we examine the surface-energy-induced selective growth of {100} grains in a controlled sulfur environment during final annealing.

We build on results from selective development of Goss texture in Fe-Si alloys, an -iron alloy that is similar to Fe-Ga. Kohler suggests that although {110} growth occurs under very clean surface conditions, {100} growth occurs under slight surface contamination with sulfur due to adsorption of the sulfur [2]. However, there is a threshold above which the selective growth of {100} grains is changed to that of {111} grains by the interfacial segregation of sulfur which is contained in the bulk interior [3]. We present results from introduction of sulfur additions to Fe-Ga arc-melted, rolled and heat treated specimen and report on resulting texturing.

Goss texturing achieves {110} surface planes, with two ‹100\› and two ‹110\› directions along the surface plane of the rolled material. Ideally, to maximize both magnetization and magnetostriction, we’d prefer development of Cube texture and {100} surface planes with four ‹100\› directions along the surface of the rolled material. For the survival of only {100} grains, the adsorption/segregation of sulfur in the surface should be appropriately controlled by annealing conditions such as time, temperature and atmospheres [2,4].

Polycrystalline Fe83Ga17 and Fe81.3Ga18.7 plus sulfur (~0.5 at.%) buttons prepared by arc-melting are investigated. Specimens with a final thickness of 0.3 mm were produced by hot, warm and cold rolling. The starting button was enclosed in a 321 stainless steel can, sealed by welding to prevent oxidation of the specimen. The canned specimen was hot rolled to give a 65% reduction to a thickness of 2.4 mm over 82 passes at 10000C. And warm rolling at 3500C provided an 83% reduction over 53 passes to give a sheet 0.4-mm thick. After the stress relief annealing step, cold rolling were undertaken until the thickness of 0.30 mm in an effort to develop stronger ‹100\› texture in the rolling direction. A subsequent annealing was conducted under various temperature of 900~12000C for 0.5~5 hours and various atmosphere such as argon, vaporized sulfur, sodium silicate and vacuum. Results summarizing texture development and the saturation magnetostriction and magnetization of rolled galfenol doped with sulfur will be presented. In future work, surface-energy-induced recrystallization may lead to further improvements in strain of annealed galfenol sheets.

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5761-26, Session 6

Investigation of magneto-mechanical properties of Galfenol for coil-less magnetic force control using inverse magnetostrictive effect

T. Ueno, Univ. of Tokyo (Japan); E. M. Summers, Etrema Products, Inc.; T. Higuchi, Univ. of Tokyo (Japan)

We are proposing coil-free magnetic force control using the inverse magnetostrictive effect. Magnetic circuit is made by a magnetostrictive material, permanent magnet and magnetic yoke, and the variation of the magnetization of the magnetostrictive material caused by an applied mechanical stress is converted to the variation of a magnetic force via magnetic circuit. So far we have used Terfenol-D for the magnetostrictive material because of large magneto-mechanical coupling, low permeability and low Young’s modulus. Fe-Ga alloy

known as Galfenol can be alternative for the use, rather more suitable than Terfenol-D because of larger magneto-mechanical coupling, low hysteresis loss, high saturation. Here we investigate the magneto-mechanical properties of FeGa, S-H, B-H (magnetostrictive effect) and Stress-B and Stress-Strain (inverse magnetostrictive effect) and the relation between the properties and bias and variation of the magnetic force. The comparison of results with Terfenol-D clarifies advantages of the FeGa, such as high magneto-mechanical coupling, high saturation and low hysteresis in the proposed magnetic force control.

5761-27, Session 6

Dynamic property determination of magnetostrictive iron-gallium alloys

L. M. Twarek, D. K. Pullen, A. B. Flatau, Univ. of Maryland/College Park

Alloys of iron and non-magnetic gallium (of the form Fe1-xGax), collectively referred to as Galfenol, have been shown to exhibit magnetostrictions in excess of 300 ppm under quasi-static magnetic fields. However, to harness the full potential of this material as an actuator, characterization of Galfenol's magneto-mechanical properties under dynamic operating conditions is required. In this paper, broadband frequency domain results including acceleration per applied magnetic field transfer functions, electrical impedance functions, and minor loop test results are presented. From these measurements, the dynamic material properties were obtained using a combination of the magnetostrictive constitutive equations, transduction equations, and a mechanical model of the test transducer. The properties investigated were mechanical rod stiffness, linear coupling coefficient, magneto-mechanical coupling factor, modulus of elasticity, permeability, and system structural damping. These properties are dependent on mechanical prestress, load, magnetic field bias, AC applied magnetic field amplitude, and temperature. For these experiments, mechanical prestress, load, and AC applied magnetic field amplitude were systematically and independently varied, all other variables were held fixed. The samples tested were poly- and single-crystal cylindrical Galfenol rods with a percentage of Gallium varying from 18.4 to 19.5. Some rods were composed of laminated strips of Galfenol to reduce eddy current effects and increase the efficiency of transduction. Rods were 0.635 cm in diameter and of varied length. Prestresses were varied from 0.1 to 20 MPa. Load masses were varied from 59 to 521 g. AC applied magnetic field amplitudes were varied from 10 and 50 Oep-p. Temperature was held nearly constant at 20-30 oC, and magnetic field bias was held at the midpoint of the linear region of the magnetostriction versus applied magnetic field curve unique to each sample. Magnetostriction versus applied magnetic field obtained quasi-statically (0.05 Hz) from the test transducer is used to determine the magnetic DC field bias for optimization of minor loop output. These results provide a preliminary database for use in Galfenol broadband dynamic actuators.

I request to be considered for the SPIE/ASME Best Student Paper Competition.

5761-28, Session 6

Texture and magnetomechanical behavior of polycrystalline Fe-Ga samples

J. Atulasimha, A. Flatau, Univ. of Maryland/College Park; E. Summers, Etrema Products, Inc.

Single-crystal Iron-Gallium alloys demonstrate moderate magnetostriction (~350 ppm) and high tensile strength (~500 MPa) making them promising materials for actuation applications1, but are expensive and slow (yield of ~2mm/hour) to manufacture. This necessitates the development of faster and less expensive manufacturing process to obtain textured polycrystalline samples.

Strongly textured polycrystalline rods using zone melt crystal growth with yield rates much larger than single crystals, have been developed by Etrema Products Inc. The magnetomechanical characteristics (λ-H and B-H curves) of four such Fe81.5Ga18.5 rods (seeded and unseeded production grade [faster grow rate] and seeded and unseeded research grade [slow growth rate]) will be compared with the characteristics of a single-crystal rod of similar stoichiometry. Furthermore, the grain orientation of each of these samples will be determined using EBSD (Electron Back-Scattered Diffraction), to evaluate the extent of deviation of the [100] axis from the rod axis. Thus, a correlation between parameters in the manufacturing process, texture and macroscopic magnetomechanical properties will be established to serve as a reference for further improvements in manufacturing of polycrystalline FeGa specimens.

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5761-29, Session 6

Generalized free-energy model for hysteresis in ferroelectric and ferromagnetic materials with application to single crystal iron-gallium alloy actuators

J. Atulasimha, A. Flatau, Univ. of Maryland/College Park

This research focuses on characterization and modeling single-crystal samples with Ga content 16%, 19%, 21%, 24.7% and 29%, chosen to capture the trends in variation of magnetomechanical behavior with stoichiometry. Quasistatic λ-H and B-H characteristics of [100] single crystal samples of Fe-Ga alloys subjected to compressive stresses from 0 to 80 MPa are experimentally determined to motivate the development of a comprehensive model.

The free-energy minimization principle, which was first used by Landau [1] to describe second order paramagnetic-ferromagnetic phase transitions, provides a qualitative picture for B-H curves well below Curie temperature. However, it is unable to predict the extent to which hysteresis occurs. More recently, Smith et al. [2] have used a piece-wise quadratic Helmoltz energy H(M) and Gibb's Energy (G=H(M)-μ0MH) in their free-energy based models for magnetostrictive materials. However, G has no dependence on stress, which necessitates identifying model parameter for every applied load. In the current model, a 90 degree domain switching model is employed as it is better suited to the formulation of a 1-dimensional free-energy model. The total free energy is constructed as a function of stress (σ), temperature, magnetic field (H) and volume fraction of 0, 90 deg and 180 deg domains. The system responds to a change in σ or H by changing the relative volume fractions of domain orientations (to minimize the total free energy) from which the macroscopic quantities M and λ are determined. A comparison of these predictions with experimental data will be made.

The advantage of this model is that it has the framework to:

1.Predict actuator performance for a range of compressive stresses and temperatures for varied stoichiometry Fe-Ga. For example, it predicts that larger the compressive stress, greater the field required to drive the material to saturation (agrees with experiment).

2.Predicts an increased hysteresis under tensile loads (to be validated with ongoing experiments).

3.If H is kept constant and σ is varied, the model has the potential to predict change in magnetization and compliance (due to domain re-orientation) with stress, i.e. sensing behavior.

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5761-30, Session 7

Integration of active Fiber composite (AFC) sensors/actuators in GFRP laminates

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A great deal of research has focused on the development of piezoelectric sensors and actuators, however little work has addressed the problems associated with integrating such devices into structures. In the current study Active Fiber Composites (AFC) utilizing Lead-Zirconate-Titanate (PZT) fibers with Kapton screen printed interdigitated electrodes (IDE) were integrated into orthotropic glass fiber reinforced plastic (GFRP) laminates to investigate integration issues associated with smart structures and host laminate integrity. To aid in this goal surrogate or "Dummy" AFC (DAFC) were designed using a GFRP core and Kapton outer layers to match the longitudinal mechanical and interface properties of the AFCs. These DAFCs were used in place of real AFCs to expediate test specimen manufacture and evaluation. This allowed efficient investigation of the impact of an integrated AFC-like inclusion on laminate mechanical integrity.

Using this testing scheme the influence of device placement in relation to position extending away from the laminate symmetric axis was found to have an effect on laminate integrity in tensile loading. Two integration techniques, cutout and simple insertion were investigated using DAFCs, with little difference seen between the integrity of laminates prepared using these two methods. As the DAFCs were placed far from the laminate symmetry axis, the ultimate tensile

strength and strain of the laminates decreased in a linear manner while the Young's modulus of the laminates remained constant. Similar trends were observed with integrated AFC specimens.

The performance of integrated AFCs was characterized using monotonic cyclic tensile loading with increasing strain levels. AFC output was monitored during testing to examine the subsequent trend in AFC sensitivity in relation to applied strain. A transition region was observed between strains of 0.05%-0.50%, with a dramatic decrease in AFC sensitivity from a maximum to minimum value. Acoustic emission monitoring was used during testing to follow damage evolution in the test specimens and then correlate with the applied strain levels to determine operating limits. The degradation in AFC performance is attributed to the combined effect of depolarization and PZT fiber fragmentation during testing. A model for the drop in AFC sensitivity in relation to fiber fragmentation behavior was proposed.

The actuation performance of AFCs was assessed by inducing beam deflection using bonded and integrated AFC as actuators. Voltages of 0-2 kV were applied in various step patterns to induce deflection in beam structures, which was measured with laser triangulation. This enabled characterization of the relationship between applied voltage fatigue and actuation performance.

5761-31, Session 7

Degradation prediction of piezocomposite actuator

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This paper is concerned with the fatigue characteristics of LIPCA (LIghtweight Piezo-Composite Actuator) device system. LIPCA device system is composed of a piezoelectric ceramic layer and fiber reinforced light composite layers, typically a PZT ceramic layer is sandwiched by a top fiber layer with low CTE (coefficient of thermal expansion) and base layers with high CTE. The advantages of the LIPCA design are using the lightweight fiber reinforced plastic layers without compromising the generation of high force and large displacement and to have design flexibility by selecting the fiber direction and the size of prepreg layers. To predict the degradation of actuation performance of LIPCA due to the repeated fatigue loading, the cyclic electric loading tests using PZT specimens were performed and the strain for a given excitation voltage was measured during the test. The results from PZT fatigue test were employed into CLPT (Classical Laminated Plate Theory) model to predict the degradation of LIPCA's actuation. The fatigue characteristic of PZT was measured using a test system consisted of a supporting jig, a high voltage power supplier, data acquisition board, PC, and evaluated.

5761-32, Session 7

Boundary condition effects on piezoelectric diaphragm actuators for synthetic jet applications

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Piezoelectric diaphragms are used as synthetic jets because of their size, rapid time response, and relatively low power consumption. Among the piezoelectric diaphragms used are unimorphs and Bimorphs. In this study, a typical bimorph diaphragm is utilized as a baseline to compare three other pre-stressed piezoelectric diaphragms, a thin Unimorph pre-stressed device, a Radial Field Diaphragm, and a Lipca-type device. A thin Unimorph pre-stressed device consists of copper, PZT, and stainless steel; a Radial Field Diaphragm consist of a layer of PZT with inter-digitized electrodes encapsulated in Kapton film; and a Lipca type device which consists of fiberglass, PZT and reinforced carbon fiber. Boundary condition effects such as applied pressure, and applied waveform are characterized and optimized for each actuator by measuring their displacement topology to maximize air volume displacement.

5761-33, Session 7

Characterization and modeling of phase transitions in relaxor single crystals

T. Liu, C. S. Lynch, Georgia Tech.; E. A. McLaughlin, Naval Research Lab.

Relaxor ferroelectric PZN-xPT and PMN-xPT single crystals exhibit extraordinary electromechanical properties. They are under development for sensors, actuators and transducers. The engineered multi-domain features of ‹110\› and ‹001\› oriented relaxor PZN-4.5%PT and PMN-32%PT single crystals have been characterized and modeled. The polarization switching and phase transition behavior of these crystals under combined external loading have been investigated. These studies elucidate the polarization switching and phase transition behavior of relaxor ferroelectric crystals at different orientation cuts under different temperature, electric field and stress loading. Experimental measurements provide data for thermodynamics analysis of the polarization switching and phase transitions. Combinations of stress and electric field drive phase transitions and the driving force required for a phase transition decreases with increasing temperature. The thresholds for the phase transitions at different temperatures are used to generate a stability map for the material. These results are important for actuator design and performance control. Phase transition criteria give a guideline in determining acceptable applied fields on the crystal to prevent depolarization, heat generation and damage.

5761-34, Session 7

Advanced piezoelectric single-crystal-based actuators

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TRS is developing new actuators based on single crystal piezoelectric materials such as Pb(Mg1/3Nb2/3)x-1TixO3 (PMN-PT) which exhibit very high piezoelectric coefficients (d33 = 1800-2200 pC/N) and electromechanical coupling factors (k33 \› 0.9), respectively, which may dramatically improve the performance of a variety of room temperature and cryogenic temperature actuators. The examples to be presented and as briefly explained below, will outline how single crystal piezoelectric based actuators are enabling the next generation of advanced smart materials systems for a variety of applications, including, active vibration damping, active flow control, high precision positioning, ultrasonic motors, deformable mirrors, and adaptive optics.

Single crystal piezoelectric actuators present a new approach that could increase the stroke of smart active control flap actuators for helicopter active vibration control. This implies a decrease of the force/stroke trade-off impact introduced by amplification mechanisms, or actuators able to withstand more demanding aerodynamic loads. TRS has investigated three types of actuators; bender, stack and shear tube, and comparison results with ceramic-based actuators will be presented.

Large stroke, low profile single crystal piezoelectric actuators have been developed for applications requiring large stroke, low volume, and low driving voltage at room and cryogenic temperatures. Single crystal plate actuators with both a special "d32" crystal cut and "33" mode plate actuators with interdigital electrodes have shown significant strain and strain per unit volume improvement, for example, non-hysteric in-plane strain as high as -1600 pm/V (d32). An effective d33 \› 1000 pC/N was observed for quasi-d33 TRS single crystal plates with interdigital electrodes (IDE). Both types of plate actuators show at least 5 times larger piezoelectric coefficient (d31) than PZT-based materials.

A novel single crystal piezomotor was developed for large stroke, high precision, and cryogenic actuation with capability of position set-hold at power-off. TRS helped develop a concept that advances state-of-art cryogenic actuation due to the single crystal's excellent cryogenic properties (d33 and d31 at 30K similar or higher than that of PZT at room temperature) and very high electromechanical coupling. The novel design utilizes a "wobbling mode" piezomotor with "33 mode" single ring stacks. A fine screw was used for linear motion translation and the exhibited a \›10mm stroke and ms response time. The positioning resolution was around 10nm and an operation temperature range of 20-300K.

Efficient nanometer-precision and high-force actuators have been developed for shape control of adaptive optics mirrors for directed energy applications. Single crystal piezoelectric actuator technology enables deformable mirrors capable of correcting larger optical aberrations while requiring less power than current adaptive optics systems. Larger than 50μm of low hysteresis displacement and 24μm of in-plane stroke could be achieved with a 20mm long crystal stacked actuator and a 15 x 6 x 0.5mm single crystal plate, respectively. The potential benefits were demonstrated by system modeling which showed that the large dynamic range and high force of the single crystal actuators will enable the design of adaptive optics for directed energy and other applications that greatly exceed the capabilities of the current generation hardware.

5761-35, Session 7

Advanced piezoelectric single-crystal-based transducers for naval sonar applications

P. W. Rehrig, W. S. Hackenberger, X. S. Jiang, TRS Technologies, Inc.; R. J. Meyer, Jr., The Pennsylvania State Univ.

High frequency sonar is becoming ever more important to the Navy through expanded use of unmanned underwater vehicles (UUV). Proposed missions for many UUV's involve shallow water operation where broad bandwidth is required

making these applications ideal candidates to use single crystal piezoelectrics. In addition, many UUV sonar systems have commercial uses including oceanographic research, oil and mineral prospecting, salvage, and undersea equipment inspection and maintenance.

TRS is developing new transducers based on single crystal piezoelectric materials such as Pb(Mg1/3Nb2/3)x-1TixO3 (PMN-PT). Single crystal piezoelectrics such as PMN-PT exhibit very high piezoelectric coefficients (d33 ~ 1800 to \›2000 pC/N) and electromechanical coupling factors (k33 \› 0.9), respectively, which may be exploited for improving the performance of broad bandwidth and high frequency sonar. The properties of single crystal piezoelectrics were exploited for broad bandwidth, high frequency sonar. Crystal sonar investigations based on Tonpilz transducers utilizing the "33" resonance mode have shown limitations on bandwidth due to less than ideal resonator aspect ratio. This is a result of the crystals' low elastic stiffness, which leads to short resonators with large lateral dimensions. To address this issue an alternative design was proposed utilizing the "31" resonance mode with the resonating length oriented along a special crystallographic cut. Crystals with this orientation are known to have high properties; d32 values as high as -1600 pC/N have been observed. Since prestress for such a design is applied perpendicular to the poling direction, "31" mode Tonpilz elements exhibit lower loss and higher reliability than "33" mode designs. The feasibility of such "31" mode Tonpilz resonators will be presented as determined through property measurements and finite element analysis. The targeted application for the work to be presented is broadband (\›100%), high frequency (45 kHz) synthetic aperture arrays for unmanned underwater vehicles.

Another area of interest is utilizing single crystal piezoelectric tonpilz elements for small footprint, high power acoustic sensors. Target applications are detection and homing acoustic sensors for small diameter (less than seven inches) vehicle platforms. Planar high power tonpilz arrays are the optimum way to obtain the required acoustic pressure and bandwidth for small footprint sensors. Tonpilz elements are designed with mechanical bias to reduce stress-induced failures and typically have electro-acoustic efficiencies greater than 70 percent. As the vehicle diameter becomes smaller, packaging the acoustic sensor power delivery electronics, energy storage, guidance and control intelligence, and propulsion become increasingly more difficult. The approach to providing viable small footprint sensors is to utilize single crystal piezoelectrics to reduce the length of the tonpilz transducer while maintaining the fundamental resonance frequency and acoustic intensity. Single crystal piezoelectrics may also reduce the size of the power delivery electronics as well. TRS will present its approach to this research that concentrates on improving the temperature dependence of properties of the material and its effect on transducer performance.

5761-36, Session 7

Electric-field-induced phase transitions of ‹001\›-oriented Pb(Mg1/3Nb2/3)O3-PbTiO3 single crystals

W. Ren, R. Wicks, G. Yang, B. K. Mukherjee, Royal Military College of Canada (Canada)

Single crystals of the relaxor ferroelectric solid solution Pb(Mg1/3Nb2/3)O3-PbTiO3 (PMN-PT) have been investigated for transducer and actuator applications. It has been found that rhombohedral PMN-PT single crystals poled along the pseudocubic ‹001\› direction possess large strain, high piezoelectric coefficients and high electromechanical coupling coefficients that are superior to those of the commonly used lead zirconate titanate (PZT) ceramics. All these properties make PMN-PT crystals a strong candidate for transducer and actuator applications.

An electric-field-induced phase transition between the rhombohedral and tetragonal phases in the PMN-PT single crystals is accompanied by a large, but hysteretic, change in the strain. In our earlier work on Pb(Nb1/3Nb2/3)O3-PbTiO3 (PZN-PT) single crystals. we found that the electric field corresponding to the phase transition depends significantly on the measuring temperature.

In this work, we have studied the temperature dependence of the electric-field-induced phase transition in ‹001\›-oriented rhombohedral PMN-PT single crystals. Two types of PMN-PT crystals with different PT contents (28% PT and 32% PT), made by TRS Ceramics, Inc., have been investigated. The strain response and the polarization were measured using a differential variable reluctance transducer (DVRT) system and a Sawyer-Tower circuit at unipolar electric fields at 1 Hz and in the temperature range from the room temperature to 115 ºC. The field-induced phase transition has been studied as a function of temperature. The dielectric and piezoelectric constants of PMN-PT crystals are determined from the measurements. The properties of the PMN-PT crystals will be compared with those determined earlier for crystals of the PZN-PT family.

The PMN-PT crystal samples were graciously provided by TRS Ceramics, Inc.

5761-37, Session 7

High-temperature piezoelectric materials for actuators and sensors

S. Zhang, R. E. Eitel, C. A. Randall, T. R. Shrout, The Pennsylvania State Univ.; E. Alberta, P. W. Rehrig, W. Hackenberger, TRS Technologies

High-temperature electronics is an area of research offering interesting materials and design challenges and one of significant industrial importance. In the aerospace and aircraft industries, electronic controls are to be placed directly inside jet engines because of reliability and noise requirements, thus sensors need to be built that can withstand temperatures greater than 300oC while allowing mission lifetimes up to 100000 hours. Piezoelectric materials used in electronic devices should possess not only high piezoelectric behavior, but also high resistivity and time constant (RC). High electrical resistivity is necessary so that a large electric field can be applied during actuations without breakdown or excessive charge leakage, or conversely, the sensor devices must develop a charge for an applied stress or strain long enough to be detected by the electronic system. The length of time the charge maintained is proportional to the RC time constant and thus, a large RC time constant is desirable for many applications.

High temperature, high performance materials in the perovskite BiMeO3-PbTiO3 family have attracted attention because of their comparable piezoelectric properties and higher Curie temperature compared to commercial Pb(ZrxTi1-x)O3 (PZT) systems. Ceramic and single crystals of BiScO3-PbTiO3 (BSPT) exhibit stable high temperature behavior near their morphotropic phase boundary (MPB) compositions (PT content about 64%). The Curie temperature of BSPT64 ceramic was found to be 460oC, with piezoelectric coefficient d33 around 500pC/N, both much higher than those values of PZT5 (Tc ~360oC, d33 ~380pC/N). The modified BSPT64 exhibited piezoelectric coefficient d33 about 370pC/N, while showing much higher resistivity and time constant (RC) compared to PZT5. The time constant of the modified BSPT64 were found to be 1.17s and 0.05s at 300oC and 450oC, respectively, while those values for PZT5 were 0.75s and 0.003s. For 0.43BiScO3-0.57PbTiO3 single crystals, the piezoelectric coefficient was found to be 1200pC/N, the electromechanical coupling factor k33 was about 90%, which was kept constant till its rhombohedral-tetragonal phase transition temperature at 350oC.

The excellent electrical behavior of BSPT system makes them promising candidates for actuators and sensors in various applications that includes distributed control systems on supersonic aircraft, accelerometers, vibration control actuators, flow control actuators, aircraft morphing actuators, squeal sensors, hydraulic fluid control valves and vibration control actuators for automotive smart brakes. A specific application is the candidates for applications in high temperature (ambient temperature ~460oC) ultrasonic drill to be used as a rock sampling tool for a Venus robotic lander and transducers for acoustic telemetry in oil and geothermal well drilling tools, which can be used to image and characterize the surround rock strata.

5761-38, Session 7

A model for frequency dependent characteristics of piezoceramic materials

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Nowadays, there are increasing interests to piezoelectric and ferroelectric materials which are especially used in scientific and engineering applications such as mechatronics area which are precision machining in manufacturing, micropositioning in metrology, commercial stack actuators and sensors, ink-jet printers, piezo controlled fuel injection in automobile industry, and electronics for instance ferroelectric random access memories (FRAM) in microelectromechanical systems (MEMS). These materials can exist in tetragonal and rhombohedral microstructure according to their constitutional elements in room temperature. BaTiO3, PZT and PLZT are some examples piezoceramic materials, which have perovskite type tetragonal microstructure. Although piezoelectric and ferroelectric materials are so perfect in applications, they are limited in high performance usage. When they are loaded under high electromechanical fields, they show strong nonlinearities, which basically stem from domain switching in microstructural level. Non-linear distortion of lattice size and electrical polarization occur during domain switching. In addition to understand quasi-static characteristics, dynamic behaviours of piezoelectric materials are also important in some special application. Since the nonlinearity is increasing when loading becomes rate or frequency dependent. In this paper rate dependent behaviour of tetragonal perovskite type piezoceramic materials is simulated using a three-dimensional micromechanical model. In the simulations a bulk piezoceramic material is considered to have 1000 grains. Each grain has random orientation in properties of polarization and strain. Randomness is given by Euler angles equally distributed between 0 and 2p. Uni-axial external cyclic electrical loading is applied

beginning from virgin state. Basic piezoelectric constitutive equations have been implemented with domain switching in the simulation. Energy equation is used for the onset of domain switching with taking in to account the probability functions that have been used for the assumption of domain switching under critical electromechanical field. It is also assumed that intergranular effects between grains can be modelled by such probability functions. In addition to this, rate dependent properties of piezoceramics are investigated by implementing various frequencies of cyclic loading during the simulations in which nucleation and propagation of domains during polarization switching have been modelled with the help of simple linear kinetics relations. Different amplitudes of alternating loadings are also applied with changing frequencies in order to understand the macroscopic behaviour of piezoelectric and ferroelectric materials such as coercive field and remnant polarization and strain characterization under various loading situations. The response of the material to the applied loading is calculated by using transformations and averaging the individual grains. PIC 151 is chosen as a sample piezoelectric material because of the experimental data that the material has been already observed in some experiments in the literature. Therefore some parameters such as spontaneous polarization, spontaneous strain, piezoelectric and dielectric constants are chosen from the experiments. The results of simulations have been given in electric displacement versus electric field hysteresis and mechanical strain versus electrical field butterfly curves under different amplitude and frequencies of high electrical field with comparison of experimental ones.

5761-39, Session 8

Anisotropic fracture in ferroelectric relaxor PZN-4.5%PT single crystals

W. S. Oates, C. S. Lynch, Georgia Institute of Technology; A. B. Kounga Njiwa, D. Lupascu, Technische Univ. Darmstadt (Germany)

The influence of crystal anisotropy in unpoled and poled (1-x)Pb(Zn2/3Nb1/3)-xPbTiO3 (x=0.045) (PZN-4.5%PT) ferroelectric relaxor single crystals was assessed. The single crystals were cut along the [100], [010], and [001] planes. R-curve measurements identified a weak cleavage plane along the [110] plane using the Single Edge V-Notch Beam (SEVNB) method. Fracture along this plane introduced mixed mode loading (KI and KII). To assess the anisotropic fracture behavior, relations between the crack tip stress fields, fracture anisotropy, and energy release rate under Mode I and Mode II loading are evaluated using Stroh's formalism. Additionally, SEM measurements of crack profiles for two different crack orientations suggest that the crack tip toughness and local energy release rate are invariant to the orientation of crystal anisotropy. This matches theoretical predictions using Stroh's formalism.

5761-40, Session 8

Toughening behavior of ferroelectric ceramics under different poling conditions

J. Wang, C. M. Landis, Rice Univ.

Mode I steady crack growth is analyzed to determine the toughening due to domain switching in poled ferroelectric ceramics. A multi-axial, electromechanically coupled, incremental constitutive theory is applied to model the material behavior of the ferroelectric ceramic. The constitutive law is then implemented within the finite element method to study steady crack growth. The effects of poling direction, either out of plane or in plane, and poling strength on the fracture toughening are investigated. Results for the predicted fracture toughness, remanent strain and remanent polarization distributions, and domain switching zone shapes and sizes are presented.

5761-41, Session 8

Finite element analysis of a multilayer piezoelectric actuator taking into account the ferroelectric and ferroelastic behaviors

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Ferroelasticity and ferroelectricity are the non linear behaviours exhibited by piezoceramics, especially in the case of high electric field or stress. Many studies have focused on the role of ferroelastic and ferroelectric switching in fracture of actuators. However, engineering reliability analyses are carried out with tools like finite element software that do not take into account these non linear phenomena. To overcome such a problem, a simplified phenomenological constitutive law has been developed and describe the hysteresis effect of piezoceramics. It is time-independent and relies on the introduction of remnant polarization and remnant strain as internal variables. Two loading surfaces, similar to the ones used in plasticity, provide the evolution laws for the internal variables. Besides, polarization-induced anisotropy in the piezoelectric tensor is taken into account. That constitutive law has been implemented in the commercial software ABAQUS. It has been necessary to develop a finite element with electrical and mechanical degree of freedom: it is an eight node hexahedron. The stiffness matrix integrates the constitutive law from the four tangent operators given by the constitutive law. The non linear problem is solved by the Newton's method.

This finite element tool is used to study the effects of applied voltage on the electroelastic field concentrations ahead of electrodes in a multilayer piezoelectric actuator. The study lies on the experimental observations made by Shindo et al. (2002). Electroelastic analysis on piezoceramics with surface electrode showed that high values of stress and electric displacement arose in the neighbourhood of the electrode tip. Thus, the strain, stress and electric displacement concentrations were calculated and the numerical results showed that ferroelectric switching arose in the area of the electrode tip, causing a change in remnant polarization and remnant strain.

5761-42, Session 8

An experimental study of domain switching criterion for soft PZT piezoceramics subjected to coaxial proportional electromechanical loading

D. Zhou, M. Kamlah, Z. Wang, Forschungszentrum Karlsruhe (Germany)

Modern piezoelectric transducers normally have complicated structures and work under severe loading conditions. Application of an external load in excess of a critical level will cause domain switching in the material and therefore lead to a significant non-linearity and hysteresis in the polarization and strain response. To develop a constitutive model concerning the large-signal nonlinear behavior of ferroelectric piezoceramics, it is desirable to determine a switching criterion in the multiaxial stress and electric field states.

In this experimental work, "soft" lead zirconate titanate (PZT) specimens in initially unpoled state were subjected to a proportional electromechanical loading, in which a compressive stress and a parallel, proportional electric field were applied simultaneously. By varying the relative proportions of stress and E-field between tests, a family of non-linear polarization and strain responses were obtained. An attempt has been made to explain the experimental findings by simultaneously taking into account the contributions of dielectric response, elastic deformation, piezoeffects, and irreversible domain switching. Based on an offset method, switching (domain reorientation threshold) surfaces were mapped out in the biaxial stress and electric field space. Finally, several switching conditions existing in the literature were summarized and compared with the experimental data obtained in this work.

5761-43, Session 8

Monte Carlo simulation of ferroelectric relaxor crystals at morphotropic phase boundary

J. Li, Univ. of Nebraska/Lincoln; K. Bhattacharya, California Institute of Technology

In this talk, we report our recent work on ferroelectric relaxor crystals at morphotropic phase boundary (MPB) using a Monto Carlo simulation, where the evolution of a two-dimensional lattice of dipoles under an applied electric field is studied. Each lattice point is either tetragonal or rhombohedral, while each dipole can take any one of the eight available polarization directions with certain probability determined by the overall energetic state. As the dipoles evolve to an equilibrium configuration, microscopic clusters and macroscopic hysteresis loop have been observed, and the effects of chemical compositions and temperature have been investigated. In particular, we have confirmed the mesoscopic polarization rotation near the MPB, which is believed to be responsible for the superior electromechanical coupling observed in relaxor crystals near MPB.

5761-44, Session 8

From crystals to devices

C. S. Lynch, T. Liu, Georgia Institute of Technology

No abstract available

5761-45, Session 8

Morphing needs and requirements

J. N. Kudva, NextGen Aeronautics, Inc.

No abstract available

5761-48, Session 8

Smart material/actuator needs in extreme space environments

S. Sherrit, Jet Propulsion Lab.

A variety of future missions to other planets and moons in our Solar System require structures, actuators and positioners that can operate in extreme environments and produce useful work or deliver high accuracy positioning. Depending on the specific mission these devices may be required to withstand milli-Kelvin environments or temperatures exceeding that of Venus (450oC). In addition these devices may have to withstand high radiation and corrosive environments and pressures ranging from high vacuum to 100's of MPa. To make matters even more challenging many of the mission requirements of these structures or actuators are pushing the limit in performance even under terrestrial conditions.

In sampling or instrument applications, motors for instrument deployment devices or actuators for sampling tools are required that can operate reliably and deliver substantial torque and power. The devices must be lightweight, compact and may be operated efficiently.

This presentation will focus on a variety of technologies based on electromechanical materials used for the applications discussed above and will present some of the challenges of developing these systems for space applications.

5761-76, Poster Session

Structural and dielectric investigations of La and Pb-doped SrBi2Nb2O9 ferroelectric ceramic: a comparative study

V. Shrivastava, Delhi College of Engineering (India)

In this paper, a comparative structural and dielectric study of Sr1-xAxBi2Nb2O9 (A= La, Pb and x=0.2) ceramics is reported. The samples were synthesized using solid-state reaction method and were calcined and sintered at temperatures 900 oC and 1150 oC respectively for 2 hours. It has been observed that the tetragonal strain increases on the introduction of lead and decreases on introduction of lanthanum. The orthorhombicity compared to the undoped SrBi2Nb2O9 sample shows a decrease with the introduction of lanthanum and lead. An increase in Curie temperature is observed due to lead doping whereas a large decrease is observed due to lanthanum doping. In addition, flattening of dielectric peak is observed in the lanthanum doped samples while for lead doped samples it sharpens. The lanthanum doped samples show large dielectric constant values with insignificant space charge polarization contribution whereas the lead added samples show lesser dielectric constant values with similar insignificant space charge contribution. The dielectric loss is reduced significantly on introducing both lanthanum and lead and loss values are found to be higher in lanthanum added samples compared to those in lead added samples. In addition, loss values for 0.2 lanthanum doped sample show regular decrease with frequency upto 1 MHz whereas those for 0.2 lead doped sample show increase after about 100 KHz.

5761-77, Poster Session

A finite element approach for domain wall dynamics in ferroelectric materials

Y. Su, C. M. Landis, Rice Univ.

The field-induced domain evolution is investigated in a single-domain ferroelectric solid undergoing spontaneous polarization or polarization reorientation. Domain wall velocities have been correlated with the thermodynamic driving force acting on the domain interface. This boundary driving force, which depends on the local electromechanical fields and local changes of the material properties due to reorientation of the crystal structure, is derived from Eshelby's energy momentum tensor. A finite element analysis that implements an efficient computation method for Eshelby's energy momentum tensor is developed. The geometry of domain boundary is updated during the finite element computation to capture the characteristic of the domain evolution. An analytical solution for the boundary driving force is given by implementing Eshelby tensor for piezoelectric inclusion. The numerical results are compared to the analytical solution to establish the validity of this approach.

5761-78, Poster Session

Active fiber composites: optimization of the manufacturing process and their poling behaviour

C. Huber, M. M. Melnykowycz, A. J. Brunner, M. Barbezat, EMPA Duebendorf (Switzerland)

Active Fibre Composites (AFC) are constituted of uniaxially aligned piezoceramic fibres (PZT) embedded in a polymer matrix and sandwiched between two sets of interdigitated electrodes. When an electric voltage is applied between the interdigitated electrodes, the electric field generated in the fibres results in an extension of the AFC in the direction parallel to the fibre axis. Inversely, the PZT-fibres generate electric charges upon mechanical deformation. Therefore, piezoelectric AFC elements can be used as both, actuators and sensors in smart composites and structures. Applications are envisaged, e.g., in structural health monitoring, active structural control, and passive or active vibration damping. Major advantages of the AFC over conventional piezoelectric elements are their flexibility and toughness, both far superior compared with monolithic PZT-wafers. The piezoelectric properties of the PZT-based AFC, on the other hand, are better than those of piezopolymers, such as PVDF. Furthermore, due to their thin, planar geometry the AFC can be easily integrated into composite laminates.

The present study aims at optimisation of the AFC manufacturing process used at EMPA, involving lamination of commercial PZT-fibres. AFC elements are characterised at various stages of the manufacturing process. On one hand, the applied cure cycle for the epoxy resin matrix and the pressure applied in the lamination process were examined, on the other hand, the parameters of the electrical polarisation (duration, temperature, voltage) were optimised based on the performance of the AFC. The optimisation of the cure cycle allows to influence the build up of internal stresses in the piezo fibre composite. Some properties of the matrix like shear modulus, fracture strain and toughness can be influenced also in order to finally optimise the behaviour of the AFC.

The pressure applied during curing allows for deformation and adaptation of the electrodes, made from silver paste screen printed on polyimide films, to the shape of the individual fibres. This yields an area of full contact and a contact angle between fibre and electrode of up to 60° - 70°. The larger the value of the contact angle, the higher the electric field that develops in the direction of the fibre axis upon application of the voltage. This significantly affects the AFC performance, e.g. as shown by the free strain behaviour measured by strain gauges applied on both sides of the AFC.

The polarisation of the PZT-fibres of the AFC is performed via the interdigitated electrodes. This yields axially poled fibres and thus coincides with the d33 piezoelectric charge coefficient. Electric polarisation of the fibres is characterised by temperature, voltage and duration. These three parameters were optimised for maximum actuation of an AFC as measured by the strain gauges.

5761-79, Poster Session

Modeling of particulate Fe/NiTi alloy (FSMA) composites

S. Gururaja, M. Taya, Univ. of Washington

Ferromagnetic Shape Memory Alloy (FSMA) is the key material for fast responsive actuators. However, the cost of processing of known FSMAs is very high and their mechanical behavior is often unsatisfactory (poor ductility). To overcome these difficulties, the concept of FSMA composites(Kusaka and Taya, 2004) exhibiting two different microstructures; laminate and particulate composites is proposed. These are processed using Spark Plasma Sintering (SPS) which is a promising method as it reduces processing time thus avoiding inter-metallics chiefly responsible for making the composite brittle.

In this talk, a model for predicting the effective magnetic properties of FSMA particulate composite for variable Fe concentrations is presented. Modified Eshelby's approach is used to make the corresponding predictions (Hatta and Taya, 1985). These predicted magnetic properties are compared with recent experimental data obtained for particulate Fe/NiTi alloy composites. The predicted results are in good agreement with the experimental data (Taya, Kang, Nakayama and Suhasini, 2004).

References:

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2.Effective thermal conductivity of a misoriented short fiber composite. H. Hatta and M.Taya. Journal of Applied Physics Vol. 58(7) 1985.

3.Design of Fe/NiTi Ferromagnetic Shape Memory Alloy Composites. M. Taya, Y.S.Kang, H.Nakayama and G.Suhasini. (Submitted for publication)

5761-81, Poster Session

Vibration characteristics in a smart bridge model using shape-memory alloy fiber reinforced composite

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The use of intelligent materials as actuating and sensing devices in active control systems has been investigated extensively. As one promising intelligent/smart material, shape memory alloy (SMA) fiber reinforced composite materials are

gaining an increased interest to build intelligent structures. SMA fiber reinforce materials could be used for active strengthening and vibration control by using not only its high recovery force but also the feasibility into active control . Vibration control can be achieved in the composite structures by moderating the dynamic responses, in terms of natural frequency and damping ratio by using the inverse phase transformation of the embedded shape memory alloy wires. The recovery stress due to the shape memory effect of the SMA fibers and the concurrent mechanical property change are taken into consideration in the vibration analysis of the laminates when the embedded SMA fibers are activated. The application of SMA smart materials with self-enhancement and active damping effect will provide more efficient and effective vibration control functions to bridge structures. Therefore active control for deflection and vibration as well as suppression on the degradation damages are becoming very important subject in developing more secure structure and preventing from damage of high building and bridge in earthquake.

The feasibility and superiority of using SMA actuators to suppress and excite the structural vibration are demonstrated in this paper. A smart bridge model was developed for vibration control using shape memory alloy embedded in TiNi/acrylic composite. In this system, an acoustic sensor is used to detect the fracture and damage in materials when earthquake or other shock occurs. And a laser sensor over the center of the bridge and strain gauge is used to detect the vibration amplitude and frequency. To obtain a prompt and complete response of the bridge system when a train passes through on the bridge, multiple strain gauges are pasted on the top and bottom surfaces to get a prompt signal. Then current is turned on to electrically heat the shape memory fiber to result in phase transformation suppression, by this way we can change the rigidity and frequency of the bridge beam.

A systemic experimental study was carried out to investigate the vibration characteristics of the bridge beam with stiffness change by shape recovery of pre-strained TiNi wires with direct electric heating. All level of deflection including static and dynamic deflections and the damping with time-lapse were measured by strain gage through changing the loading condition in various patterns and moreover in the condition of running model trains. The result revealed that the shape memory suppression effect caused by current heating could lead to stiffness strengthening and in turn increase the characteristic frequency in composite beam. It confirmed the smart bridge model of composite material beam has not only been able to reduce the vibration response, but also change the frequency of the structure. Finally, active control on the smart bridge model was discussed based on the measured results and some problems existing in the active control with SMA and the corresponding improved ways have also been pointed out for further research.

5761-46, Session 9

A three-phase model of shape-memory alloys undergoing complex thermomechanical loading paths

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In this work a three-phase constitutive model of Shape Memory Alloys which is capable of handling complicated thermomechanical loading paths is presented. Shape Memory Alloys are materials, which change their crystallographic structure due to changes in temperature and/or applied loads. The effective use of SMAs in industrial applications requires accurate constitutive models capable of predicting their response over a wide range of thermomechanical loading paths. The model presented in this work is based on thermodynamic potentials and differentiates between three different phases – self accommodated (twinned) martensite, stress-induced (detwinned) martensite, and austenite. The distinction between twinned and detwinned martensite allows for the introduction of different transformation surfaces, evolution equations and hardening laws for the stress induced, thermally induced phase transformations and reorientation of martensite in a natural way. A phase-diagram based description of the transformation surfaces is used in stress-temperature space. The proposed phase diagram extends the work of previous authors by completing the transformation surfaces so that the model is consistent when a thermomechanical loading path involves mixtures of the three phases. It also captures some recent experimental observations. The model is tested on a range of complicated, uniaxial, thermomechanical loading paths such as constrained cooling and/or heating of a SMA rod starting from different initial conditions. These types of loading paths are chosen because they typically involve more than one simultaneous transformation. Comparisons with experimental results are also performed. The model is numerically implemented in 3D using return mapping algorithms. Its capabilities to predict the SMA behavior over a wide range of thermal and mechanical loading conditions are demonstrated by a Finite Element Analysis of a thermally actuated flow regulation device.

5761-47, Session 9

Direct experimental observation of high-rate dynamic buckling of shape-memory thin cylindrical shells

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To investigate the buckling behavior of shape memory thin cylindrical shells, uniaxial compression tests are performed at 295K initial temperature, using the CEAM/UCSD's modified split Hopkinson bar system and an Instron hydraulic testing machine. For dynamic loading, a split Hopkinson bar is used. To capture the response, a high-speed camera, Imacon 200, is used. To record the quasi-static response, a digital camera is employed, together with closeup lens that is arrayed with two mirrors placed symmetrically behind the sample. We present the results of a series of tests on NiTi shape-memory shells under quasi-static and dynamic loading conditions. It is observed that NiTi shape-memory shells, at 295K initial temperature (which is above Af temperature of 281K) buckle gracefully, and fully recover upon unloading, showing a superelastic property. However, NiTi shells that are annealed at 773K for 150min, do not recover spontaneously upon unloading since the Af temperature is higher than 295K. On the other hand, upon heating, the buckled shells recover, showing a shape-memory effect. This buckling response associated with the stress-induced martensite formation has a profound effect on unstable deformations of thin structures made from shape-memory alloys. There are numerous possible applications of thin structures consisting of shape-memory alloys since they can mitigate potential catastrophic failure and lead to remarkable recovery processes.

5761-49, Session 9

Strain-rate effects on TiNi and TiNiCu shape-memory alloys

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TiNi based shape memory alloy is well known exhibiting the unique properties, which are shape memory effect (SME) and super elasticity (SE). By utilizing SME and SE, many design of actuators are proposed. We investigate in this paper the dynamic deformation behavior in TiNi and TiNiCu alloy.

TiNi and TiNiCu alloy supplied from Furukawa Techno Material Co were used. They show SE and SME in TiNi alloy and TiNiCu alloy, respectively. Both alloys were deformed dynamically using Split Hopkinson Pressure Bar equipment in University of Arizona. The strain rate was varied from 70 s-1 to 550 s-1.

The stress-strain (S-S) curves obtained by dynamic deformation in TiNi specimens exhibit super elastic behavior. The onset stress of stress induced martensite (SIM) transformation, ?SIM, and plateau stress increased with increasing strain rate. This phenomenon is similar to the temperature effect of TiNi shape memory alloy by static deformation. In the case of static deformation tested at temperatures higher than Ms, ?SIM and plateau stress increase. For TiNi alloy tested at ?' = 450 s-1, the temperature rise (?T) is estimated as 12 °C. This temperature rise is sufficient to increase ?SIM and plateau stress. Therefore, the changes in the S-S curve of TiNi alloy by dynamic deformation can be explained by temperature rise. In contrast, S-S curve of TiNiCu alloy, which shows SME at room temperature, exhibits different tendency. The plateau stress, where martensitic variants are rearranged, is increased by increasing strain rate for lower strain rates, but for higher strain rates, it decreases with strain rates. Since the plateau stress decreases with increasing in temperature by static deformation in martensite state, the former stress change cannot be explained by the effect of temperature rise. We performed also TEM study on the nanostructure of SMAs tested at quasistatic and high strain rates. In the TEM observations of TiNiCu alloy, fine grained structure was realized by dynamic deformation compared to static deformation. This implies that a larger number of slip system was activated by dynamic deformation rather than static deformation.

5761-50, Session 9

Properties and potential of two (Ni,Pt)Ti alloys for use as high-temperature actuator materials

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In order to improve the efficiency of aeronautic turbomachinery, there is a growing interest in developing compact flow control devices and various smart systems, or replacing existing hydraulic based actuation systems with less weight restrictive devices. The use of high-temperature shape-memory alloys (HTSMA) would be the most promising means of achieving these goals. Among conventional shape memory alloys for use near room temperature, NiTi has been at the forefront due to its ability to produce significant amounts of work against a biasing force when

the temperature passes through its austenite-to-martensite transformation. However, very little has been done to develop materials with comparable work characteristics to NiTi but with significantly higher transformation temperatures, for use in turbine engines and other high-temperature environments.

To this end, we have been investigating properties of various NiTi-X alloys in order to identify potential compositions that could be utilized for high-temperature actuation and control purposes. In this paper we report on two (NiPt)Ti alloys with disparate mechanical behaviors. One is a Ni30Pt20Ti50 alloy (hereafter referred to as 20Pt) with transformation temperatures above about 250 oC and the other is a Ni20Pt30Ti50 alloy (30Pt) with transformation temperatures around 600 oC. Both alloys possessed limited tensile ductility at all temperatures tested, ~4% for the 20Pt and less than 2% for the 30Pt alloy. For the 20Pt alloy, the tensile strength, modulus, and ductility increased when the material was tested in the austenitic state. This was not the case for the 30Pt alloy, where the yield strength decreased with increasing temperature, even above the marteniste-to-austenite transformation temperature. Both alloys displayed shape memory behavior and were capable of 100% (no-load) strain recovery for strain levels up to their fracture limit when deformed at room temperature. However, the two alloys displayed considerably different behaviors when thermally cycled under constant load. The 20Pt alloy behaved similar to binary NiTi with work due to the martensite-to-austenite transformation initially increasing with applied stress. The maximum work capability measured in the 20Pt alloy was 1266 in-lb/in3 and appeared to be limited only by the tensile ductility of the material. In contrast, the martensite-to-austenite transformation in the 30Pt alloy was not capable of performing work against any bias load.

The 20Pt alloy also displayed additional characteristics that would make it an attractive candidate for high-temperature actuator applications. The transformation hysteresis in this alloy was narrow, approximately 15 °C, and was independent of stress level. Also, training or thermal cycling of the alloy under a high stress, helped stabilize the strain-temperature behavior of the material. While the results are preliminary, it would appear that the current Ni30Pt20Ti50 alloy has enough positive attributes to justify further development for actuator purposes.

Finally, the results of this study drive home several basic tenets for the design of alloys for optimized shape-memory work characteristics. In general, one would prefer to 1) have a moderate stress for twinning of the martensite phase, 2) maximize the strength of the austenite phase, and 3) maximize tensile ductility.

5761-51, Session 9

Characterization of ternary NiTiPt high-temperature shape-memory alloys

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Due to their superior shape memory and superelastic behavior, NiTi alloys have found such diverse commercial application as electrical switches, eyeglass frames, appliance controllers, couplings for pipes and other tubular products, temperature sensitive valves, and countless medical and dental devices. There could be many additional control and actuation-type applications, for materials exhibiting the shape memory effect at higher temperatures, in the aeronautic, automotive, power generation, chemical processing, and other industries. However, to date, little work has been done to develop such materials.

In the past few years, several research groups have started to investigate potential high-temperature shape-memory alloys based on ternary NiTiX and other systems. One of the systems shown to exhibit a martensitic transformation over a large range of temperatures is the NiTi+Pt. In the current study, the compositional dependence of the microstructure, hardness, transformation temperatures, and electrical resistivity was investigated for a broad range of NiTiPt alloys.

A series of over twenty alloys along and on either side of the constant tie line between NiTi and TiPt were arc melted in an inert atmosphere and homogenized at 1050 °C for 72 hours. The bulk alloy compositions were confirmed by spectrographic analysis and hardness measurements were performed using a Vickers indentation technique. The dependence of hardness on Pt level for a series of Ni50-xPtxTi50 alloys was rather complicated. At low Pt levels, solution softening was observed while for high Pt levels solid solution hardening occurred. Transformation temperatures were determined by differential scanning calorimetry (DSC) for low to intermediate temperature analysis and differential thermal analysis (DTA) was used at intermediate to high temperatures. In addition, the resulting microstructures were examined by SEM followed by a more in-depth TEM examination of several key alloys.

Analyzing resistance as a function of temperature yields important design parameters including power requirements for shape memory actuated devices, and allows for a direct measurement of the transformation temperatures. Thus, resistance measurements for a series Ni50-xPtxTi50 alloys were also conducted as a function of temperature and composition. In addition, it has been shown that a relationship exists between the shape of the resistance versus temperature profile and the shape recovery performance of the alloy. This study will include a summary analysis which exploits this relationship.

5761-52, Session 9

Observed dependencies of the large thermal-compressive response of a NiTi shape-memory alloy fiber aluminum metal matrix composite

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The present work examines how the characteristics of the large thermal-compressive response of a 20 vol. % NiTi fiber 6082-To composite change with variations in the value of maximum tensile strain imposed during a preceding room temperature tensile process. The large thermal compression response is the result of the shape memory response of the composite NiTi fibers which further results in large plastic compression strains in the composite aluminum alloy matrix. We observe that the thermal compression process is shifted to higher temperatures with increasing maximum room temperature tensile strain, and that the maximal thermal compression versus temperature slope becomes larger as the maximum tensile strain is increased from 4 to 6%.

5761-53, Session 9

Analytical model for predicting internal stress and deformation of shape-memory alloy composite

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Composites containing Shape Memory Alloy (SMA) fiber and polymer (or metal) matrix are expected as smart materials and structural materials. For example, Shape Memory Alloy Composite (SMAC) exhibits creating of compressive residual stress (Creating of internal stress) in matrix and deformation of composite under thermo-loading. These internal stress and deformation have mutual relationship. These values show differences by combination of materials of composite. Therefore, it is important for controlling internal stress and deformation to grasp the change of internal stress and deformation due to combination of materials.

In the present study, the analytical model considering distribution of stress and strain in SMAC is constructed based on shear lag model. Closed solutions, such as shear stress in matrix and so on, are obtained from this analytical model. Then, some analyses are conducted for predicting internal stress and deformation of SMAC during thermo-mechanical loadings by using present closed solution. Furthermore, analytical results are compared with experimental results such as photoelasticity. Equal condition between distribution and uniform state is decided from these results of analysis. Finally, systematization of internal stress and deformation of SMAC is tried by changing combination of materials such as fiber volume fraction and Young's modulus of matrix. By conducting these investigations, it can be possible to control internal stress and deformation of SMAC.

5761-54, Session 10

Pressurized shape-memory thin foils and films

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Shape-memory films of Ti-Ni are often fabricated either by sputtering or flash evaporation. However, available experimental results have found that the recoverable deflection of pressurized Ti-Ni films is much smaller than that of identical bulk materials. There are various reasons for that. From theoretical point of view, we propose a micromechanical model based on von Kármánn plate theory and weak-convergent method to study it. We find that the estimation of recoverable deflection is very different from that of recoverable extension since the former is due to bi-axial tensile strain while the latter is due to one-dimensional tensile strain. On the other hand, Ti-Ni films are often contaminated by oxygen during sputtering, and therefore, their shape-memory recovery is degraded a lot. To avoid it, we propose two specimens: thin foil and sputtered film of Ti-Ni. Foils are obtained by rolling bulk Ti-Ni alloys first and then applied to certain special chemical treatment to further reduce their thickness to 30-40 μm. For sputtered films, we use MEMS technique to avoid the effect of substrate. Part of Si wafer and buffer layers such as Si3N4 and SiO2 beneath the central part of Ti-Ni film are carefully removed by anisotropic wet etching. Central deflection of these two specimens is measured under different bias pressure. The experimental results are found to be in fair agreement with the theoretical prediction.

5761-55, Session 10

Hybrid micro-macro-mechanical constitutive model for shape-memory alloys

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The main objectives for development of new technologies in aerospace have always been increased speed and range of aerovehicles and reduction of volume and weight of vehicle components. A substantial reduction in the size of control actuation systems employed in today's aerospace vehicles would enhance overall vehicle performance by reducing envelope volume requirements and inert weight. Functional materials such as shape memory alloys (SMA's) offer the opportunity to create compact, solid-state actuation systems by virtue of the material's ability to convert electrical energy to thermal energy to mechanical energy within its microstructure. Constitutive equations for SMA's and other materials can generally be classified according to the size of the representative volume element (RVE) considered in the modelling effort. Patoor's thermodynamic model, where the fractions of the austenite and the twenty-four martensite variants are determined by minimization of Gibbs potential, was one of the first attempts to describe the behavior of SMA's on a micromechanical level. Likhatchev's micromechanical model was similar to Patoor's in the sense that a statistical approach was used to average the contribution of each martensite variant to calculate the overall deformation. Macromechanical constitutive equations are based on RVE's that are orders of magnitude larger than the material's microstructure. Several researchers (Liang, Brinson, Huang) have refined the Tanaka model which is expressed in terms of moduli, thermoelastic and transformation tensors. The hybrid micro-macro-mechanical SMA model proposed here can be viewed as a combination of concepts originally presented by Likhatchev for microstructural modeling and Brinson for modeling of transformation kinetics. The size scale corresponding to a grain or crystal was selected as the RVE. It was assumed that, under stress, only one of the three martensite variants oriented along the local cartesian grain coordinate system could develop according to a maximum stress criterion. The variant strain was calculated with the classic Bain deformation tensor. Transformation of stress-induced or autoaccomodation martensite was described using the kinetic model that Brinson developed for a modified Tanaka constitutive law. The evolution of martensite fraction was followed with linear functions in place of trigonometric functions. Global strain of the heterogeneous solid or polycrystal, where the grains were assumed to be randomly oriented, was calculated by averaging the elastic, thermal, stress-induced and autoaccomodation strains of each grain over the total material volume. One dimensional model predictions were compared with experimental results in the shape memory effect and superelastic regimes. In superelastic temperature range, the model correctly predicted measured stress-strain behaviour with an average error of approximately 10%. As temperature was increased, it reproduced the observed shape change in the hysteresis loop. In the shape memory effect temperature range, the model predicted the measured stress-strain behaviour with an average error of approximately 5%. By increasing the test temperature, it was observed numerically and experimentally that the residual strain could be reduced. A numerical study was undertaken to understand how the number of grains used in the model affected the predicted results. It was found that at least 200 grains were needed to reach an acceptable coefficient of variation of 4% in terms of global strain. A test bench consisting of a load cell and a LVDT extensometer for force and displacement measurement, thermoelectric modules and programmable power supplies for heating and cooling control and a servo motor for force generation was built to apply and measure various force, displacement and temperature profiles on a SMA wire to validate the hybrid SMA model. The full paper will discuss the results of the validation effort.

5761-57, Session 10

Control of shape recovery force in SMA fiber reinforced composite materials

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The main influence factors to the actuator function and the sensor function in shape-memory alloy (SMA) fiber reinforced smart composite materials was examined. The 0.4mm diameter of TiNi type SMA fiber was used in this research and an embedded composite specimen as used in the polycarbonate matrix. Displacement of the specimen when heated by electric current was in real time measured and the effect of the shape recovery force (actuator function) was evaluated under ambient temperature of -40 to 80oC. After it begins to energize, the shrinkage of the specimen formed by the shape recovery force generation has the peak in 3-5sec, and displacement shift to the thermal expansion in next step. The shape recovery force has the peak within the range of the phase transformation temperature (As, Af) measured by DSC (differential scanning calorimetry). And shrinkage has decreased rapidly when the ambient temperature becomes distant more than the phase transformation region. It seems that making to the hybrid by SMA of a different phase transformation temperature is necessary to expand the ambient temperature which can be operated more widely. Then, the hybrid specimen was made by using two kinds of SMA with different phase transformation temperature, and the effect of the actuator function was evaluated. As a result, a hybrid test piece showed two kinds of SMA of combined intermediate characteristics, and confirmed the expansion of the environmental temperature region which was able to be operated.

However, it is necessary to control the electric heating condition corresponding to an ambient temperature to obtaining a steady actuator function. Then, the abnormal strain generated in the composite material was self-detected from the electric resistance change in the SMA fiber and the possibility of the system which controlled the shape recovery force by the electric heating within the wide range of an ambient temperature was examined. First of all, the temperature change of the electrical resistance of the SMA fiber of the composite material specimen was measured. As a result, the big electric resistance change distributed in the whole area of the phase transformation was measured. Then, whether the electric resistance change of SMA was able to be used as a strain gauge as well as conventional strain gauge was examined. The stress load signal of 5MPa was able to be detected clearly though an enough temperature compensating was not able to have done with the bridge circuit which composed the test piece of the compound material as an active gauge and a dummy gauge in a wide temperature region from -40 to 80℃. That is, the strain sensor function of SMA was confirmed.

A basic condition that smart composite materials which used SMA were able to be operated by the electric heating in a wide environmental temperature region stabilizing the actuator function was found by those evaluations.

It seems that problems in the future are how to do, to promote cooling the SMA fiber buried under the matrix of a low thermal diffusivity, and to achieve a high-speed response.

5761-58, Session 10

Structural applications of SMA/superelastic materials

E. I. Rivin, Wayne State Univ.

STRUCTURAL APPLICATIONS OF SMA/SUPERELASTIC MATERIALS

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Oral presentation is preferable

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SMA and superelastic materials (SEM) are mostly used for low force/large displacements applications involving tensile or bending modes of loading. The paper describes experiments on radial compression of SMA and superelastic wires and tubes between flat loading surfaces. Elastic (recoverable) deformations up to 22.5% with high damping under loads in the KN/mm range for solid wires and 10-100 N/mm range for tubes of OD = 0.4 – 2 mm have been observed. The recoverable deformation as great as 60% has been measured on a thin-walled SEM tube. This phenomenon was named a "Giant Superelasticity Effect". The experiments were performed in a broad range of load application rates. Stainless steel specimens were also tested for comparison. A close-form analysis for thin-wall tubes and some realized applications will also be described.

Keywords: structural; superelastic; SMA

5761-59, Session 11

Dynamic buckling and recovery of shape-memory thin-cylindrical shells

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Shape-memory alloys can sustain relatively large strains and fully recover without noticeable residual strains. This is referred to as superelasticity. We have been studying quasi-static and dynamic buckling of relatively thin circular cylindrical shells consisting of shape-memory alloys in order to understand the response

when used as the core of the sandwich structures. The work consists of experimental characterization of the buckling process, as well as numerical simulation. For comparison, we have also studied both dynamic and quasi-static buckling of aluminum and steel tubes of similar dimensions. This presentation will focus on numerical simulation of dynamic buckling of these tubes and correlation with experimental observations.

5761-60, Session 11

Magnetic and conventional shape-memory characteristics of Co38Ni33Al29 and Ni2MnGa shape-memory alloys

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In recent years ferromagnetic shape memory alloys have attracted increasing interest because of the ability to obtain one order of magnitude higher recoverable magnetic field induced strain (MFIS) than the other active materials. Low twin boundary energy, high strength of high temperature phase (austenite), high magnetocrystalline anisotropy energy and saturation magnetization are the main requirements for large magnetic field induced strain. A recently discovered ferromagnetic shape memory alloy; CoNiAl has promising shape memory characteristics for conventional and magnetic shape memory applications. The potential of CoNiAl and NiMnGa in actuator and sensor applications has generated considerable interest. However, their mechanical response including cyclic response is not fully understood, yet.

We have conducted extensive studies to capture several aspects of the shape memory behaviors on both single and polycrystals of CoNiAl. It has been demonstrated that these alloys have low pseudoelastic stress hysteresis (‹50MPa) high strength for dislocation slip, large pseudoelastic and two-way shape memory strain (~3%), large pseudoelastic temperature window (\›150ºC), low stress for martensite reorientation, and stable response to cyclic deformation. Selected experimental findings on single and polycrystals will be presented. The orientation dependence of the shape memory and pseudoelasticity will also be addressed in terms of the changes in transformation strain and transformation temperatures.

Magneto-mechanical response of NiMnGa and CoNiAl have also been addressed in our study. Combined effects of stress, magnetic field and temperature on shape memory behavior were revealed. Additionally, orientation dependence, cyclic response, and effects of magneto-thermo-mechanical training on strain levels and transformation temperatures will be presented. It was shown that the MFIS of about 5% could be obtained by applying magnetic field on a biased sample and stable cyclic MFIS of 1.5 % strain was observed by repeated application of magnetic field (R=-1) in NiMnGa alloys.

The effects of crystal orientation, magnetic field ramp rate and temperature were also investigated on the MFIS and cyclic response of CoNiAl and NiMnGa. Different microstructures were achieved by heat treatment to improve the magneto-thermo-mechanical response of these alloys. Our complete study of magnetic and conventional shape memory characteristics of NiMnGa and CoNiAl alloys proved the possible replacement of currently used actuators and sensors with these new alloys in the near future.

5761-61, Session 11

Modeling of the magnetic field-induced martensitic variant reorientation in and the associated magnetic shape-memory effect in MSMAs

B. Kiefer, D. C. Lagoudas, Texas A&M Univ.

As a new member of the class of active materials, magnetic shape memory alloys (MSMA) have drawn considerable attention in recent years. Research efforts have been directed towards experimental work as well as constitutive modeling. The paper begins with a brief review of the literature on MSMA. In this work the focus is placed on the constitutive modeling of MSMA, but recent experimental observations are considered to serve as physical motivation for the presented modeling approach. Experimental results are also used to provide data for quantitative model predictions.

MSMAs have been shown to exhibit temperature and stress-induced austenite to martensite phase transformations, which lead to conventional shape memory behavior. Although possible in principle, extensive magnetic fields are needed to actually induce the phase transformation with applied magnetic fields. The emphasis is therefore placed on a related phenomenon, the magnetic field controlled reorientation of martensitic variants, which makes the magnetic field-induced actuation of large inelastic strains in MSMA possible. The magnetic field-driven selection of variants is based on the fact that each of the martensitic variants possess different preferred directions of magnetization. Particular variants can thus be biased in a controlled fashion, by suitably oriented magnetic fields. The differences in crystallographic dimensions of the individual variants then cause the macroscopically observable shape change. The effect has been termed the reorientation process or the magnetic shape memory effect, amongst other names.

A phenomenological constitutive model is presented that captures the magnetic shape memory effect. First, a continuum mechanical framework is established on the basis of which the constitutive model is derived. The presented formulation incorporates the conservation laws of classical continuum mechanics as well as the magneto-static Maxwell equations. These two sets of equations are coupled through electromagnetic forces and energy sources that appear in the momentum and energy balances, as well as through constitutive relations. Furthermore, an extended thermodynamic framework is introduced that includes a dependence on magnetic state variables. A specific Gibbs free energy expression is given, in which mechanical and magnetic energy terms are considered that are relevant to the magnetic shape memory effect. The Zeeman energy, which can be interpreted as the potential energy associated with the misalignment of the magnetic field and the magnetization, is identified as the main magnetic driving force for the variant reorientation process. Other magnetic energy terms, such as the exchange energy, the magnetocrystalline anisotropy energy and the magnetostatic energy are discussed as well. Standard thermodynamic relations (Coleman-Noll procedure) are then used to deduce constitutive relations, by taking derivatives of the Gibbs free energy with respect to the independent state variables. Dissipative effects, whose influence is reflected in the hysteretic nature of the MSMA constitutive response, are incorporated by the introduction of internal state variables. In this approach the model distinguishes itself from many of the constitutive models presented in the literature, which are mostly based on the minimization of free energy expressions. Dissipative effects and the related loading history dependence of the constitutive behavior can not be directly captured in these formulations.

To physically motivate the choice of internal variables the crystallographic and magnetic microstructure is considered at different stages of the variant reorientation process. It is observed that at intermediate applied magnetic field levels, twin bands, containing different martensitic variants and magnetic domains, coexist. It is concluded that the macroscopic strain and magnetization response is directly connected to the evolution of the microstructure through twin boundary motion and magnetic domain wall motion. The influence of the microstructure is proposed to be captured through the specific choice of the inelastic reorientation strain, the martensitic variant volume fraction and the magnetic domain volume fraction as internal state variables. This procedure naturally leads to the derivation of evolution equations for the internal variables. To describe an activation criterion for the reorientation process, a reorientation function and associated Kuhn-Tucker conditions are introduced. The evolution of the variant volume fraction is thereby based on a principle of maximum reorientation dissipation and is consistent with the constraints by the second laws of thermodynamics, which is conveniently expressed in terms of the Clausius-Duhem inequality. The influence of different types of hardening functions, such as trigonometric or polynomial hardening, on the reorientation strain response is investigated.

A procedure devised to methodically fit model parameters to experimental data is derived. Then, specific numerical examples for the application of the constitutive model are given. These demonstrate the applicability and validity of the model as well as its limitations, which are a consequence of simplifying assumptions in the modeling approach. Specific results include the prediction of strain-magnetic field-hysteresis loops under varying applied stress levels. The reorientation function and the associated reorientation conditions are graphically illustrated and physically interpreted with the help of a specific stress-magnetic field-phase diagram, for the considered numerical example.

In a next step, the established phenomenological constitutive model for MSMA is utilized in solving simple magneto-mechanical boundary value problems. These solutions proof to be very helpful in the interpretation of experimental results. For example, the commonly measured strain-magnetic field curves can usually not be interpreted as purely the constitutive response of the MSMA material. The reason is the fact that the magnetic field at a material point inside of a specimen is different from the externally applied magnetic field, which is actually measured, due to the demagnetization effect. The demagnetizing field, however, depends on the specimen geometry as well as the magnetization. The measured material behavior is therefore partly due to structural response and partly material response. The demagnetizing field is calculated by solving Maxwell's equations for the associated boundary value problem, utilizing the presented continuum mechanical framework. As mentioned, the procedure of solving these equations is complicated by the coupling of Maxwell's equations with the mechanical equations through the nonlinear, hysteretic constitutive response as well as magnetic force terms. Finally, using the described procedure, the influence of magnetic field gradients and the associated magnetic body forces on the magnetic shape memory effect is also investigated. The paper concludes

with a discussion of the capabilities and limitations of the introduced constitutive model and its relation to other approaches presented in the literature. Possible extensions of the presented work and future efforts are outlined.

5761-62, Session 11

Multiscale constitutive model of magnetic shape-memory alloys

V. M. Stoilov, Univ. of Windsor (Canada)

Important advances in multi-scale computer simulation techniques for computational materials science have been made in the last decade as scientists and engineers strive to imbue continuum-based models with more-realistic details at quantum and atomistic scales. One major class of multi-scale models directly couples the atomistic detail to the macro region modelled using continuum concepts and finite element methods. Here, the development of such coupled atomistic/continuum model is presented within a single coherent framework with the aim of providing quantitative description of the constitutive behaviour of magnetic shape memory alloys. A formulation of the Helmholtz free energy potential based on one-dimensional Ising model has been derived. The developed thermodynamic potential has been used in the context of the sharp phase front-based continuum model of the first order phase transformations suggested by Stoilov and Bhattacharyya (Acta Mat. 2002). Comparison with the experimental results of the investigation on single crystal magnetic shape memory alloy (Ni-52Mn-24Ga) was performed. The obtained numerical results showed that the proposed model could capture corresponding experimental results accurately enough to be applied to smart structures design.

5761-63, Session 11

Characterization of piezoelectrically induced actuation of Ni-Mn-Ga single crystals

J. M. Chambers, S. R. Hall, R. C. O'Handley, D. C. Bono, Massachusetts Institute of Technology

A new actuation method for shape memory materials has been developed utilizing a combination of a Ni-Mn-Ga ferromagnetic shape memory alloy (FSMA) single crystal and a piezoelectric stack actuator. Single crystal FSMA actuation is typically accomplished by using a magnetic field to induce twin boundary movement and extend the crystal, and allowing a mechanical force to reverse the twin boundary movement and restore the crystal to a compressed state as the magnetic field is removed. To remove the need for a magnetic field, a novel actuation method was developed that accomplishes twin boundary movement using transient acoustic stress pulses induced by a piezoelectric actuator. The transient stresses must be large enough in one sense (compressive or extensional) to induce twin boundary motion, while remaining small enough in the opposite sense to avoid reversing said motion. In practice, these transient stresses are developed by applying a saw-tooth shaped voltage wave to a piezoelectric stack. The effect of pulse frequency, pulse shape, output load and prestress on actuator performance has been investigated. With the current device, bi-directional strains of over 3% have been accomplished; this is comparable to the strains achieved using bi-directional magnetic actuation with a bias spring restoring force. Peak to peak stresses, as expected, are lower than those achieved with magnetic actuation, around 125 kPa as opposed to 1 MPa. The combination of high static holding force and sub-micron step size may make this actuator ideal for some micropositioning applications.

5761-64, Session 11

Mechanical efficiency of acoustic-assisted, magnetic-induced-strain in ferromagnetic shape-memory alloy actuators

B. W. Peterson, R. C. O'Handley, S. M. Allen, Massachusetts Institute of Technology

A small, high-frequency acoustic energy input to a Ni-Mn-Ga crystal has been observed to increase the low-frequency magnetic-field-induced strain response by up to one order of magnitude. For the purposes of making a usable device, the relative efficiency of the acoustic and magnetic input energy (or power) needs to be determined. At this stage we ignore the output of the magnetic and piezo power supplies and consider only the energies put directly into and coming out of the NiMn-Ga crystal. These include the low-frequency magnetic field energy applied to the Ni-Mn-Ga, $\mu_0 M_s H V$, the high-frequency mechanical energy applied to the Ni-Mn-Ga by the piezo and the low-frequency output mechanical energy of the FSMA. Calculations based on measurements of the relevant quantities indicate that the mechanical energy (or power) output of the Ni-Mn-Ga is approximately 8% of the input magnetic energy when driven only with an applied magnetic field at 1 Hz. If a small-amplitude, high-frequency stress and strain is applied to the FSMA by the piezoelectric stack simultaneously with the magnetic drive, the mechanical energy output of the FSMA increased in one case by about 50%; the calculated efficiency (mechanical work out divided by the sum of magnetic and piezoelectric work input increased to ~12%. The additional power output is much greater than the piezo power input; it comes from a more efficient use of the magnetic field input energy. This has obvious beneficial consequences for the design of actuators based on magnetic-field-induced strain in ferromagnetic shape memory alloys.

5761-65, Session 11

Inductive measurement of combined acoustic and magnetic actuation

R. Techapiesancharoenkij, B. W. Peterson, J. M. Chambers, J. Feuchtwanger, D. C. Bono, S. M. Allen, R. C. O'Handley, Massachusetts Institute of Technology

The effect of acoustic energy input from a piezoelectric actuator on the magnetic-field-induced strain (MFIS) of Ni-Mn-Ga ferromagnetic shape memory alloys (FSMAs) near the composition Ni2MnGa is investigated. The MFIS response is increased by this new technique by up to one order of magnitude. To understand better the effect of a piezoelectric actuator, the dependence of the inductance, L, of a NiMnGa single crystal on applied magnetic field, Ho, and on supplementary acoustic energy is investigated. The inductance is measured in the long direction of the crystal with a magnetic field applied perpendicular to the inductance-measuring direction. Because the inductance depends on the orientation of the magnetic moments, L(Ho) is able to distinguish a) domain wall motion from b) reversible magnetization rotation or c) irreversible twin boundary motion, as a consequence of an applied magnetic field or piezoelectric actuation.

Above a threshold magnetic field, twin boundary motion is activated such that the twin variants having their easy axes aligned along the field direction grow. The inductance drops significantly at the threshold field (i.e. L(M^) < L(M//)), enabling the threshold field to be determined from the L(Ho) plot. With an introduction of acoustic energy, the threshold field is decreased from about 5 kOe to about 4 kOe for 120 V applied to the piezoelectric actuator.

It is noted that the L(Ho) plots of two Ni-Mn-Ga single crystals with similar composition but different thermal history can differ significantly. The initial variant structures of the two crystals are likely different from each other leading to different inductance characteristics. The data of L(Ho) is used to determine the initial variant structures by analyzing a free energy expression including magnetic anisotropy, Zeeman energy and the energy of the small time-dependent field used for the inductance measurements. This method may give a new perspective on the initial variant structure of an FSMA sample and shed light on the details of acoustic assisted MFIS.

5761-66, Session 12

Damping of polycrystalline ferromagnetic shape alloy bulk and sputtered thin film

D. A. Ruggles, G. P. Carman, Univ. of California/Los Angeles

An unmet need exists for damping harsh vibrations associated with MEMS inertial guidance devices. These devices include angular rate sensors used for advanced missile and munitions systems (smart cargo, compact kinetic energy missile, medium caliber munitions) and subjected to high forces (~100,000 g) and harsh in-flight vibration environments. Another such device is the phased array antenna, which does not have the same angular acceleration resolution problem as the aforementioned devices, but has a problem with the aim of the information beam when the deflection of the device is not symmetric. Development of thin film materials for passively damping the spurious vibrations associated with MEMS inertial-guidance systems (device/die level structures) is critical to the performance of these military systems. Possible solutions are using Ni-Mn-Ga or NiTi thin films with damping caused by stress activated twin boundary motions. To achieve damping via thin film Ni-Mn-Ga or NiTi, the film fabrication and processing science must be veraciously controlled. Polycrystalline Ni-Mn-Ga thin films have been deposited by sputter deposition from a composite Ni-Mn-Ga target (50:31:19 at%). Polycrystalline Ni-Mn-Ga thin films have been deposited by DC magnetron sputter deposition from a composite Ni-Ti target (50:50 at%). The effects of these processes on the film's physical properties were determined. Film structure, microstructure, composition, surface, and damping properties were measured using XRD, TEM, SEM, EDS, and RBS characterization techniques. Damping from twin boundary motion is quantified through an overall tan delta value for a given test run.

5761-67, Session 12

Temperature effect on the damping capacity of Ni-Mn-Ga/ polymer composites

J. Feuchtwanger, M. L. Richard, D. C. Bono, S. M. Allen, R. C. O'Handley, Massachusetts Institute of Technology

The use of Ni-Mn-Ga/polymer composites has been previously proposed and encouraging results have been reported. The use of these ferromagnetic shape memory alloys as a particulate filler in the polymer matrix increases the loss by means of the irreversible motion of twin boundaries. It has been reported that the loss modulus in single crystal Ni-Mn-Ga increases as the temperature of the sample approaches the martensite transformation temperature. We report the effect of temperature on the loss ratio in Ni-Mn-Ga/polymer composites and a pure polymer control sample as a function of temperature up to the martensitic transformation temperature (T ≈ 55 C). The contribution of the losses of the two components of the composites are analyzed.

5761-68, Session 12

Energy absorption and damping in NiMnGa composites

E. Gans, G. P. Carman, Univ. of California/Los Angeles

Our experiments have shown significant energy absorption in composite samples containing Ni49Mn29Ga21 Ferromagnetic Shape Memory Alloy particulate. Results are presented from two types of mechanical experiments to determine energy absorption and tan delta, a common measurement of damping. Samples were tested quasi-statically under tension and compression in the grips of an MTS Tytron at strain levels from 0.5% to 3.0%. The resulting stress-strain curves showed large hysteresis in samples containing the NiMnGa particulate. Damping capacity of the samples was determined graphically based upon the area of the hysteresis of the mechanical loops with data indicating that increasing strain levels results in increasing tan delta. Testing at 0.5% strain level results in a tan delta of 0.15 and at 3.0% strain the tan delta increases to 0.20. Several cycles were completed at each strain level to ensure the repeatability of the measurements. Various composites were fabricated to determine the effects of particle alignment as well as the contributions of the polymer matrix to the damping capacity. The samples were also tested in single fixed-guided cantilever mode within a Dynamic Mechanical Thermal Analyzer (DMTA) to allow for another measure of the damping capacity of the composite samples. The high damping capacity of NiMnGa composites shows promise for use in vibration and shock absorber systems. Currently, only viscoelastic materials, such as rubber, exhibit such a high damping capacity, but their inherently low modulus (roughly 1 MPa) limits their applications. NiMnGa composites possess the attributes of both high damping capacity and large modulus (300 MPa) making them a more suitable candidate in high shock applications.

5761-69, Session 12

Fabrication of magnetic shape-memory alloy/polymer composites

R. Ham-su, J. Healey, R. Underhill, S. Farrell, L. Cheng, C. Hyatt, Defence Research and Development Canada/Atlantic (Canada); R. Rogge, M. Gharghouri, National Research Council of Canada (Canada)

NiMnGa-based magnetic shape memory alloys (MSMA's) have attained magnetic field induced strains up to approximately 10% and have a relatively wide operating temperature range, from well below 00C to above room temperature (22 to 250C), making them very attractive for a variety of applications. However, these materials also suffer from low toughness. Using these materials in a composite could mitigate this limitation, and also overcome restrictions imposed by inertia and eddy current losses.

In this work, NiMnGa-based magnetic shape memory powders were fabricated. These were then used for manufacturing MSMA/polymer composites using different magnetic field line patterns. Clumping of particles seems to be more likely under fields with curved lines than for fields with straight parallel lines through the sample. Magnetization curves clearly show anisotropy which correlates well with the crystallographic texture obtained by neutron-diffraction. When the composites are compressed their magnetic field measured close to the surface changes. In addition, some of the composites were actuated under a 0.9 Tesla magnetic field indicating that the MSMA's particles are active within the matrix.

5761-70, Session 12

Reversible strain in Ni-Mn-Ga with collinear field and stress

L. E. Faidley, M. J. Dapino, G. N. Washington, The Ohio State Univ.; T. A. Lograsso, Iowa State Univ. and DOE Ames Lab.

Ferromagnetic shape memory nickel-manganese-gallium (Ni-Mn-Ga) is attractive for transducer applications because it has been shown to exhibit strains of 6 to 9.5% when exposed to magnetic fields of 5 kOe. Such strains are on the order of those possible from standard shape memory alloys (SMAs) but because they are generated in response to a magnetic field the capability for higher bandwidth responses have been demonstrated. As with standard SMAs the large strains in Ni-Mn-Ga are due to the psuedo-elasticity that occurs due to the reorientation of the martensitic twin variants which, in FSMAs, can be driven by a magnetic field in addition to external stresses. Unlike standard SMAs however Ni-Mn-Ga is typically employed solely in its high temperature martensitic phase and hence is lacking the restoring mechanism that the phase transformation in SMAs provides. Thus, in order to achieve the giant strains from Ni-Mn-Ga an external restoring force needs to be applied orthogonal to the applied field to restore the original orientation of the twin variants. Our tests have shown that reversible strains of -0.42%, which is almost a three-fold strain increase over Terfenol-D, are achievable without an external restoring force. Existing models for the strain created by variant reorientation in Ni-Mn-Ga do not predict such reversible strains however, therefore this paper proposes an addition to the current description of the strain mechanism which offers an explanation for both the reversibility and the smaller magnitude of the strain. Work will be presented that validates this hypothesis through experimental imagining techniques and theoretical and numerical modeling.

Note: I am submitting this paper to the student paper competition. The extended abstract is attached.

5761-72, Session 12

Magnetic shape-memory fatigue

O. Heczko, L. Straka, Helsinki Univ. of Technology (Finland); K. Ullakko, Adaptamat Oy (Finland); S. Hannula, Helsinki Univ. of Technology (Finland)

Magnetic shape memory effect (MSME) or giant magnetic-field-induced strain up to 10% was observed by our group in Helsinki in Ni-Mn-Ga martensites. The maximum of the MSME depends on the crystal lattice of martensite. For successful utilization of the MSME in various kinds of actuators the knowledge of long-term behavior is needed. There are two interconnected questions for long-term stability of the working elements in an actuator: the structural stability of the elements during large deformation and the ability to sustain the MSME without decreasing the magnitude of the effect. The single crystal specimens of various compositions close to Ni2MnGa exhibiting MSME were tested in rotating magnetic field with frequency of 6 Hz. The strength of magnetic field was enough to induce the MSME. The specimens were tested up to 35 mil cycles. The evolution of the martensitic morphology and cracks propagation in tested specimen was observed by optical microscopy. Some tests had to be disconnected due to structural failure of the specimens. We used simultaneous measurements of the field-induced strain and magnetization as a function of the magnetic field and external load to fully characterize the magnetic shape memory behavior of the tested specimens. The evolution of MSME differs for different specimens. During the first million cycles the full MSME (about 6%) decreased to about 3% and after that this value stayed approximately constant up to 36 mil. cycles. Additionally the magnetic field needed to initiate the MSME increased. However, in some specimens there was no large decrease of the MSME up to 17 mil. cycles. The observed behavior is discussed in the frame of observed martensitic band structure in the specimens and the existence of pinning centers and other obstacles for martensitic twin boundary motion.

Conference 5762: Industrial and Commercial Applications of Smart Structures Technologies

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5762-01, Session 1

Industrial and commercial applications of Metal Rubber™

R. O. Claus, Virginia Polytechnic Institute and State Univ.; J. H. Lalli, NanoSonic, Inc; B. A. Davis, J. B. Mecham, R. M. Goff, A. Hill, S. Subramanayan, NanoSonic, Inc.

This paper discusses potential industrial and commercial applications of Metal RubberTM, a new free-standing nanocomposite material that combines the properties of metals and rubber. Like metals, Metal RubberTM has high electrical and thermal conductivities. Like elastomers such as rubber, it has low modulus and can be repeatedly elongated to several hundred percent strain yet relax elastically back to its original shape, all while remaining conductive. Metal RubberTM is formed by a modified electrostatic self-assembly approach that allows the formation of thick, large surface area nanocomposites to be formed with multiple controlled constitutive properties. The largest dimensions formed to date are approximately 0.6 meter square and 1 centimeter thick. The synthesis process uses an approach similar to conventional electrostatic self-assembly to rapidly form molecular level coatings on top of a chemical release layer applied to a substrate. After the desired thickness of material is achieved, the self-assembly process is stopped, and the chemical release layer etched away to free the nanocomposite from the sacrificial substrate. Other presentations at this SPIE meeting will detail the chemical synthesis process and describe the range of conductivities and moduli achieved. This paper will discuss current laboratory experimental demonstrations of potential applications of this material as sensors, electrodes, interconnects and shielding for aerospace, microelectronic and biomedical applications.

5762-02, Session 1

Self-healing cables and composites

B. Esser, D. R. Huston, Univ. of Vermont

This paper describes preliminary results from projects focusing on self-healing structural technologies. The first self-healing technology pertains to cable and wiring systems, in which the cables respond to wear and chafing by toughening in the areas adjacent to the wear. This is accomplished through various means, but is essentially caused by a reaction at the wear site which causes the insulation on the wires to toughen in response to chafing. This type of system allows for installation of electrical systems with no added complexity, however once installed the cables can adapt in the necessary regions to prevent harmful and costly chafe failures of the cabling systems. The second topic covered involves self-healing of composite systems. Preliminary experiments are presented in which small channels are placed in a composite layup, and are then used to both monitor damage and to deliver “healing” agents to the damage sites. Construction techniques and testing results will be discussed. Both of these self healing systems are biologically inspired means of adapting to surroundings. Whereas the toughening cables add strength in the areas that need it, similar to a callus forming on a highly used part of a hand, the composite channels goes one step further to sense and deliver healing agents to a damage site, similar to the formation of a scab on a wound. Manufacturability and implementation of each system will also be covered.

5762-03, Session 1

Stoichiometric study of TbxDy(1-x)Fe1.92 composites for passive vibration damping

K. K. Ho, Fortis Technologies; G. P. Carman, Univ. of California/Los Angeles

Vibration in mechanical structures can cause unwanted noise, fatigue of the structure, and poor mechanical performance. An effective damping solution is highly desired in many mechanical situations. Magnetostrictive Terfenol-D promises to offer substantial passive damping thru magnetic domain wall motion. The material offers advantages over traditional viscoelastic damping materials, i.e. high stiffness and less temperature sensitivity. The authors varied the Tb composition in a Tbx(Dy(1-x)Fe1.92 alloy, to determine the optimum composition for damping. Magnetostrictive particulate composites of these varying compositions were subsequently fabricated and damping measurements made and compared to the bulk samples. Damping measurements performed included calculation of hysteric losses calculated from stress strain curves, as well as tan-delta measurements from a Dynamic Mechanical Analyzer. Temperature variability of damping properties in the material was examined from -50C to 100C. Results show substantial energy losses as high as 50% of the energy input, with higher damping as the composition shifted towards higher Tb compositions, peaking at Tb=0.5. Temperature variability was minor and significantly better then Viscoelastic damping solutions.

5762-04, Session 2

A high-temperature shape-memory alloy sensor for combustion monitoring and control

G. S. Shaw, J. T. Snyder, T. S. Prince, M. C. Willett, Orbital Research Inc.

Innovations in the use of SMA materials have enabled the development of a harsh environment pressure sensor useful for combustion monitoring and control. Priority development of such active combustion control has been driven by rising fuel costs and environmental. Active combustion control, whether in diesel, spark ignited, or turbine engines, requires feedback to the engine control system in order to adjust the quantity, timing, and placement of fuel charges. To be fully effective, sensors must be integrated into each engine in a manner that will allow continuous combustion monitoring (turbine engines) or monitoring of each discrete combustion event (diesel and SI engines). To date, the sensors available for detection of combustion events and processes have suffered from one or more of three problems:

1) Low sensitivity: The sensors are unable to provide and adequate signal-to-noise ratio in the high temperature and electrically noisy environment of the engine compartment. Attempts to overcome this difficulty have focused on heat removal and/or temperature compensation.

2) Low reliability: Sensors and/or sensor packages have been unable to withstand the engine environment for extended periods of time. Issues have included gross degradation and more subtle issues such as migration of dopants in semiconductor sensor materials.

3) High cost: The materials that have been used, the package concepts employed, and the required support electronics have all contributed to the high cost of the few sensor systems available. Prices have remained high due to the limited demand associated with the poor reliability and the high price itself.

Titanium nickel alloys, with platinum group metal substitution for the nickel, are deposited as thin films on MEMS-based diaphragms and patterned to form strain gages of a standard metal film configuration. These sensors are maintained at a temperature just in excess of the austenite finish temperature (Af). When the diaphragm is deformed by an applied pressure, the film undergoes the reversible martensite phase transformation. The large difference in the resistivity of the two phases results in a very sensitive strain gage, and hence a pressure sensor with a very high gage factor. The combination of the thin film and the fact that the transformation is strain induced (rather than thermally induced) results in a sensor with very high response rate. In fact, the response rate of the sensor has been shown to be strictly a function of the mechanical response of the diaphragm. Unlike other sensor systems, the temperature of the SMA sensor is controlled above the temperature of the local environment. By controlling above the temperature of the environment, the sensor is largely immune to temperature fluctuations that can affect the response of other sensors.

This technology has been demonstrated for a variety of target temperature regimes and a variety of pressure regimes. Sensor design and testing to date has ranged from 180C to \›500C; and design pressures of 50 to 3500 psi, with higher pressures acheivable. Characterization has included analysis of the response rate, the temperature sensitivity, reliability, and the effect of gross alloy changes. Some engine testing has also been completed. Ongoing work includes the sensitivity to minor composition changes, sensitivity to film thickness, and extended reliability and engine testing.

5762-05, Session 2

Shape-memory polymer mandrels

M. C. Everhart, Cornerstone Research Group, Inc.

Cornerstone Research Group, Inc. (CRG) has recently demonstrated the feasibility of filament winding complex compound-curved composite shapes on shape memory polymer (SMP) mandrels. SMP’s are polymers whose qualities have been altered to give them dynamic shape “memory” properties. Under thermal stimuli, shape memory polymers can exhibit a radical change from a rigid polymer to a

very flexible, elastic state, and then back to a rigid state again. In its elastic state, SMP will recover its "memory" shape if left unrestrained. The "memory," or recovery, quality comes from the stored mechanical energy attained during the reconfiguration and cooling of the material. SMP's ability to change stiffness modulus and shape configuration at will makes SMP ideal for use as mandrels. A bladder made of CRG's Veriflex™, a thermoset SMP, is fitted with an air fitting on one end. The bladder is then raised above the SMP material's glass transition temperature, which is designed 5 to 10 degrees above the maximum processing temperature for the composite material. This allows the SMP bladder to become pliable and rubber-like. The bladder is then inflated inside a clamshell master metal mold with a cavity in the shape of the desired mandrel for new composites. The SMP bladder is then cooled below its glass transition temperature while still under pressure. The lowering of the temperature creates a change in the SMP material's mechanical properties back to a rigid glass-like structure. After the polymer is cooled an exact replica of the cavity is retained without the need of further air pressure. The SMP mandrel maintains structural rigidity capable of holding desired tolerances during traditional filament-winding conditions. To fabricate new composite materials, the SMP mandrel is then filament wound with traditional fabrication methods, processed and post processed with traditional methods such as high temperature cure and autoclave. After the resin has cured the SMP material is again raised above the glass transition temperature. This allows the bladder to automatically deflate and allows easy extraction of the mandrel. This mandrel system demonstrates a configurable and reusable mandrel fabrication of complex-curved composites quickly, easily, and at a low cost. Veriflex™, the trademark for CRG's family of shape memory polymer resin systems, currently functions on thermal activation customizable from –20°F to 520°F. This wide temperature range allows the SMP mandrel system to be used with traditional composite cure cycles.

5762-06, Session 3

Elastic Memory Composites (EMC) for deployable space structures

M. L. Tupper, N. A. Munshi, M. S. Lake, S. C. Arzberger, R. Barrett, P. N. Keller, W. H. Francis, D. Campbell, Composite Technology Development, Inc.; K. A. Gall, Univ. of Colorado/Boulder

Composite Technology Development (CTD) has developed a novel "smart" material called Elastic Memory Composite (EMC). EMC materials are comprised of a fiber, reinforced TEMBO™ shape memory polymer (SMP) resin and are characterized by their ability to be mechanically deformed, store strain, and shape recover upon exposure to a specific thermo-mechanical cycle. CTD's TEMBO™ SMP resins are high-strain-to-failure, fully cured, low outgassing, epoxy or cyanate ester thermoset resins that provide excellent shape memory performance and enable very robust packaging and deployment of EMC structures over many cycles and a wide range of operating temperatures. These characteristics make EMC technology particularly well suited for application to deployable space applications. This technology enables the design of simple, rigid, deployable composite structures without motors, bearings, position sensors, and complex control electronics and software. EMC can be tested on the ground, then rolled or folded up before launch, and easily and reliably deployed on orbit by the application of heat. EMC materials can reduce mission risk, increase spacecraft payload capacity, and lower launch cost. These benefits of EMC are enabled by the TEMBO™ resins high elastic-strain capacity and the ability to store, and subsequently recover, mechanically induced strain in these thermoset resin. Currently, EMC technology is scheduled for application on several space flight missions. An account of the process and results of testing to space qualify these materials and a discussion of the process to design EMC components to meet specific mission requirements will be reported.

5762-07, Session 3

Light-activated shape-memory polymers and associated applications

T. H. Tong, E. Havens, Cornerstone Research Group, Inc.

Cornerstone Research Group Inc. (CRG) will present first-year results of our material development on light-activated shape memory polymer (SMP). The goal of this research is to develop and demonstrate viable material technology to support morphing and/or deployable structural applications. Veriflex™ shape memory polymer technology has been demonstrated to have great potential in enabling future smart, adaptive structural system design for various space and aerospace systems, such as morphing wings. The possibility of employing alternative deployment or actuation mechanism, such as light energy instead of direct thermal heating, in SMP will provide additional benefit, such as signature management and elimination of heat cycling during SMP deployment. We will discuss the potential in integrating this new material technology with other state-of-the-art smart materials technologies to develop smart adaptive or morphing structures for near-, mid- and far-term applications. We will also outline the issues and challenges in developing and integrating this new material into future aerospace systems.

5762-08, Session 3

Research and design of a remotely activated SMA actuated naval tie-down system

R. Shydo, Jr., Ithaca Mechanical Systems, Inc.; E. Garcia, Cornell Univ.; J. Harris, Ithaca Mechanical Systems Inc.

Ithaca Mechanical Systems and Cornell University focused their STTR efforts on the design and prototyping of advanced tie down systems for restraint of M1A1 tanks on Naval Hovercrafts. The ties were required to restrain 35,000 lbs of tensile load, interface with current craft hardware and electrical systems, as well as provide increased ease of operation as compared to current ties. The new ties were designed to accommodate the force and displacement constraints of shape memory alloy actuators, the strength of support materials, shape limitations of the assembled system, and the power limitations of energy storage and transmission devices. These tasks included the design of numerical simulations, FEA models, and plastic rapid prototypes. The functional prototype utilizes wire based SMA actuators with superelastic spring actuated power-off re-tensioning. The system was designed to utilize energy stored in batteries released remotely via RF signals provided by COT transmitters and receivers. Switching was accomplished utilizing specially designed MOSFET arrays with provisions for PWM power modulation under full SMA contraction. The system was also designed to use advanced synthetic fiber webbing as tension materials to reduce overall system weight and size. The project was funded by the Office of Naval Research under the Navy STTR program as a Phase I project.

5762-09, Session 4

A nondestructive method to estimate moisture content in grain from RF impedance measurements with a parallel-plate sensor

C. V. Kandala, C. L. Butts, USDA Agricultural Research Service

A method to measure the phase angle (θ) and complex impedance (Z) of a parallel-plate capacitor with shelled peanuts between the plates, at two frequencies 1 and 5 MHz, is described here. From the values of θ and Z, the capacitance of the parallel-plate system at each of the frequencies was obtained. An empirical equation to estimate the moisture content, using these complex impedance values, was developed. Using the values of phase angle and capacitance in the predictive equation, the moisture content (mc) of over 80% of the peanut samples was estimated to an accuracy of within 1% of the standard air-oven value. The moisture range of the peanuts tested was between 5 and 20%. The method is rapid and nondestructive and is also expected to find application in other types of grain such as wheat and corn. The study establishes a basis for the development of a practical instrument that could be useful in the grain industry.

5762-10, Session 4

Design and analysis of ultrasonic horn for a soil penetrator

Z. Chang, S. Sherrit, M. Badescu, X. Q. Bao, Y. Bar-Cohen, Jet Propulsion Lab.

Detection of fragile objects buried up to one meter underground in soil is on the interest of geologists, criminologist, and many others. Reaching such depth is a challenging task particularly when there is a need to penetrate through consolidated soil. Existing drilling techniques require large axial forces, which increase the risk of piercing through or otherwise damaging the detected objects. The current soil penetrator under investigation is based on a novel technology called ultrasonic/sonic driller/corer (USDC) which requires minimal axial force [1]. The USDC uses a piezoelectric based driving mechanism, transforming ultrasonic vibrations to sonic frequency impacts by a free-flying mass block (free-mass). The free mass then drives the drill bit. The actuator consists of a stack of piezoelectric disks in contact with a horn that amplifies the induced vibrations amplitude. To optimize the amplification of the vibration displacement and velocity that are generated by the piezoelectric materials, various horn designs were examined analytically. In addition the size of free mass was also investigated to maximize the energy transfer from the ultrasonic horn to the free mass. The results of the analysis will be discussed in this paper.

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5762-11, Session 4

Development and optimization of novel sensors for inline measurement of sand filling and compaction stages in lost foam casting

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Note: This is an extended abstract submitted for consideration in 2005 SPIE/ ASME Best Student Paper Presentation Contest. The lost foam casting (LFC), or expendable pattern casting, process is employed worldwide in foundries as an efficient casting technology that offers the advantages of consolidation of components, reduced machining, and recirculation of casting mold material. The process involves producing a blown polystyrene pattern of the desired final product that evaporates and is replaced by molten metal during casting. Compacted, unbonded granular material offers mechanical support to the pattern as well as a permeable boundary through which liquid and gaseous byproducts of foam pyrolysis can escape. The foam pattern is suspended in the casting flask and dry sand is rained from overhead at a variable rate, while the flask which is vibrated to achieve higher levels of compaction as well as to promote fluidized flow into complex cavities. The degree of compaction in the sand surrounding the foam pattern is a critical parameter in reducing casting defects, subsequent machining, and foundry waste. Insufficient compaction will provide inadequate force to prevent the advancing metal front from penetrating beyond the boundary of the foam pattern. Conversely, excessive compaction may deform the relatively soft expanded polystyrene causing dimensional defects in the final product. Additionally, heavily compacted sand has reduced permeability, which may trap foam pyrolysis byproducts and cause fold defects in the cast. Currently, many foundries develop a schedule of sand raining flow rates and flask excitation accelerations for each specific pattern through an often-lengthy trial and error procedure. Furthermore, during casting, a single flask acceleration measurement is typically the only means by which the sand compaction is monitored. The current research focuses on developing an array of measurement tools to be used in measuring parameters critical to the sand compaction stage of the lost foam casting process to aid in the development of filling and vibration schedules as well as to provide additional inline measurements during foundry operation.

Although previous studies have focused on measurements relating to sand compaction in the flask, the methods employed are typically highly intrusive to the process and better suited for studying the mechanics of the process rather than providing process measurement and control. Wegscheid1, as referenced by AFS2, studied the effects of flask frequency, acceleration, and duration of excitation on the average sand density in a flask without a foam pattern through the use of bulk density measurements. Additionally, flow into tubes clamped to the flask was monitored using linear variable differential transducers. Although this study has provided substantial insight into process parameter effects, localized density measurements are more critical that the bulk flask density and LVDT's provide no indication of the sand density within cavities. Kuraoka3 developed a three-dimensional dilatometer that measured the development of soil stiffness in orthogonal directions and identified the development of anisotropic conditions in the casting sand during the filling and compaction stage. This device as well is better suited for research into the process mechanics due to its significant size. Additionally, a parametric study was undertaken by the University of Alabama at Birmingham3,4 in which tools were developed for measuring pattern deformation and in-cavity sand densities. A thin steel strip instrumented with a strain gage and affixed to the foam pattern was used to identify deformations induced by sand pressures on the foam pattern. However, due to reinforcement effects on the foam pattern by the stiffer steel strip and the presence of a three-dimensional stress field, a single strain gage instrument can neither determine the magnitude of deformation nor designate process limits. In addition to this distortion gage, simple parallel plate capacitors as well as a commercial capacitance probe were implemented to obtain relative densities within pattern cavities. Sand in the capacitive field acts as a dielectric and produces a change in capacitance that is related to the density of the sand. Voltage outputs corresponding to an empty field as well as to maximum sand compaction were designated as the limits of the device, but the linearity of the transducer to changes in density was not discussed nor was any correlation presented. These capacitance-based transducers have been deemed promising by this author as tools for foundry use and will be developed in an alternate geometric configuration.

The current research presents tools for foundry implementation during the development of sand flow rate and table excitation schedules and subsequently inline during casting operations. In particular, the project utilizes the following sensors and sensor arrays:

1.An array of miniature accelerometers is utilized to identify the vibrational characteristics of several regions of casting flask as well as the clamping arm throughout the filling stage. A profile of acceleration measurements can be used to monitor flask distortions that affect sand flow and signal deterioration or damage of the casting flasks over time.

2.Additionally, a commercially available, extremely thin, tactile pressure measurement system is applied to measure the sand contact pressures on the deformable foam pattern6 (Fig. 1). The Tekscan I-Scan system provides real-time insight into the development of contact pressures at as many as 2288 nodes across the area of each sensor grid. The 0.1mm typical thickness of these sensors offers a minimally intrusive means of monitoring the dynamic pressures experienced on the foam pattern and subsequently correlating pressure levels with the occurrence of significant pattern distortions or casting defects.

3.Finally, capacitance-based transducers are developed in a pipeline geometry (Fig. 2) and coupled with measurement circuitry for the detection of changes in capacitance in order to detect the level of compaction within pattern cavities. The pipeline design offers greater dimensional flexibility then typical commercially available non-contact capacitance probes and allows for the measurement of the average sand density in the pattern cavity rather than a measurement of the density at a limited region surrounding the face of the probe7. Once limits are set to define the desirable levels of local sand compaction and sand-foam interface pressure for given accelerations, the proposed array of sensors act as a novel tool that can be utilized in the foundry to enhance process development for new patterns, reduce startup waste, and further improve monitoring during the sand filling and compaction stage.

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5762-12, Session 4

Structural sensor testing for space vehicle applications

J. Q. Huang, J. Rose, J. Gordon, Boeing Co.

A set of structural sensors was tested on a graphite/epoxy skin/stringer panel bonded with thermal protection system (TPS) at a simulated space flight environment. The structural component was loaded to a damage state so that the sensors could be tested and evaluated for their effectiveness for structural health monitoring (SHM). The collected data are analyzed and used for further refining the sensing techniques. This effort is to develop structural health monitoring technology in support of goals for dramatic improvement in safety, reliability, affordability and performance of advanced aerospace vehicles. The focus of the effort is on the on-board sensing and TPS related challenges. The program is funded and overseen by AFRL. NASA Langley Research Center and Dryden Flight Research Center provided technical supported on fiber optical strain sensors. Smart Layer technology sensing was provided by Stanford University. This paper will discuss some results from the test and the use of FEM as part of the SHM test. The technical and

5762-13, Session 5

NASA's research morphing technologies for aircraft

A. R. McGowan, NASA Langley Research Ctr.

No abstract available

5762-14, Session 5

Adaptive control of a scaled model of an aircraft vertical tail

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Twin-tail fighters encounter severe fatigue failure due to high amplitude vibrations induced by the buffet loads at high angle of attack flight. Besides improving the mechanical design of the tail (passive control), active control system seems to be an attractive option to reduce the vibration. In this paper the application of adaptive control systems for vibration suppression of a scaled model of a typical vertical tail is studied.

Piezoceramic actuators were bonded to both sides of a flexible fin model and accelerometers were employed as sensors to form a smart fin in this study. Using the xPC TargetBox of MathWorks a real time hardware-in-the-loop system was created. Some of the piezoelements were used as disturbance generators to simulate the buffet loads and the rest were grouped properly in order to have individual mode control authority. A frequency range of 5-100 Hz was considered to cover the first three dynamic modes in this study. However, the critical modes of vibration were the first bending mode (1st mode) and the first torsional mode (2nd mode). Thus, the efforts were concentrated on controlling these modes effectively. Single-Input Single-Output (SISO) and Multi-Input Multi-output (MIMO) adaptive controllers were designed and implemented successfully.

Sine, chirp, and random excitations were applied to the smart fin and the adaptive controllers were able to reduce the vibration significantly. System identification was done both on-line and off-line. Results showed that the SISO adaptive controller suppressed each individual mode without any spillover effect on the other modes. On the other hand, a broadband adaptive control system using two sets of actuators and sensors demonstrated successful vibration suppression in broadband frequencies particularly at the first two peaks (first two modes). First and second vibration modes were effectively suppressed individually under narrowband disturbances. A broadband vibration suppression using two properly selected sets of piezoactuators under random disturbance was also achieved. Details of the adaptive control system design and implementation in addition to more results will be presented in the full paper.

5762-15, Session 5

UAV visual signature suppression via adaptive materials

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Since the first micro aerial vehicle (MAV) effort was commissioned just over a decade ago, military and civil mission planners have worked hard to continuously shrink the size of uninhabited aerial vehicles (UAVs) with an overall goal of making them less detectable. While several dozen efforts to make functioning, small aircraft have indeed yielded both fixed and rotary-wing aircraft which measure less than 6" (15cm) in any dimension (the currently accepted geometric definition of a MAV), their performance tends to be substandard because of the nonlinear scale factors. Foremost among the scaling problems comes from aerodynamic effects which tend to retard maximum lift coefficients as Reynolds numbers decrease, followed by powerplant scaling difficulties which increases the specific fuel consumption of internal combustion engines by more than an order of magnitude over large-scale engines. Electric powerplants similarly suffer disproportionate inefficiencies and high weight fractions mostly caused by power electronics inefficiencies and losses experienced in ever smaller electric motors. Compounding these challenges are comparatively high weight fractions of guidance, navigation and control (GNC) electronics, sensors and transmission equipment. Further, challenging atmospheric conditions including wind, rain, gusts, snow and sand induce weight growth as the aircraft must possess high speed flight control actuators and various hardening mechanisms which further cuts into aircraft useful load. The combined effect of these challenging issues is that as UAV size shrinks, the useful load fraction disproportionately decreases which severely retards range, endurance and transmission range of video and data signals. Eventually, for given aircraft configurations, the useful load goes to zero, which indicates lower bounds for mission viability. Currently, several families of fixed-wing MAVs experience this lower bound at 3.0 – 3.5" (7.6 – 8.9cm) while the most advanced vertical take-off and landing (VTOL) and convertible MAVs (capable of helicopter and airplane-mode flight) are bounded at 4.0 – 5.0" (10 – 12.7cm).

Although these lower bounds for viability are indeed admirable, they typically represent aircraft which are minimally capable of carrying out only the most rudimentary missions. Because the mission capability is so compromised, there is a strong motivation to combine the greatest tactical attribute of MAVs (low visual signature), with the performance of larger scale UAVs. This paper covers a system which is shown to do just that. By treating the aircraft skin with adaptive materials, it is possible to actively change the optical characteristics of the aircraft dynamically to match the local background. This paper will show that by using optically dynamic skin (ODS) actuators, the apparent visual signature of a fixed-wing aircraft measuring in excess of 6.6 ft (2m) can be reduced to less than the signature produced by a 6" (15cm) aircraft against a mid-day blue sky. Similarly, the apparent visual signature of a 28" (71cm) convertible aircraft in hover mode can be made smaller than that of its 6" counterpart against wooded backgrounds. The paper concludes with a summary of the general properties of ODS actuators including weight, power consumption, luminosity range, color range, glint susceptibility and associated equipment weight.

5762-16, Session 5

A new class of piezoelectric grid-fin flight control actuators enabling high-speed autonomous VTOL MAVs

R. M. Barrett, R. D. Breuker, Technische Univ. Delft (Netherlands); R. McMurtry, Imperial College (United Kingdom); P. Tiso, E. Jansen, Technische Univ. Delft (Netherlands)

Just over a decade ago, the US Department of Defense CounterDrug Technology Office commissioned the first study on Micro Aerial Vehicles (MAVs). As part of this first MAV program, many novel technologies were employed, including a newly conceived class of flight control actuator using piezoelectric elements. This Flexspar actuator used bending elements to rotate an aerodynamic shell about a main spar which was placed along the line of aerodynamic centers of the fin. Since these early Flexspar stabilators first flew, much new technology has been developed with profound benefits in terms of aerodynamics and structural mechanics of flight control effectors and actuators. A significant breakthrough in control effector design was seen in the late 1990's. The development of "racking" grid fins was new to the technical community. For more than 30 years, grid fins had been designed to be structurally stable with statically determinate interlocking planar cell elements. While good for high speed flight and maintenance of low structural weight and high stiffness, this general arrangement exhibits high drag increments generally caused by interference drag at the cell corners and such high stiffness levels that the fins are fundamentally incapable of buckling or yielding when exposed to loads beyond critical. Alternatively, racking grid fins are specifically designed to rack or buckle when exposed to loads beyond critical (often described as "orange-crating"), which is a must for flight in turbulent military/urban environments. They also possess corners which are both curvilinear and specifically tailored to minimize interference drag. These benefits are combined with inherently low pitching moment coefficients and non-hysteretic normal force gradients. When matched to high bandwidth piezoelectric actuators, these grid fins provide significantly better performance in terms of speed, power consumption and system-level weight fraction than conventional electromechanical actuators.

To further the already superior performance of this actuator-effector combination, a new class of piezoelectric flight control actuator was invented, modeled, designed and integrated. The new actuator significantly outperforms Flexspar actuators by providing much higher rotational deflection levels and moment generation capability for a given amount of weight. This paper will lay out the internal structural arrangement of this class of actuators along with major design variables and analytical models. A series of experimental models were built to prove the concept. The first was designed for the benchtop and intended to be used as an unloaded actuator. Measuring 0.4 x 2.8" (1 x 7.1cm), a subscale actuator prototype was taken through static and dynamic testing showing good correlation between theory and experiment. This was followed by the addition of a grid fin, more bench testing and good correlation through rotation angles of \>±5°. The fins were then wind tunnel tested at speeds of up to 120 ft/s (37m/s). Testing showed no flutter, buffet or divergence tendencies with good maintenance of full deflection capabilities through the entire speed envelope. The paper concludes with an assessment of weight, power consumption and form factors of the actuator elements, grid fin control effectors and system. A final demonstration of the overall effectiveness of the design is shown on the system level as they were integrated and flown on one of the most advanced configurations of convertible (capable of hover and airplane-mode flight) MAVs today.

5762-17, Session 5

Optimization of selective piezoelectric actuator activation on a flexible fin using a genetic algorithm

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A numerical approach was employed to determine the optimal set of piezoelectric actuators for vibration control of a flexible fin. The surface of a judiciously

pre-selected area of the fin was completely covered by 48 non-overlapping actuators. A finite element model was used to determine the Frequency Response Function (FRF) of the system with each actuator activated in turn. Since mass and stiffness of the fin did not change significantly with the activation of individual actuators, superposition was employed to determine the FRF with multiple actuators activated simultaneously. A genetic algorithm was used to determine the optimum set of a given number of actuators in order to maximize the vibration control authority for the first three modes of the fin.

A genetic algorithm is based on a natural selection in which a large initial population of trial solutions is randomly generated, and the best solutions, subject to a fitness function, are kept while the others are discarded. In this case, many combinations of a pre-determined number of actuators randomly chosen for activation were generated. A small number (n) of combinations that provided the best vibration control were selected and the remaining were discarded. All the selected combinations were "crossed" with every other combination by randomly selecting actuators for activation from one combination or the other to yield n2 combinations. Mutation was then applied to each of the combinations to provide a small chance (5% or less) of randomly selecting a different actuator outside of the chosen set. This can be useful to select actuators that may not be represented in the original randomly generated combinations to ensure an overall optimal selection. After selecting (n) new combinations from the n2 crossed and mutated combinations, crossover, mutation, and re-selection were performed repeatedly until a specified maximum control authority was achieved. Results of the vibration control authority of these optimal actuators will be presented in the full paper.

5762-18, Session 6

Adaptive wing structures

C. D. Hemmelgarn, Cornerstone Research Group, Inc.

Cornerstone Research Group, Inc. (CRG) is developing a unique adaptive wing structure intended to enhance the capability of loitering Unmanned Air Vehicles (UAVs). By tailoring the wing design to a specific application, CRG has developed a wing structure capable of morphing in chord and increasing planform area by 80 percent. With these features, aircraft will be capable of optimizing their flight efficiency throughout the entire mission profile. Another benefit from the morphing design is increased maneuverability, resulting in improved effectiveness over the current design. During the development process CRG has had to overcome several challenges in the design of such a structure while incorporating advanced materials capable of maintaining aerodynamic shape and transfer aerodynamic loads while enabling drastic changes in planform shape. To overcome some of these challenges CRG is working on the integration of their shape memory polymer materials as the wing skin to allow morphing to occur. This paper will address the challenges associated with the development of a morphing aerospace structure capable of such drastic shape change, the materials necessary for enabling morphing capabilities, and the current status of the morphing program within CRG.

5762-19, Session 6

Mechanical properties of shape-memory polymers for morphing aircraft applications

B. P. Sanders, Air Force Research Lab.

A key technology to enable morphing aircraft is flexible skins. The skin must be able to handle the out-of-plane aerodynamic loads while simultaneously carry shear loading, which is the primary function of wing skins. Several configurations, such as sliding skins combined with novel substructure concepts, are being proposed. One of the more promising is composite skins manufactured with Shape Memory Polymers (SMP). Control of the glass transition temperature, either thermally or optically, provides on-demand control over the storage modulus. This translates into a means to control the shape of a structure, wing structure in this case, through large bending or in-plane stretching. This investigation addressed basic characterization of SMPs as a suitable structural material for morphing aircraft applications. The paper will address notional requirements and well as baseline experiments (shear modulus, rate dependence, etc) for SMPs.

5762-20, Session 6

Topology design and optimization of an active airfoil in a flow field

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The proposed paper is on an investigation of the static and dynamic aeroelastic response and design optimization of an airfoil with an actively changing shape using piezo-electric material. The analysis of the configuration requires a coupled solution of the flow field along with the elastic airfoil domain including the active material distribution in the beam. Although eventually distributed active material configurations in the domain may be considered, the present paper uses a concentrated active material in the form of a bi-morph beam positioned inside the airfoil. For the solution of the potential flow with unsteady boundary conditions we use a thin-airfoil theory. For the airfoil domain two dimensional elasticity is used. The design formulation considers the internal topology (internal passive material distribution) of the airfoil with a fixed initial shape. The final shape of the airfoil is unspecified, and is dependent on the internal topology design as well as the design objective and the constraints. Energy efficiency is used as a design metric relating the electrical energy input to the beam with respect to the energy stored in the elastic structure plus the work done against the aerodynamic loads.

5762-21, Session 7

The Ultrasonic/Sonic Driller/Corer (USDC) as a subsurface drill, sampler, and lab-on-a-drill for planetary exploration applications

Y. Bar-Cohen, Z. S. Chang, S. Sherrit, M. Badescu, X. Bao, Jet Propulsion Lab.

The search for existing or past life in the Universe is one of the most important objectives of NASA's mission. For this purpose, effective instruments that can sample and conduct in-situ astrobiology analysis are being sought. In support of this objective, a novel Ultrasonic/Sonic Driller/Corer (USDC) based mechanism has been developed to probe and sample rocks, ice and soil. The USDC consists of an ultrasonic actuator that impacts a coring or drilling bit at sonic frequencies through the use of an intermediate free mass. The USDC can produce both a core and powdered cuttings as well as emit elastic waves. For planetary exploration, this mechanism has the important advantage of requiring low axial force, virtually no torque, and can be duty cycled to require low average power. This low axial load advantage overcomes a major limitation of planetary sampling in low gravity environments and when operating from lightweight robots and rovers. The low power operation produces a minimum temperature rise which is required for the acquisition of biologically meaningful samples. The development of the USDC is being pursued on various fronts ranging from analytical modeling to mechanisms improvements while seeking a wide range of applications. While developing the analytical capability to predict and optimize its performance, efforts are made to enhance its capability to drill at higher power, and high speed. Taking advantage of the fact that the bit does not turn and that it is only subjected to minute displacements, sensors (e.g., thermocouple and fiberoptics) were integrated into the bit to examine the borehole during drilling. The sounding effect of the drill was used to emit elastic waves in order to evaluate the surface characteristics of rocks. In this paper, the latest status of the USDC development and applications that are underway will be reviewed.

5762-22, Session 7

Adapting the Ultrasonic/Sonic Driller/Corer (USDC)for walking/climbing robotic applications

M. Badescu, Y. Bar-Cohen, X. Q. Bao, Z. Chang, B. E. Dabiri, B. A. Kennedy, S. Sherrit, California Institute of Technology

NASA's missions include the search for past and existing life in the Universe and clues on how the planets in the Solar system formed and evolved. To support these objectives an ultrasonic/sonic driller/corer (USDC) device has been developed at JPL to allow drilling and coring rocks for in-situ planetary analysis [1]. The site location and method of sampling are of vital importance to scientists. Surface rocks abrasion, small depth soil drilling, and deep drilling have been proposed. Another resourceful location is the sidewall of canyons. The exploration of such sites requires the development of a limbed robotic system capable of walking and climbing slopes up to and including vertical faces and overhangs. An anchor mechanism is currently under development and each is being installed on one leg of the four legged Steep Terrain Access Robot (STAR). This paper presents the modeling, design and preliminary testing results of the USDC for use as end-effectors of walking/climbing robots.

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5762-23, Session 7

Design of torque actuators based on ferromagnetic shape-memory alloy composites

T. B. Burklin, V. J. Cheng, M. Taya, Univ. of Washington

Ferromagnetic shape memory alloys (FSMAs) are of special interest to the material science and actuator research community because of the possibility of high bandwidth and large stroke actuators being developed from them. However, they are expensive and can not provide a large force or a large moment during the actuation. We have developed new torque actuators based on the hybrid mechanism: the stress-induced martensitic transformation induced by an applied magnetic field gradient which enhances the stroke, as the stiffness of shape memory alloy reduces due to the transformation. The hybrid mechanism has been found to produce large forces/moments at a high speed. Our second-generation torque actuator with several mechanical redesigns produced up to 7.6 N-m and a 72 o angle of twist. The design consists of a freely rotating rod (the rotor) surrounded by a circular outer casing composed of a hybrid magnet made of permanent magnets and electromagnets (the stator). The rotor is attached to the stator via an FSMA composite plate spring (the flexor) composed of ferromagnetic material and Nickel-Titanium super-elastic grade SMA material. When the actuator is loaded, the rotation of the rotor causes a bending moment in the flexor, producing a spring-back force that eventually stops the load. Upon switching on the hybrid magnet in the outer casing, the resulting magnetic field will attract the flexor (because of its ferromagnetic properties) to its inner wall resulting in the rotation of the inner rod, moving the load to the maximum angle of twist position.

The third generation actuator will be the focus of this paper, which is currently in the prototype fabrication stage. The new design changes focus on the flexor, rotor, and the attachment between the two. Instead of a single flexor plate of the previous version, there are two shorter length flexors. The rotor now consists of a shaft with sprockets which are connected to the flexors via roller chains. The chains are connected to the flexor and the sprockets with pin anchors.

The mechanical changes provide the following benefits: (1) two flexors provide more spring force than one, the shorter lengths of flexor generates a higher spring force than a longer length, and allows much more stator magnet utilization. (2) the sprockets provide a larger radius for torque generation. (3) the nature of the pin joints and sprockets allow for 100% of the generated spring-back force to be applied tangentially, as opposed to using machine screws which waste some generated force in the radial direction. (4) the chain attachment keeps the flexors closer to the stator magnets, generating larger magnetic forces, and allow for a greater range of motion that could offset any losses generated by the other changes. With these changes, we estimate the 3rd generation torque actuator will increase the torque by 2-5 times while maintaining the range of motion.

5762-24, Session 7

Design of membrane actuators based on ferromagnetic shape-memory alloy composite for synthetic jet applications

Y. Liang, Y. Kuga, M. Taya, Univ. of Washington

Many researches have shown that active flow control (AFC) technology can help aircraft improve aerodynamic performance and jet noise reduction. AFC can be achieved by the synthetic jet actuator injecting high momentum air into the airflow at the appropriate locations on aircraft wings. In order to produce strong synthetic jets at high frequency operations that can be applied to AFC technology, a membrane actuator based on the hybrid mechanism should fulfill these requirements. The hybrid mechanism is based on stress-induced martensitic phase transformation caused by large force due to large magnetic field gradient, thus enhancing the displacement, as the stiffness of shape memory alloy reduces due to the martensitic transformation. It can be utilized by using shape memory alloy with ferromagnetic material as ferromagnetic shape memory alloy composite. It has been found that the hybrid mechanism can produce large force, reasonable stroke and fast response. Our new version of the membrane actuator for synthetic jet applications has been fabricated based on the hybrid mechanism. The actuator system designed by both mechanical and electromagnetic finite element analysis is made of ferromagnetic shape memory alloy (FSMA) composite diaphragms and electromagnets. The FSMA composite diaphragm consists of NiTi superelastic diaphragm and soft iron, and its cost will be lower than that made of Fe-Pd or NiMnGa FSMAs. The electromagnet is designed for high frequency use and constructed by laminated yoke, coil and permanent magnets. This new actuator system shows great improvements of dynamic performance and jet velocity from our first generation actuator. Currently, due to large force and martensitic transformation on the FSMA composite diaphragm, the membrane actuator can produce 200 m/s synthetic jets at 200Hz.

5762-25, Session 7

Miniature thin film NiTi hydraulic actuator with MEMS microvalves

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The implementation of smaller, lighter, and more agile military systems requires new actuation technologies that offer high power density in compact form factors. The Compact Hybrid Actuator Program (CHAP) is pursuing active material based, rectifying actuators to create new actuation solutions for these demanding applications. Our actuator approach is based on thin film NiTi membranes operating in parallel (high intrinsic power density, \>125 kW/kg) combined with liquid rectification, MEMS passive check valves, and commercially available power electronics. Previous results demonstrated 8 micron thick membrane actuation with 150 Hz forced convection response and force output of 100N. This paper focuses on two developments critical in scaling up previous single membrane results to power levels sufficient for military applications. This first is the development of SOI MEMS fabricated microvalve arrays which exhibit both high flow rate. The second focus area is the design, fabrication, and assembly of a form factor compact actuator. Integration of these technology elements enables a compact actuator with 5-8 Watts of mechanical power, and an overall power density of 150 W/kg. The initial prototype demonstration of this concept shows great promise for thin film NiTi based actuation both in military technologies and in other areas which demand extremely compact actuation such as embedded fluid delivery for biomedical applications.

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5762-26, Session 8

Practical issues in real-world implementation of SHM Systems

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Currently, there exist several different types of structural health monitoring (SHM) systems that are in the stage of development and/or are being tested for use in real-world applications. For a number of years, SHM systems have demonstrated feasibility in laboratory and controlled testing environments. Acellent has been developing and testing strategies to bring the SHM field to the next level. These include issues involved with system installation, calibration, reliability and connections for structures fabricated with composite materials. Composite structures are susceptible to hidden or barely visible damage caused by impacts and/or excessive loads that if unchecked may lead to lower structural reliability, higher life-cycle costs, and loss in operational capability. Current maintenance and inspection techniques for in-service composite structures can be labor-intensive and time-consuming. Utilization of an integrated sensor network system such as that developed by Acellent can greatly reduce the inspection burden through fast in-situ data collection and processing. Using a built-in network of actuators and sensors, Acellent Technologies is providing the tools required for a practical Structural Health Monitoring (SHM) system. In this presentation, key development and testing issues concerning real-world implementation of the SHM system on composite structures will be presented.

5762-27, Session 8

Concept verificaiton testing of an in-flight deformation monitoring system for uninhabited autonomous vehicles overview

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Lightweight structural health monitoring systems are an important requirement for the development of unmanned autonomous vehicles (UAVs). Ideally, such systems could be installed at critical load locations on the vehicle to continually monitor flight dynamics without increasing vehicle weight significantly. Fiber optic (fiber Bragg) strain sensors are ideal for this type of application. The sensors can be multiplexed over the length of an optical fiber at a variety of locations and installed on the aircraft's structural surface. Measurement instrumentation associated with fiber optic sensors can be lightweight and compact.

The implementation of a structural health monitoring system on UAVs could be used in real-time control and assessment of in-flight structural dynamics. This study examined the response of a carbon fiber tubular cantilever beam for the High Altitude Long Endurance Remotely Operated Aircraft (HALE ROA) under combined bending and torsional loading. The HALE ROA has a span of 247 feet

with 30 feet wing tip deflection. A set of deflection equations was developed for defining deflection and rotation of the spar using strain measurements at multiple locations. These deflection equations were developed for any spar configuration and material. Both fiber optic and conventional strain sensors were integrated and optimal sensor placement was considered. Pure bending, pure torque, and a combination of bending and torque were considered. The accuracy of fiber optic sensors was compared with conventional strain gages. Also, the accuracy of the deflection equations was determined. Results of the study show that the deflection equations predict spar tip bending deflection within vehicle requirements.

Ultimately, UAVs with structural health monitoring systems could have improved efficiency with performance based maintenance scheduling and provide better real-time health assessment for long duration missions (over 40 hours). This longevity assessment, combined with the real-time flight dynamics control, make structural heath monitoring systems a powerful addition to UAVs.

5762-28, Session 8

Structural health monitoring of advanced grid structure using multi-point FBG sensors

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There is growing demand for lightweight structures in aircraft systems for energy and cost saving. Composite materials such as graphite fiber reinforced plastics are promising candidates to meet these requirements. However, since extremely high reliability is required for aircraft systems, composite materials have not been fully applied especially in commercial aircraft. A structural health monitoring system is the most effective technology to solve this problem. The authors are developing a new lightweight grid structure for aircraft applications equipped with a health monitoring system utilizing FBG (Fiber Bragg Grating) sensors. A grid structure, comprising multiple interconnected ribs in a truss-like arrangement, has a very simple path of stress, which is easily detected with FBG sensors embedded in the ribs.

In this work, manufacturing technology for embedding optical fibers into the grid structure was studied, in order to enable an embedded multi-point FBG sensor network. First, a test panel with three straight optical fibers with FBG sensors was fabricated. After this experiment, a total of 29 FBG sensors were embedded in a 525 x 550 mm test panel. A third test panel was fabricated to evaluate the effect of steering the optical fiber through the grid panel nodes. Mechanical testing was performed on these panels, and the strain results compared to results from conventional strain gages and structural analysis. From these results, both experimental and analytical evaluations were in good accordance. Effectiveness of the health monitoring system in a new lightweight grid structure was successfully demonstrated.

5762-29, Session 8

Piezoelectric structural acoustic leak detection for pressurized pipelines

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The ability to detect in real-time leaks in pipelines will eliminate supply disruption costs and the cost of finding the location of the leak. Furthermore, catastrophic events that have claimed 66 lives and cost the US more than $200 M in the last six years could have been prevented. Historically, mechanical damage is the single largest cause of leaks that develop into failures on pipelines. Mechanical damage usually occurs after a pipeline is constructed and is caused by excavation equipment, which deforms the shape of the pipe, scrapes away metal and coating, and changes the mechanical properties of the pipe. These changes in the structural integrity of the pipe often do not cause immediate rupturing of the pipe, but rather initiates a chain of events that eventually cause leaks in pipe systems.

Midé has developed a structural-acoustic sensing and alert system, based on Midé's patented PowerAct™ conformable packaged piezoelectric actuator and sensor, that will continuously monitor a pipeline without the need of an external power source. This sensor produces voltage in response to strain induced in its active material. No auxiliary power is required to keep the sensor continuously active. When bonded to a structure such a pipe, any disturbances in the pipe will show up as a voltage trace over the poles of the sensor. These sensors are extremely sensitive with very high gain and can detect the most minute and high frequency strains. Since leaks in high-pressure gas pipes fit this description, there is currently no better sensor to apply to the specific problem.

This paper describes the prototype system design, as well as the comprehensive set of prototype tests used to assess the feasibility of the concept. A scaled pipe was constructed and instrumented. The pipe was pressurized with air and a leak was induced by means of a valve. The sensors produced measurable signals that were used to identify the magnitude and location of the leak. The sensors also demonstrated the ability to sense the location of hammer impacts on the scaled pipe. The system is estimated to cost less than $400/km of pipe. Other piping applications, such as those in typical industrial plants, automotive and aerospace vehicles, will be addressed.

5762-30, Session 8

Reliability of resonant packaged piezoelectric power generators for machinery health monitoring

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Health monitoring is a fundamental requirement across a broad range of military, commercial, and industrial systems. The cost of repairing systems from a run-to-failure strategy is many times the cost of implementing preventive maintenance and condition monitoring programs. Beyond the economic impact, the result of unexpected failures can be catastrophic. The ability to monitor systems and permit proactive measures requires a suite of distributed sensors to determine structural, machinery, process, and environmental conditions. Due to location and/or safety considerations a large number of industrial health monitoring applications requires self-powered, autonomous systems that requires little or no external intervention for operation.

Techniques for scavenging energy from the environment for powering health monitoring devices include photovoltaics, electromagnetic, capacitive, pyroelectric, thermoelectric, and piezoelectric generators. The characteristics of the operating environment and power requirements typically prescribe the most appropriate generation method but studies have shown that piezoelectric generators generally have the greatest energy scavenging density potential (excluding photovoltaics). Piezoelectric power generation using resonant cantilevered piezoelectric wafer devices have been proposed for industrial applications.

A critical success measure for any industrial application is the reliability of the power generator over extended operational life. This paper reviews generator operational requirements for industrial applications and describes long life reliability testing completed on a power generation device built using commercially available packaged piezoelectric wafers. Packaging piezoelectric wafers simplify the integration of piezoelectric wafer into a product and improve the durability of the brittle piezoelectric ceramic material. A resonant cantilevered beam piezoelectric generator was tested for power production capability over millions of cycles at very high root strains levels. Results from the testing indicate that packaged piezoelectric wafer products used in power generation devices are very reliable and well suited for harsh industrial application environments.

5762-31, Session 9

Optical table with embedded active vibration dampers (smart table)

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Optical table is a stiff platform supporting vibration–sensitive equipment. A typical optical table is a sandwich structure consisting of two faceplates and a lightweight honeycomb core. Due to low weight-to-stiffness ratio, these platforms find wide application in optical research and high-precision manufacturing, usually in conjunction with soft pneumatic vibration isolators. Although good isolation from floor vibration can be achieved in these systems, the platform deviates from the ideal rigid-body behavior at natural frequencies of its flexural vibrations. Various known passive means of reducing these unwanted vibrations add substantial mass to the table and have certain other shortcomings. This paper describes the actively damped optical table introduced as a standard product, ST series, by Newport Corporation. The active damping system is self-adjusting and robust with respect to changes in payload and vibration environment. It outperforms not only the broadband damped optical tables, but also the top-of-the-line tables equipped with tuned passive vibration absorbers. Theoretical background, analysis, design rationale and experimental verification of the system are presented, with emphasis on sensor-actuator pairs architecture, signal processing and adaptive controls.

5762-32, Session 9

Miniature vibration isolation system for space application: ground test results

M. Gonzalez, Honeywell Inc.

In recent years, there has been a significant interest in, and move towards using highly sensitive, precision payloads on space vehicles. In order to perform tasks such as communicating at extremely high data rates between satellites using laser cross-links, or searching for new planets in distant solar systems using sparse aperture optical elements, a satellite bus and its payload must remain relatively motionless. The ability to hold a precision payload steady is complicated by disturbances from reaction wheels, control moment gyroscopes, solar array drives, stepper motors, and other devices. Because every satellite is essentially unique in its construction, isolating or damping unwanted vibrations usually requires a robust system over a wide bandwidth. The disadvantage of these systems is that they typically are not retrofittable and not tunable to changes in payload size or inertias.

During the Phase I MVIS program, funded by AFRL and DARPA, a hybrid piezoelectric/D-strut isolator was built and tested to prove its viability for retrofittable insertion into sensitive payload attachments. A second phase of the program, which is jointly funded between AFRL and Honeywell , was started in November of 2002 to build a hexapod and the supporting interface electronics for a flight demonstration of the technology. The MVIS-II program is a systems-level demonstration of the application of advanced smart materials and structures technology that will enable programmable and retrofittable vibration control of spacecraft precision payloads. This paper describes the ground test results of the active and passive hexapod system mounted to a simulated optical payload.

5762-33, Session 9

High-precision active distortion control of thin membrane windows

D. R. Huston, J. O. Plumpton, B. Esser, Univ. of Vermont

Thin membrane windows are gaining increasing use in certain high-performance imaging and patterning applications. These windows typically have thicknesses less than 2 microns and spans of up to 50 mm. Patterns written onto the membranes are used in applications such as proximity (X-ray) lithography and zone plates for X-ray microscopes. The lateral position resolution requirement of these systems can extend down below 5 nm. The ability to selectively transmit energy while simultaneously maintaining precise position places extremely tight mechanical performance requirements on the system. Additional demands arise due to the pressures of production that require rapid positioning, gap setting and lateral maneuvers and small membrane to substrate gaps. Sustaining the desired position by passive mechanical means is very difficult. This paper will describe active methods of controlling mechanical membrane distortions to achieve superior positioning performance. Active thermoelastic distortion and quasi-static shimming methods for lateral position control will be discussed. Out-of-plane distortions due to aeroelastic loadings and control methods will also be examined. Experimental results that generally confirm numerical predictions will be presented.

5762-34, Session 9

Multi-mode vibration reduction concept for machine tools and automotive applications

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This paper reports a theoretical and experimental study on a new multi mode vibration reduction concept for struts of machine tools or shafts of automotives. The example described in detail is the validation of this new concept for high dynamic parallel kinematic struts. The structural advantages of parallel kinematic mechanisms are undisputed. Statical and dynamical bending and torsional loads limit the shape of the strut geometry. The accuracy of this kind of machines is defined by the joint and feed unit assemblies.:The here described new actuator concept for multi mode vibration reduction uses piezo-patches based on the MFC technology licensed by NASA and produced by Smart Material GmbH Dresden, Germany. Initial simulation and experimental tests were done at an one side clamped aluminium beam with applicated 45°-MFC's on both sides. Simulation results show that driving the piezos in opposite direction leads to a bending deflection of the beam, driving them in the same phase leads to a torsional deflection of the aluminium beam. Experimental measurements confirm the simulation results. The benefit we get is a decreased demand for actuators for multimode vibration control. Likewise these actuators allow the separation or selective combination of bending and torsion. This new actuation concept is not limited on beams. Further simulations for cylindrical struts result in a design of a MFC-ring with 8 single segments with changing fibre orientation for separation of bending and torsion on struts and shafts. The selective controlled activation of each of the segments leads to bending in x-direction, bending in y-direction or torsion.:The paper presented here describes the simulation results on a aluminium strut with 80 mm circumference as well as results of experimental measurements. An outlook for an implementation of an active strut in a parallel kinematic machine will be given.

5762-35, Session 9

Hexapod geometry optimization for passive payload isolation

S. Hadden, M. Gonzalez, Honeywell Inc.

This paper primarily summarized the efforts to optimize the performance of a compliant hexapod or Stewart Platform isolating a remote sensing payload from structural resonances on a spacecraft buss. Trade studies were conducted to determine the effects of volume constraints on vibration isolation performance for the payload consisting of viscous damped "tuned" three-parameter isolators. Increased performance was demonstrated by varying hexapod geometry within specified volume via an optimization routine in Matlab, constructed to vary isolator mounting locations, to minimize mode coupling and variation. In addition, another optimization routine was made that would keep the hexapod geometry fixed while varying the individual placement of the isolators in each of the six available mounting locations. Once a workable design became apparent, the 3 parameters were tuned in order to individualize directional stiffness and damping to compensate for the unfavorable volume constraints and offset cg.

5762-36, Session 10

Design and fabrication of a novel settled and laminated testing instrument for magnetorheological fluid

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As having ability of changing its apparent viscosity in presence of magnetic field in millisecond, magnetorheological fluids (MRF) exhibit widely potential application in devices or systems for controlling vibration and noise. In China, about one hundred MRF dampers were fixed on two cable-stayed bridges. In addition to shear stress strength, another import performance index of MRF is its stability under long time static state. For most applied conditions, without hard agglomeration is more important than higher shear stress strength. However, up to now, few reports pay attention to evaluate method of MRF's settling. In this paper, a novel method based on the changing of magnetic conductivity corresponding to the changing of magnetic particle's volume content of was presented. And a testing instrument utilizing above method was designed and fabricated. Research shows that, using that testing instrument, not only can evaluate settling stator, but also can monitor settling process of magnetic particles, and it is a useful equipment for research of MRF.

5762-39, Session 11

A two-stage actuation system using DC motors and piezoelectric/magnetostrictive actuators for controllable industrial and automotive brakes and clutches

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Controllable clutches and brakes are used in many automotive and industrial applications[1,13]. For example, with the development of Anti-lock Braking Systems

(ABS) [1,4] and advanced automatic shifting strategies, controllable clutching and braking systems play a very important role particularly in the automotive industry. The different actuation systems for brakes and clutches currently employed in the industry vary from the classic hydraulic mechanisms [2,3] to the latest Magnetorheological (MR) fluid clutches [5]. Other controllable clutch/brake actuation mechanisms include those using magnetic particles, pneumatics, electromagnetism, magnetic hysteresis and eddy currents and Electrorheological fluids to name a few [7-10]. However, all these mechanisms have their own advantages and disadvantages. For example, hydraulically actuated clutches, which are widely used in automobiles equipped with automatic transmissions, suffer from poor efficiency, low robustness due to the varying bulk modulus of pressurized fluid, and complicated system design due to intricate fluid passages and valves with moving parts [2,3]. MR fluid clutches have uncertain operation characteristics at high rotational speeds due to the effect of centrifuging of the

micronsized magnetizable particles [6]. Recent advances in the use of piezoelectric and magnetostrictive materials have led to the development of "smart" actuation systems.

Since the strains produced by these actuators are relatively small (1000-2000 microstrain) leveraging and hydraulic mechanisms must be employed for stroke amplification [11,12].

These methods however lead to difficulties like high mechanical tolerance requirements and a significant reduction in force capability. Finally electromagnetically actuated clutches require large control power due to the presence of an air gap between the rotor and the armature. Magnetic hysteresis and eddy current clutches have very low torque to size ratio characteristics. The research in this study couples the attributes of smart materials like piezoceramics with traditional DC motors in the development of braking and clutch systems that mitigate many of the previously mentioned negative attributes.

Though the stroke and force requirements of a typical clutch/brake application are high, the force-stroke relationship of the complete clutch/brake actuation process may be split into two regions as shown in figure 1. In region I, a major part of the stroke is used to move the clutch-plates (or brake pads) close enough together and the preload force required in this region is comparatively low. In region II, the plates are squeezed together, and therefore the force required is very high while the required stroke is low.

The concept behind the new actuator is the hybridization of two different actuators for these two regions or phases of the clutch/brake actuation process. Since the force requirement in the first stage (region I) is low, DC motors are used to achieve the required high stroke using a rotary to linear motion converter like a lead-screw and nut or a rack and a pinion. In the second stage (region II), the smart material actuator is deployed and produces the required high force and low stroke. When the force requirement on the DC motor becomes to large the motor will start to stall and a spike in the input current will be realized. This current signal is used as a control signal to energize the piezoceramic.

One difficulty in this method is that when the two actuators are used in series, they will encounter the same load at all times. This leads to a possible problem of making the DC motor big enough to hold the smart material actuators in place during the second stage. However, this is avoided by using a lead-screw and nut or a worm-gear mechanism [20], which have the inherent self-locking property. This property allows only the leadscrew to drive the nut, and the system locks in its place when the nut drives the leadscrew.

Similarly, the worm can drive the pinion while the pinion cannot drive the worm.

Hence one such self-locking connection is used between the DC motor and the leadscrew, thereby isolating the two stages of actuation process. Two experimental setups have been developed to highlight the system. The first setup involves the hybrid actuator and a spring and a load cell. This simple setup is used to calibrate the controls, validate the model and to demonstrate the basic concept. The second setup being developed is that of a simple 1/4 vehicle model featuring a single vehicle rotor and an active disc brake (which includes the hybrid actuator). The two setups demonstrate the working principle of the new two-stage actuation mechanism. The design procedure involves the choice of the DC motors, the lead screw assembly and the Piezo actuators depending on the force and stroke requirement of the clutch/brake application. A simple schematic of the device is shown in figure 2.

An initial control technique has been designed for a generic case that may be applied to both braking and clutching applications, wherein the system achieves a maximum braking or clutching force within a predefined period of time. As previously mentioned the key issue of the transition between the two stages of actuation is addressed by utilizing the information from the current drawn in by the stalled DC motors when the clutch-plates or the brake pads reach their maximum travel in the first stage. This method eliminates the requirement of any sensors to determine the completion of the first stage of actuation. The second stage is achieved by using a terminated ramp input voltage to the piezoelectric actuator thereby achieving a smooth engagement of the clutch-plates (smooth braking in the case of brakes). The authors have also developed advanced control strategies like Model Predictive Control and Internal Model Control (IMC) [14- 19] for the mechanism to make the system track a reference value of clutching or braking action. Finally, the authors have also integrated model predictive control with sliding mode control to achieve smooth control action.

In summary, this paper presents the design, development, analysis and testing of a two-stage mechatronic clutching/braking mechanism using conventional DC motors and smart material actuators. The paper also highlights control techniques used to achieve predefined braking or clutching actions.

5762-40, Session 11

High-power Inchworm® actuators for extended range precision positioning

G. D. Powers, Q. Xu, T. Guidarelli, J. A. Smith, EXFO

A single small actuation system that provides high resolution [step size] of 2 nanometers over an extended range of 20 mm with forces of 100 Newtons and integral power-off hold is described. Speeds of 50 mm/s can be shown but electronic efficiencies are much higher at 1-10 mm/s. Open or closed loop control is described. Heat generation at actuator is very small.

Progress on potential applications in adaptive optics, large optical beam control, and photonic and semiconductor test and measurement will be noted.

New data will be presented showing ± 5 nanometer control under loads up to 100 Newtons. Heat generation is estimated to be 110 mJ/hr while actively holding position. Comparison of encoder and capacitance gage stability over time and temperature will be discussed as it affects control in the 5 nanometer regime. This response can be contrasted with previous 2 kHz over 30 micrometer response for vibration or adaptive optics control.

Progress will be described for new Class D switching amplifier that offers higher efficiencies at peak demands. The actuator design uses sets of three piezoelectric elements. These constitute 1100 nF of load. High speeds in the 20 to 50 mm/s range [up to 2500 Hz motor cycles] significantly affect power needed and design efficiencies.

Alternative design options will be presented with rationale for present design choices and resultant performance. The basic design allows for choices based by performance needed.

5762-41, Session 11

Development of miniaturized piezo-hydraulic pumps

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A small, low cost piezo-hydraulic pump has been developed. The pump delivers 800 psi of blocked pressure and 250 cc/min of free flow, while weighing less than 90 grams. The pump utilizes cofired multilayer piezoelectric actuators for low drive voltages and low cost. The properties of this pump make it suitable for distributed actuation systems where pump, control valve and hydraulic actuator are located at the point of actuation, minimizing the system weight and length of hydraulic tubing.

5762-42, Session 11

Hierarchical actuator systems

D. R. Huston, B. Esser, Univ. of Vermont

Mechanical actuators are integral parts of many high-performance systems. However, the presently available systems lack the stroke, power, and controllability, i.e. authority, necessary to improve the performance of these systems. The hierarchical actuator is a natural extension of recent trends toward improving the performance of actuators through increments in geometric complexity and control. The hierarchical concept is to build actuators that are integrated from many smaller actuators. The smaller actuators are arranged geometrically and controlled so as to extend the performance of the total actuator into ranges that are not possible with actuators that are based on a few active elements and levels of control. Mechanics and mechanisms of hierarchical actuators are examined, along with a few experiments to demonstrate the operating principles.

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5763-01, Session 1

Post-CMOS chip-level processing for high-aspect ratio microprobe fabrication utilizing pulse plating

T. Xin, P. K. Ajmera, C. Zhang, A. Srivastava, Louisiana State Univ.

In monolithically integrated systems, devices and circuitry are fabricated on the same substrate without requiring additional bonding. This reduces the volume of the microsystem and improves system performance by minimizing parasitic capacitances and promoting improved signal-to-noise ratio. Monolithic integration of microstructures can be realized by pre-CMOS, co-CMOS or post-CMOS processing. The latter approach takes advantage of the readily available CMOS foundry services without making specific requirements on IC processing. Also, the microstructures are not exposed to harsh IC fabrication environment. On the other hand, post-CMOS processing temperature should remain below 450° C, and the process chemicals and radiation should not harm the circuit performance.

In this work, a CMOS chip with ultra-low power operational amplifiers is designed and is fabricated at an IC foundry. Microprobes of different sizes are integrated onto the chip by a post-CMOS process. The microprobes detect signals in microvolt range. The processing circuitry amplifies these signals consuming very little power. The chip size is 2 mm x 2 mm x 0.25 mm and the base of microprobes varies from 40 um to 70 um. In our chip-level integration work, the CMOS chip with circuitry is placed inside a template made from a Si wafer having a 0.25 mm deep recess that has been anisotropically etched by KOH solution. The chip lying in the recess is now in level with the template wafer. The latter acts as a support for chip-level integration. Gold wires and a special tape are utilized to electrically bridge between the chip and the template wafer. The process up to this point is performed at room temperature. A thick negative-tone photoresist SU8 is applied and processed to form molds for microprobes. The highest processing temperature of the photoresist is 96° C. Pulse plating technique is then employed to deposit nickel into these microprobe molds. Pulse plating offers special advantages for depositing high-aspect ratio structures. Appropriate pulse on and off times and current density are chosen for obtaining proper deposition of the metallic microprobes. The electroplating process is maintained at 53° C. The photoresist mold is removed in a remover agent at 75° C. Seed layers serving as electroplating base beneath the photoresist mold are stripped successively without damaging the CMOS circuitry for the nickel microprobe array. The microprobes are individually isolated. Typical height of the microprobes is over 50 um.

The microprobes are also fabricated by DC plating and the electroplating results between DC plating and pulse plating are compared. DC plating is not efficient when deposition is needed through a deep recessed mold due to depletion of reactive species at the bottom of the recess. Pulse plating circumvents this problem by manipulating on time and off time to allow diffusion of reactants into the recess during the off time. Effects due to variation in pulse plating parameters such as on and off time and current density on plated structure are given. The entire processing for this monolithic integration is performed well below 450° C and all the chemicals that are utilized are carefully tailored to avoid damage to field oxide and aluminum metallization on the CMOS chip surface. Hence, the processing meets the post-CMOS requirements for monolithic microsystem integration.

5763-02, Session 1

Charge pump CMOS circuit based on internal clock voltage boosting for bio-medical applications

R. R. Anantha, A. Srivastava, P. K. Ajmera, Louisiana State Univ.

For certain specific bio-medical applications, and for EEPROMS and flash memories, CMOS circuits operating at low power supply voltages need internal circuits to generate voltages higher than the power supply voltage [1, 2]. Devices for bio-medical applications fabricated in standard MEMS process and integrated with CMOS circuits normally require higher voltage for its electrostatic actuation [3]. Charge pump technique in CMOS is commonly used to meet such requirements. Several charge pump techniques have been reported in literature [1, 4, 5] and are being used for varied applications [2, 6]. Major drawbacks of some of these reported charge pump techniques are their incapability to provide designed output voltages and high step-up voltage efficiency, and their use of large number of transistors, which requires a larger chip area. In the present work, we report a new charge pump design wherein the clock voltage is boosted internally. This results in significant decrease in number of transistors required and also increases the output voltage compared to earlier reported charge pump techniques. We have designed 4 and 6-stage charge pumps in 1.5 μm n-well CMOS process with significantly reduced number of transistors for use in biomedical devices for 1.5 V and 3 V operation. Simulated output is 5.2 V and 7.5 V for 4 and 6-stage charge pumps, respectively with a power supply voltage of 1.5 V and a simulated output of 14.2 V and 17.1 V is achieved for 4 and 6-stage charge pumps, respectively with a 3 V power supply. These voltages are higher than those reported in references [1, 4, 5] and provide higher output drive currents. The charge pump circuits can be operated in 1.2 V – 3 V power supply voltage range and by increasing the number of charge pump stages, clock voltage can be further boosted. The proposed charge pump is area efficient, provides a high output voltage and high voltage step-up efficiency and can be used in biomedical applications like implantable pacemaker and gastric pacer circuits. The results of this new charge pump design will be presented.

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5763-03, Session 1

Remote power delivery for hybrid integrated bio-implantable electrical stimulation system

V. R. Gaddam, J. Yernagula, R. R. Anantha, S. Kona, S. Kopparthi, P. K. Ajmera, A. Srivastava, Louisiana State Univ.

Bio-Implantable devices such as heart pacers, gastric pacers and drug-delivery systems require power for carrying out their intended functions. These devices are usually powered through a battery implanted within the system or are wired to an external power source. In this work, we consider remote power delivery as a means to charge rechargeable batteries that power a bio-implanted electrical stimulation system. This approach avoids periodic surgery necessary for battery replacement and also does not tie a person to an external power source at all times. A wireless inductive power transmitter and receiver system has been used to power a bio-implanted gastric pacer. The transmitter coil is worn around the waist periodically and the receiver coil is a part of the bio-implanted system. The receiver coil, rechargeable batteries and the chip containing stimulation circuitry form a hybrid integrated microsystem which is implanted in the body.

A conventional bridge rectifier circuit is used for the conversion of ac voltage to required dc voltage. This dc voltage supplies power to the charging chip which is used to charge a rechargeable lithium ion battery. The charging chip requires a dc voltage of 6.5 V and dc current of 100 mA to charge the battery. This implies an effective load of 65 ohms and load power of 650 mW. Variation in load power as a function of frequency and axial distance of the receiver from the transmitter coil is analyzed. New coil designs with the application of ferrite cores that enhance power delivery are being considered. The Bio-Implanted Electrical Simulation System (BESS) is a special IC chip which takes power from the rechargeable batteries and provides output pulses of required amplitude of 10 V with a current drive of 10 mA. The BESS has a battery switching circuit, a pulse conditioning circuit which provides pulses of 3.7 V amplitude with 100 Hz frequency appearing periodically for 3.23 seconds with a time period of 8.4 seconds. It also has an

internal charge pump to boost the pulse amplitude to 10 V.

Hybrid packaging is considered for integrating the implantable electrical stimulation and remote power delivery system. Hybrid packaging of monolithic and discrete components saves space and weight and is suitable for many bio-implantable microsystems. Screen printed interconnects are used to integrate the BESS chip, discrete components and receiver circuit of the remote power delivery system. A patterned polyester screen of mesh count 305 with an open area of 50 % is used to screen print the interconnect pattern and bonding pads on a ceramic and a flexible substrate. The screen printer is used to obtain a 8 μm thick film print with a silver conductive paste for interconnection. The interconnect pattern occupies an area of 1" Å~ 0.5" and with the rechargeable batteries connected the package has the dimensions of 1" Å~ 0.5" Å~ 0.5" small enough to fit inside the receiver coil. The BESS chip is integrated by ultrasonic wedge bonding. The paper describes fabrication and operation of this bio-implantable microsystem for wireless gastric pacing.

5763-04, Session 1

Extending PAD (Power Allocation and Distribution)

K. D. Song, W. T. Golembiewski, Norfolk State Univ.; G. C. King, S. H. Choi, NASA Langley Research Ctr.

A power allocation and distribution system previously designed was limited by the available voltage ratings of dual gate MOSFET components. The circuit was limited to 20 volts, the maximum rated available dual gate device. The circuit has been extended to 200 volts by use of currently available small signal MOSFET's. The problems and trade offs of the replacement device will be presented.

5763-05, Session 1

Wireless microsensor network for solutions for neurological implantable device

J. K. Abraham, A. K. Whitchurch, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-06, Session 2

Design and testing of flexible dipole rectennas

K. D. Song, W. T. Golembiewski, K. Henderson, Norfolk State Univ.; G. C. King, S. H. Choi, NASA Langley Research Ctr.; J. Kim, Inha Univ. (South Korea); W. Craft, North Carolina A&T State Univ.

The concept of microwave?driven smart material actuators with various rectennas has been tested and presented in previous conferences. In order to applied this concept to real applications, the rectennas have to be flexible, so that they can be patched onto smart actuators. We will present design concepts of various flexible rectennas and their performances in terms of design parameters such as geometry of rectenna, selection of Schottky diodes, and integration into a system.

In this paper, the performance of designed rectennas will be presented. The input power, output power, and efficiencies for various shapes of rectennas in an array will be discussed. The application of this technology will also be discussed.

5763-07, Session 2

A ku-band Wilkinson power divider implemented on a surface-stabilized high-resistivity Si substrate

T. Ji, H. Yoon, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-08, Session 2

Design of 3-bit MEMS phase shifter

H. Yoon, T. Ji, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-09, Session 2

Stacked phased array antenna systems monolithically integrated on silicon

T. Ji, H. Yoon, K. A. Jose, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-10, Session 2

Organic thin-film transistor and electronics: a review

J. Xie, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-11, Session 3

The Nanostructured Origami™ 3D fabrication and assembly process for nanopatterned 3D structures

H. J. In, W. Arora, H. I. Smith, G. Barbastathis, Massachusetts Institute of Technology

Using techniques such as electron beam and x-ray lithography, nanoimprinting, and dip-pen lithography, it is now possible to reliably produce nano-scale features in the range of 10-40nm. However, these and other nanofabrication methods remain largely two-dimensional (2D) in nature. The third dimension, if it could be achieved, would enable completely new devices to be realized, such as photonic crystals with arbitrary defect structures and materials with negative index of refraction. Moreover, the third dimension would facilitate the hybrid integration of electronic, photonic, power storage, and other functions in the same nanosystem. Current three-dimensional (3D) fabrication techniques are often slow, complex, expensive, and incompatible with other micro- and nanofabrication processes. Our approach is to first pattern a large 2D membrane and then fold the membrane along predefined creases to obtain the final 3D configuration. We call this approach the Nanostructured Origami™ 3D Fabrication and Assembly process. It allows almost arbitrary 3D nanostructured systems to be fabricated using exclusively 2D lithography tools.

Alignment, spacing, and latching of folded segments are three crucial elements of the Nanostructured Origami™ process. Previously, alignment and spacing were achieved using specially designed alignment pyramids, and alignment precision was determined through an optical inspection of flaps that had been folded on top of each other. While the sub-micron level of alignment precision attained may be sufficient for many applications, a much higher level of precision is required for other applications such as folded, 3D photonic crystals. For such applications, metallic alignment fiducials are patterned on the inner layers of folded structures, so that a scanning electron microscope or the resulting moiré pattern can be used to more precisely determine the degree of alignment between folded layers down to tens of nanometers.

The actual folding mechanism is another important factor of the Nanostructured Origami™ process. In the Lorentz force method, an external magnetic field is used in conjunction with locally controlled current loops to fold the desired flaps. In the strain induced folding method, a stress-engineered bi-layer is made to curl with a process-controlled radius of curvature upon release from the underlying substrate. These folding methods are used to fold complex 3D shapes, such as multi-layer devices and corner cubes. In addition, over ten different origami shapes have been folded with the stress-engineered folding technique. They are also patterned to demonstrate functionality.

The flaps, once folded, stay in the folded position mainly due to plastic deformation of the hinges. However, a latching mechanism is needed to better hold the folded segments in place. By depositing layers of photoresist on top of the flaps, the photoresist layer can be melted to hold the structure in place after folding. The effectiveness of this method is experimentally demonstrated and compared to other methods such as a mechanical latch, epoxy, Van der Waals force, soldering, and welding techniques. Capillary forces of the melted photoresist could also be used to further help align the device.

5763-12, Session 3

Hierarchical MEMS synthesis and optimization

Y. Zhang, S. Graf, R. Kamalian, A. M. Agogino, Univ. of California/Berkeley

A hierarchical MEMS synthesis and optimization architecture has been developed for MEMS design automation. The architecture integrates an object-oriented component library with a MEMS simulation tool and two levels of optimization: global genetic algorithms and local gradient-based refinement. An object-oriented data structure is used to represent hierarchical levels of elements in the design library and their connectivity. Additionally, all elements encapsulate instructions and restrictions for genetic operations (mutation, crossover). The parameterized component library includes distinct low-level functional elements and high level clusters, which are composed of primitive elements. With a focus on the design of MEMS suspensions, the key primitive elements currently include anchors, beams, plates, comb drives, serpentine springs, and various folded flexures. Clusters of these primitive elements, such

as a dog-bone (I-shaped) center mass and a meandering (compound) spring, have also been added into the component library. High-lever clusters, such as examples of commonly used MEMS devices, will be added into the design library in order to provide a case library. During design automation process, a system level design concept is decomposed into clusters in the design component library. These clusters are further decomposed into lower lever clusters, until into the primitive modular building blocks in the MEMS design library for the optimization operations and design validation check.

A multi-objective genetic algorithm (MOGA) is used for the high-level global design optimization. The GA works with an appropriate MEMS simulation tool during the iterative design synthesis process to generate the topology and dimensions of all blocks of the designs subject to the design constraints and performance objectives. A large population size per generation is generally needed for the evolutionary process requiring a great deal of computation power and execution time to reach a near global optimum. Our previous studies of computational convergence show that GAs are best suited for conceptual design in deriving the general shape and topology, but are inefficient for fine tuning. We integrate a conventional gradient-based optimization algorithm at the end of the design synthesis process to further refine the design at less computational expense.

The design synthesis tool is applied to surface micro-machined MEMS suspensions. For our test case, the design objectives are a target resonant frequency, stiffness ratio and minimum device area. The resonator design is decomposed into an I-shaped center mass, comb drive, anchor and spring. The spring components can be of several types: serpentine spring, meandering spring, folded flexure or a mix of spring types. This paper evaluates the performance of the MEMS synthesis tool for a range of design constraint parameters and symmetry options.

5763-13, Session 3

Evaluation of novel tooling for nanoscale injection molding

S. Yoon, J. Lee, J. L. Mead, C. M. F. Barry, Univ. of Massachusetts/Lowell

Injection molding is one of the most promising candidates for the manufacturing of economically viable nanoscale parts due to its capabilities for high volume production. The composition and surface properties of tooling materials, however, become more critical as the size of the molded features decreases. Therefore, the effects of tooling surfaces were investigated for micro and nanoscale features. Tooling materials included etched and metal-coated silicon wafers as well as metal tooling. The micro and nano-featured parts were molded with optical grade polycarbonate over a range of processing conditions. Atomic force microscopy (AFM) was used to characterize the surface and evaluate molding quality. The replication quality of the micro and nanoscale features and the durability of mold surface were correlated with the tooling materials.

5763-14, Session 3

Variable surface enhanced Raman spectroscopy of molecular motors

O. Inya-Agha, J. M. Cooper, T. Davies, Univ. of Glasgow (United Kingdom)

This paper presents the use of molecular motors to explore changes in surface enhanced Raman (SER) spectra which arise from electromagnetic coupling effects as two colloid-sized metal particles approach each other.

Noble metal nanoparticles interact strongly with visible light due to resonant excitation of conduction electron oscillations, an interaction referred to as a local surface plasmon resonance (LSPR) interaction. This LSPR interaction results in an enhancement of the electromagnetic field surrounding the nanoparticle, with a concomitant enhancement of optical properties. The strong dependence of the LSPR on the shape and size of the metal nanostructures makes the electromagnetic field enhancement a tuneable effect, and tunability has made metal nanoparticles interesting in a wide variety of applications.[1]

Recent interest in SER spectroscopy (SERS) has been rekindled by the observation of single molecule SERS.[2] Nanofabrication provides a method for producing metal substrates for SERS with well-defined size and shape characteristics. Gold nanopillar structures are fabricated for this work by electron beam lithography. The size regime selected for the nanopillars used in this work is based on results reported by Gunnarson et al.[3]

Myosin V is a cargo-carrying processive motor that takes ~37 nm center of mass steps along actin filaments. It has been implicated in vesicular and organellar transport. Defects in this protein lead to immunological and neurological diseases.[4] How the two heads of Myosin V are coordinated to produce steps is an as yet unresolved question in the study of these molecular motors. This paper will present the effect on the SERS spectra of actin and Myosin of varying the distance between an electromagnetic field attached to a myosin molecule which is made to approach the electromagnetic field surrounding an actin molecule.

The technique will provide information of subtle mechanistic interactions between components of a molecular motor. It will also provide a model system for measuring the “proximity effect” in ligand binding (e.g. protein-protein and DNA-DNA interactions).

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5763-15, Session 3

Material property measurement of micro-size cantilevers using the AFM

S. Ko, H. Lee, J. Han, H. Park, POSTECH (South Korea)

Generally, the deformation in the micro-scale is dependent on the size. Some theories such as the couple stress theory and strain gradient theory in the literature explain these phenomena. The purpose of this study is to investigate the strain gradient effect in micro-scale. Specimen of the cantilevered beam that have thickness of 500 nm, 1 m, 2 m and 5 m and width of 20 m, 30 m, 50 m, 70 m and 100 m were fabricated by the MEMS technique. The aspect ratios of width and length of specimens are 1/10 and 1/15. We carry out the bending and torsion test to measure the mechanical properties such as the young’s modulus and yield strength using the AFM(Atomic Force Microscopy).

5763-16, Session 3

Microstereolithography for 3D microstructures

T. Ji, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-17, Session 4

Knowledge engineering for the 21st Century war fighters through exploitation of nanotechnology

D. C. Oberlander, U.S. Army Black Hawk Helicopters; L. Hall, Intergraph Solutions Group; E. Fuller, U.S. Army Ulitity Helicopter Project

Knowledge and IT Management are key enablers for future defense and homeland security systems. To effectively engineer and deliver knowledge to the 21st century war fighter, primary emphasis must be on Human Factors Engineering (HFE) or as the Army calls it, Manpower and Personnel Integration (MANPRINT). This is sometimes known as the man-machine interface. Think of our brain as a Digital Repository of Knowledge (DR Kno). We need a DR Kno or a digital storehouse of knowledge for each weapon system, including man. The Knowledge Engineering Officer for the Army’s Black Hawk helicopter is developing strategies to exploit emerging technologies via a Knowledge Acquisition and Management Network (KAMNET) to achieve this for BLACK HAWK. KAMNET contains the digital store of all knowledge pertaining to BLACK HAWK operation and maintenance procedures, collectively know as the BLACK HAWK Knowledge Base (BKB). A major subset of the BKB is the Digital Repository of BLACK HAWK Electronic Manuals (DR BEM).

If a digital nervous system is added to the BLACK HAWK along with “artificial intelligence”, we will have an entity we call “DR Kno”. It is analogous to the artificial intelligence entity known as Rommie (Andromeda Ascendant) in the Andromeda science fiction series on television or HAL in the movie 2001, A Space Odyssey. This electronic collaboration will provide DR Kno a rudimentary “state of consciousness” for the situational awareness or the status of whatever subsystems it is connected to on the BLACK HAWK. As part of our improvements, we need to be able to carry on “conversations” with DR Kno thru natural language processing so keyboards and mice will not be the only means to communicate with DR Kno. Aircraft components can be addressed and will be able to respond verbally.

In the future, the pilot and crew seats could also be equipped with biomedical feedback for DR Kno to help manage the readiness of the crew. In turn, this information can be integrated with the flight controls to automatically stabilize the aircraft in the event the pilots were injured or otherwise incapacitated (e.g., ignoring a errant input from a disabled pilot). This will achieve true integration of man and machine in a symbiotic relationship. The challenge is not only to create new X-model aircraft and spacecraft, but to be able to retrofit the legacy fleet. Incidentally, NASA has exactly the same challenge for them, which provides a great opportunity for cooperation and synergism since elements of NASA and the US Army are collocated at Redstone Arsenal, AL.

5763-18, Session 4

Development of a nanowire array for wireless neural probe

J. K. Abraham, J. Xie, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-19, Session 4

Nanotechnology in medicine

V. K. Varadan, K. A. Jose, The Pennsylvania State Univ.

No abstract available

5763-20, Session 5

Engineering carbon nanotube for device applications

B. Wei, Louisiana State Univ.

Carbon nanotubes have fascinating physical properties. In order to use these novel one-dimensional structures for electronic device applications the structure and properties of nanotubes need to be tailored. Some of our recent efforts will be summarized in this presentation, including growing nanotubes by chemical vapor deposition in controllable ways; modifying nanotube structure, morphology and transport property via physical and chemical routes; light emission from nanotubes; and a theoretical approach for adjusting nanotube conduction property.

5763-21, Session 5

Synthesis of aligned conducting polymer nanotubes

J. Xie, V. K. Varadan, The Pennsylvania State Univ.; G. N. Mathur, R. Dube, Defense Materials & Science Research (India)

No abstract available

5763-22, Session 5

Finite-length nanotubes, ground-state degeneracy, single-electron spectra, and conductivity

M. M. Mestechkin, Consultant; V. A. Zubkov, LSI Logic Corp.

The electronic levels of finite length nanotubes, composed of the hexagons of two types of alternating atoms are calculated analytically within the framework of tight-binding approximation through a method developed by D.E. Rutherford [Proc. Roy. Soc Edinb, 62, 229 (1949)]. It is found that in zigzag carbon nanotubes with an even number n=2j of sextets in a ring the gap in single-electron levels disappears while a zigzag nanotube with n=3j is not different from the other ones as is in the infinite case. The reason for the loss of the zero level (for n=2j) upon reaching the infinite length limit is discussed. It is proved that one hyperbolic solution with the energy close to zero exists in each zone for finite zigzag nanotubes above the found threshold. Hyperbolic solutions together with the degenerate one form the half-filled conduction band, and approximately 0.2% of all pi-electrons belong to it. An effective numerical method is developed for solution of the eigenvalue problem, and it is numerically established that for nanotubes with approximately 105 atoms a chaotic behaviour of frontier energy levels precedes the hyperbolic solution appearance.

The sample semi-empirical calculations taking into account Coulomb interaction by means of the Hartree-Fock-Roothaan approach to the degenerate open shell support some of these conclusions. A specific version of this theory [M.Mestechkin, G. Klimko, Int. J. Quant. Chem. 37, 753 (1990); Struct. Chem., 2, 489 (1991)] has been used. It demonstrates that the degenerate configuration splits into three equidistant terms two singlets and the lowest triplet in accordance with the Hund rule. This is in accordance with the recent experimental discovery of ferromagnetic behaviour of specially prepared nanotubes [O. Caspedes, M.S. Fereira, S. Sanvito, M. Kociak, J.M.D. Coey, J. Phys.: Cond. Matter 16, L155 (2004)]. These conclusions are also supported by ab initio Hartree-Fock and some more sophisticated versions of DFT calculations for small nanotubes.

5763-23, Session 5

Synthesis of carbon nanotubes from C60 and their applications in medicine

K. Mukhopadhyay, J. Yadev, G. N. Mathur, Defense Materials & Science Research (India); J. Xie, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-24, Session 5

Functionalized carbon nanotubes as bio sensors

N. Zhang, J. Xie, V. K. Varadan, The Pennsylvania State Univ.

No abstract available

5763-25, Session 5

High-perfromance sensor platform based on electroactive polymers

S. Li, Z. Li, L. Orona, Z. Cheng, Auburn Univ.

There is an urgent need for real-time biodetectors with high performance, such as high sensitivity, small size, easy deployment. Sensor platforms based on MEMS, such as microcantilevers have been studied. Using of micro-electromechanical diaphragm (MEMD) as micro-sensor platform is induced in this presentation. The principle and the simulation results are presented.

It is found that the sensitivity of MEMD is about 100 times higher than that of microcantilever. The method used to characterize the device is discussed. The high sensitivity of MEMD is demonstrated by MEMD made of electroactive polymer - P(VDF-TrFE). The polymer MEMDs with diameters from 4 mm down to 400 um were fabricated using the standard microelectronic fabrication. The devices were characterized using impedance method. The resonance behaviors of the devices are presented.

5763-26, Session 6

A novel approach to fabricate metallic nano-cantilevers

C. Luo, A. Chakraborty, Louisiana Tech Univ.

A novel approach was proposed in this work to fabricate metallic nano-cantilevers using a one-mask process and deep reactive ion etch (DRIE) technique. 40-nm-thick Al and 70-nm-thick Au cantilevers of lengths from 5μm to 20 μm and widths in the range of 200-300nm have been successfully fabricated on a silicon substrate using the approach. It is found that the silicon underneath the suspended beams had been completely removed. The fabricated metallic nano-cantilevers have potential applications in detecting molecules with high sensitivity.

Cantilevers, which resemble tiny diving boards, are the operating principle behind a host of experimental devices that could debut in the next decade.1 Micro-cantilevers have been widely applied as biosensors.2-5 The deflection of a cantilever is inversely proportional to the width of the cantilever under a lateral load, for example, a bending moment, a concentrated force, or pressure (see, for example, Equations (9.38)-(9.40) in reference 6). As a result, a cantilever of a nano-scale width has a much smaller deflection than a cantilever of a micro-scale width when they are made of the same material, have the same height and length and suffer the same lateral load. This implies that in response to an applied load, the former cantilever is more sensitive than the latter one in terms of the magnitude of deflection. For instance, a 500-nm-wide cantilever has a deflection 100 times larger than a 50-μm-wide cantilever and should be 100 times more sensitive accordingly in detection of an applied load. Micro-7-9 and nano-cantilevers10 are normally released by isotropic wet etching of sacrificial layers underneath, which face the problem of stiction. The dry release of a nano-cantilever overcomes this drawback.

The presented method includes three fabrication steps: (1) spin-coat a 100-nm-thick polymethyl methacrylate (PMMA) of a molecular weight of 495 K on a silicon wafer, and pattern it in the anchor-beam shape using electron-beam lithography, (2) deposit a thin metallic layer on the PMMA by thermal evaporation or sputtering, and transfer the PMMA pattern to the metallic layer by an ultrasonic-agitation assisted lift-off process, and (3) obtain metallic nano-cantilevers using cyclic nature of DRIE.

In summary, we have proposed a novel approach to fabricate metallic cantilevers with a nano-scale width. The fabrication process and corresponding experimental results were presented. Hundreds of nano-cantilevers can be fabricated on a silicon wafer using this simple, one-mask process within one processing cycle. In addition, nano-cantilevers can be rationally positioned on a substrate. Those nano-cantilevers can potentially function as sensing components with high sensitivity. They may also serve as valves to open and close nano-channels or actuation elements to drive fluid forward in nano-channels.

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5763-27, Session 6

New carbon nanofiber smart materials

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First, we are intersted in being considered for the award.

Abstract:This paper discusses the development of new multifunctional smart materials based on Carbon Nanofibers (CNF). The material properties of CNF are a little lower than the properties of Single Wall Carbon Nanotubes (SWCNT) and Multi-Wall Carbon Nanotubes (MWCNT). However, CNF have potential for more practical applications since their cost is low. This paper discusses the development of four CNF-based sensors and actuators. These are: (i) a Continuous Strain Sensor for structural health monitoring applications; (ii) a Biosensor to detect glucose, cancer, and osteoporosis; (iii) an Electrochemical Wet Actuator for use in a liquid electrolyte, and (iv) an Electrochemical Dry Actuator for use in a dry environment. Development of these four materials is discussed next.

1. The Continuous Strain Sensor.

The continuous sensor uses the piezoresistive property (resistance change due to strain) to detect damage in large structures. The sensor is formed by spraying a CNF mixture onto a structure to form long structural nerves. The nerves are connected to a wheatstone bridge circuit and the resistance of the nerves is monitored to detect damage such as a crack propagating in the structure. Large coverage of structures with miniature nerves is possible and provides a simple passive method for structural health monitoring.

2.The Biosensor.

A biosensor is made by functionalizing the CNF using a nitric acid treatment. The functionalized CNF with carboxyl groups is dispersed in a DMF solvent. This solution is cast on glass to form the biosensor. The biosensor is tested with a Pt reference electrode. Figure 1 shows the amperometric result for hydrogen peroxide detection. With the addition of hydrogen peroxide, the current is clearly increasing. The CNF sensor design may lead to new ultra-sensitive bioelectronic sensors to detect human disease and chemical and biological agents. These sensors can use semiconducting CNF as transistors with electrolytic gating and the cost of the sensor is low.

Figure 1. Amperometric response of the CNF-biosensor due to the addition of hydrogen peroxide.

3. The Electrochemical Wet Actuator.

A new CNF – Poly Methylmethacrylate (PMMA) composite material that has electrochemical actuation properties has been developed. A combination of solvent casting and melt mixing were used to disperse CNF in PMMA, and cast thin films of the material. A wet electrochemical actuator was formed by placing the CNF composite film in a 2M NaCl solution. EIS (Electrochemical Impedance Spectroscopy) was carried to characterize the electrochemical properties of the PMMA-CNF actuator. The actuators were tested in an electrolyte at voltages up to 15 volts as shown in Figure 2. The relationship between displacement and applied voltage is verified in this paper too. The CNF-PMMA composite actuator has a low Young's modulus but it is two orders of magnitude lower in cost than buckypaper actuator. Medical applications are being considered for this new smart material.

Figure 2. Response of the CNF Electrochemical Wet Actuator; (a) maximum displacement, (b) actuation at 0.5 Hz.

4.The Electrochemical Dry Actuator.

This section describes a CNF dry actuator developed using a Solid Polymer Electrolyte (SPE). To form the dry actuator, an SPE film was prepared from PMMA and a conductive polymer using the solution casting method. Ion conductivity studies were carried out to characterize the electrochemical properties of the SPE. EIS (Electrochemical Impedance Spectroscopy) was also performed to understand the electrochemical cell of the dry actuator. The actuator was tested in a dry environment at various voltages and frequencies, and the tip displacement was measured using a laser displacement sensor. Compared to the liquid based actuator, the dry-based actuator is relatively slower speed. However, the dry actuator may have more smart structures applications such as morphing of wings. If the elastic properties can be improved, whole structures for that actuate may become feasible.

5763-28, Session 6

Nanostructured electrodes for efficient gas ionization

N. A. Koratkar, Rensselaer Polytechnic Institute

Ionization gas detectors work by ionizing gas molecules using light, heat or radiation energy. The amount of energy needed for onset of ionization and the resulting ion currents can be measured and used to fingerprint the identity and the concentration of the analyte. In addition to light, heat and radiation exposure, another form of energy that could be used for ionization purposes is electrical energy. It is well known that every gas specie has a specific ionization potential, and this principle may be used to fingerprint the identity of the unknown gas. The main limitation of such field ionization detectors is that the electric field strength required in ionization of gases is very high and can be of the order of few V/Å. Therefore, several kilovolts are applied to a sharp tip in order to draw any useful ionization currents.

In recent work, our group has reported fabrication of a miniaturized gas ionization sensor using specially designed electrodes comprised of vertically aligned arrays of multiwalled carbon nanotubes. We showed smaller breakdown voltages (few hundred volts) for various gases including inert gases such as argon. In this paper we report new results obtained using beta-phase Tunsten (W)nanorods as electrodes for gas ionization. We show stable ionization and breakdown behavior for Ar at extremely low operating voltages (3 to 4 Volts) with ion currents of several tens of micro-amperes. The atomically sharp pyramidal apexes (tip curvature ‹ 0.2 nm) of the W nanorods provide a large number of individual ionization sites that amplify the electric field by several orders of magnitude and enable field ionization at extremely low voltages. Such voltages can be easily obtained by a single AAA size C-Zn battery, suggesting that portable micro-sensors based on the above idea can be made and utilized.

This work indicates that nanotechnology (specifically the field amplification effects associated with the sharp curvature of nanotube or nanorod tips) may be used to dramatically improve the efficiency of field ionization of gas species and mixtures, thereby greatly reducing the power required to develop a practical field-ionization-detector device.

5763-29, Session 6

ZnO nanowire field effect transistor and chemical sensor

J. G. Lu, Z. Fan, P. Chang, D. Wang, Univ. of California/Irvine

Recently, much research effort has been invested on zinc oxide (ZnO) nanowires. ZnO is a II-VI compound semiconductor with a wide and direct band gap of 3.37 eV at room temperature. It is known to have wurtzite structure with lattice constant a=3.249, c=5.207. Its large exciton binding energy (60 meV, much greater than the thermal energy at room temperature) makes it a promising candidate for applications in blue-UV light emission and room temperature UV lasing. In this paper, we present the electrical and chemical sensing properties of single crystalline ZnO nanowires. The nanowires are synthesized using a vapor trapping chemical vapor deposition method. The as grown nanowires have diameters ranging from 20 nm to 200 nm with average length about 30 m. Transmission electron microscopy and scanning electron microscopy show that the nanowires have single crystal structure and grow along (001)

direction. Individual nanowires are used to fabricate field effect transistors. Electrical transport studies show typical n-type semiconducting behavior with carrier concentration of ~107 cm-1 and electron mobility of ~25 cm2/V•s. Contact Schottky barrier height between Au/Ni electrode and nanowire is characterized from the temperature dependence of current. Thermionic emission is found to dominate the transport mechanism. Effect of oxygen absorption on nanowire transisitors' performance is investigated and ZnO nanowires with smaller radii demonstrate to be more sensitive to oxygen ambient. Also, the detection of nitrogen dioxide (NO2) toxic gase is demonstrated, and the detection limit is sub-ppm. Furthermore, the detection range and sensitivity can be modulated by gate voltage. These results indicate that ZnO holds high potential for nanoscale electronics and chemical sensor applications.

5763-30, Session 6

Photoconductivity of structures nanodimensional Ge/c-Si.

R. S. Udovitskaya, S. V. Kondratenko, O. V. Vakulenko, National Taras Shevchenko Univ. of Kyiv (Ukraine)

The spectral dependence of photoconductivity of the structures which contains Ge quantum holes on surface monocristal linings has been measured on an infra-red spectrometer ІКС-12.

The spectrum of photoconductivity of the structure "nanodimensional Ge / c-Si" is induced at room temperature. The researched sample is made by a method of molecular - beam epitaxy.

Appeared, that at the room temperature spectral position of the curve of photoconductivity was such most, as well as at a standard silicon photodiode. The spectral dependence of photosensitive silicon photodiode is induced. We compare spectra of a photosensitive of researched sample with the standard photodiode.

As is known the long-wave limit of photoconductivity is defined by width of the forbidden zone of the semiconductor. Growth at increase in energy of quantums of raised radiation (at reduction of the wavelength) occurs growth up factor absorption. The form of a photoconductivity spectrum of the photodiodes FD 142 the basic are absent recession in short-wave area (1,3-2,5 micron) specifies that speed of a surface recombination is equal to zero. For the structure "nanodimensional Ge / c-Si", significant recession in this area was on the contrary observed at the room temperature. So, samples had big (~cm/c) speed surface recombination.

To observe the contribution of nonequilibrium carriers of a charge to photoconductivity of the structure "nanodimensional Ge / c-Si" it is necessary cool up to Т <100 K. At such temperatures nanodimensional Ge there can be internal zoned transitions. Means, it is necessary to expect display of a photosensitive in infra-red area which corresponds to the energy of these transitions. Photosensitive of these nostructures is caused by interband transitions in nanodimensional Ge. The interband transitions occurs owing to Ge nanostructures on monocristal silicon due to quantum dimensional effect's.

5763-31, Session 7

Feasibility of a self-powered piezoelectric microaccelerometer

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Power consumption is a critical concern of many sensors used in diversified applications, especially where the replacement of long-life batteries is impossible. Energy harvesting technique using piezoelectric materials is an attractive approach to solve this problem. Considering that the piezoelectric strain sensor can function as a microaccelerometer as well as its integratability with IC technique, the feasibility of a self-powered piezoelectric microaccelerometer is studied in this paper. Lead Zirconium Titanate (PZT) is promising for microsystem applications. Its piezoelectric coefficient in 33 mode is 2-3 times larger than that in 31 mode. In addition, the transverse mode also eases the microfabrication process. Consequently, our design and analysis focus on the transverse mode to construct PZT based self-powered microsystems. PZT/ZrO2/SiO2 cantilever structures with interdigitated electrode and silicon seismic mass at the end are designed to have specific resonance frequencies of tens of kilohertz and hundreds of hertz. Performance of the microaccelerometer is studied. The capabilities of the energy storage and sensing of the acceleration are concurrently evaluated. The device with lower frequency has the capacity for higher power output as well as larger acceleration sensitivity. In our analysis, at higher frequency of 10 kHz, the energy density stored in the system is expected to be 0.02 uW/mm2/g with voltage sensitivity of 0.5 V/g. At lower frequency of 500 Hz, the expectation of the device turns to be about 10 uW/mm2/g and 20 V/g, respectively. A trade-off exists between these two major properties and desirable frequency. Compromise depends on the demands of particular applications.

5763-32, Session 7

A new type of microcantilever-based mass sensors

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Based on mass loading effect on a microcantilever, there are two kinds of approaches for sensing the presence of molecules: dynamic and static methods. In this paper, we demonstrate that the two methods actually use the same form of relationships for their sensing purposes, and that, without specific design of absorption region on the cantilever top surface, neither method can be applied to accurately determine the amount of molecules absorbed on a cantilever. In order to improve the precision of cantilever-based mass sensor, we developed a so-called profile approach. In this new method, the deflection profile of a cantilever due to mass loading is found using Roughness Step Tester (RST). Compared with a single feedback in the existing dynamic and static methods, i.e., frequency change in the former approach and deflection of the open end of the cantilever in the latter one, the deflection profile provides more information on the effect of mass loading on the cantilever. Consequently, the profile method has higher sensitivity in detecting loaded mass.

In the dynamic method, according to Dunkerley's equation [1], the fundamental frequencies of a cantilever before and after mass loading, and f, are related to the mass as follows:

, ... (1)

where A is the surface area occupied by the monolayer of absorbed molecules, areal mass density of molecules in A, E Young's modulus, and I moment of inertia. The relationship (1) has been applied to detect vapor adsorption [2], the amount of uniformly coated material [3], the number of Escherichia coli cells bound [4], the mass of an Escherichia coli cell [5], etc. In the static method, the deflection of the open end of a cantilever, w, is related to mass loading by

, ... (2)

where g is gravity acceleration, and l the length of the cantilever. Based on equations (1) and (2), we derived the results stated in the first paragraph. In order to accurately determine the amount of molecules absorbed when the cantilever surface is partially coated with the molecules, we proposed a new concept of detection. RST was adopted to determine the full deflection profile of a cantilever after mass loading, which was used to find the amount of loaded mass and the location of the molecules. We applied this method to detect loaded mass and material locations of a positive photoresist S1813.

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5763-33, Session 7

Thin film piezoelectric MEMS accelerometer and pressure sensor

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MEMS accelerometer using piezoelectric lead zirconate titanate (PZT) thin films as read-out have been attracted a great attention due to their simple structures and high sensitivity. This paper proposed a model of microeccelerometer with two suspended flexural PZT-on-silicon beams and a central proof mass configuration. The geometry and elastic properties of the thin films have been taken into account when formulating the acceleration-equation. To verify which vibration mode is the dominate one on the acceleration, mode analysis has been carried out by using MEMS software: CoventorWare. The analytical equation between charge and acceleration has been derived, which provides an opportunity to design the accelerometer. The research shown the proposed accelerometer is simple to manufacturing, liable, for large g conditions and wide frequency response.

We also develop a pressure sensor based on the same configuration withour proof mass.

5763-34, Session 7

Analysis and design of a novel double piezoelectric beam-driven torsional micro actuator

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The present paper attempts to analyze and design a novel double piezoelectric beam driven torsional micro actuator. The piezoelectric actuator is adopted for its actuating and sensing abilities. The emphasis is to design the micro actuator which could actuate to high rotating angles driven by a low applied voltage and also have a self detecting capability of the rotating angle. The piezoelectric beam is analyzed analytically and its responses to mechanical and electric forces are presented in the paper. Analytical expression for axial displacement with the applied voltage of a PZT-4 cantilever beam is obtained. The fabrication process of the torsional micro actuator is also presented. The analysis results indicate that the torsional micro actuator can rotate to a high angle at low voltage.

5763-35, Session 7

Ultrasoft FeAlSiBCuNb nanocomposites for GMI sensor applications

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Giant magneto-impedance (GMI) sensors has greatly benefited from the development of advanced sensing materials. This paper presents the GMI effect in Al-containing Fe73-xAlxSi14B8.5Cu1Nb3.5 (x = 0 and 2) nanocomposite materials which shows great potential for high performance magnetic sensor applications. The nanocomposite microstructures were attained by annealing the rapid quenched amorphous ribbons at 540 oC for 45 min in vacuum. The ribbons prepared have a width of 4 mm and a thickness of 15 mm. X-ray diffraction and transmission electron microscopy (TEM) analyses confirmed the amorphous and nanocrystalline states of the samples. GMI profiles were measured as a function of the external magnetic field at various frequencies up to 10 MHz. It is found that the GMI profile first increased with frequency up to ~5 MHz and then decreased at higher frequencies. The GMI profile has a single peak near zero field for f ‹ 1 MHz, this is likely due to the magnetization process of domain wall motion. However, two asymmetrical peaks appeared at higher frequencies due to the anisotropy distribution in the actual materials. More interestingly, a larger GMI effect was observed in the Al-containing nanocomposite alloy. This is attributed to the increased magnetic softness due to the fact that the Al substitution led to a reduction in magnetocrystalline anisotropy and saturation magnetostriction which, in turn, resulted in the decrease of the coercive force and the increase of the magnetic permeability. As compared with Co-based amorphous alloys which were known as good candidates for GMI sensor applications, the Fe-based ultrasoft nanocomposite magnetic materials exhibited larger GMI effects, as a direct consequence of their higher saturation magnetization and lower resistivity. It is the low resistivity that in turn led to a better performance of GMI sensors, especially at lower driving frequencies, e.g., less than 1 MHz.

In view of these results, it is proposed to construct a magnetic sensor based on the giant magnetoimpedance effect; the circuit of a GMI sensor similar to that proposed in by Atkinson et al [1] is given. In the circuit, the ribbon is connected to a bridge circuit via coaxial leads. Herein the source voltage and source resistance play an important role in the bridge balance. To use this circuit for a GMI sensor, one will need the impedance changes as a function of external magnetic field at a given frequency. This enables us to develop a high performance GMI sensor making of the Fe-based ultrasoft nanocomposite magnetic materials.

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5763-36, Session 7

Power management for energy harvesting wireless sensors

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The objective of this work was to demonstrate smart wireless sensing nodes capable of operation at extremely low power levels. These systems were designed to be compatible with energy harvesting systems using piezoelectric materials and/or solar cells.

The wireless sensing nodes included a microprocessor (MicroChip, Chandler, AZ), on-board memory (2 Megabytes), sensing means(1000 ohm foil strain gauge),sensor signal conditioning, and 2.4 GHz IEEE 802.15.4, 150 meter range direct sequence spread spectrum radio transceiver (ChipCon, Oslo, Norway), and rechargeable electrochemical battery (Infinite Power Solutions, Golden, CO). Embedded software protocols allowed for wireless offset null and wireless shunt calibration.

We have previously reported on the application of a nanopower comparator switch to prevent loading of the energy harvesting and storage elements. This technique lets energy accrue, in order to allow a sufficient amount of energy to be available for sensor excitation, data conversion, data storage, and/or wireless data transmission. In this work, we report on our second generation systems, which leverage extremely low power consumption sleep currents along with periodic, timed wake-up to minimize the average power consumption. Furthermore, we deployed pulsed sensor excitation and microprocessor power control of the signal conditioning elements to minimize the average contribution to power draw.

By sleeping in between samples, we were able to demonstrate extremely low average power consumption. The average power consumed depended on sensor update rates. At 10 Hz, current consumption was 300 microamps at 3 VDC (900 microwatts); at 5 Hz: 400 microwatts, at 1 Hz: 90 microwatts. When the RF stage was not used, but data were logged to memory, consumption was further reduced: 10 Hz: 300 microwatts; 5 Hz: 150 microwatts, and 1 Hz: 60 microwatts.

Piezoelectric strain energy harvesting systems were built and tested. These systems delivered ~400 microwatts under low level vibration conditions (12 x 12 mm PZT, 50 Hz, +/- 250 microstrain). These PZT harvesters will power our strain sensor perpetually with an RF update rate of 5 Hz. Alternatively, data can be logged to memory at 10 Hz; then only the reduced data sets (min, max, and average) were transmitted wirelessly at lower rates.

Output power levels were also measured from two miniature solar cells (Panasonic, 40 x 30 by 0.5 mm); our results indicated that indoor lighting conditions provided a wide range of output power (~100 to 1400 microwatts). Results depended heavily on the type of lighting and the distance from the light source; however, our findings indicate that solar cells will allow strain data to be monitored at 1 Hz data rates, or logged at 10 Hz rates, even indoors.

We have demonstrated smart energy harvesting systems which are capable of greatly reducing their energy consumption and operating modes in order to be compatible with the available harvested power and environmental conditions. This was accomplished by: 1) removing the load from the energy harvesting & storage elements while charging, 2) by using sleep modes in between samples, 3) pulsing excitation to the sensing and signal conditioning elements with synchronous A/D conversion, and 4) by recording data rather than transmitting data.

5763-37, Session 8

Analysis of a nonuniform cantilever beam MOEM accelerometer under closed-loop operation

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High performance accelerometers are needed in inertial navigation and microspacecraft applications. Micro-Opto-Electro-Mechanical (MOEM) accelerometers can provide better performance than conventional MEM accelerometers [1]. In this paper we present analytical results on a closed loop MOEM accelerometer consisting of a Mach-Zhender Interferometer (MZI) and a nonuniform cantilever beam on Silicon. One arm of the MZI is located on the cantilever beam and serves as sensing arm when subjected to an applied acceleration, while the other arm (reference arm) is located in a region where mechanical perturbation is minimum. The acceleration induced deformation results in a change in refractive index and inturn a change in phase. The phase change is readout as intensity change at the output of MZI using photodetection circuit. For closed loop operation an electrostatic feedback mechanism analogous to the force feedback mechanism used in the case of MEMS accelerometers [2] is considered. This is done by the application of a bias voltage to the top electrode whcih is of opposite polarity but same magnitude as applied to the bottom and each electrode. The resulting electrostatic force is a linear function of the feedback voltage assuming very small deflections of the proof mass.

The bias voltage is chosen according to the electrostatic force required to produce a phase difference of \pi./2. This limits the dynamic range of a closed loop accelerometer. The maximum acceleration for a given proof mass can be found by equating the inertial force to the feedback force. The dynamic range of the accelerometer can be increased by increasing the bias voltage and decreasing the electrode gap without affecting the minimum detectable acceleration. In our analysis for a proof mass of size 3 mm X 3 mm X 0.38 mm, the maximum acceleration is obtained as 26 g and 160 g for a electrode gaps of 5

micron and 2 micronrespectively, for a bias voltage of 23.3 V.

Our analysis of the closed loop accelerometer indicates that a significant improvement in dynamic range and bandwidth can be obtained by proper design. In a typical design we obtain a minimum detectable acceleration of 0.225 micro g /\Sqrt(Hz), range of measurement upto 160 g, and a bandwidth of 3.97 kHz, breakdown acceleration of 2987 g and cross axis sensitivity of 0.001 % for an accelerometer of size 3 mm x 3 mm x 0.01 mm, electrode gap of 5 micron, biasing voltage of 23.3 V and a sensing arm of length 3 mm.

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5763-38, Session 8

Tunable infrared filter based on elastic polymer springs

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Weihong Zhang , Mahmoud Almasri , Allen Kine , J. C. Larue , R. Nelson

We successfully fabricated a tunable fabry-perot filter with 3um and 6um air gap using homemade photodefinable elastomer springs. The filter was made of two thin film dielectric mirrors and elastic polymer posts to separate them. An electrostatic voltage was applied on the mirrors to compress the springs and hence to shift the transmission peaks to shorter wavelength. A finesse of 12 with full width at half maximum (FWHM) of 70 nm and a peak transmission of 63 % were achieved on the 125 um2 devices. In addition, the measured tunability before and after hard baking the devices were 210 nm and 120 nm, respectively. The tunability was achieved by applying a voltage of 80 volt on a 125 um thick silicon mirrors with 6 um posts height. The tunability was also measured on a thinner silicon mirror with 3 um posts height. In this case, the filter was tuned 200 nm by a voltage less than 20 volt. However, the filter finesse was 3, transmission peak was 40% and FWHM over 200 nm.

A new mask set was designed and fabricated to build the filter with 3-segment electrodes and anti reflection coating to correct the slight difference in the post heights and to enhance the transmission peaks respectively. Due to reproducibility problem and oxygen poisoning effect during patterning the posts, thermally-cured elastomer replaced the photodefinable one. A cavity filling deposition method was used to apply the material and post dimensions were under good control.

5763-40, Session 8

Feedback controlled nano-positioner using the fiber optic EFPI sensor with novel demodulation technique

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The laser interferometry is known for the most accurate measurement method ever. For the translation stage of a sub-nanometer scale, the fiber optic EFPI(Extrinsic Fabry-Perot Interferometer) sensor is suggested as a sensor of the feedback control system because of its high sensitivity, small size, simple system and relatively low cost. The novel signal processing algorithm for the real-time demodulation of EFPI output signal was developed and verified. The linearity in the mean values of interferometric light intensity among adjacent fringes was shown and used for the sinusoidal approximation of the nonlinear output signal. The nano-positioner with Piezo-electric actuators and the EFPI sensor system on the 2-D flexure was designed and tested. Principle of the scanning probe microscope is employed for the test of its resolution and stability.

5763-42, Session 9

Development of an SH-SAW sensor for detection of DNA immobilization and hybridization

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We have developed SH (shear horizontal) surface acoustic wave (SAW) sensors for detection of the immobilization and hybrdization of DNA (deoxyribonucleic acid) on the gold coated delay line of transverse SAW devices. The experiments of DNA immobilization and hybridization were performed with 15-mer oligonucleotides (probe and complementary target DNA). The sensor consists of twin SAW delay line oscillators (sensing channel and reference channel) operating at 100 MHz fabricated on 36˚ rotated Y-cut X-propagation LiTaO3 piezoelectric single crystals. The relative change in the frequency of the two oscillators was monitored to detect the immobilization of probe DNA with thiol group on the Au coated delay line and the hybridization between target DNA and immobilized probe DNA in pH 7.4 PBS (phosphate buffered saline) solution. The measurement results showed a linear response of the sensor to the mass loading effects of the DNA immobilization and hybridization with the sensitivity up to 1.5 ng/ml/Hz.

5763-43, Session 9

Piezoelectric polymer micro-sensor for biomass detection

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Most research has focused on inorganic material-based micro-sensors for mass detection. However, polymer-based micro-sensors offer several advantages over inorganic material-based microsensors, including light weight, compatibility with tissues and water, and lower cost, etc.. In order to explore fundamental research on polymer mass sensors, a few bridge type piezoelectric polymer micro-sensors (PPMS) have been developed at NASA Langley Research Center. The performance of the PPMS was characterized utilizing an impedance analyzer and a laser vibrometer. The resonance frequencies of the PPMS were theoretically modeled based on the device configuration and the properties of the materials. The experimental results are close to the theoretical prediction. The resonance frequency of the PPMS is sensitive to the added mass on the PPMS. The research also indicates that when the resonance frequency is shifted from a higher frequency to a lower frequency when an external mass is added, the bridge type sensor exhibits a lower mechanical quality (Q) factor reduction compared to the commonly used micro-cantilever. The PPMS can be used for chemical and biotechnology sensing applications.

5763-44, Session 9

Ultra-high-aspect-ratio electrochemical probe array for biological cellular monitoring

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A powerful experimental tool, ultra-sharp nano-electrode array is designed, fabricated and characterized. The application on a combination of Scanning Electrochemical Microscopy (SECM) and the Atomic Force Microcopy (AFM) is demonstrated. It can measure sample electrochemically initiated by SECM changes of topography while detecting topography using AFM. In order to realize this, a specialized probe system that is composed of a micro-mechanical bending structure necessary for the AFM mode and an electrochemical UME-tip required for a high performance SECM is crucial. The probe array is a row of silicon transducers embedded in silicon nitride cantilever array. The sharp high-aspect ratio (20:1) silicon tips are shaped and a thin layer of silicon nitride is deposited, which embeds the silicon tips in a silicon nitride layer so that they protrude through the nitride. Thus, the embedded silicon tips with a diameter less than 600 nm, the top radius less than 20 nm, and the aspect ratio as high as 20 can be achieved. A metal layer and an insulator layer are deposited on these tip structures to make each probe selectively conductive. Finally, cantilever structures are shaped and released by etching the silicon substrate from the backside. Electrochemical and impedance spectroscopic characterization show electrochemical functionality of the transducer system.

5763-45, Session 9

An innovative all-polymeric drug-supply device

C. Luo, R. Poddar, Louisiana Tech Univ.; J. Currie, M. Paranjape, Georgetown Univ.

We have successfully designed and fabricated an innovative all-polymeric drug-delivery devices, which are disposable and can be used to release drug on demand.

The drug-delivery device included a 5 x 5 array of individually addressable reservoir cells in a 50cm2 area. Each individual cell was approximately centered on a 2mm x 2mm grid. The device comprised of a stack of three layers - two SU-8 and one PMMA (polymethyl methacrylate) layers, and was disposable. The two SU-8 films were 200m and 10m thick, respectively, were stacked together, and included an array of reservoirs. Each reservoir had dimensions of 500x500x200m3 (volume was 50nL). Below the thin SU-8 layer was a 100-m-thick PMMA film. There were a 5 x 5 array of 500nm-thick gold line meander heaters between the reservoirs and the PMMA layer. Each heater had 8-m-wide, 80-m-long gold traces separated by a spacing of 8m, had an overall length of approximately

650 m, and was located underneath the center of a reservoir. The resistance of a typical heater was 41Ω. When drug in the reservoirs is needed, the array of heaters can be sequentially turned on to ablate micropores through PMMA layer for releasing the drug.

The size of an ablated micropore was mainly related to heater temperature profile, which was controlled by heater shape and applied voltage. Temperature profile on the surface of a heater was modeled using ANSYS finite-element simulation software. The software uses a heat balance equation, derived from the principle of conservation of energy, to find a nodal solution for each finite element that defines the device structure. A steady-state thermal simulation was employed to model the temperature distribution at the heater surface, and the boundaries were constrained to be at room temperature. ANSYS simulation results matched those of Fluorescent microthermographic imaging. The lowest applied voltage to make ablation occur was 2.8V, generating an elliptical micropore with long axis of 272μm and short axis of 204μm. The whole ablation process was accomplished within 15s. It was observed that the molten PMMA took the gold heater lines away from the pore area, avoiding possible block of the gold lines to the flow out of the pore. According to our experimental results, PMMA can function as a good ablation material and neither of unexposed SU-8 and PDMS (poly dimethyl siloxane) is a suitable one in this work.

In the paper, the design and fabrication of the device, selection of device materials, and themo-poration through PMMA will be detailed. The approach has potential applications in microfluidic or drug-delivery systems to release water in reservoirs or drug in capsules on demand.

5763-46, Session 9

Biosensor-based magnetostrictive microcantilever

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Biosensors for detecting and quantifying the presence of a small amount of biological threat agents in a real-time manner are urgently needed for a wide range of applications. In this paper, a novel type of micro-biosensor platform - magnetostrictive microcantilever (MMC) - is reported. Compare to the silicon and piezoelectric-based microcantilevers, the MMC has following advantages: 1) remote/wireless driving and sensing; 2) easy to fabricate. The resonance behavior and the sensitivity of MMC as sensor platform are characterized and compared to the theoretical calculation. It is found that the sensitivity of MMC is about 50% higher than that of piezoelectric-based microcantilevers. More importantly, it is found experimentally that the quality merit factor (Q value) of MMC can reach more 250, which is much higher than other cantilevers. Therefore, the development of MMC-based biosensors will significantly advance the capability to identify the biological threatening agents. The detection of yeast cells and Salmonella typhimurium cells using the biosensor made of MMC was carried out. The specifications of the biosensor is reported and compared to other biosensors.

5763-47, Session 9

Synthesis and characterization of block copolymeric vesicles integrated with energy transducing biomolecules

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Energy transducing proteins remain at the forefront of the discussions of the applicability of biomolecules as a core technology for nanobiological devices in the areas of medicine, biofuel cells, and a wide variety of other fields. While conventional methods utilizing synthetic lipid membranes for protein functionality assays have yielded a plethora of information with respects to the basic biology of membrane protein behavior, the ability to harness the efficiency and utility of these proteins in robust devices has necessitated the development of novel materials that can facilitate proper protein refolding while preserving protein function in the ambient environment. Block copolymer-based membrane technology represents a versatile class of nanoscale materials in which biomolecules, such as membrane proteins, can be reconstituted. Among its many advantages over conventional lipid-based membrane systems, block copolymers can mimic natural cell biomembrane environments in a single chain, enabling large-area membrane fabrication using methods like Langmuir-Blodgett deposition, or spontaneous protein-functionalized nanovesicle formation. Based on this unique membrane property, a wide variety of membrane proteins possessing unique functionalities including pH/voltage gatable porosity, photon-activated proton pumping, and gradient-dependent production of electricity have been successfully inserted into these biomimetic systems. Energy transducing proteins remain at the forefront of the discussions of the applicability of biomolecules as a core technology for nanobiological devices in the areas of medicine, energy harvesting, and beyond. While conventional structural and mechanistic protein studies have yielded a plethora of information with respects to the fundamentals of protein behavior, our work is focused on the integration of these components towards the development of a fully biological fuel cell. As such, the ability to harness the efficiency and utility of these proteins in robust devices has necessitated the development of materials such as the biomimetic polymer membranes that can facilitate proper protein refolding while preserving protein function in the ambient environment. The membrane protein, Bacteriorhodopsin (BR), found in Halobacterium Halobium, is a light-actuated proton pump that develops gradients towards the demonstration of coupled functionality with other membrane proteins to effect ATP production, or production of electricity through Bacteriorhodopsin activity-dependent reversal of Cytochrome C Oxidase (COX), found in Rhodobacter Sphaeroides. Using streptavidin–activated quantum dots interfaced with engineered protein constructs, we have demonstrated large-scale insertion of proteins into block copolymer Langmuir-Blodgett (LB) films as well as measurable pH changes based upon light-actuated proton pumping that are necessary for coupled protein functionality that result in BR-driven COX electricity production. Light actuated-activity across the protein-functionalized membrane when fully enclosed in a sol-gel matrix has also been observed using impedance spectroscopy. Demonstrations of resistance changes that were greater than 10kΩ have provided indications of significant protein activity over time. More significantly, using spontaneously formed nanoscale polymeric vesicles, measurement of protein activity coupling between BR and COX using cyclic voltammetry and amperometric I-t analysis has demonstrated the potential of BR-driven electricity production by COX in the microampere range. Other biofuel cell testing and fabrication strategies will also be discussed.

5763-48, Session 10

Real-time PCR detction with nanofabricated SERS microchips

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We present a microfluidic chamber used for PCR amplification, combined with the highly sensitive and specific real time detection system of Surface Enhance Raman Spectroscopy (SERS). The usual detection methods for PCR involve time consuming methods of DNA labeling, using labels that are capable of altering original DNA properties. Our method has the advantages of being label free, requiring small analyte volumes and achieving high sensitivity due to SERS enhancement. Using SERS detection during amplification means that the DNA being amplified undergoes fewer cycles [1]. As the error rate of copying increases with increasing cycle number, SERS-based detection offers higher fidelity of product along with increased sensitivity.

The fabricated microfluidic chamber is composed of a silicon substrate sealed by anodic bonding to a glass substrate. For a real time and accurate temperature control platinum temperature sensors and heaters are integrated on the bottom of the reaction chamber. The chamber is dry etched with DRIE to obtain a 40 micron deep reaction chamber, which results in a 20000 micron Å~ 10000 micron Å~ 40 micron chamber allocating 2 microliter. Two injection holes are open on the glass for the injection of the analyte to the chamber. Lift-off is used to pattern the Pt heaters once the device has been anodically bonded.

Vibrational spectroscopic detection, such as Raman spectroscopy, allows for highly specific analyte identification which avoids the use of labels (fluorescence, chemical, radioactive). Further more, when SERS is used, the detection results in increased sensitivities of up to 10^6 orders of magnitude and for some compounds it can be as high as 10^8 [1], making it possible to detect very small amounts of PCR product. SERS is based on the enhancement of the local electric field as a result from multiple interferences of the electric fields due to the rough surface. The fabrication of gold [2] nanopillars on the glass results in a well characterized, reproducible SERS environment for the microchip.

Electron beam lithography is used to defined the nanopillars on the glass. Since the glass is non-conductive a thin layer of nichrome needs to be evaporated on top of the PMMA photoresist and wet etched once the pattern has been written. Using lift-off 30 nm thick nanoparticles are achieved with a diameter of 100 nm and 10-50 nm apart for maximising the field enhancement [3].

Considering the high sensitivity of the SERS detection system and a starting DNA concentration of 10 ?g/?l, we can predict a reduction on the number of cycles needed for the detection of the DNA.

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5763-50, Session 10

Nanowire sensor array for the detection and identification of bio-hazards

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No abstract available

5763-51, Session 11

Double-microcantilever design for surface stress measurement in biochemical sensor

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Piezoresistive microcantilever has been widely applied to the probes design in scanning force microscopy. Recently, it has also been proposed to measure the surface stress change on microcantilever surface from biochemical reaction. Such direct surface stress measurement avoids the drawbacks from common optical lever detection and is advantageous to on-chip microsystem integration. However, the sensor performance is adversely influenced by the thermo-mechanical noise from piezoresistive thermal stress and by the biaxial surface stress. This paper presents a mechanics model to analyze a piezoresistive microcantilever under surface stress loading. A double-microcantilever design composed of an immobilized microcantilever and a sensing microcantilever connected by a transmitter is developed such that the surface stress loading on the immobilized microcantilever can be transferred to the concentrated force loading in sensing microcantilever to facilitate surface stress measurement in sensor applications.

Analyses show that the double-microcantilever design possesses two main advantages in enhancing the surface stress sensitivity. The biaxial effect of surface stress is limited to the immobilized microcantilever and the piezoresistor strain in the sensing microcantilever becomes mainly a uniaxial strain thus avoiding the drawback in direct surface stress measurement. The sensitivity can be effectively increased not only by micrcantilever thickness but also by careful selection of other geometry parameters. The relative length and thickness of the immobilized and sensing microcantilever dominate the measurement sensitivity. A serpent type transmitter design is preferred for providing the effects of simple supported end. Compared with the design of a single piezoresistive microcantilever for surface stress measurement in literatures, the double-microcantilever design is advantageous to reduce the unwanted thermal noise in piezoresistor and thermal stress bending of microcantilever. By separating the immobilized and sensing microcantilever, the double microcantilever achieves more than one order of magnitude in measurement sensitivity compared with the direct surface stress measurement. Fabrication by standard semiconductor process is under way.

5763-53, Session 11

Optimization of microfluidic mixing using multiobjective evolution strategies

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It is known that rapid mixing in biosensor microfluidic channels is required for such applications as immunoassays, DNA hybridization and molecular interactions. Rapid mixing becomes extremely important when diffusion coefficients are small or the mixing time scale is longer, or on the same order, as the chemical reaction or molecular event time scale. To overcome the inherent diffusion limited mixing of laminar flow many techniques to enhance microfluidic mixing are under development. These inlcude slanted wells, shallow grooves, electrokinetic instability mixing and surface layers.

In previous work, computational studies have been performed to determine the effect of microchannel wall temperature distributions in various flow-through PCR devices. The work continued to determine the wall temperature required to produce optimal mixing of binary fluids. Approximately 200 mixing scenarios were simulated by varying the Reynolds number, wall temperature distributions, binary fluid density ratios and interaction strengths, and the coupling strength between momentum and temperature. If one adds channel geometry variations, the number of parameters lead to optimizing the mixing function in at least a 9-dimensional space. This is a classical but massively computationally intensive problem which may not have a “best” design but many acceptable design configurations. The mathematical process of trading these multiple objectives is Multiobjective Optimization where the results obtained demonstrate the optimal mixing characteristics as a function of other design objectives. The developed solution methodology coupled the flow and heat transfer solver with a multi-objective optimization strategy. The optimization strategy made use of objective functions describing the relationships between channel geometry, location and magnitude of wall temperatures, ratio of binary fluid densities, fluid interaction terms and flow speed. Using these relationships and associated constraints, the quality of mixing along the micro channel was assessed using ratios of individual fluid components to the overall fluid transport. Comparison of the optimization results indicated close agreement with trial and error.

The current emphasis of this work is the development of a method by which surface property distributions can be optimized to control mixing and possibly to provide surface property directed flows. Binary fluid mixing is explored using lattice Boltzmann simulation of microfluidic channels having surface property variations which mimic the effects of, for example, hydrophobic and hydrophilic surface layers which can include surface temperature variations. The flow, heat and material transport solver is responsible for predicting the data required to determine the quality of mixing. Next, the multiobjective optimization strategy provided the mechanism to convert the constrained multiobjective problem into a form useable by the genetic algorithm which performs an adaptive search of optimal or near optimal solutions. From the set of near optimal solutions, one needs to determine which solutions provide the “best” results for the application. Examples of the method will be given starting with maximizing fluid mixing in a driven cavity. Finally, micro channel flow results will illustrate the effects of optimization of surface properties with comparisons to previous simulation results.

5763-54, Session 11

Molecular dynamics simulations of single-walled carbon nanotube tips impact processes on a silicon (001) surface

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Carbon nanotubes(CNTs) represent ideal Atomic Force Microscope (AFM) tip materials due to their unique mechanical properties. Recent developments enable quantitative preparation of individual single-walled carbon nanotube(SWCNT) tips.

For the first time, the declining/vertical SWCNT(12,12) indentation-lifting processes on a silicon (001) surface are studied by classical molecular dynamics simulations employing the Brenner’s “second generation” potential for a mixed C/Si many-body short-range interatomic interactions system, while the Lennard Jones 6-12 model for the van der Waals potential is added for the tube and surface long-range interatomic interactions. Four stages: plastic deformation, elastic bending, buckling behavior, and relaxing recovery were identified in the simulations. The mechanical microprocess of single-walled Carbon nanotube and Si surface interactions can be well comprehended from the view of nano-scale energetic evolution.

5763-55, Session 11

Simulation and design of self-heating continuous-flow PCR chip

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Continuous-flow micro-PCR chip is a novel method, which is quite different from conventional PCR and micro-chamber PCR chip. A fast and continuous DNA amplification reaction can be obtained by moving the sample through three individual temperature zones whose temperature is constant during course of the reaction. This paper presents a novel continuous-flow PCR chip adopted self-heating, passive-cooling mode to realize the DNA fragments amplification. The PCR chip is fabricated by silicon-glass anodic bonding, with two adiabatic grooves and two metal film heaters on the silicon outside the chip and a roundabout microchannel on the glass inside the chip. Using the ANSYS finite element analysis software, the temperature distribution of the chip is simulated and analyzed. Based on these, a kind of PCR chip adopting the silicon-glass bonding system is designed, the optimal size of continuous-flow PCR chip is 30Å~22mm2 , inside which the roundabout micro-channel with the 90um width，40um depth is distributed. With the silicon bulk micromachining and anodic bonding technique, two micro-heater with the nickel-chrome alloy material film are formed on the side of glass belong to denaturation and renaturation zones needed for PCR reaction, and two adiabatic structures with groove on side of silicon are etched. Based on analysis results, a simple method that can realize continuous-flow PCR on silicon–glass-bonding chip is introduced. By the mode of heating local zones at single side, three wider constant temperature zones could be formed, which are 60℃、72℃、95℃ suitable for PCR，and the temperature-difference could be restricted in less than 5℃. The whole PCR reaction system on this chip is of the advantages of smart, smaller and cheaper.

5763-56, Session 12

An experimental structural neural system

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This paper discusses the manufacturing of active fiber composite sensors, their intended application, and relative benefits of a Structural Neural System (SNS) to reduce the required number of data acquisition channels thus simplifying data acquisition and analysis. The SNS technology is a practical approach that detects Acoustic Emissions (AE) due to damage that occurs in complicated structural geometries. Testing of a scaled model of an airplane joint with a two neuron SNS is discussed in the paper. An aluminum riveted plate was used as the scale model of the airplane fuselage section. An automated damage detection and warning program has been developed at University of Cincinnati that can capture parameters associated with acoustic emissions including the number of acoustic emission events and their cumulative amplitudes that occur during the crack growth process. This information provides a qualitative view of the health of the structure and is used with a simple crack growth model for prognostics to predict the crack length and remaining life of the structure. The continuous sensor neuron is used on the aluminum rivet plate to capture the acoustic emissions and the signal is passed on to the SNS for efficient signal processing. Figure 1 shows the setup used to perform the testing.

Figure 1. The experimental setup for fatigue testing.

An experiment is performed in which a beam is loaded cyclically in bending as shown in Figure 1. The excitation frequency for loading the beam using the MTS machine is 4 Hz. The initial load applied is 900N, which is subsequently increased to 1444N, 1630N, and then set at 2049N for most of the testing. The total time that the experiment was run is 240 minutes. During the fatigue testing, the length of the crack starting from the notch grew to 21 mm. The neurons (sensors) on the structure generate voltage signals that are received by the SNS processor box. The SNS processor shown in Figure 1 contains the analog components that control the firing of the neurons. The neurons that fire pass firing signals and time signals to the A/D LABVIEW board in the PC. The PC displays a Virtual Instrument (VI) that drives the data acquisition and display. The trigger level in the neurons is set to a 0.80V. Whenever an AE occurs, the number of acoustic events on neuron-1 and neuron-2 are recorded by the VI and are counted and then plotted against the number of stress cycles that the structure undergoes. The number of stress cycles can be determined by a separate PZT sensor on the structure. In addition, the peak voltages are measured for each AE and are plotted against the number of cycles. The data generated is stored in a spreadsheet for further analysis. The VI uses visual and sound indicators to alert the operator each time an AE occurs. The time history response of the two neurons due to an AE event is shown in Figure 2(a) and the firing of the neurons is shown in Figure 2(b).

Figure 2. Response of the Neurons; (a) the AE time history signal, (b) the firing signal to identify which neuron is firing to locate the damage.

This testing showed that the SNS can detect AE if the sensor is close to the damage. The sensitivity of the monitoring scheme presented above depends strongly on the use of continuous sensors. The SNS is an important tool for highly distributed continuous health monitoring of structures. The testing indicates that the neural system can monitor complex joints and detect acoustic emissions due to propagating cracks. High sensitivity of the neural system is provided by the continuous sensors, but further sensor development and testing on different types of joints is required to optimize the system. Also indicated is that sensor geometry, sensor location, signal filtering, and logic parameters of the neural system will be specific to the particular type of joint (material, thickness, geometry) being monitored.

5763-57, Session 12

An analytical relationship to determine compressive residual stress in a doubly-clamped microbeam according to its buckled shape

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In this work, an analytical relationship was derived for a doubly-clamped microbeam when it buckled after release from the substrate. In terms of the relationship, residual stress in the microbeam can be determined according to its buckled shape. This allows one to find the residual stress directly without much experimental effort needed. Residual stresses of SiO_2 microbeams of various lengths and widths have been successfully determined, and matched the results obtained using a cantilever-release method.

Arrays of clamped-clamped microbeams of different lengths have been used to determine residual stresses in polysilicon films [1-3] and thermal SiO_2 [4, 5]. Residual stresses in doubly-clamped microbeams can be determined using a load-deflection method [6]. This method has also been widely applied to determine residual stresses and mechanical properties of thin films (see, for example, [7], and references therein). According to the method, residual stress can be extracted from experimental data using a relationship between applied lateral load and maximum deflection. However, it is not an easy task to apply a lateral load to a small structure, especially a beam with a micro-scale width. In some cases, residual stresses are compressive and large enough to cause buckling in the released. In this work, we demonstrate that residual stresses in those cases can be determined directly according to geometry of buckled microbeams without seeking the load-deflection method such that experimental effort to apply a lateral load can be avoided.

The derivation of the analytical relationship made use of the similarity between this buckling problem and oscillation behavior of a simple pendulum. According to the relationship, the applied compressive force can be determined according to the maximum absolute values of deflection and angle of deflection in the network's wrinkles. The relationship was used to determine residual stress in an array of doubly-clamped SiO_2 beams. The beams were fabricated using the technique of reactive ion etch. The buckling shapes of the beams were found using roughness step tester. Four approaches in determination of the total length of the buckled beam were discussed and compared. The residual stress determined using the relationship has a good match with that obtained by measuring released length of SiO_2 beams experiencing the same fabrication processes as the doubly-clamped beams.

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5763-59, Session 12

The micro-patterned device for cell attachment using new extracellular matrix

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Abstract

Studies of living cells, especially stem cells, are currently the core of modern biotechnology. Cells can only live at the very specific environment including temperature, pH, culture media, and etc. In addition, to induce cell growth, specific substrate, called extracellular matrix (ECM) like collagen, gelatin, or fibronectin, is required, because it control the behaviors of cells such as immobilization, attachment, proliferation, differentiation, and etc. With optimal ECM substrates, cell culture can be promoted and for the case of stem cells, they can be differentiated to the target cells more easily.

To grow cells on the specific ECM substrate, the properties of the substrate including roughness, hydrophobicity or hydrophilicity, surface charge of materials, and the existence of specific amino sequences like arginine-glycine-aspartic acid (RGD) groups are important factors to be considered invariably.

In this study, we tried to culture mouse P19EC (embryonal carcinoma) stem cell on a new ECM substrate, and we found the new source of the bio-compatible ECM material from zebrafish. The new ECM material is composed primarily of polysaccharide and cross-linked by a N-linked saccharide. We integrated the new ECM material into microwalls of a micro-patterned microdevice for cell attachment as shown in Fig. 1. The result of cell adhesion and proliferation on the new ECM was compared with those of other ECM substrates (Fig. 2). The surface morphology of the new ECM substrate was investigated using atomic force microscope and the surface properties like electrostatic potential and wettability were measured by zeta potential and contact angle, respectively.

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5763-60, Session 12

Reinforcement of PDMS using oxide-coated silicon plates

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In this work, a new method was developed to increase the stiffness of PDMS using oxide coated silicon plates for the purpose to reduce residual deformation induced during molding process. The procedure to fabricate the reinforced PDMS was presented in detail. Using this method, the maximum local strain in the released PDMS has been reduced from 5% to 0.5 %.

Polydimethylsiloxane(PDMS) has been widely applied in the micromachining field [1-5]. In particular, it has been successfully used as the master material in soft lithography for pattern transfer [1,2]. PDMS is soft, flexible, and easy to process. However, due to residual stress, PDMS may have undesirable deformation that leads to a misalignment problem even over a small distance. To solve this problem, it is necessary to increase the stiffness of PDMS and optimize the fabrication processing. Particles or fibers are often used to reinforce a material [6]. In those applications, the average stiffness of the reinforced material has increased due to the contribution of the reinforcements. Using a similar idea, we developed a method in [7] to reinforce PDMS using stiffer SU-8 particles. With the addition of SU-8 particles, average residual strain of the reinforced PDMS was reduced from 5% to 1%. However, the particle and fiber reinforcement approaches cannot have a good control of local deformations of PDMS since the local stiffness of the material between two neighboring particles or fibers still remains the same such that large local deformation may still exist. Also, particles or fibers may not uniformly distribute in the reinforced material. To avoid these two drawbacks in the particle and fiber reinforcement approaches, we chose a Si plate, instead of particles and fibers, to reinforce PDMS in this work. The Si plate was embedded throughout the PDMS, allowing us to have a better control of the whole and local deformations of the PDMS, in particular planar deformations. The PDMS is reinforced due to the high Young's modulus of Si, which is 150GPa and is 200,000 times of that of the PDMS.

The basic molding and reinforcement procedures are as follows. (1) slowly pour 10g PDMS (ratio between PDMS and its curing agent is 10:1) throughout the Si substrate to form a layer of thickness 100 μm, (2) after baking the sample for 2min at 85°C, add a Si plate on top of the PDMS, (3) coat another 10g PDMS on top of the silicon plate and heat for 20min at 85°C, (4) bake the sample in oven with 85°C for 20min and then cool it down at the wafer at room temperature for 10min, and (5) peel PDMS off with care. The reinforcement principle, fabrication of the reinforced PDMS, and characterization of residual deformation will be detailed in the paper.

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5763-61, Session 13

Lifetime characterization of capacitive RF MEMS switches

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RF MEMS switches provide a low-cost, high- performance solution to many RF/microwave applications and these switches will be important building blocks for designing phase shifters, switched filters and reflector array antennas for military and commercial markets.

In this paper, progress in characterizing of THALES capacitive MEMS devices under high RF power is presented. the design, fabrication and testing of capacitive RF MEMS switches for microwave/mm- wave applications on high-resistivity silicon substrate is also presented .The switches tested demonstrated power handling capabilities of 1W (30 dbm) for continuous RF power . In addition, the reliability of these switches was tested at various power levels indicating that under continuous RF power, A description of the power failures and their associated operating conditions is presented

The PC-based test stations to cycle switches and measure lifetime under DC and RF loads have been developed. Best-case lifetimes of 1010 cycles have been achieved in several switches from different lots under 30 dbm RF power. We present DC and RF lifetime data under varying conditions.

5763-62, Session 13

Millimeter-wave GaAs stepped-impedance hairpin resonator filters using surface micromachining

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In this paper, microstrip stepped-impedance hairpin resonator (SIR) low-pass filter (LPF) and slow-wave band-pass filter (BPF) using dielectric supported air-gapped microstrip line (DAML) of surface micromachining on GaAs substrate are proposed. The DAML structure, which is a new low-loss micromachining transmission line, is useful for the integration of MEMS and/or MMIC components. Design parameters for the proposed SIR low-pass and slow-wave band-pass filters are derived based on stepped-impedance theory.

The signal line of the DAML structure is elevated by the polyimide dielectric post using surface micromachining technique and the proposed microstrip line has the air-gapped area between the signal line and the ground metal. Hence, the substrate dielectric loss can be reduced because most of the electric field is confined in air region between the signal line and the ground, not in dielectric substrate. Therefore, with a new low loss transmission line, it is possible to realize microstrip structure easily on GaAs substrate without the complex process such as via-hole and back metallization. The DAML structure is compatible with the conventional MMIC technology and can make it possible to integrate the passive MEMS components with the active GaAs MMIC, which leads to make the cost lower and the size smaller with good performance.

The stepped-impedance hairpin resonator consists of the single transmission line ls and coupled lines with a length of lc. Zh is the characteristic impedance of the single transmission line ls. Zoe and Zoo are the even-mode and odd-mode impedances, respectively of symmetric capacitance-loaded parallel-coupled lines with a length of lc.

By selecting Zh 〉(ZoeZoo)1/2 , the size of the stepped-impedance hairpin resonator becomes smaller than that of the conventional hairpin resonator.

In this paper, the SIR LPF with the 3-dB frequency of 33 GHz and the SIR slow-wave BPF with the center frequency of 60 GHz are designed with the 3-D simulation tool, HFSS, ver. 9.1. The optimized dimensions of the SIR LPF are Lf = 0.5 mm, L1 = 0.48 mm, L2 = 0.208 mm, W1 = 0.044 mm, W2 = 0.044 mm, W3 =0.044 mm, W4 = 0.04 mm, W4 = 0.03 mm, g = 0.01 mm, and g1 = 0.01 mm. Also, The optimized dimensions of the SIR BPF are Lf = 0.553 mm, Lh = 0.553 mm, L1 = 0.92 mm, L2 = 0.4 mm, L3 = 0.15 mm, L4 = 0.906 mm, W1 =0.044 mm, W2 = 0.115 mm, W3 = 0.044 mm, g = 0.01 mm. The notations will be explained in the figure later.

The signal line of DAML structure is consisted of ground metal, dielectric post, and signal line elevated on air. The height between the substrate and the signal line is 10 um. The proposed DAML structure is formed on a GaAs substrate with the thickness of 680 um, and the ground metal of Au has the thickness of 1 um while the transmission line of Au has the thickness of 5 um from 10 um height on the ground metal. First, Ti/Au layer by thermal evaporator is deposited on the semi-insulating GaAs substrate, and then the dielectric posts with the height of 10 um are formed. Next, the circuit pattern is finished through the photolithography using AZ4903 photoresist which has higher thickness than the post height for the sacrificial layer. Finally, the metal pattern can be obtained by lift-off

process and the sacrificial layer is removed by acetone. The SEM photographs for SIR hairpin LPF and slow-wave BPF of the DAML structure on the GaAs substrate by surface micromachining will be provided.

The SIR low-pass filter shows a 3-dB pass-band from dc to 33 GHz. The insertion loss is less than 0.88 dB, and the return loss is better than 17 dB from dc to 25.57 GHz. The rejection is greater than 10 dB within 43.5 ~ 100 GHz. The ripple is 0.74 dB. The SIR band-pass filter shows a 3-dB bandwidth of 5.994 GHz at 60.04 GHz. A pass-band is from 57.043 GHz to 63.037 GHz with a return loss better than 15 dB. The insertion loss in the pass-band is 2.23 dB with a ripple of 0.21dB. The stop-band is greater than 35 dB within 34.06 ~ 43.05 GHz.

5763-63, Session 13

Applicability of holographic technique for analysis of nonlinear dynamics of MEMS switch

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Recent technological advances have enabled the fabrication of mechanical resonators down to micrometer and even nanometer scales, with super high frequencies. One particularly interesting aspect of the physical behavior of microelectromechanical systems (MEMS) is their nonlinear mechanical response at relatively small deviations from equilibrium which is caused by nonlinear electromagnetic forces, nonlinear stiffness, heat transfer porperties. It is important to understand the nonlinear behavior of MEMS in order to improve their future designs.

Hybrid numerical – experimental optical techniques are applied for holographic imaging and characterization of non-linearity in micro-mechanical relays, in particular their cantilevers. The apparent simplicity of the problem is misguiding due to non-linear interaction between the cantilever and the bottom electrode. Therefore the results of optical measurements of the cantilever dynamics are inaccurate due to the shift of the fringes in time average laser holographic interferograms. Numerical modeling helps to solve non-uniqueness of the inverse problem and to validate the interpretation of the pattern of fringes.

5763-64, Session 14

Identification of soft drinks using MEMS-IDT microsensors

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No abstract available

5763-65, Session 14

Smart Vest for physiological monitoring

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No abstract available

5763-52, Poster Session

Generation mechanism of micro/nano machined surfaces based on molecular dynamics

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Ultra-precision machining technology and nanotechnology are at the forefront of modern manufacturing industry. When the accuracy of machined surface approach nanoscale or atomic scale, some special physical phenomena will occur, such as the micro/nano scale surface relaxation, scale effects, dislocations，elastic recovery, etc. However, these phenomena can not be explained by conventional cutting mechanism based on classical continuum mechanics. This paper investigates the atomic scale cutting mechanism and the effects of surface relaxation on the micro/nano machined surfaces of monocrystalline copper with the aid of molecular dynamics simulation (MDS). The fulfillment of this study has resulted in a better understanding of the generation mechanism of micro/nano machined surfaces, and it is of significance for theoretical instruction of the practical machining process. Therefore, it will contribute to the generation of fundamental theory of nanotechnology for its further development.

A three-dimensional model of molecular dynamics (MD) was employed to study the nanometric cutting mechanism of monocrystalline copper. The model included the utilization of the Morse potential function to simulate the interatomic force between the workmaterial and a tool. By analyses of the MD simulation snapshots of the various stages of the nanometric cutting process and local radial distribution function(RDF), bulk's and machined surface's structure with no change and chip's with minimal change is observed. The generation and propagation of the dislocations around the tool are observed. Some of these dislocations are observed to travel through the entire depth of the workmaterial. Those that could mot escape completely through the machined surface due to elastic recovery were found to introduce atom step on the machined surface. By analyses of the surface energy and cutting forces(interatomic force between workmaterial and tool) during the nanometric cutting process, significant fluctuations are observed in the surface energy and cutting force curves. The amount of fluctuation is equal to dislocation energy. This indicates a large number of dislocations generate during the nanometric cutting process. The stress distribution plots of the various stages of the nanometric cutting process show that the mechanism of chip formation is significantly different from the conventional shear ahead of the tool in the case of a polycrystalline material. Most atoms ahead of tool are compressed, but forces of one or two layers atoms contact the cutting tool are tensile. With the chip formation, a minimal tensile region ahead of tool generates in the compression region and moves with the tool. Remain tensile stress is observed on the machined surface.

Machined surface has an important effect on the functionality of product, influences its physical and chemical properties. So this paper investigates the effect of surface relaxation on the machined surface in the vaccum condition. The surface energy is the most fundamental parameter, and its determination is of great importance in the understanding of a wide range of surface phenomena. The surface energy of the machined surface relaxed is less than that of unrelaxed. Roughness and stiffness are the two most characterization parameters of surface integrity and calculated. Results show that the machined surface relaxation affect roughness and stiffness. Better roughness will be attained by control the machined surface relaxation process.

5763-66, Poster Session

Stability analysis of carbon nanotubes via continuum models

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This paper presents the research on stability analysis of carbon nanotubes (CNTs) via elastic continuum beam and shell models. The estimation of the flexural stiffness of a single-walled nanotube (SWNT) via elastic beam model is proposed based on the postulate analyzed and provided in the paper. The validation of the stiffness is conducted with the ab initio calculations of the vibration of a SWNT. Based on the stiffness proposed, the stability analysis of CNTs is further conducted and validated with the well-cited research results by Yakobson and his collaborators. In addition, more predictions of various buckling phenomena of carbon nanotubes by beam and shell models are provided and studied. Finally, the kink phenomenon in a SWNT under pure bending is discussed via the continuum model. It is hoped that this paper will pave the way toward a better understanding of continuum models' application in the stability and dynamics analysis of carbon nanotubes.

5763-67, Poster Session

Design, fabrication, and simulation of cantilever-type electrostatic micromechanical switch

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A cantilever-type electrostatically actuated microelectromechanical (MEMS) switch and its fabrication technology have been developed for the first time in Lithuania, in Kaunas University of Technology. The microdevices were fabricated using nickel surface micromachining technology on substrates made of semiconductor (silicon) and insulator materials (quarts and cervit). The microswitch consists of cantilevered nickel structure suspended over actuation and contact electrodes. The width of the cantilever contacting element is 30 mm, thickness - 2 mm and length ranges from 67 to 150 mm. Implementation of microswitches as a substitute for present switching devices poses many problems. In particular lower switching speed and reduced lifetime are considered to be among the most significant ones. These characteristics are

determined both by design and dynamic phenomena that are taking place during its operation. Specifically, when the microswitch closes, it bounces several times before making permanent contact. These impact interactions greatly influence microswitch durability and switching speed. With the aim of improving these parameters a comprehensive finite element model is being developed that takes into account not only electrostatic actuation and squeeze-film damping effects but also describes important dynamic phenomena – impact interactions that take place during switching. Experimental research of electrical and dynamic characteristics are also carried out with the purpose of device model validation and correction. Configuration and fabrication process of the developed microswitch are presented as well as initial simulation and measurement results are shown.

5763-68, Poster Session

Fabrication of microfluidic systems with electrowetting-based actuation

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If we can manipulate liquid droplets more easily and the manipulation can be integrated to living cell culture system, it would be very helpful for cell biotechnology. Various methods for microdroplet manipulation have been suggested including dielectrophoresis[1], thermocapillary[2,3], electrostatic[4], electrowetting[5], electrochemical[6] methods. Among them, electrowetting method is currently regarded as the most effective method energetically and advantageous over continuous-flow system. Reconfigurable flow and the absence of permanent channels of the method also allow a highly integrated, scalable and flexible architecture. However, until now the electrowetting method was applied to general liquid or solutions not to cell culture media. To apply the method to cell biotechnology, the droplet-flow operation should be proved once again for cell culture media.

In this study, we developed a device with a simple electrical circuit for droplet flow test containing two liquid reservoirs and series of liquid-flow pads. Generally, the method is consisted of one common wide electrode and multiple oppositely charged narrow electrodes patterned on a silicon substrate. In the system like this, each droplet will be shielded between the two types of electrodes. However, in our system, the two oppositely charged electrodes are patterned together on the common glass substrate. For direct cell observation using microscope, materials for all component are chose to be transparent, for example, ITO used for electrodes and Teflon AF for thin hydrophobic cover layer on the electrodes. From experiments, droplets 0.7–1.0 ml of cell culture media was successfully dispensed between adjacent electrodes at the voltages of 25-40 Vdc.

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5763-69, Poster Session

The comparison of carbon nanotube probe and conventional atomic force microscopy probe in measuring of surface roughness

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Atomic force microscope (AFM) was a powerful tool to study surface topography and material structure at nano-scale. The high resolution imaging of AFM was based on the interactions of long-range force and short-range force between the AFM probe and the sample. If the probe had smaller diameter and higher aspect ratio(length/diameter), it would reduce interactions between the AFM probe and the sample and improve the imaging resolution. Experiments and theoretical analysis showed that AFM probe's diameter and aspect ratio were the two important factors in measuring surface roughness. Conventional silicon nitride and single crystal silicon probe used in AFM experiments were both in pyramid shape and had lower aspect ratio, which limited the imaging resolution's improvements. Carbon nanotube probe had good properties in smaller diameter and larger aspect ratio, and could improve the imaging resolution dramatically. Furthermore, carbon nanotube probe was wearproof and had good flexibility. Therefore, carbon nanotube probe was the ideal probe in measuring ultra-smooth surface or the surface characterized with nanometer-sized particle. At last, the surface roughness of indium-tin oxide film (ITO) was measured with silicon nitride probe, single crystal silicon probe and carbon nanotube probe respectively. And all of them have two different scanning areas, namely 1.0´1.0 and 5.0´5.0mm2. At the same time, factal analysis of their AFM images was carried out. Fractal diamension of the ITO film surface estimated using the structure function method. The fractal dimension (Df) of surface topography captured by carbon nanotube probe was the largest among the three kinds of probes. So, more higher frequency components and more microscopic information were measured by carbon nanotube probe. Compared with the conventional silicon nitride and single crystal silicon probe, the images captured by carbon nanotube probe had higher resolution and the measured surface roughness was more precise.

5763-70, Poster Session

Design and develpment of patch antenna at 35 GHz using MEMS technology

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Microstrip antenna is a very common element in telecommunication and radar applications. The advantages of microstrip antenna include low-profile, low-cost, light-weight and ease of integration with microwave integrated circuits which results in high-performance antenna arrays. Implementing the System-on-Chip (SOC) concept requires that all the passive and the active components must be integrated on the same substrate. Silicon is the most commonly used substrate for RF MEMS. However, its high relative dielectric constant (r = 11.9) limits the performance of the antenna fabricated on the silicon substrate. This is attributed to the easy excitation of surface waves resulting in lower bandwidth, limited power handling capability and degraded radiation efficiency of an antenna. Another issue is the losses caused by the silicon conductivity. This problem is somewhat overcome by using high-resistivity silicon (HRS) substrates.

In this paper, we propose a microstrip patch antenna designed and fabricated on a thin sputtered silicon dioxide membrane on a silicon substrate using MEMS technology. The SiO2 membrane formation is one of the last steps in the process sequence employed to realize the system-on-chip. For this reason, it would be advantageous to use a low temperature technique to form SiO2 so as not to adversely affect the already fabricated components on the same silicon substrate. RF sputtering appears to be an attractive option for depositing SiO2 films for membrane formation and this is the motivation for the present work. It has added advantage over the other low-temperature deposition techniques (plasma CVD, photo CVD etc.) as no toxic / hazardous gases are involved in the deposition process and the same sputtering system can also be used for metal layer(s) required for antenna fabrication.

The SiO2 film is deposited on a high resistivity (100) silicon substrate in a standard RF (13.56 MHz) sputtering system (Alcatel) using a 3-inch silicon dioxide target and argon ambient. The process was carried out in "sputter-up" configuration. The sputtering pressure and RF power were in the range 5 -10 m Torr and 150 - 250 W respectively. After silicon dioxide deposition, Cr-Au is sputtered in the same system and patterned to form the patch antenna. A cavity is then formed below the patch area of the antenna by completely etching silicon from the back side of the wafer using anisotropic etchant. While the patch is realized on the suspended silicon dioxide dielectric membrane, the feeding network is formed on the bulk silicon substrate.

This process synthesizes a low dielectric constant region (air cavity, r  1) around the antenna and thus results in enhanced bandwidth. The proposed configuration provides great ease in fabrication as no etch-stop layer is required.

Complete 3-D full-wave analysis is done using Agilent's High Frequency Structure Simulator (HFSS). The simulated return loss is –24 dB at 35 GHz and the bandwidth is 3.6%. The directivity and E-plane / H-plane beamwidth of the antenna at 35 GHz are 9.4 dB and 60 degrees respectively. The structure is also analyzed to study the effect of membrane thickness and dielectric constant variations.

5763-72, Poster Session

Infrared tunable filter based on photodefinable rubberelastic polymer springs

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We successfully fabricated a tunable fabry-perot filter using elastomer springs. The filter was designed with an initial air gap of 6 um. An electrostatic voltage was applied on the mirrors to compress the springs and hence to shift the transmission peaks to shorter wavelength. A finesse of 12 with full width at half maximum (FWHM) of 70 nm and a peak transmission of 63 % were achieved on the 125 um2 devices. In addition, the measured tunability before and after hard baking the devices were 210 nm and 120 nm, respectively. The tunability was achieved by applying a voltage of 80 volt on a 125 um thick silicon mirrors with 6 um posts height. The tunability was also measured on a thinner silicon mirror with 3 um posts height. In this case, the filter was tuned 200 nm by a voltage less than 20 volt. However, the filter finesse was 3, transmission peak was 40% and FWHM over 200 nm.

A new mask set was designed and fabricated to build the filter with 3-segment electrodes and anti reflection coating to correct the slight difference in the posts heights and to enhance the transmission peaks respectively. Some experimental data will be reported about the new design as well.

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5764-01, Session 1

A comprehensive model for NiMnGa magnetic shape-memory alloy behavior

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Recently, a new class of magnetically activated shape memory alloys (MSMA) has attracted much attention in the smart structures community due to their remarkable ability to recover large strains, on the order of 8%, when exposed to a sufficient magnetic field[1-5]. In addition, these materials are capable of producing the large reversible strains, at frequencies well above 1 kHz[2,3,4]. It is because of these attributes that MSM (Magnetic Shape Memory) alloys, NiMnGa in particular, are well suited for a wide range of high stroke actuator applications. Furthermore, MSMA have identical strain recovery mechanisms as NiTi, exhibiting both the shape memory effect and pseudoelastic behavior. The difference between the two materials is that strain recovery in MSMA is magnetically activated while the strain recovery in NiTi SMA is thermally activated. Yet, despite these unique characteristics, a comprehensive analytical model that completely captures the behavior of the material has yet to be developed.

Presently, a few micromechanical and thermodynamic models exist that are capable of predicting the stress and strain states of NiMnGa specimens in the presence of magnetic fields up to 1.0 Tesla[6,7,8]. However, these analytical tools are lacking in explaining detailed behavior and are not suitable for implementation in realistic engineering applications. For thermally activated shape memory alloys like NiTi, the Brinson and the Tanaka models, among others, provide reliable methods for predicting the stress and strain behavior of the material[9,10,11]. A key advantage to these models is that they are based on a series of easily obtainable material constants that make them straightforward to implement[9]. Because of the close similarities that exist between magnetic and thermal shape memory alloys, constitutive models like the Tanaka model can provide a useful basis for quasi-static MSMA modeling. A phenomenological-based model, characterized by test data, developed in parallel to the Tanaka model is the subject of this paper. The key issues to resolve with this approach involve redefining the model to allow for strains activated by a magnetic rather than thermal field and to account for behaviors unique to magnetic shape memory alloys.

In this paper, a simple constitutive model, based on experimentally determined constants, that predicts the macroscopic stress and strain behavior of NiMnGa FSMA is developed. The model is developed in parallel to the Tanaka model for thermal SMAs. The new model for MSMA behavior assumes the following form,

where σ0, ε0, ξσ0 , and Ho represent the initial stress, strain, volume fraction of stress preferred martensite, and magnetic field intensity respectively. E, Ω, λ are material functions where E represents the Young's modulus of the MSMA, Ω is a transformation tensor, and λ is related to the magnetostriction of the material. Each of these material functions are defined in relation to the volume fraction of field preferred martensite, ξσ. A magnetic field applied to the material causes the volume fraction of stress preferred martensite decreases resulting in the growth of field preferred martensite twins. This is analogous to the phase transition from martensite to austenite in NiTi SMA. However, although strain recovery in NiTi SMA occurs as a result of a phase transformation, MSMA strain recovery occurs as a result of twin boundary motion in the martensite phase only.

Tests are directed towards determining the material constants necessary for implementation of the model for a NiMnGa rod subjected to both quasi-static and dynamic, uniaxial loading conditions. There are several important constants that must be determined to properly implement this model, including critical transformation stresses at the start and end of the MSM effect, Young's modulus and magnetic threshold fields for both the stress preferred and field preferred states, free strain, and block force. Since these constants are functions of magnetic field and applied stress, tests are divided into two main categories: constant stress in a varying applied field and constant applied magnetic field in a varying stress field.

Experiments are carried out using a magnetic testing apparatus capable of producing DC and AC fields up to 1.0 Tesla. A photograph of the constant applied stress test rig is shown in Figure 1. The specimen is situated in between the two, tapered poles of the electromagnet where a uniform, transverse field is applied to the entire specimen. The NiMnGa rod is gripped between a moveable and stationary pushrod connected in series with a linear potentiometer and weight pan. The level of constant stress is adjusted by adding or removing mass to the weight pan. As the applied field is slowly varied from 0 to 1 T the strain response of the NiMnGa is recorded by the linear potentiometer. The level of applied field in the magnetic circuit is measured by a Hall Effect sensor situated in the gap between the pole and NiMnGa rod. A similar apparatus will be used for constant applied field testing.

To determine the critical transformation threshold fields that signify the beginning and end of the MSM effect, the NiMnGa rod is magnetically loaded and unloaded at various levels of constant stress. Performing this test over a range of constant loads allows a critical threshold field profile of the MSMA to be developed. Figure 2 shows this critical threshold field profile. For a given level of constant applied stress, as the field is increased slowly from 0 to 0.6 T, the magnetically induced strain begins and ends at the fields corresponding Detwinning Start (Ds) and Detwinning Finish (Df) curves respectively. As the field is removed, the strain recovery begins and ends at the Twinning Start (Ts) and Twinning Finish (Tf) fields respectively. Looking at iso-magnetic lines of this profile, the critical transformation stresses of the material can be predicted. A series of tests in which the actuator is exposed to a constant applied field as the applied stress is varied is planned to determine if the critical transformation stresses correlate with those predicted from the critical threshold field profile.

Thus far, the MSMA actuator has been tested under two constant fields, 0 and 0.6 T. Using data obtained from these tests and the critical threshold field profile, nine material parameters were defined similar to those used in the Brinson and Tanaka models, and used to characterize the analytical model. The model uses linear functions to describe the transformation of the martensite twin variants from the stress preferred to field preferred states as the actuator is exposed to an increasing or decreasing magnetic field. Figure 3 compares the simple model with experimental data. The model shows good agreement with the experimental data and can generally predict both the magnetic shape memory effect and magnetic pseudoelastic behaviors of the material. It fails, however, to accurately capture the nonlinearities in material behavior during loading and unloading. This issue will be explored in this paper and work will be directed at modifying the model to better account for these transitional nonlinearities.

In summary, this paper will develop a phenomenological model based on experimentally determined, magnetic oriented constants to predict the quasi-static and dynamic stress and strain response of NiMnGa MSMA actuators, thus providing a simple constitutive model to predict material behavior.

5764-03, Session 1

Actuation performance of conducting shape-memory polyurethane actuators

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This paper presents the actuation performance of conducting shape memory poly-urethane actuators. Last year, a concept of shape memory polymer actuated by electric power was introduced in this conference, while conventional shape memory polymer is activated by external heat. A conducting shape memory polymer was manufactured by adding carbon nano-tube to shape memory poly-urethane. The main problem was the large electric resistance, due to the irregular dispersion of carbon nano-tubes. We have tried to find a method to enhance the electrical characteristics. With a lot of works, a conducting shape memory poly-urethane with good electric property enough for smart actuators has been manufactured. Finally its actuation performance has been measured and assessed.

5764-04, Session 1

Integrated system for stimulation of mechanosensitive cells using polymeric bender elements

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It is well document that cells such as bone cells are sensitive to mechanical excitation. Mechanical stimuli increase bone mass whereas conditions of disuse, skeletal unloading and microgravity lead to a net loss of bone. Animal studies indicate a window of bone homeostasis between strain magnitudes of 250 and 1000  (0.025 – 0.1% deformation), with progressive

bone loss when mechanical strains are kept below this threshold, and strain-dependent increases in new bone formation demonstrated when moderate strains above this window (e.g., 1000 - 4000 ) are applied. In addition, this anabolic effect is frequency-dependent with evidence pointing to increased bone formation at strain frequencies (10-20 Hz) above the locomotor frequency (1 Hz).

In this paper we discuss the development of an integrated system for combinatorial analysis of mechanosensitive cells. The innovation in this system is the use of a high-strain electroactive polymer that operates under low-voltage (< 5 V) excitation. The polymer consists of an ionomeric polymer with a surface-deposited electrode. The actuation material is encapsulated in a thin layer of Mylar to isolate the material from the cell substrate that is seeded on the surface. Cells are subjected to a controllable mechanical stress through the application of an electric potential to the polymer. Feedback control is utilized to ensure a constant amplitude and frequency of excitation to the cell substrate.

Preliminary work on this system has demonstrated the feasibility of the concept. Encapsulated polymers that obtain 4000 microstrain peak-to-peak have been fabricated. Cells have been seeded on the substrate and shown to attach to the Mylar surface. Preliminary problems of premature cell death are being overcome through proper decontamination of the Mylar substrate before cell seeding is performed. Digital particle image velocimetry (DPIV) has been used to quantify the shear stress at the surface of the polymer during actuation in a fluid.

One of the major hurdles of the preliminary work is current leakage through the Mylar encapsulant. Current leakage produced large (~50 to 100 mV) potentials at the outer surface of the encapsulant. Potentials of this magnitude are problematic because they are in the range of the cell resting potential and could potentially cause interference with measurement of the mechanosensitivity of the cells. New fixture designs have reduced this potential to less than 0.5 mV, indicating that this integrated system has the potential for low-cost, miniaturized testing of mechanosensitive cells.

5764-05, Session 1

Development of a piezoelectric induced-strain actuator with an innovative internal amplifying structure

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The development of a novel piezoelectric induced-stain actuator possessing an innovative internal amplifying structure is presented in this paper. This actuator, which is called 'Pita' (Piezoelectric Induced-strain Trapezoidal Actuator), basically consists of a metal frame and two PZT piezoelectric patches. The metal frame is bent to form an open trapezoid, where its center part has a specially designed saddle-like unit and its slanting legs are attached with the piezoelectric patches. The saddle-like unit has an amplifying-lever mechanism at the corners to increase the displacement output of the whole actuator even its legs are mechanically clamped. When an electric field is applied across the thickness of the piezoelectric patches, the patches induce deformations on the whole actuator through the piezoelectric d31 effect. The saddle-like unit can relax the constraints at the joints between the unit and the legs by stretching itself during bending. Piezoelectric finite element analysis is used to maximize the work output of displacement and blocked force as well as to investigate the deformed shape of the amplifying structure under different geometric parameters. The results are in good agreement with those obtained from quasi-static measurements, showing that Pita has work output comparable to and larger than existing induced-strain actuators (e.g., Thunder) under free and fixed mounting conditions, respectively. Therefore, Pita has great potential for use in various practical smart structures and systems, including active-passive vibration isolation and micro-positioning.

5764-06, Session 2

Piezocomposite transducers for smart structure applications

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The concept of smart structures is based on intelligent materials giving the means to react on external stimulation by changing local mechanical properties. The market needs a high degree of integration of sensing and actuating functions and signal processing. Suitable composite material systems that combine load carrying, sensory and active properties are a vital prerequisite for the development of adaptive structures. Due to the overall performance, piezoceramics are considered the most promising basis for active materials. The use of thin monolithic piezoceramic wafers and fibers as actuating and sensing material has been discussed in many publications. However the production of these devices is very demanding since the extreme brittleness of the piezoceramic material requires sophisticated manufacturing techniques to avoid damages. An appropriate solution for this problem is the use of piezocomposite devices.

The present paper is giving an update on availability and developments of piezocomposites. At present, mainly low profile piezocomposite actuator types have been commercialized, as for example the ACX- module, the Active Fiber Composite (AFC) and the Macro Fiber Composite (MFC). Smart Material Corp. is manufacturing MFC actuators, licensed by NASA in a full-scale production, today. Recently, a contracting MFC has been developed with the advantage of reduced driving voltage of 360V [www.smart-material.com]. When embedded or attached to flexible structures, these actuators provide distributed solid state deflection and vibrational control. Commercial applications are still under development and are seen in vibrational reduction, shape control, micro positioning and structural health monitoring. Fraunhofer IKTS has developed three-dimensional custom shaped piezocomposites for active interfaces, especially for the machining, building and automotive industry. The designs are based on special arrangements of PZT fibers and PZT wafers.

R&D for the development of piezocomposites is still ongoing on different levels, like constitutive phases (piezoceramic, epoxy, insulating and conductive materials) scale, shape and connectivity, electrical and mechanical field distributions, interfaces and geometry, coupling to the load carrying structures (size scaling, placement), the electronics (voltage, current, time) and reliability issues. Knowledge on all of these levels is necessary to improve device performance and the efficiency for smart structure applications.

The correlation between structure and the design and placement of the actuators has also been analyzed showing a strong interaction. E.g., patches and structure must be designed in close combination. Progress has recently been attained in the availability of piezoceramic elements (rectangular and circular fibers, tubes, different materials) and device designs (geometry and materials for max authority, efficiency, lowest drive voltage).

Smart structures technology is going to be used in first applications. Because basic performance parameters are considerably improved, like for example energy economy, precision and comfort, a widespread use is expected in the next future.

The availability of piezocomposite actuators and sensors has improved considerably during 2002/ 2003. The supply of commercially available products will exceed the demand of the consuming industry by 2005causing major price reductions by 2006. Concerning applications, a shift from defense and sport items to industrial applications and consumer goods is expected.

5764-07, Session 2

Effect of electrode pattern on the performance of unimorph piezoelectric diaphragm actuators

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The ink jet printing industry has for quite some time used piezoelectric actuators as one of the driving mechanisms to force ink in printers, including both continuous and drop-on-demand ink jet printers. There has been a great deal of interest in getting better performance out of this technology, which in simple terms means getting increased actuator deflection out of smaller devices with lower input power. This paper presents a study in which a clamped unimorph piezoelectric diaphragm is tested to determine the importance of the pattern of the electrode used to supply the driving charge to the actuator. In previous work, it has been shown that such a diaphragm, when used as an energy harvesting device, can generate much increased charge in response to an applied pressure when the electrode has a "regrouped" pattern. A nominal electrode pattern is one in which the diaphragm is completely covered. Regrouping refers to the process of segmenting that nominal electrode into regions that are electrically disconnected, then reconnecting those regions such that some have reversed polarity. The electrode can be regrouped in such a way (corresponding to the underlying stress in the diaphragm) that the harvested energy is maximized. This paper investigates the same concept as applied to an actuator, which works somewhat the opposite of an energy harvester. That is, applied charge is used to generate diaphragm deflection (and pressure in the ink) as opposed to applied pressure generating charge. In this paper three unimorph diaphragms, each with different regrouped electrode patterns, were tested. It is shown that a factor of six increase in diaphragm deflection can be obtained with regrouping.

5764-08, Session 2

Micro-tailoring micro and nano composites toward variable orthotropy for biomimicking applications

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This paper promotes the general paradigm that a composite's internal structure can be micro-tailored to design objectives through the use of the Field Aided Micro Tailoring (FAiMTa) technique. The FAiMTa technique can be used to develop multifunctional materials with local variation in the material's orthotropy. Local variation of orthotropy has been used to develop functionally graded materials as well as materials that demonstrate varying physical quantities throughout the material. The FAiMTa technique relies on curing a polymer composite while in the liquid state in the presence of an electric field. The particles present within the composite will align themselves in the direction of the electric field and thus create an orthotropic composite structure. This paper expands this technology for the development of composite materials with micro tailored structure based on biological influences.

This paper is an initial investigation into the application of the FAiMTa technology towards bio-mimicking functions. To describe the materials inherent characteristics two steps will be focused upon. First, uniformly orthotropic composites obtained with the FAiMTa technique will be characterized. Different types of epoxy based composites will be considered; a composite with silica nano-spheres, micro-sized graphite particles, micro-sized ceramic particles, and micro-sized glass fibers will be studied. Initial results show that the material properties change according to the direction of particle alignment within the composite. Secondly, visual verification of created microscopic orthotropy will be presented.

Data illustrates the feasibility of the FAiMTa technology to orient the composite particulates to achieve a desired orthotropy. Future research into the FAiMTa technique will lead to both advanced design and manufacturing techniques.

The first goal will be the reduction of stress concentration by orienting composite particulates around a geometric discontinuity. For a hole in a plate it is well known that the material at the top and bottom of the hole (with reference to the loading direction) is placed into compression while the sides of the hole are in tension. Composite particulates will be aligned such that the strong/stiff direction will be in the direction of either the compression or tension i.e. the particles will be aligned circumferentially around the hole.

The second goal will be alignment of the composite particulates with the principal stress in a finite plate. We choose the principal directions of stress in isotropic plate as the initial iteration for optimal distribution of structural orthotropy in a finite plate. Further iterations and optimizations will occur as analysis is performed on previous iterations.

5764-09, Session 2

The fabrication and material characterization of PZT-based functionally graded piezoceramics

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Functionally Graded Piezoceramics, or FGP, have recently been explored as a means to increase actuator reliability and offer more complex deformations. The monolithic nature of FGP increases device reliability by eliminating the locations where debonding initiates, a failure mode which can significantly reduce actuator lifetime. The many grading approaches for creating FGP include varying the resistivity, conductivity, stiffness, piezoelectric coefficients, permittivity, or porosity of the material. Initial fabrication methods, as used for Rainbow actuators, relied on selective reduction to produce a monolithic piezoceramic that bends when activated. However, these methods commonly are limited to one-dimensional gradients and often reduce the stroke of the actuator. Other manufacturing approaches employ material doping to vary key material properties and are not necessarily limited to one-dimensional gradients; thus, enabling more complex performance such as twisting, dimpling, and warping. To achieve these higher-order deformations, it is important to understand the material properties of the various compositions and the gradient profile necessary for generating the desired behavior.

This paper presents a gradient approach developed at the University of Michigan which uses American Piezoceramic's lead zirconate titanate (PZT) based powder, APC 856, doped with Ferro's high permittivity barium titanate (BT) based dielectric powder, Z9500. This produces a variation in both the permittivity and piezoelectric properties of the ceramic. The PZT/BT gradient concentrates the applied electric field in the material with a larger piezoelectric effect, increasing device deflection and lowering the required driving electric potentials.

PZT/BT FGP were fabricated via traditional powder pressing and coextrusion methods. Powder pressed samples were created by layering different powder compositions that were pressed together and sintered into a monolithic one-dimensionally graded piezoceramic. Using this simple method, it is difficult to obtain material gradients in multiple dimensions; therefore, a second method based on coextrusion was developed that can produce the multi-dimensionally graded FGP that other manufacturing techniques cannot. The coextrusion process incorporates piezoceramic powder into a thermoplastic mixture that is extruded with other material compositions to produce multi-constituent FGP graded in two dimensions. The same media can be hot-pressed into building blocks and assembled into a monolithic graded structure, resulting in FGP graded in up to three dimensions.

To better understand how this doping technique affects material property variations; allowing for accurate FGP design and modeling, maps of the density, stiffness, permittivity, and piezoelectric coefficient variation with material composition were assembled using data from powder pressed samples and extrusion media samples. Optimal compositions for increased deflections at lower driving potentials were identified. FGP specimens with these compositions exhibit a very high level of material compatibility with smooth transitions between different compositions and similar microstructures. Several operational actuators were fabricated with gradients varying in complexity and severity, giving tailored actuator performance.

5764-10, Session 2

Studies on a multifunctional actuation system for lightweight space structures

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This paper presents results from ongoing research on a multifunctional actuation system wherein the strength-giving members of a lightweight, planar, space structure also enable the function of actuation. One such system that is currently under study is comprised of strategically embedded metal conductor wires supporting a large membrane. The wires perform the dual functions of partial load-carrying and actuation. An in-plane magnetic field is produced by suitably arranging light-weight magnets over the structure. Significant actuation forces can then be produced by driving a current through the metal members (Korde et al, 2004). This type of Lorentz-force-based actuation has been widely used in surface-acoustic wave generation (Auld, 1990) and in gas/chemical sensing applications (Martin et al, 1998).

Such multifunctionality is made particularly accessible and attractive by construction techniques such as Maskless Mesoscale Material Deposition (M3D) direct-write technology*. Furthermore, the method under development can be used to introduce localized actuation at the frequency of the drive current. Alternatively, by introducing suitable phase lags between the alternating currents driving the different sets of conductors, the same set up can, under some conditions, be used to impart rigid-body rotation on the structure.

Recent experimental work has shown that conductor dynamics plays a significant role in the overall dynamics of the membrane-conductor system, and appears to dominate the response at low frequencies (Korde, et al, 2004). This paper outlines a semi-analytical model that accounts for this effect. In addition, experimental results on scaled models showing laser vibrometer measurements of the system response are also presented. Experiences with the use of M3D for fabrication of the membrane structures with embedded conductors are summarized, and the effect of embedding the conductors as opposed to externally bonding them is discussed. Finally, results from semi-analytical and experimental work comparing the present design (i.e. with metal conductors) with (i) integrated conducting-polymer/solid-electrolyte layers and (ii) poled polyvinilidene fluoride (PVDF) rings are also included.

* This technology has been developed by Optomec Inc. (Albuquerque, New Mexico)(King, 2000), and uses an atomization process to direct-write on a substrate precursor solutions and colloidal suspensions that are subsequently laser fused. Resolutions down to 10 microns are possible. This technology is well suited for rapid prototyping as well as possible mass fabrication of micromotor components.

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5764-11, Session 3

Smart sensory system for rapid detection and identification of pedestrian impacts

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Many pedestrian fatalities occur from head injuries suffered from impacts with an automobile front end. Often, pedestrians are hit on the lower leg by the front bumper and forced head-first into the hood where the engine block, battery, and other hard components await. Future automobiles will have active protection systems such as external airbags or pop-up hoods to provide safety for pedestrians in the event of accidents. These devices provide a "cushioning layer" to protect a hit pedestrian in much the same way as airbags protect vehicle occupants. Obviously a fast and effective sensory system is needed to distinguish between pedestrian and non-pedestrian impacts in order for the system to deploy in time, maximize protection, and eliminate false firings.

A Smart Bumper sensory system has been developed and tested for active pedestrian protection systems. This system consists of shielded piezoelectric sensors mounted along the front bumper beam and smart algorithms for pedestrian identification. Impact disturbances are measured by the sensors, analyzed for frequency content, and then categorized as pedestrian or non-pedestrian using advanced pattern recognition techniques.

This paper will describe the crash sensory system for pedestrian protection systems and discuss the pedestrian recognition algorithm. Test results from numerous impacts tests with several different impact objects will be presented for system validation.

5764-12, Session 3

Investigation of the touch sensitivity of ER fluid-based tactile display

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Tactile displays are devices which can artificially stimulate the skin to generate sensations of touch such as shape, high frequency vibrations, pressure distribution and temperature, i.e. they provide force feedback and surface information to the user via the skin and the muscles. Such devices have potential applications such as virtual training for surgeons, telemanipulation or internet access for the visually impaired where a simulated tactile image maybe required for the user to actually feel.

A typical tactile display is an array of independently controllable actuator elements that are able to exert (or resist) forces in the direction normal to the user's skin surface. By proper control of these actuators, an impression, similar to that when an actual object is touched by human's finger, can be generated artificially. Researchers have proposed a wide variety of pin or vibrator arrays to present the sensation of 3 dimensional local shapes, fine textures, and slippage of grasped objects. These tactile displays use many actuating techniques, ranging from shape memory alloy, piezoelectric ceramic, ionic conductive polymer gel film or a simple mechanical approach using miniature electric motors.

In this research, a 5x5 tactile display array including electrorheological (ER) fluid has been developed and investigated. Electrorheological (ER) fluid is a fluid whose rheological (mechanical) properties can be changed by imposed an electric field. The advantages of devices based on ER fluids are: fast response time, low power consumption, easily embedded in structures with complex shape and a wide dynamic range. ER fluid's unique properties also provide the possibility to use ER fluid in tactile display devices to provide information to be felt by human touch by changing the surface profile.

In this paper, the designed tactile display has 5x5 tactels. Force responses of the tactile display array have been measured while a probe was moved across the upper surface. The purpose of this was to simulate the action of touch performed by human finger. Experimental results show that the sensed surface information could be controlled effectively by adjusting the voltage activation pattern imposed on the tactels. The performance of tactile display is durable and repeatable. The touch sensitivity of this ER fluid based tactile display array has also been investigated in this research. The results show that it is possible to sense the touching force normal to the display's surface by monitoring the change of current passing through the ER fluid. These encouraging results are helpful for constructing a new type of tactile display based on ER fluid which can act as both sensor and actuator at the same time.

5764-13, Session 3

Application of iron-gallium alloy as magnetostrictive sensors

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Structural health monitoring of equipment is a challenging task in aerospace applications. There has been a growing need to develop a non-contact torque sensor for use in real time health monitoring of rotating shafts. Fleming and Garshelis have shown promising work in this area using magnetostrictive materials and such sensors have been developed for application in racing car [1, 2, 3]. In order to be a good magnetostrictive sensor, a material should have high sensitivity to strain, large bandwidth for dynamic application, linear characteristics over a large range, low sensitivity to temperature and low hysteresis. Iron-Gallium alloys (Galfenol) appear to be a promising material for such applications and may offer improvements in performance and ease of use [4]. This paper will discuss the concepts and methods used in developing prototype Galfenol sensors for detecting vibration and torque. A basic electro-magneto-mechanical model will be presented to illustrate the capture of vibration signatures using a Galfenol sensor. Prototype apparatus are being developed and experimental results will be presented. The model is based on the linear magneto-mechanical and linear transduction equations. From basic knowledge of strength of materials the stresses induced by bending and torsional loads can be calculated. In turn these stresses produce a change in the magnetic induction in the magnetostrictive material which can be predicted from the linear magneto-mechanical coupled relationships. This can in turn be correlated to the final output voltage measured across a sense coil or a field sensor. These relations can be combined in a sensor system model using the linear transduction equations to relate input bending and torsion loads to sensor output voltage and current. Results from two prototype sensors will be presented. The prototype vibration sensor has Galfenol patches attached on the top and bottom surfaces of a beam with the ‹100\› crystal axis along the length of the beam. The prototype torque sensor has Galfenol patches bonded on the shaft surface with their ‹100\› crystal axis at +/- 45 degree to the shaft axis. In both cases, a primary coil applies a biasing magnetic field to the Galfenol patches. The compressive and tensile stresses produced during bending or torsion changes the magnetic induction in the Galfenol patches which is picked up by a secondary coil or field sensor. The strain is also measured using strain gages and bending and torsional stresses are calculated. A calibration is then drawn between the applied loads and recorded change in magnetic induction.

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5764-14, Session 3

Development of vibratory gyro-sensor using Galfenol

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This paper presents a prototype micro-gyro sensor that uses the new magnetostrictive alloy Galfenol for transduction of Coriolis induced forces into an electrical output. The concept takes advantage of the principles employed in

vibratory gyro-sensor and the ductile attributes of Galfenol to target high sensitivity and shock tolerance in a miniature gyro sensor. Vibratory gyro-sensors are used in various engineering fields such as shake detectors for hand-held video cameras, car navigation systems, and vehicle stability control systems. Vibratory gyro sensors are available in various configurations, all of which measure angular velocity indirectly. The sensors measure transverse or bending vibrations excited by the Coriolis forces that arise as they as undergo angular motion. The magnitude of the vibratory response is proportional to the magnitude of the Corilois force, which in turn is proportional to the variable of interest: angular velocity. In comparison with conventional mechanical gyroscopes with large spinning masses, vibratory gyroscopes offer significant advantages in their simplicity, weight and cost.

One of many variations on this concept includes the tuning fork resonator configuration which has a base support structure and two identical arms. Excitation of only one leg of a properly tuned tuning fork is required to produce significant displacement of the second tuning fork leg. The cross product of a rotational angular velocity w about an axis through the centerline of the tuning fork and the momentum of the arms as driven in the x-z plane produces a Coriolis force orthogonal to the driven plane.

Magnetostrictive materials are distinguished by the phenomenon of dimensional changes occurring in response to changes in magnetization of a ferroelectric material. Magnetostrictive materials also experience an inverse effect whereby magnetization changes occur in response to changes in applied stress fields. The recent discovery of Galfenol as a “large” magnetostrictive material (on the order of 100ue)offers a particularly promising candidate material for retaining largely desirable mechanical attributes with a modest compromise in magnetostrictive transduction performance relative to the extremes found in other magnetostrictive materials.

In contrast with typical piezo-ceramic materials, Galfenol is ductile and appears to have excellent ability to withstand mechanical shock. It exhibits promising transduction potential in both tension and compression. Galfenol has low hysteresis, looses less than ~10% of its transduction potential over a range of -20 to +80*C and will retain it magnetostrictive transduction even upon heating to above its Curie temperature of 670*C. Galfenol exhibits three to four times the actuation strain of standard PZT materials, with peaks on order of 400ue as the percent of Gallium in the alloy varies from ~17% to 30%.

The objective of this study is to advance the fundamental understanding the new material Galfenol and its potential for both actuation and sensor applications. An additional objective is demonstration of Galfenol-based sensor concepts that use the unique mix of mechanical, thermal and magnetostrictive transduction properties found in Galfenol to realize significant improvements in sensitivity, impact tolerance and thermal stability over existing miniature vibratory gyro sensors.

5764-15, Session 3

Bending behavior of iron-gallium (Galfenol) alloys for sensor applications

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Galfenol alloys (Fe 100-x Ga x) have been shown to combine significant magnetostriction (~ 400 ppm) with strong mechanical properties (tensile strengths ~500 MPa), making them well suited for use in robust actuators and sensors as an active structural material. Efforts are underway to grow Galfenol nanowires as small as 20 nm in diameter through the process of electrochemical deposition. This project investigates Galfenol behavior in bending at the macro-scale to facilitate the design concepts for use of Galfenol nanowires in biologically inspired sensors, mimicking the hair-like cilia of the inner ear. In order to properly design the sensor, the magnetoelastic bending behavior of Galfenol must first be characterized. To this end, a series of experiments are conducted on the magnetic response of cantilevered beams to dynamic bending loads. The samples studied include polycrystalline Fe 81.6 Ga 18.4 and Fe 80.5 Ga 19.5 (1/8 in. diameter x 2 in. long) and single crystal Fe 84 Ga 16 and Fe 79 Ga 21 (1/16 in. diameter x 1 in. long). Mechanical excitation was applied to the tip of each rod, with tests performed with sinusoidal and broadband random inputs. Measuring the magnetic response of the samples were a giant magnetoresistive (GMR) sensor located behind the beam and a pickup coil wound directly on each rod. A solenoid provided DC magnetic fields to bias the samples up to 10 Oe. Results of initial testing show that sinusoidal bending produces measurable output in which the GMR sensor agrees well with the pickup coil, and that the output increases when subjected to increased magnetic bias. Random input tests confirm that the various system resonances can be detected from the frequency spectra. Other results examine the effects of composition, crystal structure, and z-axis position of the GMR sensor. Preliminary modeling of the system is done by incorporating cantilevered beam vibration modes, classical continuum mechanics, the constitutive magnetostriction equations, and free energy magnetization models, the results of which are compared with the experimental results.

5764-16, Session 3

Principle, modeling, and testing of a magnetorheological fluid damper with an integrated relative velocity sensor

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In recent years, semiactive suspension systems based on MR dampers have received much attention. In order to control the damping force of an MR damper, the relative velocity across the damper is needed. In this case, displacement and/or acceleration sensors are used in MR damper based systems. However, these additional sensors not only enlarge the installation space but also increase the cost. Furthermore, these sensors exposed to surrounding are easily to be destroyed, which will decrease the systems’ reliability and performance. More recently, an integrated magnetostrictive position sensor for MR dampers is developed by MTS Systems Corporation. Although they can be mounted internally into MR dampers with high performance, the complex structure, the strict manufacturing processes, and the expensive materials of magnetostrictive sensors make the commercial application difficult.

In this paper, a novel integrated sensor method for MR dampers based on electromagnetic induction is presented, and the structure and working principle of a new MR damper integrated with an electromagnetic integrated relative velocity sensor (IRVS) are introduced. The electromagnetic IRVS mainly comprises an excitation coil on a piston and an induction coil wound on a high magnetic permeability bobbin, which positions in a nonmagnetic piston rod. A closed loop of the magnetic flux path is formulated along the piston, the cylinder, the upper lid, and the bobbin. A test carrier signal with a small amplitude and high frequency is synthesized with the driving current, which is the output of the current driver under the command voltage for the MR damper. Then the synthesized signal will function to the excitation coil. The test carrier signal does not affect the damping performance of the MR damper due to its high frequency and low amplitude. However, the induced voltage in the induction coil is directly proportional to the relative movement across the MR damper because the induced coil flux linkage varies linearly with the length and direction that the piston rod enters the cylinder. The relative movement signal achieved by the IRVS is used to formulate the command voltage for the MR damper and adjust the current driver to achieve the desired damping force.

In addition, a 2-D axisymmetric finite element model to identify and quantize the limiting factors affecting the sensitivity of the new IRVS and the key design parameters of the new MR damper is established with ANSYS. A prototype of the new MR damper integrated with an electromagnetic IRVS is developed and validated by experiments on the 849 Shock Absorber Test System from MTS Systems Corporation. Furthermore, the IRVS integrated into the MR damper is compared with the velocity measured by an instrument grade LVDT transducer, and the new MR damper integrated with the IRVS is compared with a conventional one.

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5764-17, Session 3

Monitoring the performance of geosynthetic materials within pavement systems using MEMS

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Geosynthetic materials have found useful applications when unbound aggregates have been placed on cohesive soil with very weak subgrade. They have also been successfully used in retarding reflective cracking in both flexible and composite pavements. There are many applications of geosynthetics in pavement engineering yet there is considerable lack of understanding in the behavior of the material. Geosynthetic materials exhibit very peculiar properties in the area of tensile strength and reinforcement.

MEMS are miniature sensing or actuating devices that can interact with other environments (provided no adverse reaction occurs) to either obtain information or alter it. With remote query capability, it appears such devices can be embedded in pavement systems as testing and monitoring tools.

The aim of this paper is to propose both field and laboratory methods for monitoring geotextile performance using MEMS.

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5764-18, Session 4

Design and evaluation of LIPCA-actuated flapping device

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Recently, interest in biomimetic design and demonstration of flapping device mimicking nature's flyers is increasing. For successful design of the device, the actuator and flapping mechanism should be able to create suitable flapping frequency of a target flyer. Even in design of an insect mimicking flapping device, we need to verify the flapping frequency that the actuating system can generate, since the flapping frequencies of insects are in wide spectrum ranging from 5 Hz(butterfly) and 200 Hz (honey bee). Therefore, design of actuation system is the most important for development of a flapping device. Next one should be design of the wing. The insect wing is totally different from a bird wing in the sense that the wing is not a living part and indirectly attached to the insect body. Therefore, the wing attachment is very important to create twist and chord-wise bending of the insect wing.

This paper address detail design and demonstration of an actuation mechanism composed of LIPCA(Lightweight Piezo-Composite Actuator) and flexural linkages that can amplify the actuation displacement of LIPCA. The device can generate high frequency flapping motion ranging from 30 to 60 Hz. The wing is made of tree-branch type vein covered by thin plastic film. The pattern of the vein is similar to a real insect wing and the cross section of the wing is zig-zag shape, which is good for flight in low Reynolds number. Lift and thrust of the flapping device are measured by a specially designed wired flight test system under head wind simulating forward flight. The paper will present detail measured data.

5764-19, Session 4

Airfoil drag elimination and stall suppression via tangential piezoelectric synthetic jet actuators

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For nearly 70 years, airfoil flow fields have been significantly manipulated through the use of various forms of active boundary layer control. Starting with variations of sucking and/or blowing flows on wing sections, boundary layers have been induced to stay attached or maintain laminar flow under conditions where they would otherwise have separated or tripped turbulent. Although quite successful, most of these methods have one or several profound drawbacks including extremely high power consumption, use of bleed compressor air from engines (which typically retards engine performance), ingestion of insects, dirt and debris. More modern investigations involving the use of synthetic jets have centered on normal blowing and sucking of air flows so as to either trip or attach gross flows over airfoil sections. Because numerous studies have shown that such normal blowing more often than not destroys good aerodynamic performance and is extremely sensitive to Reynolds number effects, a new approach is desired.

To skirt the issues of power consumption, dust, dirt and debris collection a new form of synthetic jet was designed and implemented. This new synthetic jet design employs tangential (rather than normal) suction and blowing of the flow from the surface of the airfoil using three piezoelectric diaphragm pumping plenums. Such tangential ingestion is accomplished through a unique foil thickness valving system which allows the intake of air from the upstream flow while expulsion of the air in a downstream direction. Because this valve is dynamic and employs an unsteady rocking motion during opening and closing cycles, it is highly resistant to the build up of dust, dirt and debris.

To prove the concept, a 12" (30.5cm) chord by 6" (15cm) span 2-dimensional NACA 0012 profile wing section was fabricated. A pair of upstream slots at the 30% and 50% chord were cut and steel valves were installed. A corresponding flapper valve was added at the trailing edge of the airfoil. As air would flow over the airfoil in low angle of attack operation, the boundary layer would be ingested into the upstream slots and expelled in a streamwise direction. A residual internal airflow was further directed toward the trailing edge of the airfoil and expelled from the flapper valve. The model employed three pumping plenums driven by 7.5 mil (191 μm) thick piezoelectric sheets inducing unsteady flows in and out of the appropriate slots. Bench and wind tunnel tests were conducted at frequencies in excess of 500 Hz. Wind tunnel testing was conducted from Reynolds numbers of 1,000 – 15,000 at angles of attack from 0 to 18 deg. A feedback loop was constructed to manipulate both the phase and amplitude of the plenums, thereby altering internal flows so as to alter the amount of drag reduction or stall suppression desired depending on the flow conditions. Titanium tetrachloride flow visualization was used to characterize the flow qualitatively and a momentum deficit rake was employed to make drag measurements. The test results showed that not only could detached flow be reattached after stall had occurred, but that low angles of attack drag could be countered to the point that the airfoil produced no drag at all. The paper concludes with several photos showing "system on" and "system off" flow over the wing section and implications for aircraft of several different categories.

5764-20, Session 4

Active aerodynamic control OF MAVs

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Over the past decade a considerable evolution has been made in the development of small-scale airborne vehicles also known as MAVs or micro aerial vehicles. Due to their dimensions, MAVs operate in the low range of Reynolds numbers, typically in-between 104 and 105 orders of magnitude. This type of flow regime presents several challenges. The viscous forces dominate the inertial forces causing the inclination of such platforms to flow separation and, hence, lower overall efficiency. The boundary layer of these lifting surfaces remains laminar and the flow's poor resistance to separation then dictates the reduced airfoil's performance. The goal of this research is to improve MAV performance by using smart materials to actively control the flow over a micro air vehicle.

Fair amount of work has already been done by the active flow control community to improve the deteriorated aerodynamics of UAVs and help improve the efficiency, stability and maneuverability of such vehicles by artificially controlling the boundary layer. All of the approaches were designed to energize the flow by exciting instability. Active control efforts have used acoustic drivers, oscillating wires, spoilers and flaps, dynamic blowing/suction and, most recently, synthetic jet actuators. Hassan et al from the Boeing Company have numerically illustrated the advantages of a low momentum synthetic jet over a traditional high momentum steady jet on a NACA 0012 and NACA 0015 airfoils. The trend in active separation control is away from steady inputs and towards harmonic and pulse inputs. The work of Amitay and Glezer was used by the team at the NASA Langley Research Center on a 50 degrees swept UAV to pulse modulate the driving waveform at low frequency with the resonant frequency as the carrier. This technique was successfully implemented and promising improvement in the efficiency of the control over the three dimensional wing was noted. It is the main focus of this paper to implement similar methods on a micro scale, thus investigating the possibility to actively control the boundary layer to improve efficiency and maneuverability of a micro NACA 0012 wing.

Our prototype synthetic jet actuator is a unimorph consisting of a piezoceramic bonded to a metal shim at the base of a cavity having an opening to the freestream flow. Excitation of the unimorph drives the oscillatory flow into and out of the cavity. The character of the actuator excitation is unsteady and as such induces mixing of the low momentum flow near the surface with the high momentum external flow. To implement smart MAVs and couple the synthetic jet actuators with the flow over the wing it is necessary to investigate the different parameters and configurations of synthetic jets to have them operate at their peak performance. Previous research helped us optimize unimorph parameters to be implemented as an active component of a synthetic jet actuator and helped us select a geometry that will best couple with the chosen unimorph.

To implement the effects of the synthetic jets on a micro scale fixed wing, the flow over such wings should be understood, as should the contribution of the specific synthetic jet parameters to its overall performance. Two- dimensional investigation of the effect of the synthetic jet actuators on a NACA 0012 micro size wing will be the main focus of this paper. The frame of the wing with a 3-inch chord length and 6-inch span has been manufactured and it is easily customized for different locations of the imbedded synthetic jets as well as different orifice areas and actuation frequencies. Pressure sensors have also been integrated in the test structure in order to attach a support variable to be monitored in the wind tunnel tests besides just the aerodynamic forces.

Simple flow visualization will be performed to help understand the boundary layer behavior over the wings when no perturbations are implemented. This will be used to provide a picture of flow separation over the span of the wing and aid in targeting initial locations for the synthetic jets. The same test will also be performed when the disturbances by the synthetic jets are introduced to monitor any differences.

Other work in analytically and numerically modeling the synthetic jets was used as a reference to roughly estimate appropriate actuation frequencies for the micro jets. These were used as a starting point for the experimental method. Three actuation frequencies have been determined, as potentials to drive the piezos in the synthetic jets: the resonance frequency of the diaphragm (8000 Hz), the acoustic frequency of the cavity (3000 Hz) and the frequency of the flow (175 Hz). In the preliminary experiments the actuators were positioned at the quarter chord of a NACA 0012 wing with eight pressure sensors positioned diagonally along the chord length. These initial tests suggested that lower frequencies matching the frequency of the flow should be the most efficient. It is

in this paper where we will try to vary the location and the excitation frequency of the synthetic jet actuators and with more reliable and confident experimental set-up observe how those variables produce the pressure distribution over the wing as well as the lift to drag ratio.

The experimental results will then be verified with a simulation of the same using FLUENT, a flow modeling software. If necessary, the transition location will be estimated from the flow visualization experiments and implemented in the existing code. Lift, drag and pressure coefficients will be compared to the ones obtained experimentally. The goal is to improve the synthetic jet outputs in order to maximize the changes of the aerodynamic forces when the perturbations from the synthetic jets are implemented in order to gain higher performance and more control authority.

5764-21, Session 5

Feasibility study on rotorcraft blade morphing in hovering

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The study of acoustic noise generated by helicopter main rotors, is the object of many theoretical and experimental investigations because of the complexity of the related physical phenomena and of its strong influence on the vehicle performance; in fact, the noise emission evaluation plays a fundamental role in pre-design stage for its strong impact on detection (military) and on interior comfort (civil), apart the more and more restrictive regulations on exterior noise; the results of this effort lead to significant impact on the final blade shape and the operational flight loads.

The extremely complex operating environment of a helicopter rotor contributes to noise generation through several distinct mechanisms; among them, blade vortex interaction noise (BVI), due to the shed tip vortex subsequently interacting with a following blade, results extremely annoying when it occurs.

One method for BVI alleviation is to increase the separation of the tip vortex from the rotor plane using an adaptive blade tip (dihedral-anhedral configuration); the main purpose of these advanced blade tip designs is to diffuse the tip vortex or to displace it, so that the interactions with the following blades are weaker, without sacrificing performance.

In this work, a feasibility study on blade tip morphing will be addressed; a hover flight condition will be considered to evaluate the efficiency of different smart-systems able to realise an on/off mechanism; no aeroacoustic estimation will be made, sending it back to further studies. More in detail, taking advantage of a 1D FE model of a hingeless rotor blade, undergoing flapping motion, the action due to piezoelectric-, MRF- and SMA-based devices will be estimated. Centrifugal and aerodynamic forces will be considered as external loads,; blade element will be adopted.

An innovative design strategy will be addressed in order to maximise tip deflections: MR fluid will be used to attain selective stiffness segments Thus, the actuation due to the SMA and piezoelectric devices will be increased, taking advantage of the local and controlled weakening.. In fact, after the blade tip deflection, the MR device may be activated again, in order to freeze the blade in the new configuration. The numerical results will be expressed in terms of blade elastic axis deflection.

5764-22, Session 5

Development of an active twist rotor blade with distributed actuation and orthotropic material

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Individual blade control (IBC) as well as higher harmonic control (HHC) for helicopter rotors promises to be a method to increase flight performance and to reduce vibration and noise. For those controls, an additional twist actuation of the rotor blade is needed. The developed concept comprises the implementation of distributed piezoelectric actuation into the rotor blade skin. In order to maximize the twist within given constraints, as torsional rigidity and given actuator design, the concept takes advantage of an orthotropic rotor blade skin. That way, a combination of shear actuation with orthotropic coupling generates more twist than each one of these effects alone. Previous approaches with distributed actuation used actuators operating in +/-45° direction with quasi-isotropic composites. A FE-Model of the blade was developed and validated using a simplified demonstrator. The objective of this study was to identify the effects of various geometric and material parameters to optimize the active twist performance of the blades. The whole development was embedded in an iterative process followed by an objective assessment. For this purpose a detailed structural model on the basis of the BO105 model rotor blade was developed, to predict the performance with respect to rotor dynamics, stability, aerodynamics, acoustics. Rotor dynamic simulations provided an initial overview of the active twist rotor performance. In comparison to the BO105 baseline rotor a noise reduction of 3 dB was predicted for an active twist of 0.8° at the blade tip. Additionally, a power reduction of 2.3% at 87m/s based on a 2.5to BO105 was computed. A demonstrator blade with a rotor radius of 2m has been designed and manufactured. This blade will be tested to prove, that the calculated maximum twist of +/-1.3° can also be achieved under centrifugal loads.

5764-23, Session 5

Longitudinal dynamics of a perching aircraft concept

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One of the major goals of the development of morphing aircraft structures is to enable new missions and new capabilities for aircraft. The most obvious sources of inspiration for these new capabilities are Nature's fliers. The gross extents to which birds morph their bodies allow them to perform maneuvers irreproducible by current manmade aircraft. One such infeasible maneuver is perching. Perching can be described as a high angle-of-attack approach, with the purpose of using the air flow for braking, followed by a planted landing. While vertical landings have been accomplished by rotary and VSTOL aircraft, it is desired to perch using aerodynamics alone, with little input from thrust-generating devices. This will alleviate the need for the heavy, inefficient thrust generators required to land vertically. Thus, perching will be especially useful for small, efficient reconnaissance aircraft, for example.

This paper presents a concept for a perching aircraft and an analysis of its longitudinal dynamics. This concept is based on a blended-wing body with an articulated tail boom, variable incidence wings, and an inverted V-tail. It is shown that the level of actuation required to recreate the perching maneuver in a manmade aircraft falls far outside the bounds of conventional aircraft designs. In order to maintain stability and controllability at the high angles of attack required for aerobraking, the aircraft's wings will be twisted to a negative incidence angle in order to moderate their angle of attack, and the tail will be rotated out of the resulting unsteady wake of the body. The horizontal stabilizer will also be actuated in order to remain in the linear angle of attack range as the tail boom rotates. Additionally, symmetric aileron and ruddervator deflections are analyzed for their trimming capabilities. These additional degrees of freedom will allow a larger degree of control over the aircraft's dynamics through a wider range of flight conditions.

For the purposes of this study, the aircraft is modeled in the longitudinal plane only; that is, roll, yaw, and sideslip dynamics are not considered. The fuselage and wings are modeled as a blended-wing body, and the tail is considered separately. The aerodynamic forces on the aircraft components are calculated using a modified version of Weissinger's method. This analysis assumes that the wing quarter-chord line is expressed as an arbitrary function of the span; it is not restricted to straight-swept wings. The advantage of using an analytical method such as this is its speed and reconfigurability. It allows the computation of aerodynamic properties of non-conventional wing geometries in a matter of minutes, compared to the hours (or days) a Computational Fluid Dynamics (CFD) analysis would require. Also, the quarter-chord curves, chord distribution, and twist distributions are input as analytical functions of the span coordinate; therefore, the wing geometry may be easily and quickly modified between analyses.

This model effectively breaks the 3-D wing into a series of 2-D airfoils joined by their quarter-chord curve. This enables the inclusion of 2-D airfoil data, either generated experimentally or computationally. For this analysis, airfoil lift, drag, and pitching moment data are calculated using 2-D CFD and tabulated. These same data are reused as the wing configuration changes since the airfoils themselves do not change. This method is also shown to predict where and when stall occurs since the onset of stall for each cross section has already been determined by the CFD analyses.

This modified lifting-line analysis is used to compute the downwash in the wake of the wing, specifically at the tail location. This same analysis is then used to compute the aerodynamic forces and moments on the tail, with the downwash caused by the wing added to the tail's angle of attack as an input. The analytical nature of this method allows a study of the effect of the tail's position relative to the wing on the downwash it experiences.

This aerodynamic model of the aircraft is used to study the longitudinal dynamics of the vehicle and to simulate the perching maneuver. Specifically, the variation of the trim conditions as the shape is morphed is discussed. The linearized dynamics around these trim points – the dynamic modes – are analyzed for stability and controllability. This is accomplished by the standard

trimming and linearization of the longitudinal equations of motion. Tracking of the perching trajectory using shape change combined with disturbance rejection using the ailerons and ruddervator is discussed. The aircraft's dynamics are simulated using the standard nonlinear equations of motion for aircraft and the aerodynamic model discussed above. The transition from cruising configuration to perching configuration is analyzed in detail.

Also discussed in this paper are the limitations of this model and the need for wind tunnel experimentation, currently under development at the time of submittal. Flight at high angles of attack and at low speeds is discussed briefly. Future work in the area of perching aircraft design is also mentioned, including trajectory optimization and robust flight control design.

5764-24, Session 5

Flutter boundary prediction of an adapting smart wing

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Airplanes, especially their wings are one of major systems to which smart structures technology is aimed to apply. A smart wing will be more flexible functionally and mechanically than a conventional fixed-wing. During the process of structural adaptation, it becomes much less rigid, so that it will be most likely to experience a new-type of aeroelastic instability occurrence due to an on-going structural change. In other words, in an ordinary airplane with fixed wings, the flutter boundary is reached by increasing the flight speed. On the other hand, in a smart airplane with adaptable wings, another flutter boundary would appear by performing an adaptation of structural configuration or function which would cause a decrease in wing's stiffness, while the flight speed remains the same. It is necessary, therefore, to establish a new effective means for predicting the boundary of the instability of such a smart adaptable wing which may behave as a non-steady system [1].

In this paper a new discrete-time series approach which we have developed [2, 3] for prediction of flutter of a fixed-wing induced by increasing the flow speed will be applied to the adapting smart wing. The new approach consists of an auto regressive-moving average (AR-MA) model of wing response, a recursive maximum likelihood estimation for an iterative identification of parameters of the non-steady system, and "Flutter Margin Criteria" based on Jury's stability conditions in the discrete-time domain. As a numerical example, a two-dimensional typical wing with or without a flap is used to show the effectiveness of the new flutter-boundary prediction method for smart wings during the non-steady adapting process. It is well-known that the center of mass of wing's cross-section has a strong effect on the flutter boundary. As one of the simplest examples, we examine the change in aeroelastic characteristics of such a wing by continuously changing the location of the mass center of the wing along the wing cord and predict the flutter boundary in terms of the location of the mass center instead of the flow speed.

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5764-25, Session 5

Finite element study of flutter detection and control for a simply supported flat panel

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A basic eigenvector orientation approach has been used to evaluate the possibility of controlling the onset of panel flutter using a flat panel (wide beam) as an illustrative example. The onset of flutter can be defined as the instance when two modes coalesce. Since eigenvectors for two consecutive modes are usually orthogonal, an indication of the onset of flutter condition can be when they start to lose their orthogonality. Eigenvector orientation method was developed in a previous study and allows for the prediction of the flutter boundary (indicated by a gradual loss of orthogonality between two eigenvectors) and thus can provide a 'lead time' for possible flutter control. Vibrations of the panels leading to flutter can be controlled using transverse forces and bending moments.

In this study, a basic simple beam element is used to model the panel (wide beam). As a first step, piezoelectric layers are assumed to be bonded on the top and bottom surface of the panel to provide counter-bending moments at joints between elements. The thickness of these piezoelectric layers is assumed to be small enough such that the change in structural characteristic parameters of the panel due to these layers is negligible. The standard linear quadratic (LQ) control theory is used for controller design and full state feedback is considered for simplicity. The controllers obtained modify the system stiffness matrix, and thus can re-stabilize the system at the onset of flutter; as a result, flutter occurrence is offset to higher pressure conditions. Controllers based on different control objectives are considered and the effects of control moment locations are studied as well. Potential applications of this basic method can be straightforwardly applied to plates and shells of laminated composites using finite element method.

5764-26, Session 6

Design and demonstration of a small expandable morphing wing

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Birds keep changing their wing shape during flight, so that they can adjust best fit wing configuration for current flight speed. The change in the wing shape includes variation of wing cross section and plan form. In this paper, we present a design, fabrication, and analysis of mechanism for small-scale expandable morphing wing for MAV class vehicles. The wing is separated into inner and outer wings as a typical bird wing. The part from leading edge to about 30% of the wing chord is made of carbon composite strip and remaining part of covered with multiple LIPCAs (Lightweight Piezo-Composite Actuators) and plastic film mimicking wing feathers. The actuators are activated to change wing cross section during wing expansion if necessary. Thus, the wing can change its cross section. The expandable wing is driven by a 3V, 0.3W DC motor, reduction gear, and fiber reinforced composite linkages. Rotation of the motor is switched to push-pull linear motion by a screw and the linear motion of the screw is transferred to linkages to create wing expansion and folding motions. The wing can change its aspect ratio from 6.3 to 9.4 in 2 seconds and the speed can be controlled. In the wind tunnel test, effects of the wing fold/expansion speed and activation of LIPCA on lift, drag, and pitching moment have been investigated for various angles of attack and wind speed. Lift tends to be increased 4 times as the wing expanded from stowed configuration and the pattern of the change is slightly different for different angles of attack and wind speed. The paper will present more detail test data.

5764-27, Session 6

Design of a shape-memory alloy actuated macro-scale morphing aircraft mechanism

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Using NASA Langley's HECS (hyper elliptical cambered span) wing as a testbed, a mechanism is described that can macroscopically morph the shape of the wing along its spanwise axis, using shape memory alloy (SMA) tendons as the actuating device. The wing was designed for use on an unmanned aerial vehicle (UAV), and was fabricated at the scale of a commercially available R/C trainer plane for flight testing. Due to the need for a prescribed shape change along a path in the Y-Z plane, the mechanism was designed to be hinged along the x-axis at different locations along its span, and discretized into a number of sections that could be rotated to approximate the ideal wing shape. Using a linear least-squares fit of the curve, the wing was broken into five segments per half-span in order to best achieve the desired wing shape without excessive system complexity.

Due to the high tension requirements on these wires, which function as primary load-bearing elements of the wing, each wing segment has a specific number of SMA filaments working in parallel according to the torque generated by the aerodynamic and gravity loading of the segments. The aerodynamic loading of the planar wing was determined through a Weissinger simulation in MATLAB employing Prandtl's lifting line theory, and was adapted to the case of the 'furled' wing with tips pointed downwards. Since each of the segments will be rotated to have a varying degree of anhedral, the loading for these segments is approximated by taking the cosine lift component from the horizontal for each planar equivalent section.

The wing segments are driven by SMA wire from a microprocessor with a pulse-width modulated (PWM) signal heating the wire. This is done in such a way as to

avoid exceeding the 4% strain rate for high cycle life. Feedback is employed not through thermocouples, which are inaccurate on such dynamic, small-scale systems, but through angular position sensors that rely on the geometrical data of the structure to determine the length change in each of the wire bays.

The power and thermal issues arising from actuation of such a system are addressed, along with the control system necessary to accommodate these constraints. The mechanism is benchmarked against a traditional DC motor-driven system employing non-compliant tendons, illustrating the potential use of smart materials as an actuation technique for large-scale wing morphing. Applications to ornithologically inspired wing maneuvers are discussed, indicating the geometrical flexibility of a shape memory-driven mechanism.

5764-28, Session 6

A new concept for active bistable twisting structures

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Multistable composite structures show promise as components of active morphing structures. This paper presents a research effort that demonstrates the ability piezocomposite actuators to transform such multistable structures between stable equilibrium positions. Many morphing concepts depend on a continuous supply of power to piezoceramic or shape memory alloy actuators to deform the structure elastically from its natural equilibrium configuration to a 'near-by' configuration. The advantage of using a multistable structure would be that, because the operating shapes could be stable equilibrium shapes, a source of power would only be necessary when changing the shape of the laminate, not to hold the laminate in that particular shape.

A thin unsymmetrically laminated fiber-reinforced composite laminate can have multiple equilibrium shapes. The anisotropic properties of the individual layers and the unsymmetric stacking sequence coupled with environmental factors (primarily change in temperature from the cure temperature) can cause the large out-of-plane displacements that lead to the appearance of multiple equilibrium shapes. For example, a rectangular two-layer graphite-epoxy crossply [0/90]T laminate will have two stable cylindrical shapes at room temperature if the sides are long enough and the processing temperature is high enough. The laminate can be changed from one cylindrical shape to another by a simple snap-through action by applying moments along opposite edges of the laminate. This multiple-shape phenomenon of unsymmetric composite laminates, including methods to transform between shapes, has been and continues to be studied by a number of investigators. The current study considers combining two such unsymmetric laminates to form a new structure that also has multiple equilibrium shapes.

The considered structures are made by combining two similar-shape rectangular crossply laminates, each of which has two stable cylindrical shapes, to form a multistable clamshell-type structure. The structure is formed by lining up the laminates so that they are convex outward, are lined up and touching along the long edges, and so the structure is open along the short edges. As the short edges are pressed together, twist curvature develops along the long axis of the structure, while the overall convexity of the structure is maintained. Two stable shapes of this structure exist: one shape with positive twist curvature and one shape with negative twist curvature. The structure can be transformed from one shape to another with a snap-through action. The study considers the use of the Macro Fiber Composite Actuator (MFC), an orthotropic piezoceramic actuator, to effect the snap through action. These actuators are prepackaged and the actuation is accomplished by applying a voltage to the actuator.

Experiments were performed to demonstrate the concept. A series 1 ft.-by-1 ft. [0/90]T unsymmetric composite laminates were autoclave-manufactured at NASA Langley using AS4/3501-6 graphite/epoxy prepreg. The laminates, in the two stable cylindrical shapes, had a radius-of-curvature of 3.5 in. at room temperature. Several of these laminates were then cut to smaller sizes (1.75 in. by 5.5 in.), MFC actuators were bonded to the inside of the laminates, and the laminates were combined to form the twist structure. The structure could be made to snap from one shape to another (changing the tip angle by nearly 20 degrees) and back to the original shape by applying voltage to the actuators.

A new concept for an active twisting structure has been demonstrated. The structure has two stable equilibrium shapes, one with positive twist curvature and the other with negative twist curvature. Experiments have shown that piezocomposite actuators can cause the structure to transform from one stable shape to another. Such structures could find use in many applications, for example, as a morphing wing or rotor blade where the change in twist curvature would be a change in the angle of attack.

5764-29, Session 6

The analysis of tensegrity structures for the design of a morphing wing

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Tensegrity structures are comprised of a set of discontinuous compressed struts held together with a continuous web of tensioned cables. These structures are inspiring new applications in smart systems and morphing foils. They offer high strength to mass ratios, low mechanical wear in dynamical applications, and high deformability with minimal input energy, which makes these systems excellent candidates for the structural layout of a morphing wing. This paper formulates the equations of static equilibrium for all prismatic class 1 tensegrity structures through a reduced coordinates method. Previous research on these structures using the force density method and the energy method, which were shown to be equivalent, gives little control over the actuation of elements, while some formulations of the reduced coordinates method make it difficult to constrain nodes. In this paper, a Cartesian reduced coordinates formulation allows for any combination of (1) the actuation of any cables or struts, (2) the application of any forces, and (3) the ability to constrain any of the nodes of the structure. The set of nonlinear equilibrium equations are solved numerically with Matlab. The numerical results are shown for single unit cell prismatic structures and multiple cells connected together and are applied to a morphing wing. For the design we have simulated pressure loadings to give the wing a realistic performance.

5764-30, Session 6

Load capacity and deformation optimization of a Kagome-based high-authority shape morphing structure

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One of the goals in shape morphing technology is to cause surfaces to displace even when resisted by large pressure loads (or heavy weights). The challenges become especially demanding when minimum weight requirements and power budgets are imposed. This challenge can be addressed by seeking structures that are simultaneously statically-determinate, yet stiff. Applications of such structures range from the aerospace and marine sectors to optical devices. Sensing and control circuitry facilitate a structure suitable for high-amplitude large-force vibration or displacement control.

A concept for a high authority shape morphing plate is described and demonstrated. The design incorporates an active back-plane comprising a Kagome truss, capable of changing the shape of a solid face, connected to the back-plane by means of a tetrahedral truss core. The design is performed by a combination of analytic estimation and numerical simulation, guided by previous assessments of the Kagome configuration. One of the most important benefits of this Kagome based structure results from its ability to attain several target shapes equally well while using only one configuration of actuators. Such a system is not possible with a classical hinge-design.

This work focuses on the various optimization procedures used to guide the design and application of the system. The load capacity optimization assesses the critical loads for all failure mechanisms of the components as function of the geometry. These are used to calculate the optimum dimensions and specifications for all the trusses, plates and actuators. The ensuing relations are used to choose the best material for a given shape morphing application.

The deformation optimization procedure has been devised to determine the best placement of a limited number of actuators in the structure for a given set of target shapes. The procedure is a two level optimization comprising of a heuristic algorithm with a simplex based optimization providing the cost function is used. Simulated annealing and genetic algorithm are used as first level algorithms and are compared to each other. The force capability of the actuators and failure threshold loads of the structure is accounted for in the optimization.

5764-31, Session 7

Compact actuation through magnetorheological flow control and rectification of magnetostrictive vibrations

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Compact Actuation Through Magnetorheological Flow Control and Rectification of Magnetostrictive Vibrations

There is currently a need for compact actuators capable of producing large deflections, large forces, and broad frequency bandwidth. In all existing

transducer materials, large force and broadband responses are obtained at small displacements and methods for transmitting very short transducer element motion to large deformations need to be developed. This paper addresses the development of a hybrid actuator which provides virtually unlimited deflections and large forces through magnetorheological (MR) flow control and rectification of the resonant mechanical vibrations produced by a magnetostrictive Terfenol-D pump.

Applications which can benefit from this new actuator technology include, among others, compact haptic interfaces, control surfaces for unmanned vehicles, actuator-based active suspension systems for heavy-duty commercial vehicles, adaptive airframes, and robotic locomotion components. We expect the new hybrid actuator to provide performance similar to pneumatic actuators.

Unlike pneumatic devices, however, the compression losses of the hybrid actuator are minimal since MR fluids are virtually incompressible. Furthermore, the hybrid actuator is self-contained and does not require external fluid lines and pumps.

Magnetorheological fluids undergo an apparent increase in viscosity within milliseconds of being exposed to a magnetic field~\cite{Jolly-1998-a}. While MR fluids are being increasingly used in automotive and seismic dampers~\cite{Jung-Spencer-Ni-Lee}, novel actuator concepts based on these fluids are scarce. This controllable rheological behavior is implemented here for the development of a fast acting fluid valve. The combination of giant magnetostrain and robust operation make Terfenol-D particularly well suited for driving a piston-type fluid pump, which is here operated at mechanical resonance and zero bias field.

The specific scope of the paper includes testing the MR fluid valve concept of self controlled flow, demonstrating the ability of the system to produce output mechanical work, and developing a systems level model of the actuator to be used for design and control implementation. Figs.~\ref{SPIE_DEV_02} and~\ref{SPIE_DEV_03} illustrate the hybrid magnetostrictive-magnetorheological actuator, which consists of a four-port magnetorheological fluid valve, MR fluid, Terfenol-D pump, drive piston, and driven piston. Further constructive details of the physical device can be found in~\cite{Burton-Nosse-Dapino}. To achieve rectification of the resonant vibrations produced by the Terfenol-D pump, and thus large deflections, the actuator operates through cyclic repetition of two stages, actuator motion (Fig.~\ref{SPIE_DEV_02}) and fluid refill (Fig.~\ref{SPIE_DEV_03}). At each stage the MR fluid valve completely closes one half of the fluid circuit and permits free flow through the other half by controlling the fluid viscosity near the conical valve ends. Each valve end is fitted with a permanent magnet to increase MR fluid viscosity and a solenoid to offset the field produced by the permanent magnet, thus creating a self-locking system in the absence of input power. During the actuator extension stage, the leftmost solenoid is turned on and the rightmost turned off, as shown in Fig.~\ref{SPIE_DEV_02}. This effectively thickens the MR fluid in the right path, producing a fluid path of least resistance through the left valve half. The flow produced by the Terfenol-D pump produces a pressure differential that fully closes the right valve. Once closed, the flow extends the driven piston for positive actuation. To increase the output force, a hydraulic advantage is created by implementing a driven piston diameter that is larger than the drive piston. The fluid refill stage immediately follows as the Terfenol-D element and drive piston begin to retract, see Fig.~\ref{SPIE_DEV_03}. To refill the fluid pump without also retracting the output piston, the left solenoid is turned off and the right turned on. This changes the fluid path of least resistance and creates the pressure differential necessary to begin closing of the leftmost valve half. With the left half closed, the actuator output is temporarily locked, and the free flow path through the opened right valve refills the pump. The cycle, which is reversible for actuator retraction, is repeated at high frequency to further displace the driven piston and thus achieve almost continuous motion of the load attached to the actuator. At this high frequency, a mechanical rectifier valve will not work as well as the MR fluid valve which is fast due to being activated magnetically.

A prototype four-port fluid valve was modeled, constructed and experimentally tested for proof-of-the concept purposes.

Observations and collected data show the valve's ability to self control flow using MR fluid as the working medium. Furthermore, a wide range of magnetic fields were applied that could control the valve position and flow path. Tests with zero magnetic field applied could not control the valve position and flow, thus proving the need for MR fluid.

The prototype valve will next be incorporated into a proof-of-the-concept actuator to test the ability to generate output motion. A universal compression-tension machine will initially cycle the driving piston, with manual control of the magnetic field within the valve. Advancements in this development step will proceed to computational control for improved actuator output performance and repeatability.

A multi-domain model of the system was developed for assistance in design and control implementation of the actuator. System parameters were identified from experimental data and used in fluid, electrical, and mechanical domain interaction equations to simulate output performance. The model captures the controlled opening and closing motion of the fluid valve from inputs of pressure and volume flow rate.

5764-33, Session 7

Investigation of active materials as driving elements of a hydraulic

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In recent years, there have been growing applications of smart materials, such as piezoelectrics and magnetostrictives, as actuators in the aerospace and automotive fields. Although these materials have high force and large bandwidth capabilities, their use has been limited due to their small stroke. The use of hydraulic amplification in conjunction with motion rectification is an effective way to overcome this problem and to develop a high force, large stroke actuator. In the hybrid-hydraulic concept, a solid-state actuator is driven at a high frequency to pressurize fluid in a pumping chamber. The flow of the fluid is then rectified by a set of one-way valves, creating unidirectional output flow. The unidirectional flow is used to actuate an output cylinder. Through this stepwise actuation process, the small stroke of the active material occurring at a high frequency is converted into a larger, lower frequency displacement of the output cylinder. A schematic of this concept is shown in Figure 1. Piezoelectric-hydraulic hybrid pumps have been constructed by Nasser et. al.1-2, Mauck et. al.3-5, and Konishi et. al.6-7 to investigate behavior and proof of concept. More recently, magnetostrictive-hydraulic hybrid pumps have been developed to identify any advantages in performance over piezoelectrics for this type of application.

In the magnetostrictive-hydraulic actuator, a coil generates an alternating magnetic field that is used to actuate the magnetostrictive material and pressurize fluid in the pumping chamber. The authors designed and constructed a compact magnetostrictive-hydraulic hybrid actuator for proof-of-concept and to investigate potential advantages of a Terfenol-D driven pump over a piezo driven pump (Ellison, et. al.8). The device was designed to actuate a 2" long, 0.25" diameter Terfenol-D rod at high frequencies in order to utilize its large magneto-strictive capabilities and produce high flow rates. The magnetic field generator used to produce the material actuation was assembled in house and consisted of a 28 AWG, 1700 turn coil, and a steel pump body used as a flux return path. A picture of the transducer is shown in Figure 2. Using a high-powered audio amplifier to drive current through the transducer coil, the pump was tested at actuation frequencies from 100 Hz to 650 Hz. Test results for the actuator are shown in Figure 3. The tests on the Terfenol-D driven pump verified that magnetostrictives are a feasible and attractive option as the driving material in a hybrid pump, however, it is unclear whether they are advantageous over piezostacks at higher frequencies. Because the actuator coil was wound using a high gauge wire and had a high number of turns, the inductance of the coil was also high, limiting the frequency at which sufficient power could be provided by the amplifier. Figure 4 shows the voltage clipping effect experienced by the amplifier at a frequency of 500 Hz. Note that the strain of the Terfenol-D rod occurs at twice the frequency of the input voltage. This is due to the doubling effect of an amplifier with no DC bias.

Although the results of the Terfenol-D driven pump show better output performance than the previously tested piezo-hydraulic pump (Sirohi and Chopra9-11), an accurate comparison could not be made due to the differences in size and input power of the driving elements. The present paper investigates the performance of three active materials as driving elements of a hydraulic hybrid actuator. A comparison will be made based on equal active lengths and actuator sizes, as well as equivalent input power for all three materials. High frequency tests will be systematically performed to evaluate material performance in heating, fluid flow rate, and output force. In order to drive the actuators at higher frequencies with minimum input power, two low inductance transducer coils have been designed and built specifically for Galfenol and Terfenol-D elements. Since Galfenol requires less magnetic field to achieve its maximum strain, a coil was designed to be driven at low current to avoid self-heating during high frequency tests. This may be an advantage for a Galfenol driven actuator, as self-heating is a major problem in piezostacks and in Terfenol-D when trying to achieve high output power. Terfenol-D and piezostacks have higher maximum strains than Galfenol, but the self-heating and hysteresis problems they exhibit prevent sustained actuation at high frequencies. By optimally designing the transducer and amplification system for each material, the power density and overall performance of each actuator can be accurately characterized and compared. Systematic tests across a large bandwidth of

actuation frequencies (100Hz -2000 Hz) will identify the advantages and disadvantages of the various driving elements in a hybrid actuator leading to an optimal design.

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5764-34, Session 7

Analysis and testing of a THUNDER piezoelectric actuator as an actuator in an air flow control valve

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This paper presents an air flow control valve harboring a THUNDER™ (Thin Unimorph DrivER) actuator. The THUNDER™ actuator adjusts the flow of air through a specified cross sectional area at various inlet pressures. The control valve is targeted for the use in throttling applications. The THUNDER™ actuator was introduced in 1996 by the Face® International Corporation as a high deflecting piezoelectric unimorph actuator. Today, in conjunction with its high deflection characteristic, the THUNDER™ is still more durable, flexible, efficient at low voltages and operable in harsh environments than any other unimorph actuator on the market. The THUNDER™ is positioned inside the machined Plexiglas assembly and monitored during the operation. The valve is based on the principle of a high displacement variation at the apex of the THUNDER™ caused by an applied voltage, which causes the ceramic layer to expand and contract thus changing the orifice area causing a change in flow. The flow is examined by creating a flow loop. Pressure transducers were placed along the experimental setup to observe various pressures conditions along the system. Respectively, a flow meter was inserted to measure the corresponding flow rate. The operating parameters for testing the control valve consisted of air inlet pressures up to 172.4 kPa (25 PSI) and volumetric flow rates up to 339.8 LPM (12.0 SCFM). The total modulation of flow was as high as 16% with a nominal flow of 127.4 LPM (4.5 SCFM).

5764-36, Session 7

Validation of computational models and experimental facility of a robot actuator using twin-ER clutches

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Flexibility and speed of response are two key requirements in the design of machinery for high-speed manufacturing operations. These two requirements are often conflicting and their resolution requires considerable ingenuity on the part of the designer. Several year's work at the University of Sheffield has been aimed at developing a novel actuator based upon the use of twin electro-rheological (ER) clutches. A notable application of this actuator has been to control the motion (angular displacement, angular velocity) of a robot manipulator arm, intended for use in a variety of manufacturing operations.

In the proposed contribution, the authors will describe the development of a new experimental facility involving the robot manipulator arm. This facility is attached to an existing twin ER clutch arrangement which has been described extensively in the technical literature. In the basic twin ER clutch facility, the motion of a toothed belt is controlled by manipulating the electric field applied to each ER clutch. The belt, in turn, controls the angular position and velocity of the robot arm. The use of twin clutches allows motion to be imparted in opposite directions without the need for return springs or similar mechanisms.

The new robot manipulator arm has been designed using CAD techniques to eradicate a number of minor (though potentially significant) problems which were identified in the original facility. In particular, care has been taken to minimise frictional effects and other nonlinearities, such as backlash in gears, which prevented the earlier design from operating in optimal fashion. The design of the new robot arm will be discussed in detail in the proposed paper and oral presentation.

In parallel with these practical developments, the mathematical model which accounts for the combined behaviour of the twin ER clutch / robot arm facility has been extensively refined. The mathematical model has been modified to provide a more accurate representation of the experimental facility. Moreover, the computer program which simulates the behaviour of the facility has been completely re-written in the spread-sheet based Visual Basic language. The authors' approach to programming will be described in the paper and emphasis will be placed on the ease with which graphical data can be generated.

The proposed paper presents validation of the refined mathematical model using experimental data from the new experimental facility. It will show how the facility responds to demands for motion control, supplied as input to the controller. The ability of the refined mathematical model to account for observed behaviour will also be demonstrated. Recommendations will be made for further work, both to develop the prototype facility and to extend the concept towards commercial exploitation.

5764-37, Session 7

Integrated modeling of the Utrasonic/Sonic Drill/Corer (USDC): procedure and analysis results

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Rock and soil penetration by coring, drilling or abrading is of great importance for a large number of space and earth applications. An Ultrasonic/Sonic Drill/Corer (USDC) has been developed as an adaptable tool to many of these applications [1]. The USDC uses a novel drive mechanism to transform the ultrasonic vibrations of the tip of a horn into a sonic hammering of a drill bit through an intermediate free-flying mass. As the pace of adapting the USDC to various applications increased, it was more crucial to develop a simulation to predict the performance of various designs. A series of computer programs that model the function and performance of the USDC was previously developed and tested against experimental data [2]. The combination of these programs into an integrated modeling package and the analysis of simulated results will be described in this paper.

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5764-38, Session 8

A comparison between several approaches of piezoelectric energy harvesting

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The proliferation of transducers and sensors integrated in any system, raises the problem of wires installation for power supplies and data transmission. This justifies the recent interest in miniature electrical generators, enabling to feed a wireless transducer and a small infrared or radio data transmitter. In this field, piezoelectric micro-generators are of major interest due to their solid state nature facilitating their integration.

In such a microgenerator, the ambient mechanical energy is converted into electrical energy using a piezoelectric element embedded in the mechanical structure or bonded on it. Previous works have shown that the conversion efficiency is depending on the load behaviour.

The need of a DC output voltage requires the use of a rectifier and a smoothing capacitor. The electrical network connected to the piezoelectric element has thus a natural nonlinear behaviour and the power optimization may be based on average matching impedance. Recent works have shown that a particular additional non linear process on the piezoelectric voltage such as the one referred as the Synchronized Switch Harvesting technique induces an increase of the power transfer that can reach 900%.

This paper presents four innovative energy harvesting techniques and their associated processing circuit. They are compared to the so called “standard technique” which basically consists in feeding an electronic circuit which is connected to the piezoelectric element through a rectifier followed by a smoothing capacitor..

Theoretical predictions and simulations are compared with experimental results. Interests and drawbacks of each method are discussed with regards to the mechanical host structure, power requirements of the supplied electronic circuit and piezoelectric tranducer performance.

5764-39, Session 8

A universal semi-passive technique for smart applications: vibration damping, acoustic-wave control, and energy harvesting

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Because of their high electromechanical properties and their integration simplicity, piezoelectric materials are well suitable to develop smart structures. Vibration damping, energy harvesting, health monitoring, or anechoic systems are ones of the numerous applications of these piezoelectric smart devices.

The semi passive technique for which the various applications are reviewed here is based on a non linear processing of the piezoelement voltage. This technique leads to an improvement of the piezoelement energy conversion (enlargement of the energy conversion cycle) for a given mechanical excitation. This extracted energy can be either dissipated (Synchronized Switch Damping) or stored and furtherly used (Synchronized Switch Harversting).

The piezoelements are controlled with a simple drive circuit based on electronic switches driven periodically and synchronously with the structure motion. The overall control circuit requires a very few amount of energy. This broadband and auto-adaptative technique is easy to implement and can be self powered in many cases. Unlike the standard passive piezoelectric approaches in the case of damping, this new technique which can be assimilable to a dry friction mechanism performs well in low frequency without technology burdens, is insensitive to environmental drifts (pressure, temperature...) and allows multimodal control.

This paper shows the universal character of this Synchronized Switch technique through an energetical analysis. An analytical approach interpretate and quantify the optimalization of the extracted energy by the piezoelements associated with the switch technique and shows that its performance is strongly related to the electromechanical coupling factor. In the case of weakly coupled structure, an alternative consisting in artificially increasing the piezoelement voltage compensates this drawback. In an other hand increasing the piezoelement energy conversion can be seen as artificielly increase the coupling coeficient, which is interresting for weakly coupled electromechanical systems.

The application fields covered by the technique and that are considered in this review are: vibration damping of plates and beams, acoustic transmission coefficient control, acoustic reflection coefficient control and energy harvesting.

5764-40, Session 8

Modeling of piezoelectric power generator with adaptive energy harvesting circuit

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The need to power remote systems or embedded structures independently has motivated many research efforts harvesting electric energy from various ambient sources. Among them piezoelectric vibration-to-electricity converters have received much attention as they have high electric-mechanical coupling effect and are particularly attractive for use in MEMS. In this paper we will discuss the modeling, design and optimization of piezoelectric generators with adaptive energy harvesting circuit. We have used a bimorph piezoelectric cantilever beam connected to an ac-dc bridge rectifying circuit plus a resistor as the basis for design tools. An analytic solution for such a model system is derived under the steady-state operation. With it we can determine the maximum power transferred from a vibrating piezoelectric generator to a battery load under the constraint of vibration amplitude limited by its operation environment. Besides that, the analytic model has also provided the design guidelines for determining the level of vibration necessary to power the electronic device and the optimal duty cycle at the maximum power flow. Finally we have performed a series of experiment to validate the current model and discussed the effect of the size of adaptive circuit dominated by wound inductors on the design of MEMS-based piezoelectric micro power generators.

5764-41, Session 9

Dynamic shape control of sandwich beams with chiral prismatic core

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Recently, periodic cellular configurations with negative Poisson’s ratio have attracted the attention of several researchers because of their superior dynamic characteristics. Among the geometry featuring a negative Poisson’s ratio, the chiral topology possesses a geometric complexity that guarantees unique deformed configurations when excited at one of its natural frequencies. Specifically, localized deformations or “kinks” have been observed even at relatively low excitation frequencies. This is of particular importance as resonance can be exploited to minimize the power required for the appearance of localized deformations, thus giving practicality to the concept. The particular nature of these deformed configurations and the authority provided by the chiral geometry, suggests the application of the proposed structural configuration for the design of innovative lifting bodies, such as helicopter rotor blades or airplane wings. For example, the localized deformations could be employed as vortex generators to increase lift, or to delay the dynamic stall.

The capabilities and dynamic characteristics of the considered structure are here investigated through a numerical model. The formulation uses dynamic shape functions to accurately describe the behavior of the considered structural assembly over a wide frequency range. The model, which can be denoted as “spectral”, considers the simultaneous presence of long and short beam members, as well as of curved elements, which characterize the chiral geometry. Active control strategies are implemented and used to predict frequency response functions, as well as operational deflection shapes, to investigate the occurrence of localized deformations and their influence on the dynamic behavior of the structure.

5764-42, Session 9

Diagnosis and control of 3D elastic mechanical structures

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In this paper, a model-based approach for fault detection and vibration control of flexible structures is proposed and applied to 3D-structures. Faults like cracks or impacts acting on a flexible structure are considered as unknown inputs acting on the structure. The Proportional-Integral-Observer (PI-Observer) is used to estimate the system states as well as unknown inputs acting on the system. Also the effects of structural changes are understood as external effects (related to the unchanged structure) and are considered as fictitious external forces or moments.

In contrast to other approaches, the PI-Observer does not need a model of the effects itself. The paper discusses the design of the PI-Observer for practical applications when measurement noise and model uncertainties are present and shows its performance in experimental results. As examples, impacts acting on a one side fixed elastic beam and on a thin plate structure are estimated using displacement or strain measurements. To detect the impact forces, models of the

beam and the plate structures are necessary. The plate and the beam are modeled using the finite element method. The paper shows that the estimation can be done using optical displacement sensors or also strain gage measurements, which are used for the PI-Observer for the first time in this paper. Results from previous works with the PI-Observer (applied to 1D-structures) are extended to 3D-structures in this contribution.

To control the vibration of the flexible plate, piezoelectric patches are used as actuators which are bonded on the structure. The design of such smart structures contains the passive structure, the actuators and sensors as well as the control algorithm. The control algorithm introduced in this contribution contains a state feedback control and additionally a disturbance

rejection. The disturbances could for example be an unknown external force acting on the system or virtual forces which results from model uncertainties or structural changes caused by damages. This disturbances can be estimated using the PI-Observer. A disturbance rejection control algorithm is applied to compensate the disturbances estimated by the observer. In contrast to other approaches, the proposed approach uses only 1-2 patches to control dynamically large structures for a wide frequency range resp. several modes. Experimental results show the performance and the robustness properties of the control strategy for the vibration control of a thin plate.

5764-43, Session 9

Mulitmodal active vibration suppression of a flexible structure by loop shaping

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This paper reports multimodal vibration control of a flexible beam structure with piezoceramic actuators and sensors using the loop shaping method. These piezoceramic patch actuators and sensors are surface-bonded on the flexible beam. The non-parametric identification of the flexible beam structure is carried out using the Schroeder wave. The identified open loop model is then used for loop shaping using the extended sensitivity charts. A loop shaping compensator is designed to achieve multimodal vibration suppression. Numerical simulation results showed a reduction of 10 decibels for first mode, 6 decibels for second and third mode, respectively. Experimental results closely match the simulation results. Furthermore, the results of loop shaping method are compared with those of the methods of LQR (Linear Quadratic Regulator) and pole-placement control, which are designed using state space models. Comparisons clear show that the loop shaping method requires much less control effort while maintaining the effectiveness in vibration suppression.

5764-44, Session 9

Fuzzy control of a HMMWV suspension system using magnetorheological fluid damper

Y. Liu, F. Gordaninejad, C. A. Evrensel, S. Karakas, U. Dogruer, Univ. of Nevada/Reno

In this paper, a fuzzy control is proposed for vibration suppression of a High Mobility Multi-purpose Wheeled Vehicle (HMMWV). This method generates the control action from a set of rules representing the heuristic knowledge about the system to be controlled. In order to compare their performances, both fuzzy control and a common skyhook control are applied to a quarter car model of a HMMWV with a controllable magneto-rheological fluid (MRF) damper. The displacement and acceleration transmissibility of base sinusoid excitation to sprung mass are explored. The displacement and acceleration of the sprung mass under off-road excitation are analyzed.

5764-45, Session 9

Vibration suppression of HDD spindle-disk system using piezoelectric shunt damping

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This work presents the feasiblity of the piezoelectric shunt damping for vibration suppression of a rotating HDD disk-spindle system. A target vibration mode which significantly restricts the recording density increment of the drive is determined through modal analysis and a piezoelectric annular bimorph is designed to suppress unwanted vibration caused from the target mode. The shunt circuit is constructed by considering two-dimensional electromechanical coupling coefficient of the spindle-disk system. In addition, optimal design process using sensitivity analysis is undertaken in order to maximize the shunt damping of the system. The effectiveness of the proposed methodology is verified through both computer simulation and experimental implementation by observing the displacement transmissibility of the system in frequency domain.

5764-46, Session 10

Piezoelectric-based vibration control optimization in nonlinear composite structures

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Recently, the use of smart materials-related technology for vibration control has become an alternative to traditional vibration control techniques. Vibration control of polymer-based composite materials can be can be engineered by altering the stiffness and mass distribution of the component. Unfortunately, for certain frequency sets, it is not possible to tweak the material properties to obtain the desired dynamic response. It is precisely during the excitation of such frequencies that the response of piezoelectric-based controllers can be used to obtain the desired vibration response of the structure.

Passive vibration shunt control using piezoelectric ceramic (PZT) materials and an electrical network has been studied by many researchers both analytically and experimentally. In this paper, the modeling and simulation of passive vibration shunt control of a complex non-linear structure using a proprietary finite element analysis software package is presented. It is a useful alternative to optimizing the positioning and orientation of the Piezoelectric material before physical experimental trials. The simulation shows that a considerable amount of vibration energy can be removed when the electrical shunt circuit is properly tuned. Results indicate a good match with those experimental results reported early in the literature. Through the simulation, it reveals that the material property of the structure has a significant impact on the effectiveness of the vibration attenuation using such a shunt circuit. This is because of the mechanical impedance match between the structure and PZT transducer. Experimental and analytical corroboration of the vibration control response will be made with the computational results. Particular interest will be shown to the vibration response control efficiency in non-linear structures compared with that of linear elastic structures. Another parameter that will be looked at is the relative effect of inherent damping and the impact of this characteristic on the passive vibration shunt control protocols of a complex non-linear structure.

In summary, this study has demonstrated a method for modeling piezoelectric vibration control systems using proprietary software. With such a method, the designer has more potential to design an optimal control system. The initial results were shown to be comparable to those reported in the literature. This study demonstrates that the analytical techniques developed are ideal tools with which to explore more effective and sophisticated solutions to the attenuation of structural vibration in both non-linear-anisotropic and isotropic-linear elastic materials.

5764-47, Session 10

Active vibration suppression of a satellite frame using an adaptive composite thruster platform

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Adaptive or intelligent structures which have the capability for sensing and responding to their environment promise a novel approach to satisfying the stringent performance requirements of future space missions. This research focuses on the finite element analysis active vibration suppression of an intelligent composite platform that is designed for thrust vector control of a satellite thruster and has simultaneous precision positioning and vibration suppression capabilities. This smart platform connects the thruster and the structure of the satellite and has three struts and one central support with one piezoelectric stack in each. A finite element harmonic analysis was employed to develop a vibration suppression scheme, which was then used to study the vibration control of the satellite structure using the vibration suppression capabilities of the intelligent platform mounted on the satellite. The applicability of the model is first demonstrated on a single strut using a one-dimensional approach. This approach is then extended to the full intelligent composite platform employing a three-dimensional approach. In this approach, the responses of the structure to a unit external force as well as unit internal piezoelectric control voltages are first determined, individually. The responses are then assembled in a system of equation as a coupled system and then solved simultaneously to determine the control voltages and their respective phases for the system actuators for a given external disturbance. This approach is an effective technique for the design of smart structures with complex geometry to study their active vibration suppression capabilities and effectiveness.

Conference 5764: Smart Structures and Integrated Systems

5764-48, Session 10

The Fraunhofer MAVO FASPAS for smart system design for automotive and machine tool engineering

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The Fraunhofer Gesellschaft is the largest organization for applied research in Europe, having a staff of some 12,700, predominantly qualified scientists and engineers, with an annual research budget of over one billion euros. One of its current internal Market-oriented strategic preliminary research (MaVo) projects is FASPAS (Function Consolidated Adaptive Structures Combining Piezo and Software Technologies for Autonomous Systems) which aims to promote adaptive structure technology for commercial exploitation within the current main research fields of the participating FhIs, namely automotive and machine tools engineering. Under the project management of the Fraunhofer-Institute Structural Durability and System Reliability LBF the six Fraunhofer Institutes LBF, IWU, IKTS, ISC, AiS and IIS bring together their competences ranging from material sciences to system reliability, in order to clarify unanswered questions. The predominant goal is to develop and validate methods and tools to establish a closed, modular development chain for the design and realization of such active structures which shall be useful in its width and depth, i.e. for specific R&D achievements such as the actuator development (depth) as well as the complete system design and realization (width).

FASPAS focuses on the development of systems and on the following scientific topics: 1.) on design and manufacturing technology for piezo components as integrable actuator/sensor semi-finished modules, 2.) on development and transducer module integration of miniaturized electronics for charge generating sensor systems, 3.) on the development of methods to analyze system reliability of active structures, 4.) on the development of autonomous software structures for flexible, low cost electronics hardware for bulk production and 5.) on the construction and validation of the complete, cost-effective development chain of function consolidated structures through application oriented demonstration structures. The research work will be oriented towards active vibration control for existing components on the basis of highly integrated, both, more or less established and highly innovative piezoelectric actuator and sensor systems in compact, cost-effective and robust design combined with advanced controllers.

Within the presentation the project work will be shown using the example of one demonstration structure which is a robust interface, here for being integrated within an automotive spring strut system. The interface is designed as a modular, scalable subsystem. Being such, it can be used for similar scenarios in different technology areas e.g. for active mounting of vibration-inducing aggregates. The interface design allows for controlling uniaxial vibrations (z-direction) as well as tilting (normal to the uniaxial effect) and wobbling (rotating around the z-axis).

5764-49, Session 10

Design of smart actuator based on magnetorheological elastomer sandwich beam

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The PZT bender actuator with adjustable load curve is presented theoretically in this work. The actuator is composed of a simply supported sandwich beam with magnetorhelogical elastomer (MRE) core and PZT patches are attached on the skins of the sandwich beam. The output port is at the center of the sandwich beam. MRE is a kind of smart material due to its field-dependant dynamic shear modulus. MRE is stable since it is solid and its chain-like structure is formed during curing process. Owing to such field-dependant shear modulus of MRE, the dynamic flexure rigidity of the sandwich beam with MRE core is changed with the applied magnetic field. Such field-adjustable flexure rigidity of the sandwich beam make the load curve of the proposed actuator be controllable. With high-order model of the MRE based sandwich beam, the load curves at different magnetic fields are presented. By attaching a pure mass at the output port, the resonant frequency of the actuator-mass system is also found to be changed with the applied magnetic field. The above field-dependant characteristics reveal such actuator takes the capability to be adaptable with the applied mechanical load to yield optimal driving ability and, at the same time, the applied mechanical load can be sensed from the applied magnetic field. In summation, this work provides the alternative to develop adaptable multifunctional PZT actuator through introducing MRE-based sandwich structure.

5764-50, Session 10

An MRF-based device able to control the torque stiffness of all movable vertical tails

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The efficiency of aerodynamic control surfaces like ailerons, flaps, movable tails, is among the major parameters defining the performance of generic aircraft and is strongly affected by geometric and stiffness characteristics. Adaptive variations of some of them may guarantee optimal performance for different flight conditions, especially for vehicles spanning their duties between subsonic and supersonic domains. According to this, one of the goals of the '3AS' European Project, sponsored by the EU, is to estimate the eventual benefits coming from the adaptive control of the torque rigidity of the EuRAM wind tunnel model all-movable vertical tail. The specific role of CIRA inside the Project is the design of a device based on the "Smart Structure and Material" concept, able to produce the required stiffness variations.

Numerical and experimental investigations pointed out that an excursion of the tail torque rigidity up to 20 times its lowest value, may assure higher efficiency, both in subsonic and supersonic flight. The wide excursion may be obtained by means of classical mechanic-hydraulic or smart systems. In this case, the attainable weight and reliability level may be the significant parameters to drive the choice. For this reason, CIRA focused its efforts also on the design of devices without heavy mechanical parts.

The device described in this work is schematically constituted by linear springs linked together in a serial way to the tail shaft. According to the global rigidity law, stiffness variations are achieved by locking one or more springs, in any possible combination. The MRF properties are taken advantage of, to produce the selective lock of the springs, by means of a suitable hydraulic system.

A genetic optimisation process was carried out, aimed at finding the spring constants maximising the stiffness range. After having defined the springs features, the hydraulic circuit was dealt with. Two solutions were compared, different for the MRF valve architecture: in the first one, the valve is external while the in the second one it is integrated into the piston base. This second solution appeared to be more convenient because of the limited over-all dimensions and the lower friction.

Based on numerical predictions, prototypes for both the architectures were manufactured. Experimental tests were performed to estimate both the static and dynamic behaviour of the devices.

5764-51, Session 11

The effect of mechanical training on the properties of superelastic shape-memory alloys for seismic applications

J. P. McCormick, L. Barbero, R. DesRoches, Georgia Institute of Technology

The objective of this study is to evaluate the effect that mechanical training has on the properties of NiTi based shape memory alloys. The unique mechanical behavior of shape memory alloys which allows the material to undergo large deformation while returning to its original undeformed shape through either the shape memory effect or the superelastic effect has shown potential for use in seismic design and retrofit applications for civil engineering structures. In particular, superelastic shape memory alloys provide several characteristics which are desirable for passive energy dissipation devices for structures including: (1) hysteretic damping, (2) recentering capability (i.e. the ability of the material to return to its undeformed configuration upon unloading), (3) excellent low- and high-cycle fatigue, (4) strain hardening at large strain levels, and (5) the formation of stress plateaus to limit undesired force transmission to other parts of the structure. Although several studies have shown the ability of superelastic (austenitic) shape memory alloys to provide adequate energy dissipation of approximately 5-10% equivalent viscous damping and recentering capability up to strain levels of 6-8%, it has also been shown that cyclical loading and loading rates typical of a seismic event result in a degradation of the energy dissipation capacity of the material due to a pinching of the hysteresis and an increase in the residual strain resulting in decreased recentering capability[1,2].

Several studies have shown the effectiveness of shape memory alloys in seismic applications in both building and bridge structures through analytical and experimental testing. Dolce et al.[3] has experimentally shown the effectiveness of superelastic shape memory alloys to provide a strong recentering capability when applied to a two-story single-bay reinforced concrete frame. While analytical studies by Baratta and Corbi[4] found that shape memory alloys improved the dynamic response capacity of a structure compared to the use of typical elastic-plastic tendons in a cross-bracing system. Other research has shown that SMA dampers can be implemented in bridge systems to reduce

bridge deck displacements[5]. Although these studies have shown the feasibility of implementing shape memory alloys in structural systems, the degradation of the shape memory alloys needs to be addressed. To be able to effectively implement shape memory alloys into actual applications for seismic resistant design and retrofit of civil engineering structures, stable properties are required in order to provide a more predictable response of the structure during a seismic event.

In order to stabilize the mechanical behavior of shape memory alloys under cyclic loadings, Miyazaki et al.[6] has recommended "training" or preloading superelastic shape memory alloys in order to limit fatigue effects and degradation of their properties. The problem lies in the fact that few studies have looked into the optimal strain level, cycle number, prestressing levels, and loading rate at which to mechanically train shape memory alloys in order to obtain optimal performance of the material for seismic applications. In order to address this gap in knowledge, this study uses design of experiment techniques in order to develop an exploratory study on the effectiveness of training shape memory alloys at various strain levels, strain rates, and cycle numbers. A two level factorial design is implemented in order to determine the active effects so that an optimal training regime for seismic application of shape memory alloys can be developed. Factor levels of 20 cycles and 60 cycles, 3% strain and 6% strain, and quasi-static and 0.5 Hz are chosen for the lower and upper levels of the factors (cycle numbers, strain level, and loading rate, respectively) for the two fold factorial design.

The study focuses on 0.85" diameter superelastic NiTi shape memory alloy wires. After training, the wire specimens undergo cyclic tensile loadings typical of a far field type ground motion at a loading rate of 0.5 Hz. The cyclic effects on the loading plateau stress (forward transformation stress), energy dissipation, and residual strain are then evaluated to determine an optimal training regime for the use of NiTi shape memory alloys for seismic applications with the degradation of the recentering capacity (residual strain) being the most important factor to reduce. Further training tests are conducted on 0.85" diameter superelastic NiTiCr shape memory alloy wires to determine how composition may affect the ability to train shape memory alloys to provide stable mechanical behavior.

The ability to obtain stable properties of shape memory alloys under a specified training schedule further supports the eventual implementation of the material into actual building and bridge systems as seismic design and retrofit devices. The capacity of shape memory alloys to predictably provide both energy dissipation and recentering capabilities fits the general trend of seismic design research in the field of civil engineering which over the past decade has focused more towards performance based design. Thus, this study provides further support for innovative uses of smart materials in the field of civil engineering.

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5764-52, Session 11

Design of composite structures with high-energy absorption

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Keywords: SMA, Porous SMA, Energy absorbing materials, Composites, NiTi

We propose a composite structure made of porous NiTi solid cylinder surrounded with a NiTi helical spring. Both NiTi are of superelastic (SE) grade. This composite is designed to exhibit high energy absorption during compression loading. Porous NiTi rod is found to exhibit a large energy absorption capacity (Zhao et al, 2004). Our design concept is to increase the energy absorption capacity while reducing the total weight of the structural composite. This constraint can reinforce the porous NiTi cylinder, therefore, increases the ultimate force that the porous NiTi cylinder can support effectively. Both spring and cylinder help each other in preventing them from buckling if they would behave independently. The experimental data show that the energy which the composite structure absorbs is almost as twice as the single porous NiTi cylinder does. An analytical model is proposed to predict the force-displacement curve of the composite structure. The force-displacement relation of the composite structure is expected to show three stages: (i) Initial deformation of the spring until the height of the spring becomes equal to that of the porous NiTi cylinder. (ii) Both spring and porous NiTi cylinder deform to certain level at which the buckling cylinder touches the spring. (iii) Both spring and cylinder continue to deform with mechanical constraint of the spring kept in touch with the cylinder. The prediction by the analytical model agree reasonably well.

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5764-53, Session 11

Effect of ambient temperature on the performance of shape-memory alloy seismic devices

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Shape memory alloys (SMAs) are a class of metallic alloys that exhibit unique characteristics such as shape memory effects (SME) and superelasticity effects (SE). SMAs are found in two main phases: the high temperature phase, which is called austenite (superelastic), and the low temperature phase, which is called martensite. The unique thermomechanical charatcteristics of SMAs has motivated the evaluation of the feasibility of utilizing SMAs in various engineering and biomedical applications. Civil engineering is considered to be a relatively new field for SMAs applications. Most of the applications of SMAs in civil engineering have targeted historical and cultural heritage buildings. One of the well known examples of using SMAs in buildings is the rehabilitation of the St. Francis Basilica at Assisi, Italy where SMA units made of austenite Nitinol were used to strengthen the roof of the Basilica against future earthquakes. Although there are few civil engineering applications using SMAs, there have been considerably large numbers of research studies focusing on exploiting SMAs in seismic devices for buildings and bridges.

Researchers in the field of earthquake engineering are directing more of their attention towards getting a better understanding of the mechanical properties of SMAs in its austenite and martensite phases. Since most of the civil engineering applications are exposed to various environmental and weather conditions, the effect of temperature variation on the efficacy of SMA devices that are used in civil engineering is a major concern. The phase transformation in SMAs from the austenitic phase to the martensitic phase and vise versa depends on the transformation temperatures As, Af, Ms, and Mf. The hysteretic characteristics of the material are defined based on the ambient temperature. When the temperature is below Mf, a shape memory effect is expected since the material consists of martensite in the free-stress condition. Once the temperature is raised above Mf but still below Af, both austenite and martensite will develop in the material. This mix will lead to a hysteretic behavior with a certain amount of residual strain. The amount of residual strain will mainly depend on the temperature, which will determine the percentage of austenite in the material. Again by raising the temperature above Af, a fully austenitic material will be developed leading to a superelasticity behavior. Higher temperature will lead to a higher hysteretic loop with a smaller enclosed area. Once the temperature is raised above the Curie point, hysteretic loop is no longer observed and the material acts as a linear elastic material

This paper presents an analytical investigation of the effect of ambient temperature on the performance of SMA seismic retrofit devices in civil engineering applications. A thermomechanical constitutive model is developed to describe the constitutive behavior of SMAs at various levels of ambient temperatures. The ambient temperature is varied from a minimum temperature that is below As to a maximum temperature that exceeds Af. At all levels of temperature between As and Af the model is able to capture the forward and reverse phase transformations in the alloy. The thermomechanical SMA model is implemented as a seismic device in a SDOF structure that is subjected to a suite of ground motion records. The lateral drift response of the structure is evaluated before and after the seismic retrofit of the structure. A parametric study is conducted to study the effect that structural properties, SMA transformation temperatures, and ambient temperature have on the response of the structure. The study is further extended by implementing the thermomechanical SMA model in a 2-DOF bridge model. In this study SMAs are used as seismic restrainers for bridges that are used to control the relative movement between the two bridge frames and thus limit the intermediate hinge displacement. The

bridge is subjected to a suite of 15 ground motion records at different levels of transformation temperatures and ambient temperature. The results of the study showed that SMAs are more effective when used in its austenitic phase and thus when the temperature decreases below Af SMA devices lose a major part of their efficiency. On the other hand, the study showed that when the ambient temperature reaches a certain value above Af the response of the structure is stable and unaffected by additional increase in the temperature.

5764-54, Session 11

Finite element analysis of adaptive inflatable structures with SMA strip actuator

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Inflatable space-based devices have become popular over the past three decades due to their minimal launch-mass and launch-volume. One of the most important technologies for the utilization of inflatable structures is maintaining the surface profile during the mission's life. Therefore, many studies to maintain the desired surface accuracy have been performed by integrating actuators and sensors onto the surface, as well as into the support structure of the inflatable system. Smart actuators that can be embedded on thin membrane structures are being developed to demonstrate active damping and shape control for inflatable structures.

In this paper, the thermomechanical responses of inflatable structures coupled with shape memory alloy (SMA) strip are investigated using finite element simulation. The numerical algorithm of the 3-D SMA thermomechanical constitutive equations based on Lagoudas model is implemented to analyze the unique characteristics of SMA strip such as the pseudoelastic behavior and shape memory effect. The incremental SMA constitutive equations are implemented in the user supplied subroutine UMAT by using ABAQUS finite element program.

Thermal activation causes the shape change of inflatable column structures by initially strained SMA strip bonded on the surface of structure. The inflatable columns are observed to behave like beams and their natural frequencies change according to both the film thickness and pressure inside the structure. The mode shape variations of inflatable column depending on internal pressure are investigated. In breathing mode, the inflatable column structure is unstable with bending load and it is very undesired on operating condition. Numerical results show that SMA strip actuator can generate enough recovery force to change the shape of the inflatable structure. However, depending on both the film thickness and pressure inside the structure, SMA strip can deform the inflatable structure to a desired shape or not. Therefore, the interactions between the SMA strip and the inflatable structure should be investiagted with various film thicknesses and internal pressures for the development of an active shape control system.

In this paper, we present several numerical examples of the thermomechanical responses of inflatable structures with SMA strip actuators. It is found that small SMA strip actuators can effectively adjust the overall shape of the inflatable column structure with the proper film thickness and internal pressure.

5764-55, Session 11

Experimental and numerical characterization of multi-actuator piezoelectric device designs using topology optimization

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Multi-actuators piezoelectric devices consist of a multi-flexible structure actuated by two or more piezoceramic portions, whose differing output displacements and forces are tailored according to the excitation properties of the piezoceramic materials and the desired working locations and directions of movement. Such devices have a wide range of application in performing biological cell manipulation, for microsurgery, and in nanotechnology equipment, and the like. However, the design of multi-flexible structures is a highly complex task since the devices have many degrees of freedom and, employ a variety of piezoceramics, but must carefully tune the movement coupling among the device parts to prevent motion in undesirable directions. In prior research, topology optimization techniques have been applied to the design of devices having minimum movement coupling among the piezoceramic parts, and a number of these devices were manufactured and experimentally analyzed to validate the results of the topology optimization. X-Y positioners consisting of two piezoceramic portions were addressed and designs considering low and high degrees of coupling between desired and undesirable displacements were investigated to evaluate the performance of the design method. Prototypes were manufactured in aluminum using a wire EDM process, and bonded to piezoceramics (PZT5A) polarized in the thickness direction and working in d31 mode. Finite element simulations were carried out using the commercial ANSYS software application. Experimental analyses were conducted using laser interferometry to measure displacement, and load cells to measure force, while considering static excitation. The displacement response was obtained over a range from 0 to 10 volts. The coupling between the X-Y movements was measured and compared with FEM results, which showed that the coupling requirements were adequately achieved.

5764-56, Session 11

Three-dimensional electromagnetic finite element models of actuator driven by a magnetostrictive iron-gallium rod

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This paper addresses the 3D Finite Element Modeling (FEM) of the magnetic circuit of an actuator driven by magnetostrictive 18.5% single crystal Iron-Gallium rod. This is considered in the context of control applications that require accurate characterization of the relation between input currents and magnetic induction of the magnetostrictive rod and ultimately for prediction of the actuator output displacement. The characterization considered here is based on 3D time-harmonic quasi-static electromagnetic FEM giving a solution to the Maxwell's equation for specific set of boundary conditions. The solution is computed using the FEM software FEMLAB 3.0 developed by Comsol ©. The model includes a 1/4-inch diameter, 2-inch long, magnetostrictive rod surrounded by a driving coil. The steel cap and piston are located on opposite ends of the device and are connected by steel housing shaped as a hollow cylinder surrounding the driving coil.

One of the major interests in employing a 3D model is to understand the effect of asymmetric slits in the housing components for minimizing of eddy current losses. The model shows that for an input current of 3A at 2000 Hz, an 11% increase in magnetic induction could be obtain by slitting the steel housing along it's full length. Slitting the along half of the length result in a 5% increase. Models with laminated rod are currently being computed.

A full 3D magnetomechanical model outputting magnetostrictive rod displacement and accounting for the nonlinearity of the magnetostrictive alloy properties due to its mechanical and magnetic state is under construction. The major challenge of this task is to solve both the mechanical and electromagnetic model simultaneously since these models are coupled.

5764-57, Session 12

Early detection of local buckling in structural members

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Most structural health monitoring analyses to date have been concentrated on the damages in metallic as well as composite materials in form of crack, crack growth and delamination or other types of damage. However, in many applications, local instability in the form of buckling is considered to be an important mode of failure which has been received little attention .Unlike other types of failures, if buckling could be detected in the very early stages, the structure can be stabilized or saved through simple control methods. It is possible to recover the structure by reducing the load on the structure. In the case of the wind turbine blades, furling of the wind turbine blade (rotating the turbine blade's flat face out of the wind direction) could easily accomplish this.

Relatively few investigations have addressed this type of damage initiation in structures. Two different techniques were used to detect the precursors to buckling in this column. The first identifier is the change in the vibration mode shapes and natural frequencies of the column. The second is the change in the characteristics of diagnostic Lamb waves during the buckling deformation. Experiments indicate that very small changes in curvature during the initial stages of buckling are detectable using the structural health monitoring techniques. The experimental vibration characteristics of the column with slight initial curvatures compared qualitatively with finite element results. The finite element analysis is used to identify the frequencies that are most sensitive to buckling deformation, and to select suitable locations for the placement of sensors to detect the onset of local buckling. A laser vibrometer will be used for more investigations.

Introduction

Advances in sensor and instrumentation systems, signal processing techniques, computational methodologies, structural health monitoring is poised to make significant contributions to assure the safety and reliability of infrastructure systems, such as buildings, bridges, wind turbines, aircraft, ships and spacecraft. Through the use of a variety of sensor systems the response of the

structure to conditions such as vibration, acoustic emission, thermal emissions, strain, chemical changes, and electrical conductivity can be measured and from these responses it is possible to arrive at the state of health of the structure. The issues related to structural damage detection have been widely investigated in recent years because of the large impact that safety and reliability have on the economy.

Recently, during the structural health monitoring of a wind turbine blade using stress wave propagation, local buckling was identified as the cause of premature failure. A stress wave propagation technique was used in this test to detect the precursor to the buckling failure in the form of early changes in the local curvature of the blade. These conditions have also been replicated in the laboratory. A composite column was subjected to axial compression to induce various levels of buckling deformation as illustrated in Figure 1.

A COMPOSITE COLUMN SUBJECTED TO BUCKLING

A composite bar 37.25 inches long , 4 inches wide and 0.125 inch thick is instrumented with two PZT patches as shown in Figure 1 for exciting different modes or patterns of vibration. Accelerometers at several locations were used for determining the natural frequencies and vibration patterns as the column is forced to go through different levels of buckling. This specimen is first supported in the straight unbuckled condition. The ends were clamped using 0.25x2.5x6 inch plates. The left end of the bar was kept stationary while the right end of the plate was translated to introduce the desired level of buckling. The central buckling displacement was measured using a caliper. The PZT patches or the accelerometers were used to monitor resonant frequencies and the vibration pattern of the bar in various levels of buckling. The first set of experiments simply used a 5 cycle gated sine pulse at 72 Hz to excite one of the natural frequencies of the unbuckled bar. As the bar starts buckling, this resonant frequency progressively shifts away from the exciting frequency of 72 Hz, and the amplitude of oscillations progressively decrease indicating the onset of buckling. The behavior was repeatable and even in the early stages of buckling with a displacement of 0.2" at the center of the bar the change in vibration is clearly detectable as seen in Figure 2.

FINITE ELEMENT ANALYSIS OF THE VIBRATION OF BUCKLED BAR

A finite element analysis of the bar both in the straight configuration as well as in various levels of buckling was carried out. A four node brick element with six degrees of freedom at each node was used in this analysis. Approximately 12,000 elements were used in these models. The woven fabric glass/epoxy laminate was modeled as an orthotropic material. A comparison of the natural frequencies for the unbuckled bar obtained through beam theory, finite element analysis, and experimental measurement as well as the mode shapes showed good correlation.

However, the vibration patterns obtained for the buckled configuration with central displacements of 0.4 inch and 0.6 inch showed noticeable changes in the frequencies. In particular, the first, the second and the third modes have significant change in the frequencies as well as the vibration pattern.

EXPERIMENTAL RESULTS

The oscillations at the resonant frequencies were excited using one of the two PZT patches. Only the left half of the bar was instrumented with accelerometers. A total of eight accelerometer readings were used in constructing the pattern of oscillation for the bar. The natural frequencies obtained from finite element analysis agreed well with the experimental and analytical results.

The mode shapes obtained from the finite element analysis qualitatively agree with those obtained experimentally. Experimental results also indicate that the first resonant frequency, the second and the third and their corresponding mode shape are the most sensitive indicators of the impending buckling instability.

The onset of buckling instability using vibration characteristics is proposed. The early detection of buckling instability is of practical interest and can lead to improvement in safety and reliability of engineering structures.

5764-58, Session 12

A benchmark problem for structural health monitoring based on a real bridge structure

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Shandong Binzhou Yellow River Highway Bridge of No. 205 China National Highway is the forth cable-stayed bridges in China and the first spans the Yellow River. The main bridge is cable-stayed by three towers, with 768 meter length, 30.7 meter width. It was open to traffic in July 18 2004. This bridge is the important component part of No. 205 China National Highway in Shandong Province. For comprehending the work state during active time and ensuring the security, integrality, applicability and durability of the bridge, a set of Structural Health Monitoring System was set in this bridge. In this SHMS, more than 150 sensors belong to four types and other data acquisition devices were located in the cables, towers, decks and the control room. The corresponding software system based on the web was running real-time simultaneously.

However, acquisition of sensor information is not a crucial issue currently. But many SHMS studies apply different methods to different structures, often making comparison of kinds of methods difficult. So the benchmark study, where participants apply a number of monitoring techniques to a common structure with common objectives, provides a platform to facilitate the comparison of kinds of modal identification methods, damage identification methods and structural safety evaluation methods. Since the SHMS of Binzhou Yellow River Highway Bridge is running real-time based on the web and the sensors data and the damage identify results can be issued real-time by the internet, a benchmark model was developed by the research group based on the real bridge structure simultaneously. In this benchmark problem, a common analytical Ansys finite-element model based on the real bridge structure was given to facilitate the structural analysis firstly, and for help building other finite-element model, the main AutoCAD drawings were released too. The types, number and locations of all sensors were stored in detail in Structure Information Database that may be visited by Internet. Data of all sensors were stored in system database in the same way and can be obtained free by Internet.

For implementing common structural analysis, the three standard excitation cases were provided, including ambient vibration, static load and dynamic load, which were applied during the whole bridge test. The corresponding structural response data were given. Then, the classic modal identification methods, damage identification methods and structural safety evaluation methods were applied by the research group firstly, and the results are listed in detail. At last, the use methods, for example the issue of user's analysis results, were introduced in detail on the webpage. The complete benchmark system is available on the website of SHMS for Binzhou Yellow River Highway Bridge.

5764-59, Session 12

Development of specifications for an integrated piezoelectric wafer active sensors system

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This paper describes work performed in the development of a set of specification for the construction of an integrated electronic system for piezoelectric wafer active sensor (PWAS). The paper starts with a comprehensive review of the PWAS material properties, dimensions, and electrical characteristics. PWAS of various shapes and sizes are considered. Two boundary conditions were examined: free PWAS and PWAS attached to actual structures. For both, the PWAS immittance and the allowable dc and ac voltages were considered. The predicted values were compared with measurements performed over a wide frequency range (10 kHz to 2 MHz).

Next, the electronic-equipment specifications were considered. The PWAS can be used in a number of different ways to actively detect damage in structures. Our aim was to develop electronic-equipment specifications that would extract the optimum performance from the PWAS, i.e., maximize the coupling with the structure and obtain large-amplitude Lamb wave transmission and reception. Analytical predictions were compared with measurements made using current laboratory equipment. The comparative analysis revealed that the current electronic equipment does not fully exploit the PWAS capabilities. Hence, the PWAS equipment specifications were divided into two categories: "existing" and "desired". The former category designates integrated electronic equipment that would offer the same PWAS performance as the existing lab equipment, but be of a lower volume/weight/cost. The latter category refers to advanced electronic equipment that will exploit the full potential of PWAS transducers while being of lower volume/weight/cost than the lab equipment. Both categories are presented and discussed in the paper.

5764-60, Session 13

Fault tolerant design and improved availability of active composite elastic structures

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New functionalities, higher comfort and increasing performance requirements are often be solved by adding new technologies to existing (passive) solutions. Monitoring and control approaches uses additional sensors and actuators, new materials, microprocessors and new devices realizing new and improved functionalities. Two effects are becoming more and more interesting:

i) the lifetime of new actuators/materials strongly depends on the usage-history,

ii) the functionality of the new composed systems depends on the functionality of all elements.

In the consequence, the availability of such new systems is decreased by the number of elements and depends strongly on the use. These effects are known and act against new developments improving performance behavior also in mechanical engineering, automotive systems etc. This will be also the case for multifunctional composite or compound systems and is actually within the focus of the Structural-Health-Monitoring (SHM)-community.

Concepts of reliability engineering are known and applied successfully to safety critical systems. Within this contribution a concept will be given to understand system performance as a combination of systems structural design, useful application of modern control and diagnosis approaches and the control of the operating parameters affecting the failure rate of operating systems. The innovation is:

a) the combination of structural design (how to locate sensors/actuators; how to get safe sensor informations; how to ensure acting forces (by which actor)),

b) methods of analytical redundancy increasing systems availability for online-use,

c) an approach to monitor systems failure rate and affecting the control and/or operating systems to ensure stability and integral functionality of the whole system.

Briefly explained, the subject of the contribution is that the complex adaptronic system (plate, sensor, actuator, internal or external control realization) should be understood as a dynamical, fault tolerant, and variable-structure which realizes functionality, performance, availability and works safe. The contribution will illustrate the concept in general and uses therefore the practical example given in the submitted parallel contribution [Krajcin,Söffker]. Core of the health monitoring concept is that changes by altering and also wear and usage are understood as effects leading to failures. The monitoring concept will use diagnostic approaches and a dynamical model of the system changes to realize a complete diagnosis and supervision concept based on the model-based fault diagnosis illustrated in the submitted parallel contribution [Krajcin,Söffker] and probability models about assumed life-time distributions of piezoelectric materials.

Based on a similar approach given in a previous work [Söffker,Wolters], here, the concept is illustrated for the experimental system and first results with this experimental system will be given.

5764-61, Session 13

Decision uncertainty in a structural health monitoring system

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Structural health monitoring (SHM) systems are being developed to rapidly assess the structural integrity of future launch vehicles.

This paper presents results from a SHM project to investigate detection and localization of loose fasteners in a thermal protection system (TPS) panel. The TPS consists of a carbon-carbon panel fastened to a titanium backing structure using fifteen surface bolts and intermediate brackets. The TPS is considered healthy when all bolts are at a nominal torque. A single bolt is loosened by one-quarter turn to simulate damage. Active SHM techniques are employed, with excitation and response signals provided by four piezoelectric transducers attached to the backing structure. A swept frequency sinusoid signal is sent to one piezoelectric transducer and the resulting response measured at the remaining three piezoelectric sensors. A brief summary of the experimental testing of the TPS structure is given, as a detailed description has been previously published. The primary focus of this paper is on feature extraction and classification.

Feature extraction involves identifying key characteristics of the measured data with the ability to distinguish between various damage states. Experimental testing is performed for the various healthy and damaged states to be discriminated. For the TPS investigations, features have been based on time signals from the individual sensors.

These features do not involve manipulation of two of more response signals, such as required to obtain transmissibilities or cross-power spectra. The time signals are gain normalized by dividing each response by its variance. The response is then partitioned into non-overlapping time segments and the standard deviation, corresponding to the RMS energy contained in that segment, is computed. This process is repeated for each sensor, providing a pool of potential features.

A subset of these features are selected for the final classification system using an adaptive sequential forward-floating search method.

The damage detection and localization problem is essentially a 16-class problem, corresponding to the unique states of the TPS structure (one healthy state and damaged states corresponding to each of the 15 bolts loosened independently). Therefore, a classifier architecture has been chosen to be a bank of 16 quadratic discriminant functions. Based on a set of measured data, each discriminant function produces an estimate of the likelihood that the TPS structure is in the corresponding state. Initial class assignment corresponds to finding the discriminant function with the largest output value. However, two tests are performed prior to accepting the class assignment. First, checks are performed to verify that the winning discriminant has a value greater than a specified threshold value. This step provides a form of outlier rejection, with the intention to classify only those measurements corresponding to one of the structural states.

For the second test, the difference between the values of the two largest discriminant functions is computed. This difference is also required to be above a specific threshold value before a final class label is assigned. This second test provides a measure of the certainty associated with the assigned class label.

5764-62, Session 13

Damage criticality assessment in complex geometric structures using strain and dynamic response-based signal processing techniques

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The use of glass-reinforced plastics (GFRP) as a structural material is widespread because of their high strength and stiffness, low mass, excellent durability and ability to be formed into complex shapes. For maritime applications, composites also offer improved corrosion resistance, improved fuel efficiency and reduced magnetic signature. However, GFRP composite structures are prone to delaminations which can lead to a significant degradation in structural integrity. A number of non-destructive inspection methods have been devised to inspect such structures. And various structural health monitoring (SHM) systems have been proposed. Although such system may readily detect damage, the characterization of the damage is often much more difficult to achieve. One class of SHM system relies on the examination of the strain distribution of the structure due to its operational loads. A research program has been undertaken to develop techniques to determine the size and location of a delamination in a GFRP structures based on its strain distribution. This paper considers the strain distribution in a GFRP beam subject to three-point bending. The strain distribution due to delaminations of various sizes and locations along the centerline of the beam has been determined by finite element analysis (FEA). A technique called the Damage Relativity Assessment Technique (DRAT) has been developed and implemented to process the data. An Artificial Neural Network (ANN) has been trained to relate this strain distribution to damage size and location. This ANN has been shown to predict the size and location of damage for a number of simulated cases. The extension of this technique is to detect multiple cracks in a complex structure with multiple loading sets and loading history. These studies will be carried over even for beams subjected to impulse loading. A major aspect of this effort will include the pseudo-automated assessment of the criticality of the damage. The aforementioned work above provides the platform for the extension of this diagnostic technique to 3-D and more geometrically complex structures. Results from computational and experimental work, in this regard will be presented and used in conjunction with the DRAT and the ANN techniques described above.

5764-63, Session 13

Flow-variance method for damage identification

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A new method called flow variance for multidimensional damage identification is introduced. It can be considered a simplified practical implementation of the phase space warping concept. In a system subjected to damage accumulation parameters drift causing the alteration of the trajectory flow in its phase space. A flow variance metric is used to quantify these changes in the direction of the flow. In an experimental context, a phase space trajectories are reconstructed based on delay coordinate embedding of measured scalar time series. In this reconstructed phase space the flow variance metric is calculated by estimating the average gradient of reconstructed trajectory in small disjoint sections of the

phase space. It is hypothesized that a feature vector composed of flow variance metrics can be projected to actual damage states. A mathematical model of a harmonically driven cantilever beam in a double-well potential force field is used to validate this method. Two-dimensional damage process is introduced trough the electromagnets altering the beams potential field. Demonstrating the existence of the affine projection validates the hypothesis. The smooth orthogonal decomposition based damage identification is also able to recover the active damage states. This method is simple to implements and requires modest computational resources.

5764-64, Session 13

Structural health monitoring(SHM) of co-cured composite structures using fiber Bragg grating (FBG) sensors

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Currently the trend is an increasing usage of composites in aircraft structures due to the advantages of high strength-to-weight ratios, good fatigue properties and ease of fabrication of complex shapes. The most common fabrication technique for aerospace structures is the autoclave molding technique, which is used to co-cure or co-bond the skin and substructure. The main concern in this technology is the debond between the skin and the stiffener (sub-structure) which goes unnoticed during visual inspection and can be detected only through a rigorous non-destructive testing (NDT) technique. It is necessary to be able to detect and assess skin-stiffener separation in a composite structure before it reaches the critical size thereby increasing its damage tolerance. Hence there is an urgent need to develop structural health monitoring (SHM) systems that can detect and monitor in real time such damages in the structure.

Fiber optic sensor technology has many advantages and has matured to an extent to be considered as a viable sensor in Structural Health Monitoring systems for aerospace composite structures. The work presented here is based on strain measurements obtained using Fibre Bragg Grating (FBG) sensors embedded inside or surface mounted on the structure.

Composite test boxes made of glass-epoxy have been designed, fabricated and tested. The boxes have been fabricated using prepreg from HEXCEL Composites Pvt. Ltd and cured in an autoclave. The test boxes are either assembled (i) using bolts, wherein the separation between the skin-stiffener can be achieved by removing the bolts, or (ii) bonded, in which case the adhesive is suitably applied to create debonds of required size. The strains of the healthy box are compared with the unhealthy box. The strains in the experiments are monitored using both strain gauges and Fibre Bragg Grating (FBG) sensors. The experimental results show that there is significant change in the measured strain both at the debond location and in close vicinity of the debond location. The finite element analysis of the box is done using ABAQUSTM and the analysis has been validated with the experimental results. A comparison of the bolted construction to the bonded one is made and these results show that the bolt removal is a fairly good way of simulating a debond. This analysis will be further used for conducting parametric studies to obtain various strain patterns for different damage levels and locations in order to provide guidelines regarding sensor locations and spacing. It was seen that the FBG sensor captures strains accurately and was in close agreement with the strains measured with the strain gauges. With the other inherent advantages that the FBG sensor possesses, it is a very promising candidate for health monitoring applications. The results obtained in this study will be presented in the paper. This paper also describes the efforts in developing a neural network based methodology for detecting skin-stiffener separation in bolted and bonded composite structures.

Publications

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“Structural health monitoring of composite structures using Fibre Bragg Grating sensors”, National seminar on Smart structures in civil engineering, Bangalore, 2003

2.G. N. Dayananda, G.M. Kamath, Ramesh Sundaram and M. Subba Rao, “Smart structures for Aerospace Applications”, Monograph on Smart structures, UVCE Bangalore, 2003.

3.Ramesh Sundaram, G.M.Kamath, M.Subba Rao, “Structural Health Monitoring Concepts for Co-cured/Co-bonded Composite Aerospace structures”, Second ISAMPE National Conference on Composites (INCCOM-2), Sept. 2003, Bangalore.

5764-83, Session 13

Elastic wave propagation in delaminated composites using piezoelectric-wafer actuators and sensors

X. Zhou, A. Chattopadhyay, Arizona State Univ.

Unlike traditional nondestructive testing techniques applied only on accessible surfaces, piezoelectric wafers are able to generate/receive wave propagation from desired positions of the structure. Therefore, they offer tremendous potential in structural health monitoring by identifying the scattering and the changes in transmission phase and velocity associated with the onset and progress of structural damage. The present paper will investigate elastic wave propagation in composite laminates with delaminations, through piezoelectric actuation and sensing. Two-step effort will be conducted. First, a piezoelectric actuator/sensor model involving both longitudinal and transverse couplings will be developed. It has been shown that the induced stress field around a piezoelectric actuator can be expressed in terms of interfacial shear stress and transverse displacement of the transducer. In this research, piezoelectric sensing signals associated with the resulting waveform from actuation will further be modeled through a pseudo incident wave technique. This leads to an accurate characterization of two-way electro-mechanical coupling. Next, the major research effort will be conducted on the modeling of wave propagation in composite laminates with the presence of delaminations. The wave deformation, spatially, contains two components: the known incident wave and the unknown scattering in the delaminated composite. Since these two components must satisfy Helmholtz equation, general solutions can be obtained by using the series representation of Bessel and Hankel functions. To determine the unknown parameters in the scattering wave, the Chebychev functions of the second kind will be used to describe the delamination opening conditions (discontinuity conditions at delamination faces). By combining this with Helmholtz equation, an equation containing the relationship between actuation, sensing, and delamination parameters will be obtained. Therefore, the developed procedure and computational technique are able to provide the observation of sensing signals perturbed by the existence of composite delaminations, under dynamic electrical loading. That is, such perturbations in sensing signal can be expressed as a function of delamination natures. By successfully characterizing and identifying the scattering wave due to delaminations, health monitoring techniques can be developed by measuring the contour or the time-of-flight of scattering wave fronts, through piezoelectric sensor arrays.

5764-65, Session 14

Wave-based signature characterization of damage using response-surface method

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In structural health monitoring, the fundamental goal is to address the problem of damage identification, location and quantification. A non destructive evaluation (NDE) method is used in this research to accomplish this task. An acoustic based sensor network, associated with optimal placement of sensor sets, has been developed based on the characterization of sensors’ sensing region and performance [1] to investigate the existence of damage in composite structures. By incorporating sensor certainty region and sensing density, the developed optimal sensor set is able to provide the accurate description of the perturbations caused by the presence of damage. Convergence of sensing regions with the required level of inspection accuracy leads to the certainty region of detectability, implying that perturbations caused by damage in that region with severity greater than the threshold value can be detected. Such perturbation can be characterized in terms of source of the perturbation at any surface point (x, y) on the structure, threshold value, and distance between any point (x, y) on the plate and the sensor node located at the centre of the plate.

In the present study, the main focus is directed towards the development of the surface response model which would include the dominant physical parameters associated with structural damage(s). This is followed by an investigation into the significant influences of those input parameters on the perturbation generated due to the presence of damage. In acoustic based approach, the presence of damage is visualized in terms of the changes in the signature of the resultant wave that propagates through the structure. Since surface mounted piezoelectric transducers have been used for monitoring purpose, the voltage output of each sensor is used for signature characterization. The first step in this work is estimation of the response surface model with the approximation of an unknown functional relationship that exists between the controllable set of input damage parameters and the simulated response parameter. However in

structural health monitoring problem, the simulated response may not be unique for all different combinations of input parameters. This means that several combinations of damage parameters could result in similar changes in the wave signatures. The final objective of the study would be to investigate cases with non-unique solutions and develop signal processing strategies to address the inverse problem.

[Reference:

1. Aditi Chattopadhyay, Santanu Das and David Miller, "Acoustic Based Structural Health Monitoring for Composites Using Optimal Sensor Placement: Analysis and Experiments," International conference on computational & Experimental Engineering and Sciences, Madaria, Portugal, 28th July, 2004.]

5764-66, Session 14

Crack detection using vibro-acousto-ultrasonics

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Health monitoring of many structures is currently based on scheduled inspections which are often time/labour consuming and expensive. Furthermore, statistics show that unscheduled maintenance, which still accounts for a significant percentage of inspection effort, is even more expensive. Although a number of NDT approaches have been developed for structural damage detection over the last fifty years, it appears that the majority of these techniques is ground-based, impractical in terms of human involvement, expensive in terms of equipment and staff training and often require lengthy teardown procedures. Recent years have shown a number of new damage detection techniques based on smart, often multifunctional, sensor technologies which allow the sensors to be integrated within monitored structures and provide in-time (real-time or near real-time) indications of possible structural damage.

The paper presents an application of the Vibro-Acousto-Ultrasonic (VAU) technique for crack detection in metallic structures. The method combines high-frequency propagating elastic waves with low-frequency vibration which are generated and sensed by traditional sensor technologies used for ultrasonic (or guided ultrasonic) inspection and vibration analysis. The paper consists of two major parts. Firstly, a simple one-dimensional model of wave propagation is used to present the method. Secondly, the VUA technique is applied for crack detection in metallic specimens. The study involves low-profile piezoceramic transducers bonded on a metallic specimen and used for actuating and sensing. The results show that this new approach provides an extremely effective and reliable method of damage detection and monitoring which is more robust and accurate than current techniques utilising guided ultrasonic waves. Furthermore, it overcomes major difficulties associated with guided waves propagating in monitored structures.

5764-67, Session 14

Monitoring of crack growth in aluminum 7075 T6 using distributed sensor

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Introduction

The recent development of a new structural health monitoring system that employs a "continuous acoustic emission sensor" is described in this paper. The continuous sensor has multiple sensor nodes distributed on the structure and offers the simplicity of monitoring a wide area with a single channel instrument. Crack growth in the riveted joint in aluminum panels is of practical interest because of the large number of aging aircrafts that are in operation. The objective of this paper is to establish a correlation between the acoustic emission signal amplitude and crack growth rate in the aluminum 7075 T6 materials. The continuous sensor system provides a significant increase in the sensitivity with a simultaneous reduction in the number of instrumentation channels. Such a system can reduce the cost, complexity, and weight of the required instrumentation.

Experimental Details

The relationships between crack growth rate and acoustic emission parameters were measured on three different types of aluminum 7075 T6 specimens.

(a) 2 inch wide aluminum coupon,

(b) 6 inch wide aluminum panel, and

(c) bolted lap joint of 6 inch panel

The dimensions of the coupons were 2" wide, 15" long and 0.125" thick. A 0.25" central circular hole was drilled on it; two notches along the horizontal diameter were cut for initiating fatigue crack in the coupon. The specimen geometry and the sensor arrangement of the coupon specimen are shown in figure 1. From this test the adequacy of signal to noise ratio and a qualitative relationship between AE amplitudes and crack growth rates were established. Subsequently a bolted joint fabricated from a 0.125" 7075-T6 aluminum sheet was monitored. This specimen was fabricated to approximately simulate an aircraft fuselage joint. The similar tests were conducted 6 inch wide panels also.

These specimens were first subjected cyclic load to initiate fatigue cracks of about 0.1 inches before any acoustic emission signals were collected. The specimens were instrumented with two different types of acoustic emission sensors and with individual nodes of continuous sensor. These were loaded in a MTS testing machine at a frequency of 5 cycles per second. The crack growth rates were measured using an optical microscope. These specimens were subjected to constant amplitude tension-tension fatigue load. The cracks exhibited the typical exponential crack growth behavior, starting with a slow crack growth rate in the beginning and accelerating as the effective crack length increased. Three different cyclic amplitudes were used to produce a wide range of crack growth rates in this material and collect the corresponding acoustic emission signals. The signals from the acoustic emission sensors and continuous sensors were typically amplified by 34 dB, and digitized using a LeCroy digital oscilloscope. These signals were further processed to extract the AE parameters corresponding to crack growth events. The sensitivity of the continuous sensor is found to compare well with that of wide band AE sensors and is adequate for monitoring fatigue crack extensions. Signal processing techniques including wavelet analysis are used to extract time-frequency information in the acoustic emission signals.

Figure 2 shows the response from the AE sensor due to crack extensions. As the size of the crack extension increases, both the amplitude of the AE signal and the frequency components present appear to change. The crack growth lengths used in the above discussions were the average crack extensions per cycle measured over segments of 1000 cycles each. It is expected that crack extensions do vary from one cycle to the next because of several reasons.

The performance of continuous sensor and the AE processor emulator was evaluated by mounting two sensors connected in series to form a two node continuous sensor on the specimen. The output from this sensor was collected and processed by the AEP emulator. The AEP emulator measured the time of occurrence, event duration, rise time, amplitude, RMS voltage, and the energy content for each of the AE signals.

Conclusion

A new structural health monitoring system based on the acoustic emission technique is described. This system consisting of a single channel distributed sensor termed a "continuous sensor" and an embeddable local AE processor offers important advantages for practical applications. The performance of the prototype of the local AE processor was evaluated in a laboratory setting for monitoring fatigue cracks growth in aluminum joints. The presence of mode I damage in an aluminum bolted joint panel is successfully classified and quantified the crack growth rate using different types of sensors. Further evaluation of the continuous sensor as well as the prototype of the local processor is underway.

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5764-68, Session 14

Life prediction and life extension of composite specimens

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Introduction

In recent years, composite materials have received wider acceptance as structural materials in the design of many components. These materials have high specific strength and stiffness, which make them attractive materials for the automotive and aerospace industries. Since composite materials are being used where they are subjected to cyclic loading, it is important to predict the fatigue

life and understand their damage mechanisms using suitable test techniques.

Acoustic emission techniques have been found to be very useful in monitoring and collecting information about the damage in materials. This technique can detect the presence of flaw growth activity in composite materials in a relatively simple manner, and its ability to provide indications of damage growth in real time can be considerable value in proof test applications. However, its major limitation has been that, in most cases, it can provide only qualitative indication of the flaw growth rate. For structural composite applications, quantification of damage growth in terms of determining the crack growth rate in metallic materials and determining the mode of failure in material has been difficult.

Life Prediction and Structural Health Monitoring

In an earlier study [2] acoustic emission technique was used with reasonable success for predicting the fatigue durability of carbon fiber thermoplastic hip prostheses. The technique involved tailoring the acoustic emission monitoring technique so as to capture the crucial damage related events occurring during the fatigue degradation of the composite structural member. Specifically the acoustic emission was recorded during the proof test shown in Figure 1. Based on the acoustic emission data obtained prior to the fatigue loading it was possible to differentiate the highly durable composite specimens from those, which failed prematurely during the fatigue loading.

The feasibility of predicting the durability of a structural element that will encounter cyclic load during its service life is more rigorously being explored in this research effort. The concept is being verified using glass fabric epoxy composite coupons. The specimens were flat coupons, whose thickness, width, and length were respectively 0.125", 1", and 12". The static strength and fatigue durability of the baseline undamaged specimens were first determined. It was determined that the cyclic amplitude for these coupons to last a minimum of 106 cycles is 40% of the average static strength. Five of these baseline specimens were also subjected to an instrumented proof loading cycle. During the proof loading cycle two AE sensors were attached to the coupon as shown above. The AE parameters collected during the proof test are amplitude, counts, duration, rise-time and energy via 60db pre-amplifier and Mistras 2001 data acquisition software.

In the next phase defects were implanted into these coupon specimens through impact of a spherical indenter. The coupons were supported in a suitable fixture and subjected to impacts of various energy levels. First these specimens were subjected to static strength and their strength distributions corresponding to each damage level was determined. This was followed by testing another group of specimens with implanted damage using the instrumented proof testing procedure. Based on the AE results obtained during the proof cycle an attempt was made to predict the durability of the composite coupons. Reasonable correlations between fatigue durability and AE energy is seen for these specimens. Figure 2 shows the correlation between the cumulative acoustic emission energy and number of cycles to failure of various specimens instrumented. This result should not be tempered with the observation that while the correlation between AE cumulative energy and fatigue life was excellent for the majority of the specimens, there were two coupons for which AE data did not correctly predict fatigue life. Perhaps more sophisticated AE signal analysis based on identification of failure modes, damage locations and elimination of mechanical noise will be able to improve this correlation.

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5764-82, Session 14

Characterization of impact damage in laminate composites with numcerical simulation for health monitoring

S. J. Kim, S. H. Paik, S. H. Park, Seoul National Univ. (South Korea)

Modern aircraft construction increasingly uses composite materials due to lower mass compared with isotropic metallic ones. However, composite materials can be easily damaged by various impacts such as tool drop during manufacturing or bird strike in flight. Although such damage may have a serious effect on the safety of the whole structure by locally forming matrix cracking, delamination and fiber fracture, the invisibility due to the damage location hidden inside makes it difficult to identify it. For many years, damage identification methods, specially nondestructive evaluations (NDE) have been studied by a number of researchers. One of the most famous methods capturing the impact damage without destruction is to measure the acoustic emission (AE) at the event of impact. The AE waves generated by impact loads are mixed with other waves and noises and therefore undistinguishable by the conventional analysis methods in time or frequency domain. It is known that the wavelet transform (WT) or wavelet packet transform (WPT) can effectively decompose the AE signals from other waves. In addition, there are many researches which try to catch even the difference of the AE signal characteristics between various kinds of damage mechanism in time and resolution domains by WT and WPT. So far, most researches have dealt with detection of impact damage by analyzing the AE signal by experiment. However, only by the experiment with limited cases, it is impossible to reproduce the various event of impact damage.

In the present research, the numerical simulation is performed for AE and wave propagation event by the finite element transient analysis. The numerically reproduced wave signal is transformed by WPT to analyze the frequency and resolution characteristics between the AE signals of various damage mechanisms. The high velocity and the small wave length of the AE require a refined analysis with dense distribution of finite element and small time step. In order to fulfill the requirement for capturing the exact wave propagation and cover the 3-D simulation, we utilize the parallel FE transient analysis code and high performance computing(HPC) technology.

5764-69, Poster Session

Mechanical properties of metal-core piezoelectric fiber

H. Sato, National Institute of Advanced Industrial Science (Japan); M. Nagamine, Nagamine Manufacturing Co., Ltd. (Japan)

We produced a piezoelectric fiber with in a metal core by two methods, hydrothermal method and extrusion method. Both fibers can use sensor and actuator by piezoelectric effect. And we developed a vibration board using these fibers. In this paper, we measured mechanical properties of our piezoelectric fibers and show that the mechanical strength of piezoelectricity fiber increases, by putting in the metal wire inside.

5764-70, Poster Session

A thin-film Nitinol heart valve

L. L. Stepan, D. S. Levi, G. P. Carman, Univ. of California/Los Angeles

The medical community is still searching for a gold standard in heart valve replacement therapy. Mechanical heart valves are noisy and require anticoagulation therapy. Calcification of bioprosthetic valves sacrifice their fatigue properties and often result in repeat surgeries. Using thin film nitinol valve leaflets in an artificial heart valve may avoid the shortcomings of traditional mechanical and bioprosthetic valves.

A "butterfly" valve design has been developed to test the feasibility of using thin film nitinol as a heart valve leaflet. The valve has been tested under in vitro pulsatile flow conditions. Flow results and pressure traces from these experiments will be presented. The biocompatibility of thin film has been examined via in vitro immersion tests and in vivo porcine studies to determine thin film nitinol's corrosion resistance and antithrombogenic properties.

Nitinol's shape memory characteristics could also be exploited to design a percutaneously delivered valve. Percutaneous procedures are associated with less trauma to the patient and are inexpensive when compared to traditional open heart surgery currently required to implant artificial heart valves. A prototype of a thin film nitinol percutaneous valve will be presented and its deployment method will be discussed.

5764-72, Poster Session

Characterization of energy harvesting potential of Terfenol-D and Galfenol

M. E. Staley, A. B. Flatau, Univ. of Maryland/College Park

This research focuses on characterizing the electrical energy output potential of Terfenol-D and Galfenol under a vibrating mechanical input. A test stand will be constructed to allow initial prestress variability up to 5 ksi in .25 ksi increments. Prestress will be monitored with a static load cell. A shaker will be used to mechanically actuate the Terfenol-D and Galfenol rods in the range 0 to 50 Hz. This range matches the vibration frequency range of various ships. The test rods themselves are ¼" in diameter and 2" long. The test stand will also allow for magnetic bias variability. Experimental and theoretical coil optimization with

respect to wire gauge, coil diameter, coil length, and number of turns will be performed to maximize the electrical energy output. The performance comparisons will consist of electrical energy output vs. mechanical energy input for different inputs and also energy output for constant mechanical input while varying prestress, magnetic bias and coil parameters.

5764-73, Poster Session

Analytical, numerical, and experimental investigation of self resonance in vibration excitation systems

K. Ragulskis, R. Palevicius, M. Ragulskis, D. Rubliauskas, A. Palevicius, Kaunas Univ. of Technology (Lithuania)

Eccentric angular motion transfer mechanisms are analyzed in the paper. The debalancing mass has an additional degree of freedom in these mechanisms. It was found that certain types of such mechanisms posses interesting nonlinear dynamical features when a self-resonance motion mode occurs. Such self-resonance motion mode takes place when the main driving element rotates with relatively high angular velocity, but low frequency vibrations are generated in the range of fundamental frequency of the system.

Analytical, numerical and experimental investigations of nonlinear vibration excitation systems were performed. The zones of existence of self-resonance were determined. Such vibration excitation systems have high practical value as there is no necessity for complex vibration control equipment – the stability of operation is guaranteed by non-linear dynamical interactions.

Laser velocity measurement system was used for experimental investigations of the dynamical properties of the system. The results of the investigations validated the results of the theoretical analysis and provide a background for developing new type of dynamical mechanisms.

5764-74, Poster Session

Vibration isolation modeling of Stewart platform through Newton-Euler approach

P. Xu, D. Wang, Chongqing Univ. (China)

The Stewart platform, which is generalized from the mechanism proposed by Stewart (1965) as a flight simulator, is a 6-DOF (degrees of freedom) parallel mechanism with two bodies connected together by six extensible legs. A general Stewart platform has a base-platform and a payload-platform connected by six extensible legs through a spherical joint at the top of each leg and a universal joint at the bottom, which is referred to as the 6-UPS (universal-prismatic-spherical) Stewart platform. The 6-UPS Stewart platform known as one of the most widely used kinematic structures of parallel manipulators is regarded as the basic configuration model of Stewart platform.

In the last two decades, the Stewart platform has been used widely in three basic fields: vibration isolation, mechanical machining, and precision positioning. Although the vibration isolation based on Stewart platforms is regarded as one of the most important applications, the dynamic formulation of the Stewart platform is rarely established in this field. Some dynamic formulations of the Stewart platform are presented only when the base-platform is considered to be static and not motion at all. For example, Miller (1992) built a dynamic formulation of Stewart platform through Lagrange approach; Dasgupta and Mruthyunjaya (1998) deduced a closed-form dynamic formulation of the Stewart platform successfully through Newton-Euler approach; Codourey and Burdet (1997), Wang and Gosselin (1998), and Tsai (2000) solved the inverse dynamics for the Stewart platform through the principle of virtual work. Thus all the models that do not consider the vibration of the base-platform can not be used as the vibration isolation modeling of Stewart platform. That is to say, these models can not be used to analyze the vibration isolation problems of Stewart problem.

This paper addresses the closed-form dynamic modeling of the Stewart platform for an application of vibration isolation through the Newton-Euler approach. In this paper, the vibration of the base-platform is considered to be a motion state of the whole system and is integrated into the Newton-Euler dynamic equation of the Stewart platform. One advantage of the dynamic equation is that the role of vibration is shown clearly in the equation, which makes the dynamic equation of the Stewart platform more completely. The other advantage is that a set of control algorithms used in attenuating the vibration effect of the base-platform based on the dynamic equation can be developed well and easily. The vibration isolation model derived in this paper is implemented for the forward dynamics of the Stewart platform and some simulation results are also presented.

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5764-75, Poster Session

Dynamic and control characteristics of 3-axis active mount using piezoelectric actuators

S. Choi, J. Kim, J. Shon, Inha Univ. (South Korea)

In this work, a 3-axis active mount using the piezoelectric actuators is developed and its dynamic and control perofrmances are evaulated. The dynamic motion of the mount is modeled with 6 degree of freedom and principal characteristics are investigated through system identification method. In order to establish the 3-axis dynamic motion, three piezostack actuators are adopted and oriented to generate active forces in three different directions. A theoretical model to predict the active mounting force is derived before constructing the mount. The magnitude of the generated force and dynamic bandwidth are experimentally evaluated with respect to the frequency and intensity of the input voltage.

5764-76, Poster Session

Integration of novel MEMs valve for improvement of piezohydraulic actuator performance

R. M. Tieck, D. G. Lee, G. Carman, Univ. of California/Los Angeles

Piezohydraulic actuators are a new frontier in the search for small scale, high power devices, and they currently exhibit a specific power density (W/kg) on the order of 100 W/kg. This work outlines efforts to improve the available power output (W) and the specific power density of a Piezo Hydraulic Pump (PHP). The PHP is intended for use in aircraft control surface articulation, and uses novel passive micro-check valves that allow the PHP to be operated at 10 kHz. The PHP was baseline tested using conventional passive check valves proprietary to the manufacturer (Kinetic Ceramics, Hayward, CA) using both de-ionized water (DI water) and commercially available hydraulic fluid. The micro-check valves were then integrated into the structure and the tests repeated using both test mediums. The results are compared. An increase in available specific power density to approximately 1000 W/kg is expected.

5764-77, Poster Session

A new technology for fabrication, excitation, and control of high-density actuators

A. R. Bowles, A. Rahman, J. G. Gore, P. Morris, T. Jarman, QinetiQ (United Kingdom)

A new, low cost technique for fabrication, excitation and control of high-density actuators has been developed. Primarily aimed at the tactile display of universal text, Braille and graphics for the Blind community, magnetic forces are utilised to actuate and hold individually addressable pins. Current tactile displays that allow Blind people to interact with the world via electronic media are expensive and due to their inherent complexity can only be made to display the Braille language, which on average only 10% of visually impaired people in Western society are able to read. There is a need for a more flexible communication device.

Magnetic bistability is used to facilitate matrix addressing of the individual actuator elements in the array, thus allowing a massive reduction in the number of necessary electronic drive circuits. This gives good energy efficiency as power is only required when the system is updated and not when holding the static display. An error correction technique is used that automatically corrects a bistable actuator if it has mistakenly moved into an incorrect position. A low cost technique for producing and assembling the magnetic actuators has been developed. A 360-actuator demonstrator has been produced which displays alphanumeric text or graphics via a PC interface.

5764-78, Poster Session

Direct adaptive control of a smart projectile fin by piezoelectric

W. Yim, S. Mani, S. N. Singh, Univ. of Nevada/Las Vegas

Presently, the use of piezoelectric actuators for the shape control of intelligent structures

has gained widespread acceptance. Applications can be found in many areas like shape control of metallic or composite plates or beams. The main advantage of using piezoelectric actuators is in saving space required for servomotors, force transmission devices etc. This advantage becomes more important in small aerial vehicles such as unmanned aircrafts, missiles and projectiles.

The contribution of this paper lies in the derivation of a new adaptive control law for the control of the rotation angle of a smart projectile using piezoelectric

actuator for aerospace applications. The smart projectile fin consists of a flexible cantilever beam with a piezoelectric active layer, which is mounted inside a hollow rigid fin and is hinged at the tip of the rigid fin. The rotation angle of the fin can be controlled by deforming the flexible beam. The dynamics of the flexible beam with active layer of piezoelectric actuator is described using finite element approach. The beam is modeled into a series of finite elements satisfying Euler-Bernoulli's theorem. In this paper, the beam is divided into 5 elements and has state space form of dimension 20.

For the purpose of control, only the input (voltage), output (fin angle) and the reference command input signals are used for the synthesis of the control system. Although, one can design an adaptive controller using the available results in literature, the objective of this paper is to design a simple direct adaptive control system, which requires filters of low-order (only 4), for trajectory control of the fin angle. It may be pointed out that if one applies the standard adaptive control scheme one has to use filters of net dimension 75. Apparently, the new control law yields significant reduction in the dimension of the dynamic feedback compensator. It is shown that in the closed-loop system, fin angle asymptotically follows the reference trajectory. Simulation results are presented to show the effectiveness of the controller in spite of large parameter uncertainties.

The simulated responses show that the trajectory tracking of the fin angle can be achieved in less than 3-4 seconds. The fin angle smoothly follows the reference command trajectory. The control input needed for this maneuver is quite reasonable. There exists enough flexibility in the control system, which can be exploited to obtain desirable responses using permissible control magnitude.

5764-80, Poster Session

Unsteady fluid flow in smart material actuated

S. John, C. Cadou, Univ. of Maryland/College Park

No abstract available

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5765-01, Session 1

Recent developments in MEMS

A. Duwel, Draper Lab.

No abstract available

5765-02, Session 1

What do earthquakes do? Measurement and control challenges for earthquake engineering

S. Mahin, Univ. of California/Berkeley

Earthquake engineers are making great strides in the development of new and more reliable seismic-resistant structures and in devising high performance computational frameworks for simulating the highly nonlinear dynamic response of these structures during catastrophic earthquakes. At the forefront of these efforts are activities aimed at aquiring the rich sets of data needed to validate computational models, update behavioral theories, and controling or assess the response of structures during and following earthquakes. In this paper, some of the methodologies currently being explored for next-generation instrumentation of structures are reviewed considering the multitude of damage information required. These range from simple descrete instruments for measureing local strain, displacement, temperature, pressure, acceleration and so on, to more complex technologies based on photographic or videographic machine vision, laser scanning, and interpolated virtual environments. Issues related to establishing data structures and metadata suitable for the diverse and dense information obtained are described. Lastly, the paper describes recent trends in hybrid simulation where seismic effects are simulated over large and complex systems where portions of the system are concurrently modeled numerically on one or more computers, and other portions are physically tested at one or more networked laboratories. The ability realistically simulate in near real time the seismic behavior of large systems using such geotraphically distributed network-enabled control methodologies will vastly improve our ability to design critical infrastructure facilities. Nonetheless, an abundance of challenges remain.

5765-03, Session 2

Temperature and humidity variation of specific resistance of carbon fiber-reinforced cement

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Recent research shows that carbon fiber reinforced cement (CFRC), which mainly composed of hardened cement and short cut carbon fibers, possesses piezoresistive effect, and could be used to produce new type of compressive stress sensors. As having character of low cost, good compatibility with concrete and high durability, CFRC sensor extraordinary adapt to be used in the field of long time health monitoring of concrete structures. In this paper, based on large quantity of duplicate tests, the influence and its mechanism of temperature and humidity on electrical specific resistance of CFRC was studied; moreover, the function of volume content of carbon fiber on above influence is also discussed. Furthermore, the experimental results of durability of carbon fiber reinforced cement were also presented.

5765-05, Session 2

An improved damage identification method using tunable piezoelectric transducer circuitry

L. Jiang, Pennsylvania State Univ.; J. Tang, Univ. of Connecticut; K. Wang, Pennsylvania State Univ.

Structural damage detection based on changes in vibration characteristics has received much attention in recent years. Among all the vibration-based detection methods, the ones based on changes in natural frequencies or frequency response functions are considered to be the easiest to implement. However, such frequency shift-based damage detection has severe limitations in practical applications; namely, the number of natural frequencies that can be measured is normally much smaller than the degrees of freedom required for accurate damage identification; and even very precise measurement cannot lead to the detection of small damage due to the usually low sensitivity of frequency shifts relative to damage effect. In order to resolve these difficulties while maintaining the advantages of frequency shift-based detection, Tang and Ding [2004] recently proposed a frequency shift-based damage detection approach using piezoelectric transducer circuit with tunable inductance. The basic idea is to use the tunable inductance integrated to the piezoelectric transducer to favorably alter the dynamics of the integrated system. The inductance circuit can introduce additional resonant frequencies at arbitrary frequency band, and through tuning the inductance, one can result in a family of frequency response functions. In all, this idea could allow us to more completely and accurately capture the system dynamic response variation. Although the concept is promising, the inverse sensitivity based algorithm used in their approach was insufficient to provide quantitative evaluation on the performance improvement, due to its first order approximation and the assumption of no mode shape change after damage. This may seriously affect the effectiveness and accuracy of the method. In addition, due to this shortcoming, the important issues of simultaneously detecting multiple structural damages and the effect of sensing noise have not been addressed in the previous investigation.

The objective of this research is to advance the state of the art of frequency-shift-based damage identification method and to take full advantage of the idea of using piezoelectric transducer circuit with tunable inductance. More specifically, we aim at improving the current methodology by taking into account the sensor noise and multiple-damage case. A novel, iterative modal estimation method is proposed. The basic principle of this new approach is to include the high order terms in the eigensolution formulation, whereas the mode shape change information can be obtained from estimating the eigenvectors of the damaged structure through an iteration method.

To evaluate the proposed concept, analyses are carried out for damage identification in several beam structure examples. For the cases of single-element damage, it is shown that the first step of the iteration can identify the exact location but not the severity of damage, and the exact severity of the damage is obtained after the modal iteration. For the cases of multi-element damage, the iteration process becomes even more important because both the exact location and severity of the damage can only be correctly identified after the modal iteration. Sensing noise is then added into the process to examine the system robustness. Experimental investigation is also carried out on a table top test stand to validate the predictions. Based on these results, it is shown that the new method is very efficient, robust, and accurate in identifying the locations and severity of the structural damage.

5765-06, Session 2

Characterization of concrete stress by measuring dissipation factors of embedded piezoelectric ceramic discs

Y. Wen, Y. Chen, P. Li, H. Guo, Chongqing Univ. (China)

Piezoelectricity has found wide uses in the field of smart material and structural system. Piezoelectric devices are either used as actuators or sensors because of the bidirectional piezoelectric transduction. To achieve the sensory function of structures, piezoelectric devices are embedded in underlying materials or modules. However they are not preferable choice to be embedded with forming sensory concrete structure. This is caused by the complex sensitivity resulting from piezoelectricity meeting tough civil engineering settings: under un-controlled operational conditions, various external actions may produce similar or even identical responses according to the well established analysis scheme of piezoelectric transduction response. This paper presents a novel technique that may characterize stress in concrete free of the constrain of unique action. The technique is realized by using common piezoelectric ceramic discs (PZT-4, various phases of lead zirconate titanate), which are embedded in concrete. The piezoelectric ceramic discs are easy to be buried in concrete when pouring, and of higher mechanical robustness. Further, to ensure that the electrodes are isolated from the concrete, TDL-704 (one component RTV silicone rubber) is smeared on the surfaces of piezoelectric ceramic discs. The rubber layers also release stress concentration on the edges of ceramic discs.

Traditional analysis on piezoelectric transducer behaviors is based on the electromechanical equivalent circuit of piezoelectrics (the Mason model). The circuit has two end-ports, one is mechanical and another electric. For a

piezoelectric sensor, the mechanical port is taken as input and the electric one is output. According to the model, mechanical action will produce due electrical response and any variation in electrical parameters may also cause output to change.

Piezoelectric dissipation factors (dielectric, elastic and piezoelectric dissipation factor) have been proposed to distinctly describe electric, mechanic and piezoelectric movements. In this paper it is desirable to use these factors to account for the complex responses of devices exposed in tough ambiences, such as being embedded in concrete. We first discussed the physical significances of three dissipation factors. Then the complex coefficients of piezoelectric ceramics are utilized in piezoelectric equation system and accordingly the complex equivalent circuitry parameters are obtained. Resultantly, the paper derives the three factors in terms of the complex equivalent circuitry parameters. This way the dissipation factors are attainable through the measurement of the equivalent circuitry parameters.

Experiments are conducted to detect the changes of equivalent parameters and dissipation factors of the PZT-4 discs embedded in cubic concrete specimen under various stress and temperature. It is found that the dielectric and elastic dissipation factors keep almost constant at lower temperature range and have their own peak values at about 90℃, at which point the piezoelectric ceramics lose the piezoelectricity and show the ferroelectric phase. While the piezoelectric dissipation factor keeps linear to the temperature. When stress is applied on the surface of concrete specimen, a rough linear variation to stress is observed in three dissipation factors. This is explained by the theory that losses are considered to consist of four portions: domain wall motion; fundamental lattice portion; microstructure portion and conductivity portion. As desired, the experiments justify that dissipation factors can account for and distinctly characterize responses resulting from different actions.

5765-07, Session 2

Integrated charge sensors for electrostatic MEMS

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The “snap-through” or “pull-in” phenomenon limits the operating region of an electrostatic MEMS device controlled using a constant bias voltage to only one third of its physical deflection range. It has been shown that by controlling the charge on the actuator any static deflection inside the full gap range can theoretically be stabilized.

Some existing approaches to this problem use passive charge feedback, implemented, for example, through a series capacitor. Others use open-loop charge control, involving the application of charge to a fixed capacitor, and the transfer of that charge to the MEMS. We report the fabrication of a fixed capacitor, integrated into the MEMS device as part of the fixed drive electrode. Such an on-chip series capacitor has the potential to significantly improve device performance by eliminating the parasitic effects observed in an off-chip series capacitor. Benefits claimed by the use of the proposed common electrode design include the elimination of the need for extra wiring, which may introduce inductance, capacitance, and induced voltage to the measurement circuit. With a known value of series capacitance, charge on the actuator can be calculated and used in off-chip control circuits. Electrostatically-actuated MEMS structures are fabricated at Texas Tech University using surface micromachining methods. The devices are intended to test voltage control laws now under development. The test structure includes the auxiliary electrode described above, to establish an integrated capacitor in order to make the desired charge measurement. This paper will compare several device designs. All are specifically tailored to investigate characteristics of the charge control performance. An additional comparison is made, between the developed on-chip sensing capacitor and commonly used off-chip series capacitance measurement techniques.

5765-126, Session 2

Computational tool for the design of structures with built-in piezoelectric-based sensor networks

Y. Kim, F. Chang, Stanford Univ.

A computational tool is developed to analyze structures with built-in piezoelectric-based sensor networks. The tool serves two purposes: to understand fundamentally the interaction between sensors/actuators and the host structure in high frequency domains; and to optimize the design of sensor networks for maximizing sensor sensitivity and energy efficiency.

A spectral element approach is adopted in this study. The software includes an equation solver and an interface program to link with pre/post-processing software. The elastodynamic equation solver is developed based on the spectral element method (Fig. 1), which provides an excellent solution in wave propagation problems. Furthermore, the solver includes an algorithm to solve the coupled electro-mechanical field in piezoelectric materials. The interface program links to commercial finite element pre/post-processing software such as ABAQUS/CAE to grant access to the geometrical complexity of host structures and to facilitate understanding of the physical phenomena.

This paper reports the efficiency and accuracy of the code using comparisons to FEM. The code is verified (Fig. 2) by matching the spectral-element solutions with experimental results. Sensor size, shape and location are also examined using the code to optimize sensitivity to damage.

5765-08, Session 3

Dynamic displacement measurement accuracy of GPS for monitoring large civil engineering structures

W. S. Chan, Y. L. Xu, X. L. Ding, Y. L. Xiong, W. J. Dai, The Hong Kong Polytechnic Univ. (Hong Kong China)

Structural displacement is a key element to assess the safety of large civil engineering structures subjected to strong winds. Because of its global coverage and continuous operation under all metrological conditions, Global Positioning System (GPS) technology has been becoming an important tool for monitoring both static and dynamic displacement responses of large civil engineering structures under strong winds. The accuracy of GPS for dynamic displacement measurement at the sub-centimeter to millimeter level, however, depends on many factors such as the sampling rate of a GPS receiver, satellite coverage, multi-path effect, and GPS data processing. Therefore, this study focuses on the assessment of dynamic displacement measurement accuracy of GPS using a newly-developed 2-D motion simulation table.

The 2-D motion simulation table developed can simulate various types of 2-D motion of large civil engineering structures with a frequency range from 0.025 Hz to 2 Hz and an amplitude range from 2 mm to 40 mm in two orthogonal directions. With a sophisticated control system implemented in the 2-D motion simulation table, the motion generated by the table is of high accuracy, and the table can thus be used as a test bed to assess the performance of a GPS system. The GPS system being assessed in this study mainly consists of two Leica AT504 Choke Ring Antennae and two Leica GX1230 GPS receivers with a sampling rate of 20 Hz.

A series of field measurements were carried out in an open area in Hong Kong for the assessment of the GPS system. The static tests with stationary antennae were first performed to assess the background noise of GPS. The examination of the static test data of 9 hours duration showed that the background noise was dominated mainly by low frequency components. A band-pass filtering scheme was thus designed and applied to all the motion data recorded by the GPS system. The dynamic tests were then carried out to assess the accuracy of the GPS system in measuring sinusoidal and circular displacements. The comparison of the table motions recorded by the GPS system with the original motion generated by the table showed that the GPS system could measure sinusoidal or circular dynamic displacements accurately if the displacement amplitude was more than 5 mm and the motion frequency was less than or equal to 1 Hz. The dynamic displacement measurement accuracy of GPS was finally assessed using complex signals which include 1-D white noise random wave with a range of frequencies from 0.025 Hz to 1.8 Hz and 2-D wind-induced building motions measured from the Di Wang building during Typhoon York. The comparative results demonstrated that the GPS system could trace wind-induced dynamic responses of tall buildings satisfactorily.

5765-09, Session 3

High-speed hybrid active system

I. F. Gonzalez, Univ. Politecnica de Madrid (Spain) and Stanford Univ.; F. Chang, Stanford Univ.

A novel piezoelectric/fiber-optic system is developed for long-term health monitoring of aerospace vehicles and structures. The hybrid diagnostic system uses the piezoelectric actuators to input a controlled excitation to the structure and the fiber optic sensors to capture the corresponding structural response. The aim of the system is to detect changes in structures such as those found in aerospace applications (damage, cracks, aging, etc.). This system involves the use of fiber Bragg gratings, which may be either bonded to the surface of the material or embedded within it in order to detect the linear strain component produced by the excitation waves generate by an arbitrary waveform generator. Interrogation of the Bragg gratings is carried out using a high speed fiber grating

demodulation unit and a high speed data acquisition card to provide actuation input. With data collection and information processing; is able to determine the condition of the structure. The demands on a system suitable for detecting ultrasonic acoustic waves are different than for the more common strain and temperature systems. On the one hand, the frequency is much higher, with typical values for ultrasonic frequencies used in non-destructive testing ranging from 100 kHz up to several MHz. On the other hand, the related strain levels are much lower, normally in the μstrain range. Fiber-optic solutions for this problem do exist and are particularly attractive for ultrasonic sensing as the sensors offer broadband detection capability. This will become important when the technique is extended to include the study of the use of changes in the propagation properties of Lamb waves as a method of damage detection. Results on the interaction of the Lamb waves with the grating and the extraction of information from the response in order to know changes in the structure is presented.

5765-10, Session 3

Concrete-filled steel pipes inspection using electro-magnetic acoustic transducer (EMAT)

W. Na, Pukyong National Univ. (South Korea); T. Kundu, Univ. of Arizona; Y. Ryu, J. Kim, Pukyong National Univ. (South Korea)

Concrete-filled steel pipes have been used as piles for supporting civil and marine structures. These piles provide good bending resistance, and can be easily spliced for long depth installation. However, these piles are usually exposed in hostile environments such as seawater and deicing materials. Thus, the outside corrosion of the steel pipe can reduce the wall thickness and the corrosion-induced delamination of internal concrete can increase internal volume or pressure. In addition, the void that can possibly exist in the pipe reduces the bending resistance. To avoid structural failure due to this type of deterioration, appropriate inspection and repair techniques are to be developed. The acoustic method is attractive for this inspection since it is relatively simple and versatile. Especially, guided wave techniques have strong potentials for this inspection because of long-distance inspection capability. There are different transducer-coupling mechanisms available for the guided wave inspection techniques. Electro-magnetic acoustic transducers (EMATs) give relatively consistent results in comparison to piezoelectric transducers since they do not need any couplant. EMATs are used for transmitting and receiving cylindrical guided waves through concrete-filled steel pipes. It is shown that EMAT-generated cylindrical guided wave techniques have good potential for the interface inspection of concrete-filled steel pipes.

5765-11, Session 3

Control of distributed sensors by dynamic Bayesian networks

S. Ferrari, M. Qian, Duke Univ.

Recent developments in autonomous-vehicles and wireless-communication technologies are producing surveillance systems with increased flexibility and functionality, where the sensors and their platforms are characterized by a high degree of autonomy, reconfigurability, and redundancy. The tactical performance of these systems can be optimized by allocating available resources intelligently, taking into consideration real-time measurements and information collected by the surveillance system. In this paper, modeling and control techniques are developed for systems where multiple heterogeneous targets are detected, classified, and, possibly, tracked by means of multiple heterogeneous sensors installed on dynamic platforms. These techniques are applied to a demining system where Ground Penetrating Radar (GPR), Electromagnetic Induction (EMI), and Infrared (IR) sensors installed on ground and air vehicles are used to detect and classify objects buried underground, under diverse environmental and operating conditions.

Existing methods address the problems of sensor fusion, target classification/tracking, and platform deployment individually, without taking advantage of the combined information about all system components (i.e., sensors, platforms, and targets). The main challenge in developing an integrated approach to these problems is the heterogeneous and distributed nature of the system components. In this work, a common formalism based on dynamic Bayesian networks (BNs) is used to represent all components and relevant interactions, obtaining a probabilistic and distributed graphical model of the surveillance system. This model is then used to infer or estimate unobservable variables, and to perform sensor fusion, target classification, and platform path planning, optimizing the overall probability of detection and identification.

Using the surveillance system BN model, resources such as sensors mode and location can be allocated to maximize the probability of detection and minimize the probability of false alarms by means of decision-making algorithms. In this work, approximate dynamic programming (ADP) is applied to the BN model to compute a nearly-optimal decision policy in real time, when knowledge of the targets and the environment can be substantially improved. The method is demonstrated by using the information inferred (and fused) from GPR, EMI, and IR measurements and BN models as a feedback to the sensor manager, which plans their motion and operation over time. These sensors are installed on overpass-capable (OC) and non-OC ground platforms and uninhabited air vehicles (UAVs) that are used to demine a field in the presence of obstacles and constraints, such as time, limited energy and bandwidth.

5765-12, Session 3

Forisome as a biomimetic smart materials

A. Shen, Washington Univ.

With the discovery of the plant protein forisome, a novel, smart non-living, ATP-independent biological material became available to the designer of smart materials for advanced actuating and sensing. The in

vitro studies show that forisomes (1-3 micron wide and 10-30 micron long)can be repeatedly stimulated to contract and expand anisotropically by shifting either the ambient pH or the ambient calcium ion concentration.

We probe the forisomes conformation change inside a microfluidic device with the pH modulation. We demonstrate that the surface properties of the

channel wall and the flow condition can influence the anisotropic shape change of forisomes, and their actuation kinetics significantly. This study provides insights for multifunctional actuation and sensing for

potential health monitoring applications.

5765-13, Session 3

Health monitoring of a reinforced concrete bridge bent-cap using piezoceramic materials

H. Gu, Univ. of Houston

Health monitoring for reinforced concrete bridges and other large-scale civil infrastructure has received considerable attention in recent years. However, traditional inspection methods (x-ray, C-scan etc.) are expensive and sometimes ineffective for large-scale structures. Piezoceramic transducers have emerged as new tools to health monitoring of large size structures due to the advantages of active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation. In this research, piezoceramic transducers in the form of patches are used to detect internal cracks of a 6.1-meter long reinforced concrete bridge bent-cap. Eight piezoceramic patches are embedded in the concrete structure at pre-determined spatial locations prior to casting. To induce cracks in the bent-cap, the structure is subjected to loads from four hydraulic actuators with capacities of 80-ton and 100-ton. In addition to the piezoceramic sensors, strain gages, LVDTs, and microscopes will be used in the experiment. During the experiment, one embedded piezoceramic patch is used as an actuator to generate high frequency waves, and the other piezoceramic patches are used as sensors to detect the propagating waves. With the increase of number and severity of cracks, the magnitude of a sensor output will decrease. Wavelet packet analysis is then use to analyze the recorded sensor signals. A damage index is formed on the basis of the wavelet packet analysis. The experimental results show that the proposed methods using piezoceramic transducers along with the damage index based wavelet packet analysis is effective in identifying the existence and severity of cracks inside the concrete structure. The experimental results also show that the proposed method predicts the failure of concrete earlier than using the results from conventional microscopes (MS) and LVDTs.

5765-14, Session 3

Monitoring liquid and solid polymers through electroactive response

H. Y. Lee, Y. Peng, Y. M. Shkel, Univ. of Wisconsin/Madison

Dielectrostriction, which is defined as a variation of dielectric response with deformation, provides a new approach for in-line monitoring properties and structure of a material. The dielectrostriction effect resembles a well-known birefringence phenomenon which has been widely used for NDE of transparent materials. While birefringence is described by the strain-optic rule, the strain-dielectric rule applies to dielectrostriction. However, dielectrostriction measurements can be administered to any, even non-transparent, dielectric material, require a much simpler measurement technique, are capable of local

measuring stresses/strains and can be implemented for material processing and health monitoring of strucutres. In this study, we present the theoretical background of the dielectrostriction phenomenon and experimental data of dielectrostriction responses of both liquid and solid polymeric materials. The experimental evidences of the dielectrostriction effect and the linear stress-dielectric relationship are presented for two representative liquid polymers. Similarly, for solid polymers the dielectrostriction response is linearly proportional to the strain during uniaxial tensile test. We propose the sensor configuration capable of decoupling and measuring the electrostriction parameters. In addition, we introduce a new concept of a solid-state capacitance sensing method for monitoring dielectrostriction phenomenon and develop simple planar capacitance sensor to measure the dielectrostriction responses under shear and normal deformations.

5765-15, Session 4

Design of sensors/actuators for structural control of continuous CMA systems

H. Irschik, M. Krommer, U. Pichler, Johannes Kepler Univ. Linz (Austria)

Smart structure technology has become a key technology in the design of modern, so – called intelligent, civil, mechanical and aerospace (CMA) systems. Similar to human beings, these intelligent systems are capable to react to disturbances exerted upon them by the environment they operate in. The design is a highly multi – disciplinary task, which involves the modeling of the structure, the interrogation and communication of the structure with the controller by means of suitable sensing and actuation, the integration of the smart system in the structure and the implementation of the system. One key aspect for a successful design is the communication between structure and controller. Sensors and actuators are responsible for the functioning of this communication. Sensors provide information about the state the structure is in; this information has to be interpreted and properly processed by the controller to provide the actuator with information about what to do.

In typical continuous CMA systems a crucial point is the distribution of sensors to obtain proper information and the distribution of actuators to influence the behavior of the structure properly. Finding these distributions is the topic of this paper.

A common strategy for the modeling of continuous CMA systems is based on the linearized theory of elasticity; within this paper we consider a three-dimensional linear elastic background body with sources of self-stress. These self-stresses can be produced by smart materials which exhibit the well known stain induced actuation mechanism; as many of the modern smart materials have both, actuation and sensing properties, we assume the sensing be based on the same mechanism. We base the sensor/actuator design on three aspects:

- Mechanical interpretation of the sensor signal and of the action of the actuator;

- Design of collocated sensor/actuator pairs;

- Suitability for application of common control strategies;

We show that a suitable distribution of sensors results into a sensor signal proportional to kinematical entities (e.g. displacement), whereas a suitable distribution of the actuation results in actuators that act like dynamical entities (e.g. force). These distributions are found to coincide with statically admissible stresses due to systems of forces, which are not necessarily the ones actually acting on the structure. Using the same system of forces we automatically end up with collocated sensor/actuator pairs; this design allows the implementation of self-sensing systems, in which actuators can be used as sensors too. Moreover, it is highly suitable from a control point of view, because it allows the application of common control strategies in a straightforward manner; e.g. a simple PD – controller ensures stability of the closed loop system. Finally, we show some results of our strategy applied to simple structures, such as beams and plates.

In this paper we focused on one key aspect in the design of CMA systems, namely properly distributed sensors and actuators. Our design, which was based on a structural analysis, proofed to be highly advantageous for the applicability of common control strategies. We are convinced this is an important aspect in the development of intelligent continuous CMA systems.

5765-16, Session 4

Sonic infrared imaging NDE

X. Han, Wayne State Univ.

We will describe Sonic Infrared Imaging NDE for materials and structures. In this imaging technique, a short ultrasonic pulse is applied to the structure/material to cause heating of the defects, while an infrared camera images the time evolution of the heating effect to identify the defective areas in the target. The heating effect is astonishing. In this paper, we'll include our study of Sonic IR imaging NDE on aircraft structure specimens, automotive specimens, etc. for metals, composites, ceramics addressing fatigue cracks, delaminations/ disbonds, corrosion.

Fundamental issues related to Sonic IR imaging NDE will also be discussed in this paper.

5765-17, Session 4

Development of vehicle intelligent monitoring system (VIMS)

Y. Fujino, K. Kitagawa, H. Ishii, Univ. of Tokyo (Japan)

In an urban highway network system such as Tokyo Metropolitan Expressway, to detect road pavement and expansion condition is a very important issue. So far road profiler system to measure the road surface condition has been used. Although accurate surface condition can be captured by this method, the operating cost is rather expensive and development of a simpler and more inexpensive system is expected.

Vehicle Intelligent Monitoring System (VIMS) developed for this purpose is discussed in this paper. Accelerometers and GPS are installed to ordinary road patrol cars. GPS is used to identify the location of the vehicle. Dynamic response measured in the vehicle is used as a measure of the road pavement surface condition as well as the expansion joints.

A pilot system is made and tested in the Tokyo Urban Expressway. It was found that the GPS can identify the location of the running vehicle very accurately, so the acceleration time history measured by the accelerometers can be corresponded to the location of the highway very precisely. The correlation between the acceleration level and the pavement condition (measured by a road profiler) is shown to be very high.

The system is still under development and improvement, but it can be expected that continuous measurement by the road patrol cars with VIMS can identify the deterioration of the road pavement and the expansion joints.

5765-18, Session 5

Development of a multi-variable wireless sensor for structural health monitoring in civil engineering

Y. Yu, Harbin Institute of Technology (China)

In recent years, structural health monitoring (SHM) has been an important research area for evaluating and designing reliability of civil engineering structures. With the development of the technologies in sensing, wireless communication, and micro electro mechanical systems (MEMS), wireless sensing technique has been caused much more attentions and used gradually in the SHM. The wireless sensors and network has lower capital and installation costs as well as ensures more reliability in the communication of sensor measurements, but there exits the key problem of the finite energy and this is a primary design constraint. Therefore, some measures must be adopted to make wireless sensor work more effectively.

In this paper, a kind of wireless sensor with 3 variables，temperature-acceleration- strain, is proposed. Such several modules as sensing element, micro-processing element, power element and wireless transceiver are constructed using commercially available parts, and integrated into a complete wireless sensor. The fusion arithmetic of the temperature-acceleration is embedded in the wireless sensor so that the measured acceleration values are more accurate. Measures are also adopted to reduce the energy consumption. Experiment results show that, the wireless sensor could monitor the temperature-acceleration-strain of the structures real time and precisely, and pre-process and pack the measured data to reduce the data volume to be transmitted and save energy.

5765-19, Session 5

Energy efficiency analysis of a self-powered acoustic wireless pressure sensor: a bond graph approach

Y. Cui, R. X. Gao, Univ. of Massachusetts/Amherst; D. O. Kazmer, Univ. of Masachusetts/Lowell

A self-powered acoustic wireless sensor for the process monitoring in high energy manufacturing systems is presented, with injection modeling as an example of application. The sensor consists of an energy converter, an energy modulator, and an acoustic signal transmitter. Power supply to the sensor is realized through energy extraction from the polymer melt by the energy

converter, which converts mechanical pressure into proportional electrical charges. The charges generated in each molding cycle activate the signal transmitter, which in turn transmits a series of ultrasonic pulses through the injection mold steel to an external receiver. Such an acoustic wireless sensing technique avoids shielding of electromagnetic signals from being transmitted out of a metallic enclosure such as the injection mold, and enables efficient measurement of continual pressure variation in the mold by means of acoustic digitization.

This paper presents an energy efficiency analysis of the developed pressure sensor, from the point of view of energy flow (Figure 1). Generally, energy efficiency can be analyzed if an analytical model that considers the dynamic behavior of the sensor in each molding cycle is available. Given the multi-domain (e.g. mechanical, electrical, thermal) nature of the sensor and its structural complexity, setting up an system model using conventional block diagram or circuit modeling techniques is difficult. In this paper, the Bond graph modeling technique is demonstrated to establish a unified energy efficiency model of the entire sensing system consisting of the sensor, the injection mold, and the ultrasound signal receiver, as shown in Figure 2.

Comparing to block diagram and circuit modeling techniques, the Bond graph approach uses the energy flow in the system as the common descriptor of cross-domain physical systems. This approach has four advantages. First, the Bond graph uses a relatively small number of symbols and elements to represent a system that otherwise would need a large number of differential equations to be adequately represented. Secondly, the Bond graph models developed can be processed in a standard procedure to produce block diagrams or differential equations for easy post-processing. This makes it possible to quantitatively determine a specific variable for the intended energy efficiency analysis. Thirdly, the Bond graph models can be incrementally refined by graphically adding more elements such as the thermal loss. As each component of the system can be represented correspondingly in the Bond graphs, junctions and elements are added into or deleted from a model without causing substantial model changes. Finally, Bond graph models of a system with complex dynamics can be used directly for system simulation, which makes it easy to improve the system design.

Based on the Bond graph system model, the energy efficiency of the pressure sensor is characterized as a function of the configuration of the piezoelectric stack within the energy converter, as well as the molding cycle of the energy modulator. The obtained energy model is then used to identify the minimum level of signal intensity required to ensure successful detection of the signal by the receiver outside of the injection mold.

The Bond graph analytical models developed suggest that the energy efficiency of the self-powered sensing approach is predominantly determined by the charging time and the piezoceramic stack configuration. As is experimentally verified, a stack with multiple thin rings can extract more electrical energy than a stack with less but thicker rings, under the same total stack height and mechanical energy input. The output voltage of the signal receiver is a function of the input electrical energy and ultrasonic transmitter geometry. Under the same electrical energy input, a transmitter with thicker piezoelectric layer will generate higher ultrasound pulse output. Two case studies were investigated to experimentally evaluate the accuracy of the Bond graph energy efficiency model. The results are in good agreement with the simulations. The Bond graph models developed in this study can be used to further optimize the design of the wireless sensing system.

5765-20, Session 5

Development of wireless smart sensor for structural health monitoring

L. Liu, F. Yuan, North Carolina State Univ.

As dense sensor networks are being designed in structural health monitoring field, especially in aerospace applications, smart sensors with wireless communication are attracting more and more attention. With local computing capability and wireless information transmissibility, smart sensors are more reliable than traditional sensors and possess many other attractive advantages such as easier installation, less maintenance cost and more flexibility for renovation. Furthermore, smart sensors can easily implement distributed computation and data correlation, thus play an important role in the development of smart materials if they are embedded in structural health monitoring system.

Although there are several prototypes of smart sensors, none of them has high frequency data acquisition rate, which is critical for SHM especially in aerospace field. There are two major reasons for that: one is high speed sampling is a power-hungry application in most cases; the other is that high frequency microcontroller is required to control the logic of high speed sampling. Both obstacles are needed to address from low power consumption viewpoint, which is an essential limitation for embedded applications. However, in most applications, effective sampling especially in high speed usually is transient and system would spend most of time in waiting status. This gives us a motivation that we can overcome the obstacles by using high frequency microelectronics to control the sampling logic during working status. In this approach, sampling logic controller will not be CPU itself, but a peripheral device which can be individually shutdown. Thus, we can still use low frequency microcontroller and keep power consumption still low.

A prototype of smart sensor to integrate wireless communication, distributed computation capability with low power consumption into a single small unit is proposed by North Carolina State University. Each unit provides mega-Hz level actuating or sensing function and hardware associated local computation. Multiple units can be organized into a sub-network and can cooperate together to share or correlate data via wireless communication.

The proposed unit will mainly be based on Atmel's FPSLIC and SmartRF chip. The FPGA part of FPSLIC will act as reconfigurable device controller for ADC/DAC and SRAM in the hardware level and run at high frequency to realize high speed data acquisition, up to 10MHz. Other DSP IP cores for mathematical purpose, such as FFT, DSC and wavelet, will be also implemented if applicable; The AVR part will behave as a powerful computation core and provide power management for FPGA part, RF chip and other applicable chips.

5765-21, Session 5

The SHM system using self-diagnosis material and wireless data measurement device

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In recent years, structural health monitoring techniques are attracting wide attention to detect deterioration or damage using sensors attached to the structures. The authors have been continuously conducting a series of research works on the development of the simple SHM system by integrating self-diagnose material and wireless data measurement device.

The self-diagnose material is comprised of the glass fiber reinforced composites with electrical conductivity by adding carbon particles. It performs not only a structural member but also a strain sensor which can memorize the maximum strain during its damage histories by measuring its electrical resistance change. It is very suitable property for SHM, because maximum strain is an important index to evaluate structural damage.

We have also developed the small and low cost wireless data measurement device, because it may be very troublesome and time consuming work to measure a large number of self-diagnose materials dispersed in large structure such as bridges and tunnels.

The authors carried out cyclic loading tests on the reinforced concrete beam specimens with these self-diagnose materials and wireless data measurement device, resulting that these materials and device were very effective for the SHM system.

5765-22, Session 5

Development of an off-the-shelf field programmable gate array-based wireless sensing unit for structural health monitoring

C. Kapoor, J. Pei, Univ. of Oklahoma; T. L. Graves-Abe, Princeton Univ.

This paper presents preliminary results of an investigation of applying Field Programmable Gate Arrays (FPGAs) to civil infrastructure health monitoring. An off-the-shelf FPGA development board available at a comparable price with microcontroller development boards is adopted in this study. Advantages, disadvantages, feasibility and design concerns of using such a reconfigurable architecture for implementing algorithms for structural health monitoring in a wireless sensor unit are studied in a showcase of implementing Fast Fourier Transform (FFT) in a wireless data transmitting setting.

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5765-23, Session 5

Health dynamic measurement of tall building using wireless sensor network

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Health Monitoring is very important for large structures like suspension- and cable-stayed bridges, offshore platforms, tall buildings and so on. Due to recent developments in new sensor systems, wireless communication systems, Internet-based data sharing and monitoring, advanced technologies for structure health monitoring (SHM) have been caused much more attentions, in which the wireless sensor network is recently received special interests. Wireless sensor networks (WSNs) consist of large populations of wirelessly connected nodes, capable of computation, communication, and sensing. In this paper, a wireless sensor networks based health monitoring system for tall buildings has been explored integrated with wireless sensing communication, computation, data management and data remote access via Internet.

Firstly, a laboratory prototype was designed and developed to demonstrate the feasibility and validity of the proposed system. Wireless sensor nodes were deployed on a test structure, the data being sensed by the sensor nodes in the network is eventually transmitted to a base station, where the information can be accessed. Through a Wireless Local Area Network (WLAN, IEEE802.11b), the simulated data was transferred among personal computers and wireless sensor nodes peripherals without cables. And then, a Wireless Sensor Network (WSN) includes eight sensor nodes and one base station was installed on Di Wang Tower to verify the performance of the present system in-depth. The acceleration of the building, temperature and noise of the environment were measured by the sensors embedded in the wireless sensor nodes. Finally, comparisons between WSN and cable-based monitoring analytical acceleration responses of field measurement have been performed. The proposed system is shown to be effective for structural health monitoring.

5765-24, Session 6

Flexibility-based damage identification algorithm embedded in sensor network emvironment

A. Masuda, A. Sone, Y. Hashimoto, Kyoto Institute of Technology (Japan)

The aim of this paper is to develop a damage tracing method to detect and track the evolution of structural damages in structures, in particular, frame structures, considering the applicability in a decentralized computing environment of wireless sensor networks. We first present a modal flexibility-based damage indices that have simple and intuitive physical interpretation. Since the damage indices are computed using angular mode shapes of the lowest several modes, vibratory gyroscopes are adopted as the sensing device in this approach. The damage evaluation algorithm is then modified to a decentralized form, which is to be implemented as the local computation of mode separation at each sensor unit and the global computation of the damage index at the central monitoring station. Some illustrative experiments simulating both stationary damages and sudden damages are conducted using an off-the-shelf prototype of sensor network system to show that the proposed method is capable to indicate the location of the damages and the time when they occur.

5765-25, Session 6

An energy-efficient data processing scheme for wireless sensor networks

Z. Fan, R. X. Gao, Univ. of Massachusetts/Amherst

Wireless sensor network (WSN) has been viewed by researcher as a promising platform for monitoring spatially distributed targets. Through the deployment of a large number of untethered and self-contained sensors, WSN provides physical-level information of the targets being monitored. Given that these sensors are typically operated on power-limited batteries, efficiently utilizing the power available to increase the service life of the sensors becomes a key challenge in the design of WSN.

Energy is dissipated in a WSN through three mechanisms: data sampling, data processing, and data communication. This paper addresses the data processing aspect by presenting an energy-efficient in-network data processing scheme. The scheme is motivated by the concept of Dynamic Voltage Scheduling (DVS), which minimizes energy consumption through dynamically adjusting the voltage supply to and clock frequency of the individual sensors. Unlike the traditional approach where a uniform data processing speed is employed to all the sensors, the new scheme adjusts the speed for each sensor individually to utilize the processor idle time for prolonged computation latency. By means of employing DVS, substantial amount of energy can be saved on each individual sensor, thus improving the overall energy efficiency of a WSN. Especially when a large amount of raw data needs to be processed locally at each sensor to reduce overall data communication and thus the associated network energy cost, the new scheme is advantageous. A WSN application model in which 40 vibration sensors are deployed for machine health monitoring is constructed to test the new data processing scheme. Simulation results have shown that the average clock speed for the sensors can be reduced by over 70% under the time constraint of 50 ms per data set, and an overall computation energy saving up to 59% is achieved.

The major contribution of this paper lies in exploiting the processor idle time (while a sensor is waiting for data communication) to enable energy-efficient data processing. Since the length of each data communication cycle is dependent on the total number of the sensors involved in the WSN, the length of the transmitted data, and the transmission rate, it is possible to exploit the processor idle time to enable adaptive energy saving, even for the case of real-time sensing. Analysis based on realistic data from a customized bearing test bed has shown that the new technique was able to effectively reduce the energy consumption for different number of sensors and network structures.

5765-26, Session 6

Sensitivity vector fields for damage detection and sensing

A. I. Hashmi, B. I. Epureanu, Univ. of Michigan/Ann Arbor

A novel approach to determine very accurately multiple parameter variations by exploiting the geometric shape of dynamic attractors in state space is presented. The approach is based on the analysis of sensitivity vector fields. These sensitivity vector fields describe changes in the state space attractor of the dynamics and system behavior when parameter variations occur. Distributed throughout the attractor in state space, these fields are used in conjunction with proper orthogonal decomposition of the parameter space to identify multiple simultaneous parameter variations. The method presented is shown to be robust over a wide range of parameter variations and to perform well in the presence of noise. The proposed approach is highly sensitive, and is shown to be able to reconstruct parameter variations as low as one percent. Furthermore, the proposed method may be used to detect small as well as large parameter variations. The main applications of the proposed technique are sensing and detecting multiple simultaneous damages in vibration-based structural health monitoring. This high sensitivity technique is an enabling method for damage detection technology by allowing for the identification of multiple simultaneous damages of low level (incipient damage). As an example, a simplified model of an aeroelastic system is used herein to simulate the system behavior. The system chosen is a set of coupled nonlinear oscillators which resembles a plate model which, in turn, approximates a skin panel or a thermo-shielding panel of an aircraft.

Detecting parameter variations is one of the common techniques used in system identification, sensing, damage detection, and other areas. For example, detecting parameter variations is used for early detection of degradation of structural integrity, which is critical for successful exploitation and life-cycle management for many systems. As a result, the area of damage detection has received much attention. Identifying qualitative changes in the system behavior has been the first approach used in the early work on structural health monitoring. Detecting and quantifying system damage from limited measurement data presents a significant challenge. Most of the early work has been devoted to linear methods, which have been used to identify changes in natural frequencies and mode shapes. Several other techniques are based on system identification, while others use generic models such as neural networks or alternate forms of excitation. Some of these methods, such as employing neural networks, do not necessarily result in physical models, and that limits their applicability. Others, such as system identification techniques, have been used to match/fit numerical models to measured system dynamics, and to obtain the damage location and level based on the values of the model parameters. However, the complete picture provided by system identification (i.e. the knowledge of all the values of all parameters) is difficult to obtain because of the need for highly detailed measurements. Distinct from other system identification problems, damage detection requires the identification of parameter variations rather than the precise values of the parameters. Thus, a highly sensitive identification of damage by means of identifying parameter changes does not always require the values of the system parameters per se, but just their variations. This may be accomplished by parameter reconstruction, and plays an

important role in applications such as sensing and structural health monitoring, which in turn, provide numerous benefits. For example, structural monitoring provides increased safety, enhanced asset availability and readiness, reduced logistics burden and cost of operation, and it is a pervasive need in air (e.g. air-frames, unmanned air vehicles, the joint strike fighter), space (reusable launch vehicles), sea and land structures (vehicles, buildings and bridges). Furthermore, current vibration-based methods for detecting parameter variations are well developed primarily for linear systems and rely on linear structural models which are inherently limited to linear model forms and cannot account for nonlinear damage scenarios (such as the opening and closing of a gap). Also, nonlinearities interfere with linear behavior which makes it difficult to detect small parameter variations (incipient damage) using linear methods. Distinct from previous methods, the approach presented here is based on nonlinear methods, and it is focused on high-sensitivity identification of multiple parameter variations by the exploitation of the geometric properties of attractors.

The approach proposed herein for high sensitivity detection of parameter variations may be used to monitor both single and multiple parameters simultaneously. Thus, the approach proposed is well suited for detecting multiple simultaneous parameter variations (e.g. multiple simultaneous damages). Previous techniques used for damage detection of a similar type are based on vibratory responses and are designed for linear vibrations, while far fewer apply to nonlinear systems. Some nonlinear methods are based on phase space reconstruction, or Lyapunov exponents. These nonlinear methods have some have difficulty tackling high-dimensional systems and usually do not detect simultaneous parameter variations. Some of these previous limitations are eliminated by a novel approach to determine very accurately multiple parameter variations by means of proper orthogonal decomposition of the parameter space. The approach is based on the analysis of sensitivity vector fields. Sensitivity vectors describe the deformation of the attractor due to variations in system parameters. The parameter changes are reconstructed by means of an optimal basis that captures the deformations of the attractor in state space.

The method proposed here is novel in a few aspects. Notably, the method characterizes attractor deformations on a local level, and it is highly sensitive with respect to the extent of phase space. The local attractor deformation is captured by individual sensitivity vectors which are grouped as vector fields. Hence, a global picture is constructed over the entire dynamics. Previous methods aimed at characterizing state space deformations by means of global statistical measures rather than local attractor deformations. Thus, the resulting metrics were scalar, and effectively smoothed out the attractor deformations. In contrast, the proposed approach uses vector metrics in combination with proper orthogonal decomposition of the parameter space. Note that the use of proper orthogonal decomposition of the parameter space is distinct from other uses which focus on state space reconstruction or reduced order models.

5765-27, Session 6

Prototype of sensor network with embedded local data processing

Y. Hashimoto, A. Masuda, A. Sone, Kyoto Institute of Technology (Japan)

In this paper, we design an off-the-shelf prototype of sensor network system, which consists of a central monitoring station and a sensor unit with local data processing capability, to develop and test the network-conscious data processing algorithms embedded in sensor network environment. In the sensor network, one of the most serious problems may be the increasing computational load of the centralized host computer, which has to process large amounts of data collected by the sensor units. In this study, we design each sensor unit to share the data processing locally to decrease the computational load of the central monitoring station. The sensor unit is developed based on the micro T-engine platform, which is one of the most promising open platforms of embedded micro-computing systems, integrated with accelerometers, analog-to-digital (A/D) converters and a network interface. It has capacity of acquiring, processing and transmitting the data in real time. In this paper, we implement wavelet transform as the data processing algorithm to detect abnormal events in the measured structural responses. Some experiments using a structural model demonstrate the performance of the developed sensor network system.

5765-28, Session 6

Architecture optimization for wireless sensor networks

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Wireless networks are pursued in most of Civil Engineering structural monitoring applications. Nevertheless, there are several solutions available under current technology development and to select the more suitable system architecture for any specific case is not always evident.

This paper pursues a classification of the main sensor network system architectures. Then structural monitoring cases are then chategorized and a sensor network architecture is associated with each chategory.

Some case studies are discussed.

5765-29, Session 7

Simulation of the Lamb-wave interaction between piezoelectric wafer active sensors and host structure

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Piezoelectric wafer active sensors (PWAS) are small, inexpensive, unobtrusive devices capable of generating and detecting Lamb waves in thin wall structures. PWAS are directly attached to the surface of a metallic structure or inserted between the layers of a composite structure. PWAS interact with the structure through surface shear stresses that couple the in-plane motion of the PWAS with the in-plane motion of the structure undergoing Lamb wave motion. The paper will present a simulation of the Lamb wave interaction between piezoelectric wafer active sensors and host structure using analytical solutions in axisymmetric formulation. The Bessel function solutions are used to model the Lamb waves emanating from the PWAS. The time domain Fourier transform is used to process the excitation signal into its frequency components. The frequency domain excitation is used to modulate the Fourier transform of the Bessel function solution in the frequency domain. Inverse Fourier transform is used to return from the frequency domain in to the time domain. Simulations will be presented for symmetric and antisymmetric Lamb-wave modes at various frequencies and mode numbers. The influence of the mode number and frequencies upon the efficiency of the Lamb wave interaction between PWAS and host structure is studied and exemplified with numerical solutions and visualizations.

5765-30, Session 7

Efficient electromechanical (E/M) impedance measuring method for active sensor structural health monitoring

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Electro-mechanical impedance method is emerging as an important and powerful technique for active sensor structural health monitoring. The E/M impedance method utilizes a main apparatus, an impedance analyzer that needs the in-situ E/M impedance of piezoelectric wafer active sensors (PWAS) attached to the monitored structure. Presently, impedance analyzer equipments (e.g.HP4194) are bulky, heavy and expensive laboratory equipment that cannot be carried into the field for on-site structural health monitoring. To address this issue, several investigations are refered which explored means of miniaturizing the impedance analyzer to make the impedance analyzer more compact and field-portable. Next in this paper we present an improved algorithm for efficient measurement of the E/M impedance using PWAS transducers. Instead of applying a sinusoidal input to the PWAS and slowly

changing its frequency, this new method utilizes a chirp signal which is abundant in frequency components. By applying Fast Fourier Transform (FFT) to both the input and the response signals, the impedance spectrum of the PWAS is acquired. The hardware system architecture

consisting of reference signal generation, voltage and current measurement and digital signal acquisition are explored as well, followed by the discussion of the size of the overall system and the implementation using either a laptop or a digital signal processor (DSP). Finally, practical results are presented and comparatively examined.

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5765-31, Session 7

Use of Lamb waves to monitor plates: experiments and simulations

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Lamb waves at ultrasonic frequencies travel with little attenuation in thin elastic plates, and we demonstrate their use in pulse-echo behavior to monitor plate integrity. We employ a single PZT wafer-type transducer to generate waves and to receive reflections from distant flaw or boundary locations; excitation at 10 V produces reflected signals of ample strength (tens of mV) from boundaries roughly 1 m distant. However, Lamb waves generally have multiple modes, each of them highly dispersive, and in consequence pulse dispersion can become pronounced and can make difficult or impossible the interpretation of pulse-echo responses. We show that selective generation of the So wave will overcome those difficulties; therefore, selection of transducer dimensions and pulse characteristics to achieve selective generation should be considered mandatory for most intended applications. We first review the work of others identifying a basic relationship between transducer dimension and excitation frequency for selective generation of the So wave. We then summarize our extensive experimental studies of wafer-type transducers with particular attention to So and Ao mode behavior, both in transmission and reception. We next report our two-dimensional finite element simulation of the same problem performed in FEMLAB, requiring transient simulation of the coupled electromechanical problem. We simulate the piezoelectric response of the wafer-type transducer coupled to the elastic plate, both as transmitter and receiver, as well as the development of Lamb waves within the source region and their subsequent propagation along the plate. Simulations illustrate the development and separation of the So and Ao modes and reproduce the expected group velocities and dispersion behavior. We show good agreement between our experiments and our simulations regarding So mode behavior, and we summarize the results to guide a designer in choosing transducer dimensions. In particular, good selectivity between the So and Ao mode generation can be obtained with appropriate choice of transducer size and center frequency. We then show successful experimental results monitoring plate integrity with wafer-type transducers. Cracks within the plate, or losses along the boundaries or corners of a brittle elastic plate, produce recognizable changes in the signals received at the transducer.

5765-32, Session 7

Validation of a Lamb wave-based structural health monitoring system for aircraft applications

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Structural Health Monitoring (SHM) technologies have the potential to reduce life-cycle costs and improve reliability for commercial and military aircraft. Previous research conducted by the Metis Design Corporation (MDC) has demonstrated the ability of Lamb wave methods to provide reliable information regarding the presence, location and type of damage in coupon-level composite specimens. Several critical SHM system components have also been developed during the course of this research, including circuitry, packaging and a battery, to be integrated into MDC's Monitoring & Evaluation Technology Integration System, or M.E.T.I.-system. In order to demonstrate the validity of the M.E.T.I.-system for aircraft applications, a representative testbed has been fabricated. The testbed, fabricated of aircraft grade 7075 aluminum, has been divided into four equal quadrants by a pair of bolted c-channel ribs. A M.E.T.I.-Disk sensing node was then placed in the center of each quadrant, and data was collected and interpreted by the METISv4 software package. This initial data validated the ability of the software to use a single cell to calibrate the system, and then correctly identify that there was no damage present in the remaining quadrants. Next, damage was introduced in two of the quadrants, and the software was executed again to query the structure. The resulting data revealed the presence and location of both impact and through-hole damage, while still identifying the two undamaged regions. This experiment was then reproduced under other harsh conditions, including elevated temperature and electrical and vibrational noisy environments, again demonstrating the same results. Future work at MDC will aim to package the other supporting electronic components such as the function generator, datalogger and wireless transceiver, as well as integrating all of these components together for operation. SHM technology will enable the elimination of scheduled inspections, and will allow condition-based maintenance for efficient structural design, increased reliability and reduced overall life-cycle costs.

5765-33, Session 7

Interdigitated PVDF transducer for crack and corrosion detection

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PZT ceramics have been widely used in generating ultrasonic waves. It is a common application to attach PZT buttons to the surface of structures for detecting cracks in nondestructive testing (NDT). However, due to the fact that these materials are rigid, they are not suitable for being applied to surfaces with different shapes. Piezo film transducers have attracted more and more attention in recent years to be an alternative for PZT ceramics, given that they are thin and flexible. In this paper, an interdigitated polyvinyldine fluoride (PVDF) transducer for actuating and sensing Lamb waves has been introduced. A specific etching technology is employed for making the surface electrodes into a certain finger pattern, the spacings of which yield different single mode responses of Lamb waves. Experiments have been done on carbon graphite plates for crack detection and have been further extended on steel plates for corrosion detection. Results from PVDF transducers have been compared with those from PZT ceramic transducers. The electro-mechanical impedance (EMI) method for analyzing the dynamic response of active material systems has been imported. An EMI model has been set up and simulations have been performed.

5765-34, Session 7

Finite-actuator modeling for piezoelectric-based Lamb-wave structural health monitoring

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Lamb-wave testing has been proven to be a very promising option among various schemes being explored for Structural Health Monitoring (SHM) in aerospace and mechanical structures. While Lamb-wave testing for Non Destructive Evaluation during offline maintenance using handheld transducers is well established, Lamb-wave testing using structurally integrated piezoelectric wafer transducers for SHM is relatively a new field. Few studies have addressed the important issue of modeling and characterization of Lamb-wave excitation and detection using surface-bonded/embedded piezoelectric wafer transducers (hereafter referred to as "piezo") for SHM, and often the various parameters involved are chosen without mathematical foundation. Moulin et al. [1] used a coupled finite element-normal modes expansion method to determine the amplitudes of the Lamb-wave modes excited in a composite plate with surface-bonded/embedded piezos. Lin and Yuan [2] modeled the diagnostic transient waves in an infinite isotropic plate generated by surface-bonded circular actuators using Mindlin plate theory incorporating both transverse shear and rotary inertia effects. This is sufficient to model the fundamental anti-symmetric mode (Ao) mode excited by the actuators in this configuration; however it cannot model the excitation of symmetric Lamb modes or the higher antisymmetric modes. Giurgiutiu [3] studied the harmonic excitation of Lamb-waves in an isotropic plate to model plane Lamb-wave excitation for the case of an infinitely wide surface-bonded piezo actuator using the 1-D Fourier transform applied to the simplified 3-D linear elasticity based Lamb-wave equations. In our previous work [4], a 3-D model for the special case of circular Lamb-wave field generation using surface-bonded piezoelectric actuators on isotropic plates was presented. The piezo actuator was modeled as causing shear forces on the plate free surface along the piezo's edges. The spatial Hankel transform was applied to the governing 3-D elasticity equations which were simplified using axisymmetric considerations. Using the harmonic response, an approach to find the response to transient time signals was outlined. A general expression for the response of piezoelectric sensors in Lamb-wave fields was derived and experimental results for the case of the 2-D model were discussed which supported the theoretical formulation. Finite Element Method (FEM) results were presented for the case of circular Lamb-wave field excitation and these showed excellent agreement with the theoretical derivation. In the present work, results from experiments conducted to investigate the validity of the derived circular actuator model are presented. A 3.15-mm-thick Aluminum alloy plate was instrumented with a pair of circular actuators on either face at the center and the response of a surface-bonded piezoelectric sensor in the circular Lamb-wave field was recorded at various frequencies. The experiment was conducted for the first fundamental symmetric and antisymmetric Lamb modes. A sample result for the So mode sensor response of a 0.5-cm x 0.5-cm piezo-sensor placed at a radial distance of 5 cm in a circular Lamb-wave field generated by a pair of 1.3-cm diameter circular piezo-actuators excited in phase is shown in Fig. 1. The results from these experiments are in good agreement with the predictions based on the developed theory. The marginal error observed is possibly caused by shear lag introduced by the imperfect bond between the piezo and the substrate, due to which the

effective actuator length is less than the actual physical length, thereby causing a slight increase in the frequency of the peak sensor response. This will be discussed and analyzed in detail in the final paper.

Fig. 1: Experimental and theoretical So mode sensor response of a 0.5-cm sensor placed in a circular Lamb-wave field due to a 1.3-cm diameter

Subsequently, a new theoretical formulation is derived for the more generic case of a finite dimension rectangular actuator surface-bonded on an infinite isotropic plate. In this case, the 2-D spatial Fourier transform is used on the governing 3-D elasticity equations to solve the problem of forced Lamb-wave propagation in the isotropic plate and obtain an expression for particle displacement in the Lamb-wave field. A closed-form asymptotic representation is also derived for the far-field using the method of stationary phase. The developed formulation suggests that the radiation from a rectangular actuator has significant directional-dependence and the amplitude of the excited Lamb wave at a given point on the plate. This dependence is an intricate function of the actuator dimensions and harmonic excitation frequency. Also, it is seen that the Lamb-wave field asymptotically tends to a circular-crested field in shape, but with directionally-dependent amplitude. Thus, by proper design of the actuator, focused radiation in desired structural areas can be achieved using a single actuator. Fig. 2 shows an example of the harmonic wave field from a rectangular actuator as obtained using this model. An expression for the response of a sensor placed in the Lamb-wave field due to the rectangular piezo actuator is also derived. Preliminary analysis indicates that the sensor size should be as small as possible to maximize the magnitude of its response to harmonic excitation, as in [4] for the plane and circular Lamb-wave field cases. FEM and experimental results supporting this developed formulation will also be presented. The procedure used to model rectangular actuators can be extended to model Lamb-wave excitation by arbitrary shape piezo actuators as well as piezo actuators with interdigited electrode pattern (e.g., Macro Fiber Composite (MFC) actuators) that are surface-bonded on isotropic plates. These models can provide valuable insights into the nature of the excited Lamb-wave field and will be very useful in designing Lamb-wave SHM systems using piezos.

Fig. 2: Harmonic radiation pattern for out-of-plane surface displacement due to a rectangular actuator (in gray) at 100 kHz (Ao mode) in a 2-mm thick Aluminum plate

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5765-35, Session 7

Wavelet-based built-in delamination detection for composites

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Composite materials are increasingly used to take advantages of their excellent specific strength and stiffness properties, fatigue performance in both commercial and military vehicles. However, composite materials are vulnerable to multi-mode damages such as fiber breakage, matrix cracks, and delamination, during their manufacturing, transporting and operating process. Therefore, one of the biggest challenges in the design of aircraft structures in future's day is to develop in-situ structural health monitoring system (SHMS) to continuously monitor the composite structures and respond to any abnormalities in (near) real-time. In this study a wavelet-based built-in delamination detection and identification system for carbon fiber reinforced plastic (CFRP) laminates is developed. Lamb waves propagating in laminates and its interaction with the delamination are examined analytically using approximate plate theory at first. Distributed piezoelectric transducers are used to generate and monitor the ultrasonic Lamb waves in the laminates with narrow band frequencies. Then a signal processing scheme based on wavelet analysis is applied on the sensed original wave signals to extract the wave speeds propagating in the laminates. Combined with the theoretical computed wave speeds, an optimization routine is developed to identify the location of the delamination. In addition, a damage index focusing the energy of the scattered waves represented by wavelet coefficients is established to indicate the extent of the delamination. Finally, the applicability of the proposed method to dalamination detection will be demonstrated by experimental studies on a composite plate.

5765-36, Session 8

Finite element model updating of structures using a mixed optimization technique

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Chaos of motion is a common nonlinear phenomena. It looks like randomness on one hand, and has intrinsic elaborate orderliness on the other hand. Taking the advantage of detail-searching capability of chaos, numerous optimization techniques have been developed, which can escape from the local traps effectively. But chaos-based optimization techniques may take tremendous computing time and large amount of saving space in dealing with complex nonlinear optimization problems. Trust Domain method is a kind of Newton optimization technique. Is has a very high searching efficiency. A mixed optimization method is proposed by combining the high efficient searching capability of Trust Domain technique and the detail-searching capability of Chaos-based technique. The proposed method is tested with a two dimensions testing function. It is shown that the proposed method is more efficient and more prone to global optimization result.

Structural model updating is to update the analytical finite element model with the experimental modal data to achieve a model compatible with actual one. The procedure for model updating usually ends up as a problem of optimization. The objective function is usually nonlinear and with many local minimum. The more complex the structure, the more the optimization variables, and the more complex the objective function. It is crucial t for the optimization method to be able to reach global minimum. The proposed mixed optimization procedure is employed to update the analytical model of a truss beam structure. This structure is made up of 56 nodes and 164 members. The proposed method solve the optimization problem with 328 variables successfully, and an updated analytical which has consistent dynamic properties with actual structure is obtained.

5765-37, Session 8

A new approach to designing multilayer feedforward neural networks for modeling nonlinear restoring forces

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This study investigates the possibility of injecting parametric features into nonparametric identification techniques like neural networks in modeling nonlinear dynamic restoring forces. This affords the potential of creating relationships between model parameters in data-driven techniques and phenomenological behaviors in physics-based modeling, which is prompted by the needs in structural health monitoring and damage detections. Here a linear sum of sigmoidal basis functions is used in modeling nonlinear hysteretic restoring forces of single-degree-of-freedom oscillators under the force-state mapping formulation to showcase this idea. A constructive approach is proposed to guide the neural network initial design, where the number of hidden layers and hidden nodes as well as the initial values of the weights and biases are decided upon the characteristics of the nonlinear restoring force to be modeled rather than through indiscriminate numerical initialization schemes. Numerical simulations are presented to demonstrate the efficiency and engineered feature of this approach. A training example is provided to show that this approach enables neural networks to carry either physical or phenomenological "meaning" while remaining adaptive and thus powerful in system identification.

5765-38, Session 8

A new design strategy for optimal distribution of dampers in smart building structures

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A new strategy for structural control systems using passive dampers is proposed. In our current design practice, when we use some energy absorption devices, such as viscous dampers, in a building structure, the devices are uniformly distributed over the stories so that the input energy should not concentrate on a specific story. However, this design strategy is not always the optimum one in terms of their efficiency and costs. A unique strategy that does not utilize the uniform distribution of dampers is presented here. Dampers and story

stiffnesses are optimally designed so that the number of dampers needed is drastically reduced to achieve the same structural control performance. Our strategy is somewhat similar to the soft-first-story mechanism but is extended to more flexible and feasible.

There are many advantages in our proposed strategy. First, in the story which does not have dampers, more space can be used for offices and other purposes. And by reducing the number of dampers, it is also possible to lower the cost significantly. In addition, by making the energy flow much simpler, the reliability of the structural system is drastically improved. This fact implies that the damage scenario becomes clearer so that the structure should be more suitable for installing a structural health monitoring system because we need less sensors.

In this paper, the relation between distribution of dampers and the modal damping ratios is carefully examined to seek for the optimal solution. Then, the rigidities of the stories are adjusted to maximize the efficiency of the structural control systems. The performance of the control systems were evaluated using complex eigenvalue analyses. In addition, time series analyses were conducted considering several earthquake ground motions.

5765-39, Session 10

Efficient use of Lamb waves and their wavelet coefficients for damage detection of steel plates

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For the in-situ health monitoring of critical member used in civil engineering, ultrasonic guided Lamb wave-based non-destructive evaluation (NDE) is very suitable. However, a chief drawback of the Lamb wave techniques is that multiple modes exist at all frequencies and the modes are generally dispersive, which means that the received signals may be very complicated. To overcome these complications, selective transmitting and receiving of a single Ao mode within a frequency range can be adopted. Furthermore, a wavelet technique can be utilized to decompose the Lamb wave response into wavelet coefficients as a powerful tool for signal processing. The changes in the Lamb waves interacting with damage in the steel plates are successfully characterized by this wavelet technique, through the amplitude change of the wavelet coefficients. In this paper, the feasibility of detecting a line crack on the surface of a steel plate and loosened bolts in a joint steel specimen using the Lamb waves is investigated and the wavelet technique also shows great sensitivity in detecting any defect of the steel plates.

5765-40, Session 10

Distributed sensing of RC beams with HCFRP sensors

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Structural health monitoring (SHM) and damage detection have become increasing attractive for civil engineering structures. As a result, a number of novel sensors have been developed, recently. For monitoring the health of civil engineering structures, the sensors are required to be characterized with long-term durability, distributed and broad-based sensing feasibility. This paper addresses a novel type of sensor suitable for the SHM requirements in civil engineering, which is made of hybrid carbon fiber reinforced polymer (HCFRP) composite. The active materials are carbon fibers due to their electrical conduction, piezoresistivity, excellent mechanical properties and good resistance to corrosion. The HCFRP sensors are designed to consist of three types of carbon tows—high strength (HS), high modulus (HM) and middle modulus (MM), in order to realize a step-wise sensing function. The HCFRP sensors were bonded with epoxy resins on the bottom concrete surface and mounted with rebars in the RC beams to monitor the steel yielding, the occurrence and propagation of cracks. As designed, according to the electrical behavior of the HCFRP sensor and the mechanical state of the RC beams, the monitoring of the RC beams can be divided into four stages. In stage I before the yielding of rebars, there are no macro-ruptures of carbon fibers, and the electrical resistance changes slowly in proportion to the applied load. In stage II where the rebars yield, the HM carbon fibers are designed to rupture, which results in a sudden and obvious jump in electrical resistance. Thus, the yielding of the rebars can be clearly monitored by measuring the jump in electrical resistance. Stage III corresponds to the strain-strengthening stage, where the gradual ruptures of MM carbon fibers can further enhance the fractional increase in electrical resistance. At the end of this stage, the sudden rupture of MM carbon fibers can also result in a sudden and finite jump in electrical resistance. And the strain softening corresponds to stage IV, during which the HS carbon fibers begin to rupture. For this reason, the electrical resistance increases quickly and becomes infinite, finally. From the experimental results, it is revealed that the mechanical stages of RC structures can be clearly monitored with HCFRP sensors, and that the HCFRP sensors are characterized with broad-based and distributed sensing functions.

5765-41, Session 10

A heterogeneous network of vertical seismic arrays

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We are currently developing Terra-Scope, which is an extremely sensitive, high-fidelity, vertical seismic array that is inexpensive to construct and easy to install. Downhole instrumentation provides a unique opportunity to directly measure the effects of site geology on seismic waves. Vertical arrays have been very expensive to install and maintain , much like traditional structural seismic instrumentation. Due to limited technology, the traditional downhole array instrumentation is expensive and cumbersome. Also, there are significant uncertainties associated with the shortage of orientation devices.

The Terra-Scope system is an affordable 4-D seismic monitoring system based on independent, microprocessor-controlled Pods. The pods are nominally 50 mm in diameter, and about 120 mm long, and are expected to cost approximately $6000 each. An internal 16-bit, extremely low power MCU controls all aspects of instrumentation, 8 PGAs, and local signal storage. Each pod measures 3-D acceleration, tilt, azimuth, temperature, and other parametric variables such as pore water pressure and pH. The following parameters are independently controllable at each pod: pre-trigger length, post-trigger length, trigger time stamp, sampling rate, trigger level, trigger parameters, non-volatile storage, and calibration and self-evaluation. Each pod communicates over a standard digital bus (e.g. RS-485) through a complete GUI interface.

At the head of each array sits a local gateway (LG), about a 75 mm cube. The LG is based on a variable clocked RISC-based LINUX machine with large static memory and an embedded ethernet server. The WAN connection is wireless (e.g., direct radio link, two-way satellite) or wired as is convenient. The LG will aggregate and process the multiple data streams from array stations, and either push the data onto the web or store it until queried by the main server. Included in the LG is a GPS which will provide exact timing for all the array stations, as well as providing accurate array location. Local batteries are charged by an attached solar array, and when possible a hard-wired powered ethernet link will provide ample power for the entire array. The system architecture addresses the possibility of disconnection at every level. Each layer (sensor nodes, gateways, base stations) has some persistent storage which protects against data loss in case of power outage. Each layer also provides data management services.

5765-42, Session 10

Application of EM stress sensors in large steel cables

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In this study, the calibration and workability of elastomagnetic(EM) stress sensors on steel cables of Qiangjiang No. 4 Bridge in China are discussed. As an engineering application of ferromagnetic magnetoelasticity, the EM sensors make possible non-contact stress monitoring for steel cables and pre-stressed tendons on suspension and cable-stayed bridges, and the other ferromagnetic structures. With the steel structure itself as the actual sensor, and via quantifying the tension dependence of magnetic property represented by relative permeability, the EM sensor reliably evaluates the stress levels. The correlation of the relative permeability and tensile stress was derived through the calibration. The temperature influence was also tested. For the sake of automatic maneuvering, the calibration function incorporating the temperature-influencing factor was formalized. Calibration revealed that the magnetoelasticity of the multi-wire hanging cables performs similarly to each other, while that of the pre-stressed multi-strand cables are close to the single wire. In-situ measurements on Qiangjiang No. 4 Bridge demonstrated the reliability of the EM stress sensors.

5765-43, Session 10

Toward crack mapping of reinforced concrete members with distributed cable sensors for their coupled flexural-shear-torsional behavior

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Torsion combined with other actions such as shear and bending moments are major factors to consider in the design of reinforced concrete (RC) structures. The post-cracking behavior of such structures is yet to be fully understood and

various theories have been developed to study the issue. The internal stress distribution and the resulting deformation of the cross-sectional and the member are very complex. Issues related to this challenging deformation scheme are the surface shear strain that obeys the Mohr's circle, the shear flow zone resulting from the thin-tube analogy and the strain gradient along the depth of the cross-section resulting from warping of the cross-section that may obey the Bernoulli's law of deformation. Crack distribution and openings are function of several parameters including the reinforcement index and distribution. To address these issues, it is critically important to develop a viable means for surface crack mapping and to develop a framework of relating the measured surface crack information to the internal strain distribution in main reinforcements of an RC member. In doing so, the structural condition of the member can be assessed with the measured surface crack distribution and sizes.

In this paper, an attempt will be made to establish the relation between surface crack measurements and internal strains in rebar through mechanical analysis and validate it with the extensive measured data from the full-scale testing of a 48-foot-long girder. The conventional sensors such as extensometers that are deployed at discrete locations can not give crack opening and distribution due to unknown crack locations. However, recent developments in distributed cable sensors made it possible to automatically map surface cracks. For correlation studies, strains in main reinforcement are measured with strain gauges at select locations and the average, or smeared, strain on the surface of the member are also measured between two points by using linear variable differential transformers (LVDT). The information gathered from the distributed cable sensors will be used to refine existing theoretical and semi-empirical models for the evaluation of crack mapping in RC structures.

5765-44, Session 11

Conductivity-based strain monitoring and damage characterization of cementitious structural components

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The emergence of new structural materials opens exciting venues for improving the strength and durability of civil structures. High-performance cementitious composites (HPFRCC) are a special class of fiber reinforced cementitious composite (FRCC) that combine short polymer, steel or carbon fibers with a cement matrix to produce a material that undergoes strain-induced hardening when loaded in tension. While ultra-ductility and high damage tolerance are key mechanical attributes, this study explores the use of FRCC electrical properties to directly measure strain and the evolution of structural damage. In this study, the piezoresistive properties of HPFRCC structural specimens are exploited to directly measure levels of tensile strain and the initiation of strain hardening. To optimize the resistivity properties of the material without disrupting mechanical strength, small volume fractions of short steel or carbon fibers are included within the HPFRCC matrix. A low-cost wireless sensing unit is employed to directly impart electrical signals into HPFRCC structural components and to measure their corresponding electrical response. Data processing capabilities of the wireless sensing unit are exploited to locally interrogate electrical conductivity measures for identification of structural damage (micro- and macro-scale cracking). This novel sensing technology holds tremendous promise for advancing the ability to diagnose the health of civil structures in real-time. Towards this end, a realistic HPFRCC frame structure is employed with wireless sensing units monitoring the frame while it is cyclically loaded to failure.

5765-45, Session 11

Evaluation of impact-echo technique for structural components

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The effectiveness and accuracy of employing the impact-echo for NDE is examined via series of experimental studies using concrete and aluminum specimens with artificially induced flaws. Three aspects of the technique are examined, namely, (a) the principles and assumptions adopted, (b) apparatus used for testing and data acquisition, and (c) the method of data analysis. Plausible modifications are explored on the conventional impact-echo technique and their efficiency compared. These provided recommendations to increase the robustness of damage detection using the impact-echo technique. Experimental results showed that by replacing the conventional steel ball impactors with controlled actuators, a desired band excitation is possible. This reduces the complications due superposition of multiple frequency components and hence improving the accuracy in anomaly detection. It is found that by adopting more advanced signal processing techniques to the conventional Fast-Fourier transform (FFT) for signal analysis, the localization of defects can be improved. Lastly, by considering the dispersion nature and mode conversion of the traveling wave, complications exhibited in previous studies (Sansalone, 1997) due presence of a dynamic phase velocity can be accounted. This shows to give better interpretation and explanation of an erroneous margin encountered when the signal arrival times of wave reflections about flaw and boundary are not well spaced out. In general, this study illustrates the numerous issues relating to practical use of the commercialized impact-echo technique which can be improved by adopting recent advancement in smart materials and signal processing technologies.

5765-46, Session 11

Smart RC elements for long-life monitoring of civil infrastructure

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A research effort is launched at the University of Trento, to develop an innovative low-cost distributed construction system based on smart prefabricated concrete structural elements, capable of real-time assessment of the condition state of bridge structures. These elements will be produced with an embedded low-cost high-durability sensing system based on Fiber Optic Sensors (FOS), permanently connected to the Internet during the construction and the operation of the bridge. A Web-based Network of Tools translates the physical quantities appraised by the system into condition-state and safety indices, and makes them available to all of the actors involved in the production/maintenance process line of the structure. During the construction phase, the users can directly monitor the behavior of each single element, and control all the mounting operations such as assembling and post-tensioning. During the operation phase, the owner is provided with management tools for the day-to-day measurement of the condition state and the safety level of the structure. Fiber optics has been chosen as the most suitable sensing technology, in view of their durability and their expected low future cost: the target sensing system identified is a multiplexed FBG-based system capable of measuring finite displacements both in statics and dynamics. Damage detection strategies include the employment of strain-mode-shape-based vibration techniques. The performances of the system have been validated in the laboratory on two experimental prototypes of instrumented element. Each specimen consists of a 0.20.35.6m RC beam specifically designed for permanent instrumentation with 8 long-gauge FOS at the lower edge. The sensors are arranged inside a 3050mm cavity, and connected to the structure by means of steel supports. These consist of small drilled steel plates which have been welded to the stirrup reinforcement before casting the concrete. The system uses a single commercial interrogation unit and a software-controlled optical switch, allowing acquisition of dynamic multi-channel signals from FBG-FOS, with a sample frequency up to 625 Hz per channel. The scope of the laboratory experiment is to correlate the changes in dynamic response of the RC beam with different damage levels, using a direct modal strain approach. For each specimen, the testing protocol included three static load tests in which increasing damage is produced in the beams by means of hydraulic actuators. The maximum load levels applied during each test are associated to the opening of the first crack in concrete (A_1), the design serviceability load (A_2), and the first yielding of the reinforcing steel (A_3) respectively. The specimen is dynamically characterized in the undamaged state A_0, and at each level of damage A_1 A_2 A_3. The location and the extent of damage are evaluated through the calculation of damage indices which take into account the changes in frequency and curvature-mode shapes. The outcomes of the experiment show how the damage distribution automatically detected by the system is fully compatible with the damage extent appraised through visual inspections performed in accordance with popular bridge management systems, such as PONTIS. The experiment also demonstrates how a dynamic FO-based technology is feasible and technically effective when compared with the classical accelerometer-based approach. In addition, FOS exhibit features, such as durability and stability that make them definitively more attractive than electrical gauges for long-term monitoring of civil structures.

5765-47, Session 11

SMA-based smart damper/displacement transducer

C. Mao, H. Li, Harbin Institute of Technology (China)

Abstract: An innovative smart shape memory alloy (SMA) –based damper/displacement transducer was proposed in this paper. This damper/displacement transducer has comprehensive energy dissipation and strain self-sensing abilities (i.e. electric resistance vs. applied strain relationship) simultaneously. A smart SMA-based damper, incorporated into a building or a bridge, provides the potential to rapidly assess post-earthquake structural safety. First, tests were conducted on the hysteresis stress-strain-electric resistance relationship of SMA wires (diameter 1.2mm). These tests were carried out under sinusoidal

excitations with different loading frequencies at different ambient temperatures, to investigate the energy dissipation ability and strain self-sensing property of SMA wires. The experimental results indicate that the pseudoelastic hysteresis loops of the SMA wires are dependent on loading frequency. Moreover, the average sensitivity coefficient of electric resistance vs. applied strain of the SMA wires was identified to be 5.948 from the test results. Thereafter, conceptual design of the smart SMA damper/displacement transducer was presented. The main advantage of this damper is that the SMA wires in kernel of the damper are always in tension when subjected to earthquake excitations, which could avoid the buckling of the SMA wires even with small diameter wire. At the same time, deformation of the SMA wires is equal to the interstory displacement of structure if the damper was installed appropriately on the structure. Finally, shaking table tests for a scaled 5-story steel frame with and without the SMA dampers/displacement transducers, subjected to various earthquake excitations, were conducted respectively. This test aimed at verifying the effectiveness of this SMA damper/displacement transducer to mitigate structural earthquake response, at the same time, monitor structural interstory displacement response. During the test, the interstory displacements of the structure, which equals to the deformation of the SMA wires, are recorded by measuring the electrical resistance of the SMA wires. These interstory displacements measured by the SMA displacement transducer are compared with that measured by the LVDT displacement transducers attached to the structure. Furthermore, a dynamic one-dimensional constitutive model of SMA wire, proposed by Li and Mao (2004), is used to reproduce the force-displacement hysteresis loops of the SMA damper after the shaking table test. The results of the shaking table test indicate that the SMA-based smart damper/displacement transducer can not only mitigate structural seismic response effectively, but also monitor structural interstory displacement response accurately.

5765-48, Session 11

Design, characterization, and experimental use of an optimized MEMS acoustic emission device

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We describe the design, fabrication, testing and application (in structural experiments) of our 2004 (second generation) MEMS device, optimized for acoustic emission sensing based upon experiments with our 2002 (first generation) device. Both devices feature a suite of resonant-type transducers in the frequency range between 100 kHz and 1 MHz. The 2002 device was designed to operate in an evacuated housing because of high squeeze film damping, as confirmed in our earlier experiments. In additional studies involving the 2002 device, experimental simulation of acoustic emissions in a steel plate, using pencil lead break or ball impact loading, showed that the transducers in the frequency range of 100 kHz-500 kHz presented clearer output signals than the transducers with frequencies higher than 500 kHz. Using the knowledge gained from the 2002 device, we designed and fabricated our second generation device in 2004 using the multi-user polysilicon surface micromachining (MUMPs) process. The 2004 device has 7 independent capacitive type transducers, compared to 18 independent transducers in the 2002 device, including 6 piston type transducers in the frequency range of 100 kHz to 500 kHz and 1 piston type transducer at 1 MHz to capture high frequency information. Piston type transducers developed in our research have two uncoupled modes so that twofold information can be acquired from a single transducer. In addition, the piston shape helps to reduce residual stress effect of surface micromachining process. The center to center distance between etch holes in the vibrating plate was reduced from 30 m to 13 m, in order to control squeeze film damping. As a result, that the Q factor was increased to 2.37 from 0.18 for the 100 kHz transducer, and therefore the 2004 device operates at atmospheric pressure. Sensitivities of transducers were also increased, by enlarging transducer area, in order to capture significant small amplitude acoustic emission events. The average individual transducer area in the 2004 device was increased to 6.54 mm2 as compared to 2.51 mm2 in the 2002 device. In this paper, we report the new experimental results on the characterization of the 2004 device and compare them with analytical results. We show improvements in sensitivity by capacitance measurement, as capacitance is directly proportional to sensitivity of transducers, and by acoustic emission simulation using pencil lead break. Improvement in damping is also evaluated by admittance measurement in atmosphere, where the mechanical admittance effect is observed because the Q factor is sufficiently high. Pencil lead break simulations in atmosphere also show that transducers can operate in atmospheric pressure. Finally, we present acoustic emission application of the 2004 device on the crack propagation problem using a steel beam specimen, precracked in fatigue, in a four-point bending test.

5765-49, Session 11

GPS monitoring in urban zones: calibration and quantification of multipath effects

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The issue of accurate assessment and evaluation of aging Civil Infrastructure Systems (CIS) is of growing concern in this country and has stimulated interest in continuous monitoring programs. Such health monitoring has traditionally utilized strain gages and accelerometers, both of which are not capable of completely capturing the global displacements of the structure. An alternative sensing technology, Global Positioning Systems (GPS), can overcome these limitations and track both the static and dynamic displacements of the structure so that settlement, thermal expansions, permanent offsets, and the background component of wind-induced response can all be measured.

The present study is an extension of an on-going project in which GPS is being utilized for long-term monitoring of tall buildings in Chicago [1]. This early work has verified the viability of GPS for structural monitoring through field calibration studies and full-scale deployment. However, through the latter, the impact of multipath effects and nonstationarity of the GPS reference was underscored. In particular, multipath effects produce the largest untreated error source for differential GPS monitoring, especially in urban canyons. The errors are generated as satellite transmissions are reflected and these reflected versions of the original signal arrive at the antennae with a slight time delay. While multipath can be countered by utilizing choke ring antennas, these can only defray reflected signals bounced from low elevations relative to the antenna plane. As common in urban zones, taller buildings adjacent to the antenna can send reflected signals from higher elevations, where the antenna's concentric rings can do little to intercept them. This has motivated the present effort to further validate the performance of GPS in urban canyons via a comprehensive calibration study, utilizing next generation real time kinematic (RTK) systems and scalable networks within the context of structural health monitoring.

This paper discusses the experimental program that established a scalable, local GPS network with portable shaking tables to mimic dynamic motions of structures serving as reference and rover stations in the array. Performance is validated by benchmarking GPS displacements against simulated target motions and positions measured by more traditional sensing technologies: accelerometers and total station rapid scan surveys. The tests include controlled multipath introductions using deployable reflective surfaces in various orientations, allowing the characterization of multipath distortion and its systematic removal. Thus, the efficacy and accuracy of the RTK network in the context of structural health monitoring is evaluated in this study, using newly developed software capable of providing warnings for infrastructure owners and management, enabling GPS to be successfully deployed for structural monitoring in dense urban zones.

Reference:

[1] Kijewski, T. and Kareem, A. (2003), "GPS for Monitoring the Dynamic Response of Tall Buildings: Experimental Verification and Full-Scale Application," Proceedings of Structures Congress 2003, ASCE, Seattle, May 29-31.

5765-50, Session 11

Wireless sensors for wildfire monitoring

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Wildfires are increasingly expensive disasters in terms of both property damage and life safety. One way to monitor wildfires and impending wildfire conditions is by using wireless sensor technology to collect environmental data such as temperature, relative humidity and barometric pressure. In this paper, we describe the design of the FireBug system for wildfire monitoring incorporating wireless sensors, and report results from field testing during a prescribed burn near San Francisco, California.

The sensors are aggregated on a printed circuit board which plugs into the Mica2 mote. The Mica2 mote, manufactured by Crossbow Technology, Inc.,hosts an Atmel 128L CPU running the Tiny operatingsystem (TinyOS), executing programs written in thenesC programming language. The collected data is stored into a MySQL database, which is queried by a browser-based client interacting with a webserver database bridge.Performance of the FireBug system during a prescribed burn at Pinole Point Regional Park (Contra Costa County, California, near San Francisco) is promising. Sensors within the burn zone recorded the passage of the flame front before being scorched, and sensors outside the flame front recorded temperature increases and humidity decreases as the flame front advanced. Temperature gradients up to 5 C per second were recorded. The maximum temperature recorded was 95 C, the minimum relative humidity 9%.

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5765-04, Poster Session

Review of in-situ fabrication methods of piezoelectric wafer active sendor for sensing and actuation applications

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Structural health monitoring (SHM) is important for reducing maintenance costs while increasing safety and reliability. Piezoelectric wafer active sensors (PWAS) are used in SHM applications are able to detect structural damage using Lamb waves. PWAS are small, lightweight, unobtrusive, and low cost. PWAS achieve direct transduction between electric and elastic wave energies. PWAS are essential elements in the Lamb-wave SHM with pitch-catch, pulse-echo, and electromechanical impedance methods.

Traditionally, structural integrity tests required attachment of sensors to the material surface. This is often a burdensome and time-consuming task, especially considering the size and magnitude of the surfaces measured (such as aircraft, bridges, structural supports, etc.). Temporary sensors are a hassle to install; there are some critical applications where they simply cannot accomplish the task required. PWAS can be permanently attached to the structure and offer a permanent sensor solution. Existing ceramic PWAS, while fairly accurate when attached correctly to the substance, may not provide the long term durability required for SHM. The bonded interface between the PWAS and the structure is often the durability weak link. Better durability may be obtained from a built-in sensor that is incorporated into the material. This paper gives a brief literature review of the state of the art on the in-situ fabrication of PWAS using different approaches, such as piezoelectric composite approach; piezoelectric thick film; nano-fabricated piezoelectric films. This literature review will present the principal fabrication methods and results existing to date. Directions for further research will be also explored.

5765-114, Poster Session

Nonlinear observability of the extended Kalman filter

J. Pan, Zhejiang Univ. (China); R. Wang, Univ. of California/Irvine

System identification and damage detection for structural dynamic systems have received more and more attention in recent years. One of the time domain methodologies, the extended Kalman filter (EKF), has been widely applied in identifying the states and parameters of dynamic systems simultaneously. In EKF algorithm, the original dynamic systems have been transformed into nonlinear state-space system models. Therefore, the observability problem of the nonlinear state-space systems is required to be investigated before the application of EKF algorithm. In this paper, the definitions and the rank criterion of nonlinear observability for continuous-time systems are presented, which are only discussed in a few areas involved nonlinear systems previously. The analysis on the nonlinear observability of single-input, single-output and single-input, multiple-output state-space structure systems show that the rank criterion presented can provide sufficient conditions for the observability of the nonlinear systems to be identified. In practice, this criterion gives out a theoretical guideline for the selection of appropriate sensor types and locations before putting up the system identification, which is quite important but neglected in most of the EKF-identification literature thus far.

5765-115, Poster Session

Smart vibration-control analysis of seismic response using MR dampers in the elevated highway bridge structures

S. Yan, H. Zhang, Shenyang Jianzhu Univ. (China)

Elevated Highway Bridge (EHB) is one of the most important bridge structure types and plays more and more rule in the city transportation with the development of transportation enterprise and construction technology. The seismic performance of the bridge has been paid attention by scientists and engineers all the time in the world. However, numbers of these kind bridges were damage even collapse during earthquakes especially during the Kobe earthquake in Japan in 1995. It is shown that serious problems exist in design and construction of HEB. Rubber bearing isolation technology that is one of the most important structural vibration control ones has been applied in real civil engineering and has a lot of benefits from its implementation. The magnetorheological (MR) fluid is a kind of smart materials and the damper made of it has efficiency in structural vibration control during wind and earthquake ground motion. A new smart control method that combines MR damper and rubber bearing isolation technology is put forward to increase damping and control effects of EHB in the paper. The dynamic calculating model and equation of motion of the system are set up theoretically and the LQR semi-active control algorithm of seismic response for HEB is discussed to reduce effectively the responses of the structure; The non-linear calculation model of the piers that rigid degradation is considered and numerical simulative calculation is carried out by Matlab program. The number and location of the dampers as well as the maximum control force of the damper are the most important parameters for the controlled system, and the rubber bearing and connection forms of the damper play also important rule in the control efficiency. A real EHB structure that is located in Ashan city, Liaoning province in China is used as an example to be calculated under different earthquake wave records. The results of the calculation show that it is effective to reduce seismic response of the elevated highway bridge structures by combining vibration insulation with semi-active control technique under the earthquake ground motion. The locations of MR dampers and structural parameters will influence seriously to the effects of structural control. The conclusions that are more similar to reality will be gained if non-linear affection of the piers is considered.

5765-116, Poster Session

Self-diagnosing and self-healing mortar using conductive additives and microcapsules

S. Park, Daejeon Univ. (South Korea)

Two new materials were tested and their applicability was investigated so as to give the capabilities of self-diagnosis and cure to mortar.

In the research for giving self-diagnosing capability, conductive mortar intermixed with cokes and milled carbon fiber was first produced. Then after examining change in the value of electric resistance and AE characteristics before and after the occurrence of cracks at each weight-stage, the correlations of each factors were analyzed.

The core materials which is using for self healing are encapsulated for having long term resisting properties to the mortar. Various membrane structures of microcapsule are tested and material properties of mortar and concrete which contain microcapsules are examined.

The capsuled are confirmed by SEM and optical microscope. The damages and survival of the capsules are confirmed by chemical HPLC methods. Finally the microcapsules which can be used for self healing of cracks or defects of mortar are developed through the various experiments. The curative capability resulted from the action of repairing material inside the capsules when cracks take place is examined.

5765-117, Poster Session

Interface transferring mechanism and error modification of FRP-OFBG strain sensor based on creep theory

J. Li, Z. Zhou, J. Ou, Harbin Institute of Technology (China)

As the strain-sensing element of structural health monitoring, the study and application of the Fiber Reinforced Polymer-Optical Fiber Bragg Grating (FRP-OFBG) has been widely accepted. Although there have been some significant results on the interface transferring mechanism and error modification, the creep influence on them were not taken into account when long time used and under high temperature. This paper takes the FRP-OFBG sensor as an object of study. Firstly, creeping cures and functions have been obtained through the unilateral tensile creep experimentation. Secondly, making use of the above, the interface strain transferring mechanism of FRP-OFBG strain sensors has been derived. And then, according to the average stain, the error modification expression based on the creep can be obtained. Finally, comparing with the researches before, the creep of FRP-OFBG sensors is the one of important reasons, which affects the longer monitoring results. The achievements not only deepen the interface transferring mechanism, but also establish the base of the life estimating of sensors.

5765-118, Poster Session

Studies on the mechanical properties of carbon fiber reinforced porous concrete for planting

S. B. Park, Chungnam National Univ. (South Korea); J. Kim, Hanil Eco-Concrete Co. (South Korea)

The mechanical properties of fiber reinforced porous concrete for use as a planting material were investigated in this study. Changes in physical and mechanical properties, subsequent to the addition of carbon fiber and silica

fume, were studied. The effects of recycled aggregate were also evaluated. The applicability as planting work concrete material was also assessed. The results showed that there no remarkable change in the void and strength characteristics following the increase in proportion of recycled aggregate. Also, the mixture with 10% added silica was found to be most effective for strength enforcement. The highest flexural strength was obtained with 3% added carbon fiber. It was also noticed that PAN-derived carbon fiber is superior to pitch-derived ones in view of strength. The evaluation of its use for vegetation showed that the growth of plants was directly affected by the existence of covering soil, in case of having the similar size of aggregate and void.

5765-120, Poster Session

Strain transfer of embedded fiber Bragg grating sensors

D. Li, H. Li, Dalian Univ. of Technology (China)

The relationship between the strains measured by a fiber Bragg grating sensor and the actual structural strains is deduced, then the average strain transfer rate computed by the formulation developed in this paper is compared with available experimental data. The critical adherence length of an optical fiber sensor is determined by a strain lag parameter, which contains both the effects of the geometry and the relative stiffness of the structural components. The analyses shows that the critical adherence length of a fiber sensing segment is the minimum length with which the fiber has to be tightly glued to a structure for adequate sensing. The strain transfer rate of an optical fiber sensor embedded in a multi-layered structure is developed in a similar way, and the factors that influence the efficiency of optical fiber sensor strain transferring are discussed. It is concluded that the strains, sensed by a fiber Bragg grating, have to be magnified by a factor (strain transfer rate) to equal exactly to the actual structural strains.

5765-121, Poster Session

Piezoelectric paint sensor for real-time structural health monitoring

Y. Zhang, S. Zhu, Lehigh Univ.

Civil and mechanical systems are critical to the nation's economical growth and public safety. However, they are susceptible to deterioration and damage over their service life time due to environmental loading, material aging, misuse and fatigue. Without proper structural health monitoring and subsequent corrective actions, the flaws in the aging structures could eventually lead to catastrophic failures. Monitoring the structural health condition of civil and mechanical systems generally leads to a prolonged life and enhanced reliability through information-based operation and maintenance. The replacement of our present-day manual inspection with automatic health monitoring would substantially reduce the associated life-cycle costs and improve the operating efficiency of structural condition assessment procedures as well as reliability of the results. Sensors, which collect data for further information processing, are core component of any viable structural health monitoring system. Continuous on-line structural health monitoring can be achieved through the use of advanced sensors developed for real-time structural health monitoring applications. Piezoelectric materials, because of its electro-mechanical coupling property, can be used as sensors and have recently gained an increasing popularity in structural health monitoring applications. However, most piezoelectric materials are typically brittle; prefabricated piezoelectric sensors do not fit surfaces with complex geometry, and these sensors do not work well where strain is large as the sensor may crack. To overcome these problems, a polymer-based piezoelectric paint material has been developed and recently used for sensors. The piezoelectric paint is composed of tiny piezoelectric particles mixed within polymer matrix and therefore belongs to "0-3" piezoelectric composite. A novel in-situ fabrication technique has been developed at Lehigh University to apply large area of piezoelectric paint directly onto the surface of host structures in a very efficient manner. Because of the electro-mechanical coupling properties of piezoelectric paint, the dynamic responses of host structures can be monitored by measuring the output voltage signals from the piezoelectric paint sensor. Piezoelectric paint sensors hold a great potential for dynamic strain sensing applications due to the ease with which their mechanical properties can be adjusted, low fabrication cost, ease of implementation, and conformability to curved surface Additionally, a novel surface crack detection technique has been conceived and validated experimentally, in which cracks of the host structure is detected by observing the measured signals from an piezoelectric paint sensor with multi-electrode configuration. The piezoelectric paint sensor is ideal for surface crack detection in locations with complex geometry, such as welded joints, which conventional sensors are ill equipped to do.

5765-122, Poster Session

A new, low-cost, stress sensor for battery-free wireless sensor applications

A. R. Bowles, J. G. Gore, QinetiQ (United Kingdom); J. G. Tomka, Charles Darwin Univ. (Australia)

Battery-free, wireless sensor systems would benefit from the availability of a stress or strain sensor that exhibits a large enough property change to allow simplification and power reductions in the associated measure and transmit circuitry. A new sensor has been developed specifically for this purpose which uses the large inductance changes exhibited by ribbons of cobalt rich amorphous soft magnetic alloy under applied stress. In comparison to semiconductor strain gauges, which show a maximum change in resistance of 10% under stress, the new inductive sensor demonstrates a change in inductance of 350%, when strained to its maximum working level. The current realisation of the stress sensor changes from 54 microHenries and an electrical quality factor of 4 to 190 microHenries and a quality factor of 2.5 over its full stress range. Although, amorphous magnetic alloys are inherently sensitive to external magnetic fields, a simple, biasing technique renders the stress-sensing device magnetically insensitive. As the amorphous magnetic alloys are used in transformer cores, they are produced in large volumes and therefore realise an extremely low cost sensor.

A simple, cheap and low power electrical circuit has been designed that, in combination with the sensor, functions as a battery-free sensor 'tag'. The tag incorporates the sensor in a LC resonant circuit, which derives its power inductively from a transceiver system via a tuned antenna. The resonant circuit of the sensor in turn modulates the resonant frequency of the tuned tag antenna to influence the electromagnetic coupling between the tag antenna and the transceiver. As the inductance of the sensor changes with stress loading, the modulation frequency of the tag antenna changes. The transceiver detects periodic power fluctuations, which correspond directly to the resonant frequency of the tag circuit and hence the stress being experienced by the inductive sensor. The transceiver to sensor tag range has been extended up to 1m, which is achieved through the extremely low power demands of the sensor tag and its electronics.

Demonstration units have been developed as vehicle tyre pressure monitoring systems and as a polymer patch sensor for measuring planar strains. It is believed that the sensor and associated tag electronics could be manufactured for less than $1.

5765-123, Poster Session

A novel fiber Bragg grating-based geophone for seismic exploration

Y. Zhang, H. Cui, Z. Yin, Stevens Institute of Technology

In the oil and gas exploration industry, seismic reflection surveys from artificially created seismic waves are performed to delineate subsurface structure of the Earth. By measuring the reflective sound wave, one obtains information as to the possible presence of oil and gas reserves beneath the Earth surface. During the survey a highly sensitive geophone is especially important to collect the reflected seismic waves effectively.

In this paper a new type of geophone based on the fiber Bragg grating (FBG) sensor is introduced. The fiber Bragg grating sensor has a number of intrinsic advantages such as lightweight and compact, sensitive to dynamic strain signals, low power consumption and resistant to corrosion and fatigue. The principal advantage over the conventional geophone design is that the FBG geophone is immune to electromagnetic interference because there is only optical signal in the fiber involved. Multiple FBG sensors are also suited for multiplexing, making them ideal for networked/array deployment on a large scale.

We have developed an eight channel FBG sensor geophone detection system which consists of a broadband light source, eight channel FBG sensors array, demodulator fiber gratings, optical coupler, signal detection and processing hardware. The FBG sensor array is formed by eight FBG sensors which are multiplexed by space division multiplexing (SDM) and wavelength division multiplexing (WDM) technology.

The basic principle of the FBG geophone is that the sensor responds to the seismic wave by means of the acceleration-induced strain change on the fiber grating. The strain variation can be transformed into the fiber Bragg grating wavelength shift through a spring-mass mechanical design. Our design of the demodulation system converts the wavelength shift into light intensity variation

after demodulation, and subsequently transferred to an analog electronic signal processed by custom-designed electronic filters and amplifiers. In this way, a very small strain change can be readily discerned through the detection of wavelength shift in FBG sensors.

By adjusting the mechanical parameter of the spring/mass configuration, the natural response frequency of the system can be mechanically tuned within certain range to get more information from deep layer effectively. Several mechanical damping techniques are compared and discussed as an essential supplementary to the design. Temperature compensation is also discussed as an important concern in this sensor system.

The seismic field test was carried out with the help of an oil field survey company in May, 2004. The eight FBG geophones were formed in a linear array with 50 meter separation, connecting each other with commercial optical cable. Ten explosives with 8 meter depth were used as sound sources and the conventional geophones (model 20DX) were taken for comparison. A high dynamic range of 80 dB is achieved in this system. Data processing and analysis also shows the system response frequency bandwidth at 10-100Hz in shallow layer and 10-140Hz in medium and deep layer separately.

Some extensional works are scheduled in the near future, which will enable the FBG geophone to become a practical product for application of seismic exploration in oil and gas industry.

5765-124, Poster Session

A new kind of ice-pressure sensor based on FBG

Z. Zhou, C. Lan, J. Ou, Harbin Institute of Technology (China)

Ice-pressure is one of the most important load for the offshore structures, especially for offshore platforms, in the high-latitude area. Traditional ice-pressure monitoring devices based on strain gauge lack good durability and stability, whereas FBG shows great advantage of corrosion resistance, absolute measurement, high accuracy, electro-magnetic resistance, quasi-distribution sensing, absolute measurement and so on, which is proper to make ice-pressure sensor to adapt aggressive condition. In this paper, a novel ice-pressure sensor has been developed based on FBG's strain sensing properties.

Firstly, based on the mechanics of quasi-strength cantilever, the structure of ice-pressure sensor is designed. And the structure shows the feature of temperature self-compensation. The other prominent feature is that the pressure gotten from the ice-pressure sensor is independent of the load position, which satisfies the ice condition.

Secondly, such ice-pressure sensor's sensing prosperities based on FBG have been tested. And the experiment to test its fatigue properties has also been carried out.

Finally, according to the need of practical application, the size of the ice-pressure sensor is optimized.

The research results show that ice-pressure sensor based on FBG has good linearity and repetition. And it is not affected by temperature changes. It can be used to monitor ice-pressure of offshore platform conveniently.

5765-125, Poster Session

Healable polymer composites

T. A. Plaisted, J. B. Isaacs, S. Nemat-Nasser, Univ. of California/San Diego

We are developing a fiberous composite that utilizes a healable polymer as the matrix phase of the material. Damage in the form of cracking in the polymer, for instance, may be healed by application of moderate heat to repair covalent cross-links within the material. The healing mechanism is a result of thermally reversible Diels-Alder bonding between constituent furan and maleimide monomers, such that the repair process may be carried out numerous times. Novel apparatus and procedures are developed to obtain controlled cracking within the material and further to allow quantitative measurement of the healing process. The healing properties of this material make up one component of a larger multifunctional composite with other integrated properties, including electromagnetic, thermal, and sensing functions also being developed at the University of California, San Diego.

5765-128, Poster Session

Influence of optical fiber coating damage in the light-transmissivity characteristics of microbend sensors

F. Campero Verdun, Florida Institute of Technology and GFA International; P. J. Cosentino, Florida Institute of Technology

A laboratory testing and engineering modeling study was completed to determine the influence of fiber optic coating damage caused by microbend contact on the performance of microbend sensors developed based on relatively low cost single-sided microbending technique using a multimode optical fiber. A testing method was designed, developed and implemented to determine the loads that caused optical fiber glass-coating debonding and coating fracture.

Finite Element models of the fiber-deformer system were developed to study the failure modes and predict the stresses that caused this failure. Loads and displacements predicted by Finite Element models were found to be in good agreement with load and displacement values observed during the experimental analyses.

It was found that optical fiber coating physical damage caused by contact, such as coating delamination and fracture does not affect the recovery of the light transmissivity properties of the optical fiber. After coating failure, contact between deformer and glass (core and cladding) occurred, resulting in noticeably greater light transmissivity losses. Viscoelastic effects were found to influence the behavior of the fiber-deformer system. It was also found that glass-coating debonding and coating fracture during a load-unload cycle are major causes of variability and error during microbend sensor calibration.

5765-129, Poster Session

Development of automatic data collection for PWAS-based structural health monitoring

W. Liu, V. Giurgiutiu, Univ. of South Carolina

Crack detection through piezoelectric wafer active sensors (PWAS) is emerging as an effective and powerful technique in structural health monitoring (SHM). PWAS act as both transmitters and receivers of guided Lamb waves. In one application, PWAS are used as phased arrays for far field damage detection using Lamb-wave scanning. This method was named embedded ultrasonic structural radar (EUSR). In another application, PWAS are used for near and medium field damage detection using standing Lamb waves and the electrome-chanical (E/M) impedance technique. One important issue associated with the PWAS-assisted SHM is the connectivity between the PWAS arrays and the measurement instruments. An automatic signal collection unit is essential in the automatic data collection of PWAS signals. In EUSR applications, the transmitter and receiver PWAS have to be switched several times in a round-robin fashion. In E/M impedance applications, measurements of impendence of large number of PWAS need to be done with an impendence analyzer. A program-controlled unit can quickly and precisely execute the data collection in a way which is more efficient and reliable than the manual switching operations. In this paper, we present an innovative design of a LabView-controlled signal collection unit for PWAS-assisted SHM. This paper presents the hardware circuit construction and the qualification test along with the control LabVIEW program for automatic collection of EUSR and E/M impedance data. The control program is easy to implement and can be integrated into an upper level program that executes the whole task of signal acquisition and analysis.

5765-130, Poster Session

An initial investigation of the large strain and fatigue behavior of piezoelectric wafer active sensors

J. E. Doane, V. Giurgiutiu, Univ. of South Carolina

The goal of research presented in this paper is to develop the characteristics of piezoelectric wafer active sensors (PWAS) under large strain and fatigue conditions. To test the characteristics of the PWAS under large strain conditions, the sensor was bonded to an aircraft grade 2024 aluminum tensile test specimen and subjected to monotonic tensile loading. The baseline impedance was recorded at zero strain and additional readings were recorded at 200 micro-strain intervals until failure of the PWAS occurred. Minimal changes occurred to the impedance signature until 5000 micro-strain was exceeded. Eventually the PWAS failed in tension at approximately 7200 micro-strain. Theoretical data is being developed to determine how the frequencies and resonance qualities change due to increased tensile loading to compare to the experimental data.

For fatigue testing, the PWAS was again bonded to a 2024 aluminum test specimen and the specimen was loaded in fatigue. Appropriate mean loads and amplitudes were calculated to cause failure of the substrate at various values between 100 thousand and 10 million cycles. The baseline impedance reading was taken with the mean load applied at the beginning of the tests and at predetermined cyclic intervals. Small settle-in changes occurred in the impedance readings in the first 30 to 40 thousand cycles. Beyond this the PWAS readings were relatively unchanged until the metallic specimen finally broke under fatigue. At the time of submitting this abstract, measurements have indicated that the PWAS survived in fatigue up to 500 thousand cycles. Additional testing for up to 1, 5, and 10 million cycles is under way and will be reported in the full paper.

5765-131, Poster Session

Embedded wavelet packet-based signal compression algorithm in wireless sensors for structural health monitoring

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Structural health monitoring (SHM) is very important for large structures like suspension- and cable-stayed bridges, towers, offshore platforms, tall buildings and so on. Some advance technologies for infrastructure health monitoring have been caused much more attentions, in which the Wireless Sensor Networks (WSNs) is recently received special interests. Many projects and diverse applications for these systems are currently being explored. The WSN would have lower capital and installation costs as well as ensure more reliability in the communication of sensor measurements. However, in the context of untethered nodes, the finite energy budget is a primary design constraint. Therefore, one wants to process signal as much as possible at the sensor nodes to reduce the number of bits transmitted, particularly over longer distances.

In this paper, a WSN is proposed for health monitoring of the structures, and a laboratory prototype was designed and developed to demonstrate the feasibility and validity of the proposed WSN. To minimize the energy consumption and prolong the lifetimes of sensor nodes, the wavelet packet transform (WPT) is introduced as an alternative approach to reducing and compressing the data to be transmitted. To test the effectiveness of the proposed method, the ASCE structural health monitoring benchmark data were analyzed. The effect of noisy data is considered and demonstrating that proposed method can be used not only for effective transmission of the data but also for denoising and feature extraction.

5765-51, Session 12

Corrosion and corrosivity monitoring system

R. D. Braunling, P. F. Dietrich, Honeywell International

Maritime aircraft operate in a particularly hostile corrosive environment. Salt is always present on the carrier deck and can be encountered at altitudes up to 1500 feet above sea level. Severe corrosive attack can cause rapid damage to flight critical structure, which has a detrimental effect on operational capability. In order to minimize the effects of corrosion, maintenance personnel must regularly schedule expensive and time-consuming inspections. Currently, maintenance uses visual inspections, man-in-the-loop inspections with various types of NDE equipment, and regularly scheduled strip and search inspections. Clearly, there is a need for an autonomous corrosion monitoring system that provides reliable early warning corrosion information suitable for the implementation of Condition Based Maintenance.

Honeywell International has developed and flight-tested a Corrosion and Corrosivity Monitoring System (C2MS) for the Office of Naval research. The C2MS is a multi-function corrosion sensing system for Navy helicopters. It detects galvanic corrosion in the main gearbox and monitors environmental conditions in the floorboard compartments to determine the need for structural maintenance. The C2MS sensors on the main gearbox periodically send a small electrical signal through the main gearbox fastener and housing to measure the conductivity of the assembly. The conductivity information is used to determine if galvanic corrosion is present in the gearbox. The floorboard compartment sensors use a surrogate metal coupon for the measurement of the corrosivity of the environment. The information from this sensor is used to recommend extensions to the calendar based maintenance schedule.

The C2MS has two Data Collection Units (DCUs) to store the corrosion data. One for the main gearbox and one for the floorboard compartments. Long operational life (greater than 2 years) for the sensors and compactness are addressed in the DCU design. The data from the DCUs is collected by a Personal Digital Assistant and downloaded to a Personal Computer where the corrosion algorithms reside. The personal computer display provides the location(s) of galvanic corrosion in the main gearbox as well as the recommended date for floorboard compartment maintenance.

This paper presents technical details of the corrosion and corrosivity algorithms for condition based maintenance. Some practical design issues for low-power, long-life, battery operated sensor systems are discussed. Flight test results of the C2MS are presented.

5765-52, Session 12

Wireless low-cost corrosion monitoring sensors for reinforced concrete structures

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Corrosion of embedded reinforcing steel and the resulting deterioration of concrete structures is a worldwide problem. Structures exposed to marine environments or deicing salts are particularly at risk. Corrosion damage reduces the service life of a structural member and can create a serious safety hazard. Visual inspections are not effective in identifying the initiation and extent of corrosion that remains concealed until cracking and spalling occur. Traditional techniques for determining the presence, extent, and rate of corrosion are invasive and may be time consuming, expensive, and difficult to interpret. They are often employed only after corrosion damage is detected. Early detection of corrosion within reinforced concrete structures would give the owner the opportunity to remedy the situation before structural damage occurs.

Three types of corrosion monitoring sensors are under continuing development. The sensors provide a method of non-invasive and low cost early detection of corrosion in reinforced concrete. The embedded sensors are wirelessly powered by inductive coupling, and therefore, do not require batteries. Unlike traditional techniques that require an electrical connection to the reinforcing steel, the sensors use steel wires as sensing elements that are exposed to the same environmental conditions as the embedded reinforcement. The behavior of these sensors has been extensively explored in wet and dry, hot and cold, chloride and non-chloride concrete environments.

All three types of sensors detect corrosion thresholds and respond at a different characteristic frequency depending on the condition of the external steel sensing wire. The sensors provide binary information about the extent of corrosion within the concrete member. Different corrosion thresholds may be detected by varying the diameter of the steel wire. The first type of sensor uses a single characteristic frequency, while the second type of sensor uses a reference characteristic frequency and an additional sensing frequency. The third type of sensor is completely hermetically sealed and relies on the phase dip and quality factor of the characteristic frequency to determine the state of the external steel sensing wire.

The feasibility of the threshold sensors has been demonstrated through accelerated corrosion tests of reinforced concrete members. Further accelerated corrosion testing is underway. Research is also continuing in obtaining analog information about the extent and rate of corrosion of the steel wire from these sensors.

5765-53, Session 12

Quantitative corrosion monitoring and detection using ultrasonic Lamb waves

G. A. Gordon, R. D. Braunling, Honeywell International

Corrosion is a major problem for airframe operators. On some aircraft, the United States Air Force expends up to 50% of their maintenance effort responding to corrosion related issues, which has resulted in yearly documented costs of over $800 million. For the aircraft industry in general, the direct costs of corrosion are estimated at $2.2 billion. As part of their strategy to control corrosion, airframe operators constantly seek to improve their ability to anticipate, manage and identify corrosion activity. Although ultrasonic techniques are an accepted approach for the direct measurement of corrosion, they are most widely used for periodic monitoring in a point measurement modality.

Ultrasonic Lamb wave inspection is potentially an attractive method for monitoring shell structures continuously. One of the drawbacks of using Lamb

waves is their dispersive nature that dictates a variation in velocity with frequency and mode type. In this paper, we report on a technique capable of imaging local areas from a fixed location using a dispersion-compensated Lamb wave synthetic aperture approach. The test apparatus is described and results are given for the fundamental symmetric and antisymmetric mode detection of corrosion pitting.

Ultrasonic synthetic aperture imaging is inherently a spatial averaging technique that benefits from an attendant improvement in signal to noise performance. Nonetheless the processed images contain distorting components and speckle structure. In order to develop an automated detection approach it is important to quantify the impact of these image-degrading mechanisms. The sources of these image features, including both deterministic and random sources, are examined and modeled. Weibull statistics are used to characterize the ultrasonic backscattered noise and the distribution parameters are shown to vary with image location since the noise statistics are not spatial stationary. An algorithm is developed to quantify the uncertainty in the corrosion detection and is extended to allow assign of a constant false alarm probability to any region of the monitored area.

5765-54, Session 13

A novel intensity and wavelength-division multiplexing FBG sensor system

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We propose a novel intensity and wavelength-division multiplexing (IWDM) fiber Bragg grating (FBG) sensor system using a tunable multiport fiber ring laser. In contrast with the broad-band source, a laser source provides a higher power within a narrow spectral width and, thus, improves the signal-to-noise ratio (SNR). The light source of this sensor system is a tunable fiber ring laser with a Fabry-Perot filter for wavelength selection. The laser output consists of three ports of a 2x4 couple that is connected by three fiber couples with different coupling ratios. The output ratio between the different lasing branches can be designed according to the coupling ratios of the three fiber couplers. The different output powers of a multiport fiber laser are used to address the information reflected from the sensing FBGs, even if the Bragg wavelengths of the FBGs connected at different laser output ports are identical. So it is unnecessary for us to fabricate specified peak reflectivities of FBGs for intensity multiplexing. In the WDM technique, the multiplexing number of the sensing gratings is limited by the reflective band of each FBG sensors and the whole bandwidth of the light source. Therefore, the wavelengths of sensing grating cannot cross each other. On the contrary, our proposed scheme for the IWDM technique allows for the peak reflectivity of each grating at different lasing branches crossing each other. When spectral overlap occurs between two sensing gratings, the output intensity is the sum of each grating's output intensity. As a result, the overlap output still can be used to address the sensing information without the unmeasuable gap. For the IWDM technique, our proposed fiber grating sensor system can enhance the sensing capacity, signal-to-noise ratio, and sensing resolution.

5765-55, Session 13

Distributed strain measurement of a large-scale reinforced concrete beam-column assembly under cycle loading

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Fiber optic sensing technology has been treated as an innovative monitoring strategy for civil structures. As a distributed sensing technique suitable for large-scale civil infrastructures, fiber optic sensing technology is being considered as a promising method for structural health monitoring, damage assessment and performance evaluation. As an attractive sensing method, Brillouin Optical Time Domain Reflectometry (BOTDR) is based on the propagation of a train of incident pulses and Brillouin scattering that occurs whenever light is transmitted through an optic fiber. The fiber optic sensor was mounted on the surface of a 80% scale beam-column assembly with two kind of installation methods called Point Fixation Method and Overall Bonding Method. The beam-column was loaded cyclically to simulate the practical load condition until the shear crack occurred. For comparison, Electric Time Domain Reflectometry (ETDR) cable sensor was mounted near the surface of 80% scale beam-column assembly. The embedded depth was 0.5 inches. Both fiber optic sensor and ETDR cable sensor were subjected both to tension and compression in one loading cycle. Strain distribution determined from the BOTDR sensing system under different cycle loadings were obtained and compared with the traditional strain gauge and ETDR cable sensor method. Moreover, nonlinear characteristics in the strain distribution because of the occurrence of shear crack was illustrated by the measurement results.

5765-56, Session 13

Fiber optic sensor protection system and its practical for structural integrity monitoring of concrete structures

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The structural integrity monitoring (SIM) in-service is very important and definitely demanded for safely working of engineering structure such as concrete structures. It is very difficult to carry out by using conventional methods. New reinforced concrete construction would benefit greatly from in-situ structural monitors that could detect a decrease in performance or imminent failure, for example, variation in strain, temperature, corrosion, or crack formation. The ability to interrogate numerous sensors multiplexed along a single fibre permits an entire structure to be outfitted with sensors with a manageable number of leads routed to central access points. In response to the increased need, various techniques are being developed and some of the most promising are based on the use of fibre optic sensors (FOS).

Fibre optic smart structures are an enabling technology that will allow engineer to add a nervous system to their designs, enabling damage assessment, vibration damping, and many other capabilities to structures that would be very difficult to achieve by other means. The potential market for the application of smart civil structures can be quite large. The most probable candidates will be smart civil structures such as smart building and skyscrapers, smart bridge, dams, bridge decks etc. Fibre optic sensors (FOS) can offer many potential advantages for application to civil structural systems. In fact, a lot of fibre optic sensors have been developed for use in smart civil structure such as polarisation FOS, Extrinsic Fabry–Perot interferometric (EFPI), and fibre Bragg gratings (FBGs), multimode FOS, etc..(1-8) However, the vulnerability of fibre optic sensor is difficult to protect the fibre from concrete aggregate in the pour duration. That is the FOS could be very easy to damaged and corroded during the practical application of long term. This reason really limits the application of fibre optic sensor in concrete structures.

This paper is concerned with the design concepts, modelling and implementation of various fibre optic sensor protection systems for development in concrete structures. The design concepts of fibre optic sensor protection system and on-site requirements for surface-mounted and embedded optical fibre sensor in concrete structures have been addressed. The aspects of finite element (FE) modelling of selected sensor protection systems in terms of strain-transfer efficiency from the structure to the sensing region also been focused in this paper. Finally, the experimental validations of specified sensor protection system in concrete structures have been performed successfully. Protected Extrinsic Fabry–Perot Interferometric (EFPI) and Fibre Bragg Grating (FBG) sensors have been used to monitor the structural health status of plain and composite wrapped concrete cylinders.

Results obtained indicate that the protection system for the sensors performs adequately in concrete environment and there is very good correlation between results obtained by the protected fibre optic sensors and conventional electrical resistance strain gauges.

5765-57, Session 13

Failure and damage identification in woven composites with fiber Bragg grating sensors

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PRESENTATION PREFERENCE: Oral

PRINCIPAL AUTHOR'S BIOGRAPHY: James Pearson received the B.S. degree in Mechanical Engineering from North Carolina State University in 2003. His current research is focused on developing experimental techniques for the identification and control of fracture in heterogeneous systems.

ABSTRACT TEXT: Woven composites subjected to low velocity impact can fail due to simultaneous failure modes, such as matrix cracking, delamination, and fiber debonding and breakage. If woven composites are to be widely used within structural and mechanical elements, then the accurate identification and control of these failure modes is essential. In this study, measurements obtained from a

specialized drop-tower apparatus are used with measurements obtained from embedded and surface mounted optical fiber Bragg grating (FBG) sensors to obtain a detailed map of damage progression in two-dimensional laminate composites. The woven composites were subjected to multiple strikes at velocities ranging from 2-3m/s, until perforation occurred. The impactor position and acceleration are monitored throughout each event, resulting in a measurement of dynamic energy dissipation and the contact force. FBG sensors were also embedded and surface mounted at different locations near severely damaged regions. The transmission and reflection spectra were continuously monitored throughout the loading cycle. From these spectra, we were able to obtain measurements of the residual strain pertaining to the embedded FBG, and the axial and transverse strains pertaining to the local strain-fields due to the impact-induced damage progression of the woven systems. We used the residual strain measurements to determine that embedding these sensors did not affect the integrity of the woven systems. Once, the residual strains were delineated, we were able to show how transverse and axial strains evolved from the initial compressive residual strain. From our spectra measurements, we determined when the FBGs completely debonded, and we were able to separate sensor failure from failure in the surrounding host material through the identification of cladding and radiation modes at lower wavelengths than the Bragg reflection. This provided an independent feedback on the integrity of the Bragg gratings. These modes can be detected without additional instrumentation required other than that used to measure the sensor response.

We then correlated the axial and transverse strains with the contact force to failure, the dissipated energies, and post-mortem characterization to obtain a detailed quantitive measurement of low-velocity damage. We did this by relating the axial strains to the predicted strengths of the composites, where were obtained by finite-element calculations of woven composites. The FEM predictions were based on micromechanical RVE formulations that account for damage progression. Hence, through coupling our experimental measurements and computational predictions, we were able to spatially and temporally identify that matrix cracking and delamination were the dominant failure modes for two-dimensionally woven composites subjected to low velocity impact.

5765-58, Session 13

Fiber Bragg grating array calibration

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A three element, 15.3 cm, Fiber Bragg Grating Array (FBGA) operating at 1550 nm is fabricated using a single mode photosensitive fiber. The FBGA is initially simulated using in-house developed software based on the Transfer Matrix Method, then fabricated using a double frequency Argon Laser and a phase mask technique, and interrogated using Optical Frequency Domain Reflectometry. A single fiber Bragg grating (FBG) is accurately strain calibrated using a Fabry-Perot interferometer and PZT actuation. The PZT is linearly ramped, and the shifts in the Bragg wavelength along with the fringe count from the Fabry-Perot interferometer are recorded. The fringe count is then used to determine the strain on the FBG and compared to changes in the Bragg wavelength in-order to calculate the strain gage factor. This result is used to calibrate the FBGA for strain measurements. The FBGA is then bonded to a cantilever beam with three electric strain gages attached next to each FBG in the array. The axial strain results obtained from the electric strain gages and FBGA are compared for various displacements of the cantilever beam. The Fabry-Perot interferometer and PZT calibration method is a non-destructive process that eliminates the need to bond the FBG to an external support during the calibration process, and can also be used to calibrate electric strain gages.

5765-59, Session 13

Characterization of long-gauge fiber optics sensors for broad-based structural dynamic measurements

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To monitor and characterize structural behavior of large-scale civil infrastructures such as long-span bridges it is often necessary and effective to measure directly and accurately the “macroscopic” dynamic strain profiler, especially in the case of earthquake and other dynamic events. Moreover, multi-point measurements allow for determining locations and values of measurands along the entire length of structure. In this contribution, fiber optic Bragg gratings packaged in different long gage configurations with composite material are designed and attached on a group of beams with different boundary condition and mass distribution under free vibration. Compared with the strains obtained theoretically and measured with traditional resistive strain gages, the ability of FBG sensors to measure structural dynamic macro-strains is characterized. The influence of gauge length and bonding method on measurements is discussed as well. In addition, a case study of shake table experiment, with a series of FBG sensors bonded on multi-locations of the object structure, is carried out. Using two kinds of damage identified methods of PSD (power spectral density) analysis and NN (neural network), the feasibility, validity and efficiency of the proposed monitoring method for determination of the geometric location and quantification of the severity of the damage based on the measurements of long gage FBG sensors are testified.

5765-60, Session 14

Health monitoring of Binzhou Yellow River Highway Bridge using fiber Bragg gratings

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Binzhou yellow river Highway Bridge with 300 meter span and 768 meter length is located in the Shandong province of China and is the first cable stayed bridge with three towers along the yellow river, one of the biggest rivers in China. In order to monitoring the strain and temperature of the bridge and evaluate the health condition, one fiber Bragg grating sensing network consists of about one hundred and thirty FBG sensors mounted in 31 monitoring sections respectively, had been built during three years time. Signal cables of sensors were led to central control room located near the main tower. One four-channel FBG interrogator was used to read the wavelengths from all the sensors, associated with four computer-controlled optic switches connected to each channel. One program was written to control the interrogator and optic switches simultaneously, and ensure signal input precisely. The progress of the monitoring can be controlled through the internet. The sensors embedded were mainly used to monitor the strain and temperature of the steel cable and reinforced concrete beam. PE jacket opening embedding technique of steel cable had been developed to embed FBG sensors safely, and ensure the reliability of the steel cable opened at the same time. Data obtained during the load test can show the strain and temperature status of elements were in good condition. The data obtained via internet since the bridge’s opening to traffic July18 2004 shown the bridge under various load such as traffic load, wind load were in good condition.

5765-61, Session 14

Application of fiber Bragg grating sensors for structural integrity test of nuclear power plant containment structure

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In this paper, a Fiber Bragg Grating (FBG) sensor system for smart structures is described. FBGs are well-suited for long term and extremely severe experiments, where traditional strain gauges fail. In the system, a reflect wave-length measurement method which employs a tunable light source to find out the center wave-length of FBG sensor is used. The real field test was performed to verify the behaviors of fiber Bragg grating (FBG) sensors attached to the containment structure in Uljin nuclear power plant as a part of structural integrity test which demonstrates that the structural response of the non-prototype primary containment structure is within predicted limits plus tolerances when pressurized to 115% of containment design pressure, and that the containment does not sustain any structural damage. The FBG system applied to the structure works very well and shows the structural behavior according to various pressures. It is expected that it can be used for a real-time strain, temperature and vibration detector of smart structure.

5765-62, Session 14

Damage detection from dynamic SOFO experimental data

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Dynamics tests were conducted at the University of Pavia on a steel frame equipped with a dynamic SOFO device.

One of the leg of the frame was then progressively damaged, by reducing several cross-sections. The response to base excitation was measured and recorded in the different situations.

This paper presents a re-elaboration of the data with the purpose of identifying the technique which better detects and quantifies the damage.

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5765-63, Session 14

A Brillouin smart FRP material and a strain data post processing software for structural health monitoring through laboratory testing and field application on a highway bridge

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Brillouin distributed fiber optic sensing is a promising technology for Structural Health Monitoring (SHM) whose industrial diffusion is however at present limited by the unavailability of proper products and tooling specifically addressed to the building industry. In comparison with other Fiber Optic Sensor (FOS) technologies, the advantages of Brillouin based systems are evident in terms of capability of large low cost sensing network and of distributed sensitivity. These advantages make Brillouin particularly attractive for strain monitoring of large structures, that would otherwise require a great number of expensive sensors with a complicated cabling and multiplexing system. Among the factors that are slowing down the Brillouin diffusion, some such as the high equipment cost and its poor strain sensitivity, can be solved only by the optical industry trough technical enhancements and better industrialization, while others, such as the lack of sensor products ready for field use and the translation of the Brillouin raw data into more structurally significant informations, require a building engineer approach.

In this work an enhanced Fiber Reinforced Polymer (FRP) “smart” material with embedded optical fibers for Brillouin strain and temperature sensing has been designed and manufactured. The thermal and strain sensitivity of the new engineered material have been investigated trough laboratory testing, retrieving its calibration curves both for strain and temperature.

Furthermore, the “smart” Brillouin material was used in a real field SHM application on the A6358 High Performance Steel (HPS) bridge located at the Lake of the Ozarks in Miller County, MO (USA). Two of the five continuous 42m spans of the bridge have been instrumented with the “smart” FRP material on 4 of the five girders, using a special maintenance vehicle. The overall length of the fiber optic sensing system was of 1.3 km, with a severe total optical loss of 6dB due to the bad environmental conditions of the splices. After the installation of the Brillouin monitoring system, a 24h temperature testing and a load testing were separately run on the structure, collecting a huge amount of strain data that were successively processed using a rendering software made specifically for the purpose, capable of real time thermal compensation and spatial recognition.

The strain distribution profile obtained has been then compared with both theoretical model and with other experimental data collected trough traditional resistive strain gauges, evidencing the advantages of the Brillouin SHM technique.

The overall sensitivity and stability of the spontaneous Brillouin scattering based technique has been definitively assessed as satisfying for SHM application similar to that completed, especially considering the incidence of problems such as the low strain level (300me) and the high optical attenuation involved.

Furthermore, the field experience produced a great number of additional suggestions regarding the real problems of Brillouin field applications and their possible solutions, including fiber connection and calibration, and of the survival rate of “smart” FRP sensors in comparison with that of bare optical fibers.

5765-64, Session 14

Discontinuous Brillouin strain monitoring of small concrete bridges: comparison between near-to-surface and ‘smart’ FRP fiber installation techniques

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Brillouin distributed fiber optic sensing is a promising technology for Structural Health Monitoring (SHM) whose industrial diffusion is however at present limited by the unavailability of proper products and tooling specifically addressed to the building industry. In comparison with other Fiber Optic Sensor (FOS) technologies, the advantages of Brillouin based systems are evident in terms of capability of large low cost sensing network and of distributed sensitivity. These advantages make Brillouin particularly attractive for periodical strain monitoring of unattended infrastructures that may be exposed to vandalism, especially considering that the sensors required are low cost and very simple to connect as a single circuit. Despite the high Brillouin equipment cost, the technique is to be considered economically interesting if the investment cost can be amortized over a large number of even small infrastructures periodically monitored. However, the wide use of such a technology for industrial purposes is strongly contrasted by a number of uncertainties related to the poor sensitivity and rough length resolution of the Brillouin equipment currently available.

In this work, the capability of using Brillouin based FOS systems for discontinuous monitoring of small Reinforced Concrete (RC) bridges has been experimentally explored and verified on the field on two different structures.

Bridge #1330005 in Phelps county, MO (USA), a 7.93m span RC girder type structure, has been equipped with FOS for Brillouin strain monitoring using bare fibers Mounted Near to the Surface (NSM) of the concrete, with a technique inspired to that developed for strengthening of concrete structures with composite bars.

Bridge on Walters Street in St. James county, MO (USA), a 6.58m span composite-RC slab type structure, has been equipped with a “smart” Fiber Reinforced Polymer (FRP) tape carrying embedded fiber optic.

Structural performance of each of the two bridges was then assessed trough a complete load test carried out using both the Brillouin FOS and other traditional Bragg grating and electrical gauges. Testing was performed during night in order to minimize thermal drifts of the Brillouin sensors.

The data obtained from the different systems were then compared and discussed.

The analysis of the experimental data evidenced how the mounting technology of the fiber optic for Brillouin strain sensing can affect the performances of the Brillouin system, in terms both of noise, accuracy, attenuation and final usefulness of the retrieved data.

Other considerations from the experience on the field supplied various additional suggestion on how to design and install the sensing fibers and on the management of similar monitoring system.

As a final result, using the right mounting technique and following the additional suggestions, Brillouin based systems have been found to be effective even when dealing with small structures and moderate strain levels.

5765-65, Session 15

Structural health monitoring system using FBG sensor for simultaneous detection of acceleration and strain

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Approximately half of the bridges in Japan will be more than 50 years old by 2030. Thus, in order to maintain the aging bridges effectively, it is gradually recognized that the structural health monitoring systems are promising tools for reducing the maintenance costs effectively. Up to now, many damage evaluation methods have been proposed using strain and natural frequencies of structures. Natural frequencies are suited for global monitoring, and the strain is mainly used for local monitoring. In this study, a novel fiber Bragg grating (FBG) sensor that measures both of these physical values, acceleration and strain, simultaneously is proposed. The proposed sensor has an automatic temperature compensation device and utilized the tension mechanism to detect tension and compression strain. In addition, the sensor is equipped with a acceleration detection mechanism in addition to detecting strain values. Thus, a single FBG sensor can detect both physical values simultaneously.

Using this innovative sensor, a new detection algorithm is developed. First, comparison between the global monitoring based on acceleration measurement and the local monitoring based on strain measurement are analytically carried out. Some damage situations for bridge models are simulated. This simulation clarifies the difference of sensitivity for these two damage modes to several damage modes. The result shows that the sensitivity of strain and natural frequency monitoring is clearly different depending on the damage modes. Thus combined use of acceleration and strain measurement enhances the performance of the system significantly.

5765-66, Session 15

Using fiber Bragg gratings to measure dynamic soil-shear response

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Experimental testing of soil shear responses under dynamic ground excitations currently require expensive and unwieldy accelerometer arrays to record measurements, requiring double-integration to determine displacements. This work proposes a new measurement technique, incorporating optical fiber with

multiplexed fiber Bragg grating strain sensors. This fiber, attached to a thin, flexible metal strip, may be inserted into the ground and used to measure strain as the strip bends with soil shearing during ground motions. Real-time displacements can be determined using two-dimensional linear and nonlinear elastic bending models. Validation of this method was obtained through a simple bending test of the strip, as well as a liquefied soil shake table experiment.

5765-67, Session 15

Development of a new structural monitoring system using optical fiber technology

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In recent years there has been increasing interest in investigating methods that give structures the ability to monitor their status and health during their life so that deterioration and remediation can be more efficiently managed. Increasingly, fiber optic technology is being viewed as a potential method to monitor the condition of structures with the information transmitted through telephone lines or satellite links to a central monitoring station. This paper focuses on the development of an optical fiber based system for monitoring existing tunnels.

Monitoring the movement of existing tunnels when new tunnel construction or other construction activities occur in close proximity is important to the tunnel owners. Existing manual monitoring systems, although considered most reliable, require access to the tunnel outside of passenger traffic hours and thus only provide measurements during a limited time of the day and under non-operational conditions. Remote monitoring systems are currently available based on electrolevels (e.g. the Bassett Convergence System, Bassett et al., 1999) and automatic motorised theodolites (Beth et al., 2003), although the theodolite system requires a relatively large clearance for its installation. It is hoped that the proposed system will be more versatile and economic to install and operate. While the existing measuring systems are very good at measuring specific displacements of the tunnel (i.e. convergence or rotation), the new system has the potential to measure a number of different parameters with one unique system.

The new retro-fitted optical fiber system is developed for monitoring tunnel displacements, but with the potential for general structural monitoring. The system is based on embedding multiple optical fiber sensors with Fiber Bragg Gratings (FBGs) in a continuous fiberglass rod. The interface bonding between the optical fiber and the fiberglass rod has been investigated and will be described in this paper. Although the results show that there are some air pockets between the fiber and the rod, their size and extent are considered small enough, and are demonstrated by experiments, not to affect the strain transfer. By fixing the fiberglass rod rigidly to the structure at discrete points, strain is transferred from the structure to the fiberglass rod and hence into the FBGs.

This paper will describe several full- scale laboratory experiments that are being used to investigate the sensitivity of the rod to several types of displacement for different configurations (circumferential and longitudinal) of the rod. The paper will also detail a bench test that allows for very accurate movement of the fixing positions with four degrees of freedom. Initial tests using this equipment indicate an encouraging degree of sensitivity, with vertical and horizontal displacements of the order of 0.1 mm recorded by a longitudinal rod fixed at 0.6 m intervals. Combining the known strain measurements and information on the geometry of the sensor placement, the movement of the structure can be deduced. Applying structural analysis, the measured strain can be converted to a displacement using 'back analysis'. The new system allows remote and continuous monitoring of the structure and is a positive step towards smart sensing technology and hence smart infrastructure maintenance, management and operation.

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5765-68, Session 15

Identification of damage location in advanced- grid structures using fiber Bragg grating sensor

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Grid structures are the structures made of the trusses consisting of simple ribs. In recent years, carbon fiber reinforced plastic (CFRP) unidirectional composites are used as ribs in order to make use of the strong anisotropy of the CFRP composites effectively and realize the high specific stiffness of the structures. These structures are called advanced grid structure (AGS). The AGS has the following advantages: (1) Since ribs are only subjected to axial forces, the weakness in the transverse direction of the CFRP unidirectional laminates is negligible. (2) The AGS is a damage tolerant structure, because the fracture of a rib does not lead the fracture of whole structure. Taking advantage of these properties, AGS is attempted to be applied to space structures and airplanes. Moreover, by addition of health monitoring system that can detect the damages to the structure, the structures will be high reliable, lighter, and low-cost. The damage detection system suitable for the grid structures is the strain monitoring using fiber Bragg grating (ABG) sensors embedded in all ribs. This is because FBG sensors are easy to be automatically embedded in AGS during the fabrication process. In this research, the authors tried to identify the damage location in AGS from the structural strain distribution measured by the FBG sensors embedded in all ribs. When some damages appear in the AGS, the structural strain distribution in the AGS changes according to the location and the types of the damages. Then, the strain distribution is theoretically calculated with finite element method (FEM). This calculation is repeated changing the damage locations and types, and the calculated strain distribution is fitted to that measured by the FBG sensor network. As a result, the damage types and locations are identified. This is the concept of the damage identification in AGS. At first, three point bending test was applied to a specimen of the AGS plate whose dimensions were 460mm * 498mm. This AGS was made by the arrangement of equilateral triangles formed by three ribs. Each rib was made of CFRP unidirectional laminate of 105mm * 2mm * 10mm. Three FBG sensors were embedded in three ribs of the center triangle. Under the bending loading, the FBG sensors could measure the strain of the ribs. Next, strain gauges were glued on all the ribs of the AGS and the center rib was removed by cutting in order to simulate the fracture of the rib. By using this specimen, the change in the strain distribution due to the rib fracture was measured under three point bending. On the other hand, in order to calculate the structural strain distribution of AGS including the rib fracture, an analytical method was constructed. The authors introduced an equivalent stiffness model (ESM) into the FEM. Though the ESM that homogenizes the grid are not so accurate, this method is relatively simple and efficient. With this calculation system, the measured strain distribution of the AGS with the rib fracture could be well reproduced. Hence, this combination of the FBG sensor network and the analytical method using ESM and FEM was found to have a potential to identify the damage location in the AGS.

5765-69, Session 15

Polymer-based optical fiber sensors for health monitoring of engineering structures

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Optical fibers are well-known sensors for structural health monitoring applications particularly where their unique features may be exploited in specific applications. These advantages over conventional electrical-based sensors include their insensitivity to electromagnetic interference, multiplexing capability, long term strain monitoring, light-weight and the possibility of embedding them in layered structures. However, these fiber sensors are, in general, based on glass fibers and due to their low fracture toughness they are highly susceptible to accidental damage when employed in field e.g. in construction sites. High degree of care is required during the installation and surface preparation (ensuring surface is contamination- and nick-free) in order to achieve optimum signal interrogation; In view of these issues, this paper describes the design of a new simple extrinsic optical fibre sensors based on poly(methamethycrylate) for structural health monitoring. This polymer-based optical fiber sensor relies on the modulation of light intensity and is capable of monitoring the response of the host structure subjected to either static or dynamic load types. A series of mechanical tests have been conducted to assess the response of the plastic optical fiber (POF) sensor in both surface-bonded and

embedded configurations. The readings of these sensors attached to aluminium bars as well as concrete beams were found to compare well to electrical strain gauge response. Static and cyclic loading tests were also performed and the sensor was shown to exhibit excellent strain linearity and repeatability. Additional tests on a cantilever beam set-up in which the POF sensor was surface-bonded to a composite beam were also conducted. The results obtained highlight the capability of the sensor to accurately monitor the dynamic response of the beam; Impulse-type dynamic response of the sensor was also conducted and the POF sensor demonstrated potential for detecting the various modal frequencies of the host structure. The potential of the POF sensor to monitor the modal response was further developed to detect and locate damage in the host structure demonstrating the feasibility of the sensor for structural health monitoring applications.

5765-70, Session 15

Applications of FBG sensors on bridge cables

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Cables are the key member of cable-stayed bridges, suspension bridges, hanging bridges and so on. The bridge cables in service are easily damaged due to the factors of environment corrosion, fatigue, materials aging, stress redistribution, etc. Besides, the stress states of different tendons are quite different due to the difference of outside condition. So the cables can not endure as long as designed. Owing to lack of reliable measurement techniques, how to evaluate the damage or stress state of the cables in service has always still been a big challenge for civil engineers.

It is a good idea to estimate the damage state of bridge cables by monitoring their deformation. Nowadays, engineers depend on manometers and accelerometers, even electro-magnetic sensors to measure the cable stress, which can not satisfy the need of practical applications. In this paper, a new kind of smart cable based on FBG sensors is developed. And the feasibility and advantages of this cable are discussed. The sensing properties of FBGs installed in the bridge cables under dead load are tested. The experimental results and practical applications show that the smart bridge cable based on FBG sensors is proper for bridge cables transfer, construction control and long-term health monitoring. The deformation gotten from the FBG sensors can be used to evaluate the damage of cables, which shows good prospect in the area of bridges as well as other cable-stayed structures.

Aimed at structural health monitoring (SHM) of bridge cables, 24 smart cables for Binzhou Yellow River Bridge and 4 for Luoguo Bridge have been developed, which are now in service. The cables with installed FBGs show the advantages of FBG sensors such as high accuracy, electro-magnetic resistance, quasi-distribution sensing, absolute measurement and so on.

5765-71, Session 15

Demonstration of a fiber grating based SHM system for bridges

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Blue Road Research, in cooperation with the University of California at San Diego, is developing a structural health monitoring system for bridges based on inputs from fiber Bragg grating sensors and modal analysis. As a demonstration of the technology, Blue Road Research constructed a single span steel truss bridge and installed 20 ruggedized long gage length fiber grating sensors. Static and low speed dynamic tests were conducted as well as high-speed modal analysis tests. The developmental system acquires data from 20 sensors simultaneously for low speed measurements and from six sensors simultaneously in a high speed and high sensitivity mode. In order to evaluate the performance of the system in structural heath monitoring and damage detection, bolts were loosened during testing and the bridge's response to dynamic excitation was observed. A damage detection algorithm developed by UCSD was used to perform system identification on the structure in order to indicate the location of damage. Results from these tests are presented here.

5765-300, Poster Session

Sensor technologies and multifunctional structures: Air Force perspective

C. L. Allred, B. L. Lee, Air Force Office of Scientific Research

No abstract available

5765-301, Poster Session

Wireless sensing systems for machines and structures

S. W. Arms, MicroStrain, Inc.

No abstract available

5765-302, Poster Session

Development and application of sensors at the Federal Highway Administration

R. A. Livingston, Federal Highway Administration

No abstract available

5765-303, Poster Session

Programs on sensors and sensing technologies at the National Science Foundation

S. Liu, National Science Foundation; M. Tomizuka, Univ. of California/Berkeley

No abstract available

5765-304, Poster Session

Sensors and controls for energy efficiency in industry, public/private partnerships in the national interest

T. J. McIntyre, Oak Ridge National Lab.

No abstract available

5765-305, Poster Session

Smart actuators for steerable munitions

D. J. Pines, Univ. of Maryland/College Park

No abstract available

5765-306, Poster Session

To be announced

K. Thirumalai, U.S. Department of Transportation

No abstract available

5765-307, Poster Session

Usage of fiber optic grating sensors for nondestructive evaluation of composite structures

E. Udd, Blue Road Research

No abstract available

5765-72, Session 16

Design guidelines for open-loop vibration control of stay cables using MR dampers

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In this paper, a mathematical model based on the complex modal theory is formulated to evaluate the damping ratio of the cable-damper system in the open-loop control mode, which takes into account the damper coefficient, damper stiffness, damper mass, stiffness of the damper support, and nonlinearity of the damper, as well as the cable sag and inclination. Based on the asymptotic solution of the proposed mathematical model, a 'generalized universal formula' is proposed to facilitate the damper design. Using this formula, design guidelines for open-loop cable vibration control using MR dampers are developed, for either multi-mode suboptimal control or single-mode optimal control. The guidelines facilitate the engineering applications of MR dampers for open-loop cable vibration control.

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5765-73, Session 16

Modeling of a full-scale MR damper and its application in open-loop vibration control of stay cables

J. Ko, Y. Duan, Y. Ni, Hong Kong Polytechnic Univ. (Hong Kong China)

In this paper, a parameter-adaptive three-element model is first developed for a full scale MR damper based on laboratory tests. The parameters of the model are represented by a set of empirical formulae on displacement amplitude, voltage input, and excitation frequency. The damper model is then integrated with a mathematical model of cable-damper system proposed earlier, for investigating the open-loop vibration control of a 114 m long cable in Dongting Lake Bridge, with single- and twin-damper setups. The concept of the optimal voltage/current input achieving the maximum damping ratio is put forward. Based on this, the multi-mode and multi-switch open-loop control strategies for single- and twin-damper setups and the strategies for determining the optimal geometric configuration for the twin-damper setup are developed. These design procedures and strategies contribute to consummate the design specifications/guidelines for open-loop cable vibration control using MR dampers.

5765-74, Session 16

Smart systems for short-duration impulse loads

A. Rajaraman, Indian Institute of Technology Madras (India)

Short duration high amplitude impact loads can cause considerable damage to civil engineering structures as happens in a cyclone or earthquake or blast effects. It is unwise to design for such loads resulting in considerable weight and cost as the duration is very

short.Here the role of 'smart system' concepts will considerably help in providing resistance without causing damage for such short duration loads and the need for such systems is rising with man-made attacks adding a new dimension. In this study a plate problem

is studied for different impulses and an adaptive device is designed to handle these impulses for displcements or stresses or even partial damage. It is found that considerable savings both in terms of materials and cost and an increase in resistance can be realised making smart applications mandatory for

such systems.

5765-75, Session 17

Educating next-generation civil engineers about smart structures technology

Y. Zhang, Lehigh Univ.

The implementation of smart structures technology in the design, construction and maintenance of civil and mechanical systems have been shown beneficial to the performance enhancement, operating efficiency and reliability of structural systems, especially for those located in regions prone to natural hazardous events such as strong earthquakes and hurricanes. The concept of smart structural systems – equipping structures with networked sensors, data processing unit, controller and actuating devices that would allow them to respond "adaptively" to environmental changes - might revolutionize the design, construction and life-cycle performance management of future structural systems and has been receiving growing interests among researchers, practicing engineers, and decision makers. Sensing technology is a vital component of smart structural systems. However, most of today's engineering students are unaware of the remarkable properties of smart sensors and many applications of smart structures technology. It is thus desirable to prepare the future engineers of the society for the cutting-edge technologies in smart structures, for which they may see broad application in their generation. Pioneering work in incorporating smart structures technology into civil engineering curriculum has been done by the writer at Lehigh University and is described in this paper. In particular, a graduate-level course entitled "Smart Structural Systems" has been taught in the Spring Semester of Year 2004 at Lehigh University. To better convey the course material to students, a teaching lab with an emphasis on smart sensing technologies is currently under development at Lehigh University. The second part of this paper therefore describes the smart structures test-bed, which is used not only to showcase various technological aspects of a smart structural system but also offer students an opportunity to gain hands-on experience by doing experiments has also being developed at Lehigh University. The hands-on experience that could be developed with the smart structures test-bed is believed being essential for students to have a good understanding and mastering of the smart structures technologies. Samples of students' work in the smart structures technology are also being described in this paper.

5765-76, Session 17

Auxiliary particle filtering for structural system identification

H. Tang, Kyoto Univ. (Japan); T. Sato, Kyoyo Univ. (Japan)

Sequential based Bayesian filtering (namely particle filter, it is also known as SIR filter, Monte Carlo filter, Bayesian bootstrap filter, condensation, etc) is to use sequential Monte Carlo and recursive Bayesian estimation for nonlinear/non-Gaussian filtering problem, which uses a number of independent random variables called particles, sampled directly from the state space, to represent the posterior probability and update the posterior by involving the new observations; the "particle system" is properly located, weighted, and propagated recursively according to the Bayes rule. Unfortunately, for most real-world problems, the optimal Bayesian recursion is intractable and approximate solutions must be used. A popular solution is provided by the importance sampling framework, the idea is to sample from a density that is simple to sample from, the importance density, instead of the complex a posteriori density. The most common choice of importance density is the transition prior density function for particle filter, since it is intuitive and simple to implement, but using the prior as the importance density suffers from drawback of without any knowledge of the observations, and hence the state space is explored without direct knowledge of the observations, maybe lead to poor performance for the particle filtering. To overcome this defect, it is necessary to incorporate the current observation in the importance density. In this paper, we propose an auxiliary particle filter (APF) method to identify the system parameters of nonlinear structures. In the APF, the importance density is proposed as a mixture density that depends upon the past state and the most recent observations, and hence which is more suitable for the system identification than the conventional particle filters. The numerical simulations confirm effectiveness of the proposed method for the structural system identification.

5765-77, Session 17

Support vector regression for structural identification

J. Zhang, T. Sato, Kyoto Univ. (Japan)

Structural damage detection based on the vibration data is still a challenging topic especially when the input and output (I/O) measurements are corrupted by high-level noise. In this paper, we propose a new structural parameter identification method based on the Support Vector Regression (SVR) which has been found to work very well in many fields as an exclusively data based non-linear modeling method. The theoretical relations between structural response under random excitations or earthquake and its discrete representation in the form of Autoregressive Moving Average (ARMA) models has been suggested by many papers. By taking ARMA model derived from the governing equations of motion, how to identify the structural dynamic properties such as the modal natural frequencies and damping ratios by SVR is studied in detail here. Due to the "max-margin" idea used in SVR, the identified results are robust and very accurate under different kind and amplitude noise. Furthermore, how to choose the parameters of SVR is also studied here because these parameters have a considerable influence on the identified result. At end, numerical examples for identifying ARMA modal and structural parameters by SVR are given to demonstrate that the proposed method is very effective and powerful compared to Kalman filter and H-infinity method even though the high level noise in I/O measurement.

5765-78, Session 17

An adaptive extended Kalman filter with unknown inputs for on-line identification of structural parameters

J. N. Yang, S. Pan, S. Lin, Univ. of California/Irvine

The identification of structural damages is an important task of structural health monitoring. Various analysis techniques have been presented in the literature to identify the structural parameters based on the vibration data. When the measured vibration data contain damage events, tracking techniques in the time-domain have been studied recently, including the least-square estimation (LSE) and extended Kalman filter (EKF) approaches. With an appropriate tracking technique, the extended Kalman filter approach is quite suitable for the identification of structural damages on-line. Such an approach, however, requires that the input excitations should be measured, which may not always be the case in practice.

In this paper, we propose an extended Kalman filter with unknown inputs (EKF-UI) approach to identify not only the structural parameters but also the unknown

(unmeasured) input excitations. Further, an adaptive tracking technique is implemented in the proposed EKF-UI, referred to as the adaptive extended Kalman filter with unknown inputs (AEKF-UI), to track the parametric variations on-line when vibration data involve damage events. The proposed AEKF-UI approach is capable of tracking not only the unknown inputs but also the structural parameters and their variations due to damages. Simulation results using nonlinear structures are presented to demonstrate the effectiveness of the proposed technique in identifying structural damages on-line.

5765-79, Session 17

System identification of buildings equipped with closed-loop control devices

A. Mita, Keio Univ. (Japan); M. Kamibayashi, East Japan Railway Co. (Japan)

The purpose of this study is to provide a system identification tool to obtain dynamic structural properties of buildings when closed-loop control devices are in operation so that we will be able to detect possible damages or changes in the building structures without suspending the control devices. The difficulty associated with closed-loop systems, where noise, input and output signals are correlated, can be resolved using the output inter-sampling approach. By introducing the approach, we were able to successfully obtain the open-loop properties of the building structures. In practical situations, most likely the closed-loop control circuits are temporarily suspended to avoid the difficulty associated with the closed-loop systems. Then a control device is used as an exciter for the buildings structure. It is noted that the control device should be operated as an open-loop system when used as the exciter. However, the true dynamic properties of the building when subject to control forces generated by the control devices that are operated as closed-loop systems may be different from those obtained when the control devices are not in operation as the buildings would have nonlinear characteristics.

As an example of the control device, an active mass damper (AMD) was selected. The AMD has a feedback closed-loop with respect to measured response of a building. The existence of the closed-loop in a system makes the online identification very difficult. If we apply a method developed for open-loop systems directly to the closed-loop systems without careful consideration, the correlated noise, input and output signals would result in inaccurate estimation. The output inter-sampling approach employed here is known as a system identification tool for closed-loop systems developed for other engineering fields. Applicability of the approach was extensively examined by simulations and experiments for the example system.

From our extensive study, it was shown that the output inter-sampling approach was indeed able to estimate the dynamic properties of the building when the AMD is in operation under the condition that the control system can hold the control signals for certain duration. It was found that, however, when the observation noise is higher than a threshold value, the method might fail. Thus, by keeping the observation noise lower than the threshold value, identification of buildings equipped with closed-loop devices can be stably achieved.

5765-80, Session 17

Application of a maximum entropy method to estimate the probability density function of nonlinear or chaotic behavior in structural health monitoring data

R. A. Livingston, Federal Highway Administration; S. Jin, Wiss, Janney, Elstner

Bridges and other civil structures can exhibit nonlinear and/or chaotic behavior under ambient traffic or wind loadings. One way to describe this behavior in structural health monitoring is in terms of a probability density function (pdf) of the observed physical responses of the structure. The pdf thus plays a role in identifying system changes due to structural damages. Changes in the pdf over time are important for tasks of long-term structural health monitoring and the distribution of the large structural response values in the upper tail of the pdf curve can be used in LRFD and fatigue life analysis. However, the actual pdf from collected structural response data often has a very complicated shape due to its fractal nature. Various conventional methods to approximate it can often lead to biased estimates because of the drawbacks in the interpolation methods used.

This paper presents recent research progress at the Turner-Fairbank Highway Research Center of the FHWA in applying a novel probabilistic scaling scheme for enhanced maximum entropy assessments to find the most unbiased pdf. In particular, the maximum entropy method is applied with a fractal interpolation formulation based on contraction mappings through an iterated function system (IFS). Based on a fractal dimension obtained by considering the spatial variation nature of the entire response data set, a characteristic uncertainty parameter, called the probabilistic scaling factor, can be computed with its bounds determined by an algorithm involving the information dimension. This probabilistic scaling method allows significantly enhanced maximum entropy assessment through the added inferences about the fine scale fluctuations in the response data. Case studies using the dynamic response data sets collected from a real world bridge (Commodore Barry Bridge, PA) and from the simulation of a classical nonlinear chaotic system (the Lorenz system) are presented in this paper. The results illustrate the advantages of the probabilistic scaling method over conventional approaches for finding the unbiased pdf especially in the critical tail region of large structural responses.

5765-81, Session 18

A guided-wave system for monitoring the wing skin-to-spar bond in unmanned aerial vehicles

H. M. Matt, F. Lanza di Scalea, A. Marzani, S. Coccia, J. A. Oliver, J. B. Kosmatka, P. Rizzo, G. Restivo, Univ. of California/San Diego

Unmanned Aerial Vehicles (UAVs) are being increasingly used in military as well as civil applications. A critical part of the structure is the adhesive bond between the wing skin and the supporting spar. If not detected early, bond defects originating during manufacturing or in service can lead to inefficient flight performance and even catastrophic failures.

This paper will present laboratory results from a bond inspection system based on attached piezoelectric disks probing the skin-to-spar bondline with ultrasonic guided waves in the hundreds of kilohertz range. The test components were composite panels of three different fiber lay-ups bonded to an aluminum spar and to a composite spar. Four types of bond conditions were simulated, namely regions of poor cohesive properties, regions with localized disbonds and regions with varying adhesive thickness, in addition to well bonded regions. The wave features of amplitude, phase, group velocity, peak frequency shifts and discrete wavelet coefficients were extracted for the dominant modes propagating through the various bond regions in three different inspection configurations. Theoretical analyses based on multilayer wave propagation were carried out to predict those wave mode-frequency combinations most sensitive to the bond condition. Baseline tests were performed at varying temperatures in order to determine the statistical distribution of the features in various operating conditions. Unsupervised defect detection based on outlier analysis was then attempted to assess the effectiveness of the bond inspection system in a varying temperature environment. The results will help designing a built-in system for monitoring the structural integrity of bonded joints in UAVs and other aerospace structures.

5765-82, Session 18

Terahertz plasmonic composites

A. V. Amirkhizi, S. C. Nemat-Nasser, W. J. Padilla, S. Nemat-Nasser, Univ. of California/San Diego

Introduction of thin wire arrays into a matrix material modifies the composite's effective electromagnetic properties. This effect has already been investigated for microwave regime in structural composites. Reducing the length scale has enabled us to show the same effect in terahertz regime. This collaborative work between UCSD and Harvard University starts with design and numerical analysis of the electromagnetic field. The samples are then fabricated. The transmission of far infrared is measured using a Michelson interferometer. The transmitted power is then used in Kramers-Kronig relations to extract the phase and finally the overall material properties. To our knowledge, this is the first design and experimental verification of the modified dielectric constant at the terahertz frequency regime.

5765-83, Session 18

Verification of a built-in health monitoring system

J. Yang, J. Park, F. Chang, Stanford Univ.

The excellent characteristics of the carbon-carbon composite thermal protection systems (C-C TPS), such as high temperature insulation capability, light weight, and high strength, enable them to be applied to the hottest spots of a space vehicle. These C-C TPS panels are mounted to the base structure using mechanical fasteners rather than adhesive materials due to the temperature constraint. However, the mechanical fasteners of the C-C TPS panels are susceptible to damage in the form of bolt loosening under the harsh vibration and acoustic environments during the mission.

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Undetected damage or failure of the C-C TPS panel can lead to catastrophe. Therefore, knowledge of the integrity of the C-C TPS panels is essential to the success of the mission. A novel sensor has been designed and evolved after in-lab tests, and was integrated to the prototype of C-C TPS panel which is equipped with C/SiC brackets and metallic base structure. The installed sensors were connected to the external computing unit using an advanced wiring technique for the minimum risk of electric connection failure. In addition, an algorithm and graphic user interface has been developed to make easy the access of the health monitoring system from a user. The technology of the developed health monitoring system includes the investigation of the loosening of bolts which connects C-C TPS panel to the base structure and the identification of impact on the panel, in terms of its location and force.

As a succession of design work of built-in health monitoring system for the C-C TPS panel, the verification of the developed health monitoring system was performed on a shaker to assess the functionality of the health monitoring system under the simulated vibration environments. The results are such that the health monitoring system has the potential to be applied to the real system to enhance the safety of TPS panels, as well as to lower inspection and maintenance time and costs.

5765-84, Session 18

Mechanical properties of composite materials with integrated embedded sensor networks

K. L. Schaaf, S. Nemat-Nasser, A. F. Starr, B. Cook, Univ. of California/San Diego; F. Ghezzo, Univ. degli Studi di Bologna (Italy)

We present efforts to develop structural composite materials which include networks of embedded sensors with decision-making capabilities that extend the functionality of the composite materials to be information-aware. The next generation of structural systems will include the capability to acquire, process, and if necessary respond to structural or other types of information. We present work related to the development of embedded arrays of miniature electronic-based microsensors within a structural composite material, such as GFRP. Although the scale and power consumption of such devices continues to decrease while increasing the functionality, the size of these devices remain large relative the typical scale of the reinforcing fibers and the interlayer spacing. Therefore, the question of the impact of those devices on the various mechanical properties is both relevant and important. We present work on characterizing some of those effects in specific systems where sensors, or suitable dummy sensors, are arrayed with ~1 cm spacing between elements. The typical size of the microelectronic sensing element is ~ 1 mm, and here is orthorhombic. Of particular importance are the effects of inclusion of such devices on strength or fatigue properties of the base composite. Our work seeks to characterize these effects for 1 and 2 dimensional arrays lying in planes normal to the thickness direction in laminated composites. We also seek to isolate the effects due to the sensing elements and the required interconnections that represent the power-carrying and data communications capabilities of the embedded network.

5765-85, Session 18

Sensing technology for integrated embedded sensor networks in composite materials

A. F. Starr, S. Nemat-Nasser, P. Rye, Univ. of California/San Diego

We present efforts to develop structural composite materials, such as glass-fiber reinforced polymers (GRFP), with networks of embedded sensors that possess decision-making capabilities. Networks extend the functionality of the composite materials to be information-aware. The next generation of structural systems will include the capability to acquire, process, and if necessary respond to structural or other types of information. In general, the networks are envisioned to include multiple sensing modalities as well as other needed functionality such as power and resource management. This work brings together many important developments over the last few years in a number of engineering disciplines: the emergence of a broad range of new sensors including MEMS fabricated transducers, smaller and lower power microelectronics with increased and multiple integrated functionality, and greater composite fabrication capabilities. Strategies for large number arrays of networked devices are discussed. Example sensor node prototype arrays have been built using existing miniature microprocessors. Advances in this area afford new opportunities in structural performance and health monitoring, as well as means of detecting or monitoring the external environment or applied loads. Application specific microelectronic devices and sensors, as well as integrated subsystems fabricated for this type application are needed to show the power and potential of this approach.

5765-86, Session 19

Vibration-based piezoelectric micro-power generator: design and optimization

R. X. Gao, Y. Cui, Univ. of Massachusetts/Amherst

Prolific applications of sensors for the health monitoring of mechanical and civil systems has made sensor power supply an increasingly critical issue for effective sensor deployment. Battery-based powering, while enabling mobile operations, requires periodic replacement of worn batteries, which presents a potential environmental hazard. In comparison, extracting energy directly from the environment and/or structures being monitored has the intrinsic value in eliminating dependency on external power supplies, enabling self-contained sensing while reducing burden to the environment. The ultimate goal of energy extraction is to minimize the complexity and cost of the health monitoring device itself to enhance reliability, flexibility, and service life.

Of the various possible energy sources available in the environment, e.g. mechanical structure vibrations, changes in the atmospheric pressure, wind, light intensity, human motion, and temperature variations, low level vibration in the 50Hz ~ 400Hz range presents an attractive energy source. Such vibrations are commonly seen in the real-world, such as office buildings, transportation vehicles, manufacturing equipment, and homes appliances.

This paper presents a design optimization approach to using piezoelectric elements for energy extraction from low level vibrations, as a new source of power supply to wireless sensor networks. Theoretical analyses have concluded that power generation from environmental vibrations on the order of 300 μW is feasible, using a centimeter-sized d energy extraction device. Such a power output level is sufficient to drive various types of sensors and low power microcontrollers. However, experimental studies so far have only demonstrated power extraction on the order of 0.3~200μW, which is much lower than the theoretically predicted value.

To improve the power generation efficiency, optimized designs, analysis, and modeling of the energy extraction devices need to be developed. In this paper, the design of a non-uniformly shaped beam consisting of piezoelectric elements on the order of (3 x 1.5 x 0.1 cm) is proposed. An analytical model of the beam is derived and used to predict its dynamic response when subject to low level vibrations, and to predict the power output. Using coupled-field analysis, the coupling between the mechanical and electrical domains of the piezoelectric energy extractor is analyzed. Simulations show that more than 300 μW can be output by such a beam type of energy extractor. A prototype design is experimentally tested, where the device is installed on the housing of a lathe, which serves as a vibration source with peak acceleration of 2.1 m/s^2 at 85Hz. Finally, issues regarding device packaging and installation are addressed.

5765-87, Session 19

Generalized harmonic wavelet as an adaptive filter for machine system health diagnosis

R. Yan, R. X. Gao, Univ. of Massachusetts/Amherst

Vibration signals measured from a machine contain rich physical information about the health status of the machine. Proper analysis of such signals is a critical prerequisite for clear identification of the hidden defect and timely diagnosis of potential machine failure. Of the various techniques commonly used in vibration signal analysis, wavelet transform has been increasingly investigated, due to its ability in capturing transient phenomena that characterize the presence and type of defects. Such ability is based on the nature of wavelet transform that expresses the correlation or similarity between the signal to be analyzed and the wavelet template function, at a specific scale and an instantaneous time. The transient information embedded in the vibration signals from the machine being monitored is identified by local maxima of the wavelet coefficients.

This paper describes an adaptive filter construction technique based on the generalized harmonic wavelet transform, for applications in machine system health diagnosis. Specifically, a series of sub-frequency band wavelet coefficients, which possess the same bandwidth, are constructed by choosing different wavelet level parameters. The energy and entropy associated with each sub-frequency band are then calculated. The filtered signal is finally obtained by choosing the wavelet coefficients, whose corresponding sub-frequency band has the maximum energy-to-entropy ratio.

The contribution of this work is two-fold. First, it introduces an adaptive filtering band selection scheme based upon the statistical characteristics (i.e. energy and entropy) of the wavelet coefficients in each sub-frequency band. Secondly, the

new scheme is computationally efficient, since the generalized harmonic wavelet transform can be implemented through a compact algorithm based on the Fast Fourier Transform (FFT). Experimental studies using rolling bearings that contain different types of structural defects have confirmed that the developed new technique is effective in machine failure detection and health diagnosis.

5765-88, Session 19

Measuring inclination in geotechnical applications using a low-g low-cost accelerometer

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Digital inclinometers are used in geotechnical engineering applications to monitor lateral movements due to deformations of excavation walls, deflections of retaining walls and piles, and failure in embankments and landslide areas. Obtaining slope inclination measurements using current methods is a costly and labor-intensive process. An automated slope inclinometer system has the potential to significantly reduce the labor and cost involved with monitoring lateral movements in geotechnical applications. A critical component of an automated system is the use of low g, low cost accelerometers for tilt measurements. The research described in this paper seeks to determine if currently available off-the-shelf, low cost, low g, accelerometer systems are capable of achieving the accuracy and repeatability typically reported for more expensive, widely-available inclinometer systems. Issues such as filtering and analog-to-digital conversion rates are addressed. The trade-offs associated with increased resolution at the expense of decreased angle range are analyzed and discussed. A feasibility analysis is performed, comparing theoretical and field-collected data using a modified G-link wireless accelerometer system from Microstrain Inc. with established inclinometer system specifications.

5765-89, Session 19

Development of multivariate statistical tools for damage detection of bladed disks

J. Tang, Univ. of Connecticut

The timely detection of damage in aero-engine bladed-disks (e.g., compressor fans) is an extremely important research topic. Currently, blade damage/crack detection is mostly exercised by using eddy current and ultrasonic technologies. These methods, while having good reliability, need significant amount of human involvement, have narrow field coverage and are position sensitive. It is also difficult to implement these methods as true in situ approaches. Measuring the vibratory responses of bladed-disks under operating condition, on the other hand, has become possible with blade-tip timing (BTT) sensing technology, which provides a possible new opportunity for in situ damage detection. While various damage detection schemes for general structures using vibration signals have been explored, detecting damage in a bladed-disk is significantly more challenging. Bladed-disks have high modal density and, particularly, their vibration signals are subject to significant uncertainties due to manufacturing tolerance (blade-to-blade difference or mistuning), operating condition change and sensor noise. Clearly, any deterministic detection approach could suffer from large number of false alarms.

In this study we present a new methodology of damage detection using the bladed-disk vibratory responses during spin-up or spin-down operations which can be measured by BTT sensing technology. A simplified bladed-disk model which consists of cantilevered beams coupled with springs is used in the simulation. Fracture mechanics based approach is used to quantify the crack damage effect in the model. The bladed-disk has inherent mistuning and the responses are contaminated by noise. We first apply a principle component analysis (PCA)-based technique for data compression, feature extraction, and denoising. The non-model based damage detection is achieved by analyzing the vibratory response changes between the intact structure and the damaged one in directionality. Following that, multivariate control limit using Hotelling's T2 statistic is used to interpret which characteristic or group of characteristics of the directionality is out of control that corresponds to abnormal signal condition. This allows us to declare damage occurrence under various noise/uncertainty with deterministic confidence level. A series of case studies are performed. Specifically, the effects of bladed-disk and excitation properties, noise level, mistuning level, damage severity, and the size of baseline dataset on the detection sensitivity are discussed. Qualitative understandings on sensor data analysis are obtained. The numerical analyses show that this multivariate statistical analysis procedure based on frequency responses can successfully detect small damage under very significant structural uncertainty and noise, which provides a new means for on-line bladed-disk damage detection.

5765-90, Session 19

Active motion artifact cancellation for wearable health monitoring sensors using collocated MEMS accelerometers

P. T. Gibbs, H. H. Asada, Massachusetts Institute of Technology

While wearable health monitoring sensors are expected to be revolutionary in many application areas in the future, the ability to record reliable, uncorrupted bio-signals during everyday activities has been a major challenge in their development. Since most of the potential applications for such bio-sensors are for field use, wearable sensors must be robust against all disturbances, but most importantly, the motion of the wearer. In this paper, a new method for motion tolerant sensors using MEMS accelerometers will be presented, which eliminates motion artifact and recovers signals corrupted with body motion. This is achieved through the use of an active noise cancellation method using a MEMS accelerometer. The method is developed for a finger ring PPG sensor, the signal of which may be distorted due to the hand motion of the wearer. The MEMS accelerometer is integrated into the PPG sensor, and detects hand acceleration. An adaptive filter then produces an estimate of the distorted portion of the signal in response to the measured acceleration. This estimated distortion is removed from the original PPG signal to give an estimate of the "true" signal for the physiological measure of interest. The adaptive filter comprises of a dynamic model whose parameters are estimated in real time with a recursive least squares method, thus continually updating the dynamics of the distortion process. Prior to the design of the adaptive filter, the correlation between the finger acceleration and the distorted PPG signal was analyzed based on experiments using the integrated PPG/MEMS accelerometer wearable ring sensor. Preliminary results provided much insight into how acceleration influences PPG signal. It was seen that acceleration in the longitudinal direction of the finger is strongly correlated with the corrupted PPG signals, indicating that the desired PPG signal can in fact be predicted by using the measured acceleration. Furthermore, a high level of correlation is observed only for a limited time window, highlighting the dynamic characteristics of the finger arterial system. The adaptive filter was then designed based upon these correlation results for an individual. Results from the implementation and testing of the active noise cancellation method are summarized in this paper. A hand wearing a ring sensor was shaken at different accelerations. The recovered PPG signal was then compared to a separate PPG signal captured at a remote, stationary point on the body. Using the Motion Artifact Cancellation method, the recovered PPG signal was correctly able to show the first peak in each and every heartbeat. Experiments show that the active noise cancellation method can recover ring PPG sensor signals corrupted with up to 2G of acceleration in the longitudinal direction of the digital artery.

5765-91, Session 19

Detection of crack in thin cylindrical pipes using piezoactuated Lamb waves

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The detection of cracks in beams and plates using piezo-actuated Lamb waves has been presented in the last SPIE Symposium. This paper is an extension of the technique to pipes. It has been shown that for a thin-walled pipe, the assumption of Lamb wave propagation is valid. Such waves can be efficiently excited using piezoceramic transducers (PZT) with good control on the pulse characteristics to assess the health of structural components, such as the presence of cracks. In this paper, a systematic methodology to detect and locate cracks in homogenous cylinder/pipe based on the time-of-flight and strength analysis of propagating Lamb wave is proposed. By observing the attenuation in strength of the direct wave incidence at the sensor, the presence of a crack along the propagation path can be determined. At least four actuation positions, two on each end of the pipe segment of interest, are needed to exhaustively interrogate for the presence of cracks. The detailed procedure for locating and tracing the geometry of the crack(s) is described. It is shown experimentally that the detection using circular PZT actuator and sensor, with dimensions of 5.0 mm diameter and 0.5 mm thick, is possible for an aluminum pipe segment of up to at least 4.0 m in length. The proposed methodology is also explored for the aluminum pipe under more practical situations, such as burying it in sand with only the actuator and sensor positions exposed. Experimental results obtained showed the feasibility of detecting the 'concealed' crack on the pipe buried in sand.

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5765-92, Session 19

Performance of MICA2 Mote for civil engineering applications

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Structural health monitoring using the forefront of science and technology is expected to provide many new opportunities for earthquake engineering. The authors have investigated the Berkeley Mote, which is a commercially available wireless sensor network [1]. The Mote has a CPU, wireless radio, antenna, memory and batteries, and is supposed to be a ubiquitous “smart dust.” Many kinds of sensor boards can be attached on the Mote. It can be used as a wireless sensor node and a base station, which is a receiver and a gateway to the internet. TinyOS, the operating system for the Mote, is distributed through the web-site of the University of California at Berkeley, and supports an “ad hoc” network and a “multi-hop” communication. The latest version of the Mote is the MICA2. Compared with the previous version, the CPU clock and radio power of the MICA2 were greatly improved. The authors carried out shaking table tests to verify the performance of the MICA2 as a wireless sensor [2]. The MICA2 could measure the acceleration of a test structure on the shaking table and wirelessly detect damage caused by the input earthquake motion. It is also important to investigate possible distance to communicate each other wirelessly between nodes. In this paper, the communication ability of the MICA2 is discussed. Possible distance between the MICA2 nodes and the base station was experimentally verified. Through the experiment, it was recognized that the MICA2 is practical for civil engineering applications.

References

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5765-93, Session 20

Advanced technologies monitoring safety of water conservancy and hydropower engineering

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To monitor water conservancy and hydropower engineering, data on safety need be obtained, managed and analyzed. A system of advanced technologies was proposed to implement the above function. It consists of data acquisition module, data management module, analysis and evaluation module, and support environment of computer and communication network. Data acquisition module is composed of sensors and survey equipments. It can implement the transform of A/D, and long distance transmission of digital observations. This paper presents the applications of fiber optical sensing technology, CT technology, GPS technology, laser sensing technology to monitor safety of water conservancy and hydropower engineering. Data management module is used to manage prototype observations, information on design and construction. Errors are identified and processed. According to concerned standards, observations are reorganized and analyzed primarily. The logical model of this module is composed of four bases, viz. project archives base, original database, reorganized database and generated database. Based on observations, analysis and evaluation module is used to implement the analysis and back-analysis for observed data, structure and seepage. Monitoring models and criteria are built. Knowledge base is established to manage the information and knowledge on design, construction, operation, rule of law and criterion. According to observations, the safety characteristic of construction is analyzed and assessed with above methods and knowledge. The factors causing abnormal behavior can be diagnosed, suggestions can be presented to help decision-making. To implement above functions, analysis and evaluation module included six sub-modules, viz. data assessment, comprehensive analysis, observation check, analysis for physical genesis, expert diagnosis, auxiliary decision-making. To supply quantitative resource, this system has a supporting base cluster. The base cluster is composed of database, method base, knowledge base, graphics base. Lastly, the paper proposed the topological structure, operation manner of computer network.

5765-94, Session 20

Offshore platform real-time health monitoring system based on fieldbus CAN and OPC

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Abstract: A large-scale real-time ealth monitoring system of offshore platform using the techniques of fieldbus and OLE (Object Linking and Embedding) for Process Control (OPC) is presented in this paper. The fieldbus is a data transmission protocol designed especial for the offshore platform structural damage monitoring in order to be competent for the harsh and extreme environments under ambient excitation by the ice or wind or flow or earthquake dynamic load. The data control protocol of fieldbus is Control Area Network (CAN). The CAN protocol based on the opening system interconnection/reference model has only three layers structures with the bottom physical layer and data link layer and the top application layer. CAN’s transmitted speed is much higher than the usual TCP/IP protocol. Another character of fieldbus is that the pre-magnifier and sensor muster device are added into the system. The communication rate of CAN fieldbus can reach for 1Mbps/40m and the direct transmission distance arrives at 10000m/5kbps. The third merit is twisted-pair can be used to as transmission medium so the cost of the system is much less than others. The CAN signal transmission uses the short-frame structure whose effective byte number is eight bits so the consumed time in transmitted is short and the disturb probability of noise is lower than others.

The function of OPC is to make different signal acquisition and/or control device which runs in various operation link smoothly so as to transfer data each other. OPC is the bridge of linking the fieldbus signal and monitoring software and all various sensors with intelligent DSP (Digital Signal Processing) which is came from different manufacturer. Because it adopts the OPC protocol and corresponding technique the developer and maintainer of monitoring system has not to dive into the interface problem of various device including sensor and actuator and so they can devote into the realization of automation and intelligence of monitoring system. On the other hand, OPC stands the Component Object Model (COM) and Distributed Component Object Model (DCOM) so the monitoring system is standard and brief-simple to the data exchange in all devices.

The main processing of monitoring system is parameter identification real-time and valuating the propagation of damage of structure by obtaining data from the acquisition part that gets the vibrating data and the acoustic emission information from the important location of offshore platform real-timely and endlessly. The identification module can select sensor optimum placement through the technique of the second sensitivity and tolerance domain under the modal independence principle. It also has ability for extracting the modal frequency and shape and damping ratio under ambient excitation using the method of varying time base and dynamic time series in time-domain and frequency-domain. The model updating technique is used to determine the damage situation. The Integral Development Interface (IDI) of monitoring system is all graphic and the personality interface is given to the post-processing including the help how to use it.

5765-95, Session 20

Adaptive systems for truss and tower systems

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Truss and tower systems mostly in steel are being used profusely in India and every year the failures of at least ten percent of these systems are reported during cyclone or seismic effects. This paper focusses on providing in-built smartness to handle both force and

deformation when unanticipated loads of 50 to 100% increase over design loads and of short duration act on these systems.Different combinations of solutions are presented and compared for ease of implementation and anticipated resistance increase so that an optimal solution can be arrived at. Typical examples of truss and tower system are given with member and node adaptation for best results, thus reiforcing the need for development of such systems to prevent future losses..

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5765-96, Session 21

Statistical detection method for time of arrival and frequency of waves

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This paper illustrates the development of a statistical detection method via time-frequency representations to detect the time of arrival and the frequency of wave signals in a noisy environment. Recent research has shown that nondestructive testing using

Lamb waves can detect the crack/anomaly of structures. The estimation of the time of arrival(TOA)of each Lamb modes, and the frequency of modes buried in the noise is a key first step in detection and localization of flaws using Lamb waves. This paper shows that the time of arrival and the frequency of waves can be detected with low false-alarm

probability and high detection probability using a correlation detector operating on time-frequency

representations. Numerical and laboratory experiments were conducted to verify and validate the capability of the proposed method. The results of experiments demonstrate the utility of the proposed method.

5765-97, Session 21

Wavelet coefficient analysis for the quantitative determination of damage in tendons and cables

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Wires, bars, multi-wire strands made of steel or composite materials are widely used in civil infrastructures as tensioning members in cable-stayed bridges, suspension bridges and prestressed concrete. The health monitoring of these components is a long-standing challenge in the NDE community. In the last few years, the authors have been conducting a study on the application of ultrasonic guided waves for the structural health monitoring of bars and multi-wire strands. This paper presents an application of a signal processing technique based on the Discrete Wavelet Transform (DWT) for the detection and the quantification of damages in loaded seven-wire steel strands. The DWT is applied to ultrasonic signals generated and detected via magnetostrictive transducers. The detection and the quantification of damage in the strands are accomplished by computing the variance and the root mean square of the wavelet coefficient vector of the ultrasonic damage signatures. It is shown that the logarithmic value of these features is linearly dependent to the damage size.

5765-98, Session 21

Multicomponent signal decomposition techniques for structural health monitoring

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Most of structural responses can be considered as the superposition of some monotonic components. These monotonic components contain modal characteristics information that can be used for structural damage detection and health monitoring. This paper presents a comparative study of three techniques for signal decomposition and analysis. These techniques are the wavelet transform (WT) technique, the empirical mode decomposition (EMD) technique, and the proper orthogonal decomposition (POD) technique. These techniques are all capable of decomposing multi-component signals into a summation of mono-components without resorting to the traditional frequency-domain approach. All three techniques can estimate the natural frequencies, damping ratios and mode shapes of a structure from its time-domain vibration responses and hence can be used to monitor the structural condition. A numerical study on a three-story shear-beam building frame is performed and presented to show the accuracy of these techniques.

5765-99, Session 21

Identification of nonlinear normal modes of structures using the empirical-mode decomposition method

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The Hilbert-Huang method, which consists of Empirical Mode Decomposition (EMD) and Hilbert transform (HT), has been used successfully to identify the dynamic characteristics of linear multi-degree-of-freedom structures. In this study, the EMD method is applied to the identification of nonlinear normal modes (NNMs) of structures. It is shown that the intrinsic mode functions (IMFs) obtained from the EMD of the structural response agree quite well with the nonlinear modal responses obtained from the invariant manifold approach. The result suggests that the IMFs can be used to determine the nonlinear amplitude-dependent mode shapes of a structure. To determine these NNMs, the structural response measured at one location on a structure is first processed through the EMD. The IMFs obtained at this location are then used as the regressor variables for the responses measured at other locations. Through a regression analysis, the NNMs of a nonlinear structure can then be obtained. This technique leads to the possibility of determining time-dependent physical properties including both their locations and magnitudes of a nonlinear structure. A two-degree-of-freedom building model with nonlinear stiffness is used for illustration. It is seen that this EMD-based technique is fairly accurate to determine the nonlinear stiffness characteristics of the model.

5765-100, Session 21

Structural damage detection using wavelet packet decomposition and probabilistic neural network

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A new damage detection approach using Wavelet Packet analysis and Probabilistic Neural Networks (PNN) is proposed. PNN, based on probabilistic statistics theory and Bayes classification rules, is an effective tool for classification. Since damage detection can be seen as a kind of classification problem, PNN is suitable for structural damage identification.

Defining suitable parameters as input vectors to PNN is a vital step for damage identification. To take advantage of high frequencies information in measured data, the Wavelet Packet decomposition is employed to produce wavelet packet component coefficients. Wavelet Packet transformation decomposes the signals equally in high frequency band as well as low in frequency band, and it prevents the loss of information in high frequency, to which damage is sensitive. Energies of wavelet packet components of Covariance functions of responses, instead of responses themselves, are calculated as inputs to PNN.

Finally the proposed method is applied to the benchmark problem by the IASC-ASCE Structural Health Monitoring Task Group. The analytical model with 12 degree of freedoms provided by the task group is used in this study. Up to 24 damage patterns are simulated. These damages include taking out of braces, loss of section and change of node connection. The outputs of the wavelet packet decomposition are energies of 8 wavelet packet components. An 8 inputs and 25 outputs PNN is designed. The simulated samples are input to the PNN for damage diagnosis. The example shows that the proposed method identifies the damages with very high probability.

5765-101, Session 21

Bridge health assessment system based on fuzzy logic algorithms

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A modern bridge is such a complicated system that it is difficult and inefficient to analyze it by conventional mathematic tools. The fuzzy logic theory overcomes the difficulty of defining an explicit relationship between the current system states and the actions required to achieve a certain system performance by using linguistic rules. These rules could be determined with an expert knowledge and simply by stating the required cause effect relation in common languages, which has the form of if-then statements. Furthermore, the rules could be learned during some kind of training algorithm. The goal of this research is to provide a practical expert system in bridge health evaluation. Efforts to develop a practical bridge monitoring expert system have mostly concentrated on how to implement experienced-based machine learning successfully. The reliability of the techniques adopted for damage assessment is also important for bridge monitoring systems. Traditional bridge health diagnostic assessments can not systematically cover all relevant modelling possibilities for explaining observations from the field measurement. The introduction of a fuzzy logic algorithm into this system facilitates the rule-based bridge monitoring expert system. By applying the system on an in-service PC bridge, it has been verified that this fuzzy logic expert system is effective and reliable for the bridge health evaluation.

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5765-102, Session 22

Performance of neural networks for simulation and prediction of temperature-induced modal variability

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Vibration-based damage detection methods use changes in modal parameters to diagnose structural degradation or damage. In order to achieve reliable performance of these methods, it is important to discriminate normal changes in modal parameters induced by environmental and operational causes and abnormal changes due to damage, in recognizing that the modal parameters are also susceptible to ambient factors such as temperature, wind and traffic. Based on one-year measurement data of dynamic response and temperature of the cable-stayed Ting Kau Bridge that has been instrumented with a long-term structural health monitoring system, neural network models have been developed by the authors to correlate the measured natural frequencies and temperatures of the bridge.

In this paper, the performance of neural networks in simulating and predicting the temperature-induced variability of natural frequencies for the Ting Kau Bridge is examined. With one-year measurement data of the natural frequencies for the first five modes and the temperatures at twenty locations, two kinds of neural networks are constructed for the mapping between the measured natural frequencies and temperatures. The first kind of neural networks, each having 20 input nodes (temperatures at 20 locations) and one output node (natural frequency of one mode), is formulated to establish relationship between the measured temperatures and the corresponding natural frequency of individual mode. As a result, one independent neural network is formed for each mode. For the second kind of neural networks, the neural network is designed with 20 input nodes (temperatures at 20 locations) and 5 output nodes (natural frequencies of the first five modes) to simultaneously map between the measured temperatures and the natural frequencies of the first five modes. Each of the neural networks is trained and tested with the following two approaches: (i) the former half of the one-year measurement data for both temperatures and natural frequencies are taken as training data, while the latter half of the measurement data are used as testing data; (ii) the whole measurement data are alternately selected as training data and testing data, respectively. After completing the network training, the temperature training data are fed to the trained neural networks again to produce natural frequencies, which are used to compare the natural frequency training data for the assessment of simulation capacity of the neural network models. Then, the temperature testing data are presented to the neural networks to produce natural frequencies, which are used to compare the natural frequency testing data for the assessment of prediction capacity of the neural network models. The study shows that the first kind of neural networks is much easier to achieve convergence in training than the second kind of neural networks, and the simulation capacity of the neural network models is better than their prediction capacity.

5765-103, Session 22

Damage assessment of bending structures using support vector machine

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To reduce maintenance costs or extend the life of structures, a concept of Structural Health Monitoring (SHM) is attractive. Many methods for the structural health monitoring have been proposed for the purpose of maintenance cost reduction or performance guarantee of civil and building structures.

For the purpose of realizing practical SHM systems, many advanced sensors and system identification tools have been proposed. Therefore, it is not difficult to obtain the detailed health information of a structure if sufficiently many sensors are installed and good identification tools are available. However, it is not practical to assume experts are always available to explain the measured data. The budget available for a structural health monitoring system is usually very limited. If we assume an occasion of applying the system to a tall building, it would be unrealistic to say it is economically feasible to deploy several acceleration sensors to each floor for the monitoring purpose. Thus, automatic systems and innovative diagnosis mechanisms are necessary for SHM. In line with this scenario, the purpose of this research is to propose a system that can obtain the detailed damage information by installing the minimum number of sensors. The system is optimized to minimize the possibility of incorrect judgments.

Modal frequencies of a structure are used for pattern recognition in the proposed method. A natural frequency change associated with a certain mode does not provide the spatial information of structural damage. However, multiple natural frequency changes can provide the spatial information on the location of damaged stories. Typically only two vibration sensors on the roof and the ground detecting a single input and a single output for a structural system are needed to determine modal frequencies. Out of many pattern recognition tools, we propose to use Support Vector Machine (SVM). The SVM was recently proposed as a new technique for pattern recognition and is effectively utilized in the system to achieve this purpose. Based on the modal frequency changes, the damage location and its severity are defined by the SVM.

In our previous studies, it was shown that our proposed method worked very well for structures modeled by shear frames. However, this modeling is only appropriate for low-rise building structures and is not appropriate for tall buildings. Therefore, it is our purpose here to extend the method to bending frames that are appropriate models for tall buildings. In the analytical evaluation, we constructed the finite element models to represent bending structures. Then, we conducted a series of experiments for verification. We could show that the damage detection method using SVM was also effective for bending structures.

5765-104, Session 22

Structural health monitoring using FFT

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STUDENT PAPER CONTEST

Composite materials have found a wide range of applications in engineering due to their high strength-to-weight ratio, resistance to fatigue, and low thermal expansion. However, composites present challenges for damage detection since much of the damage often occurs beneath the top surface of the laminate and is not readily detectable. Furthermore, inspection usually takes place after the damage has already occurred, leaving the inspection process to look for residual signs of the failure condition. There is therefore a current need to develop real time and in situ health monitoring techniques that enable a rapid assessment of the materials state of health.

There have been a number of efforts aimed at incorporating non-structural elements into composite materials for damage detection and assessment. This work is part of an ongoing effort to develop a new type of smart composite material that monitors its health using embedded micro-sensors and network communications nodes. Integrating such devices will allow the material to internally acquire and process structural information. Some of the challenges involved in this project include mechanical integration, electronics requirements and limitations, and sensor selection. This paper addresses the issue of data management through the development of localized processing algorithms.

As the number of network nodes increases, the ability to efficiently manage data becomes an important issue. For even moderately sized structures, shuffling the data from the embedded network to an external processor would require unreasonable bandwidth. It is therefore necessary to develop localized processing algorithms that can analyze the data in an efficient manner. This paper investigates the implementation of the two dimensional Fast Fourier Transform (FFT) as one such algorithm. The 2D FFT essentially decomposes a discrete signal into its frequency components (of varying magnitude), and shuffles the low frequency components to the corners. It is shown that the 2D FFT can be a useful tool in revealing the relative magnitudes of different spatial wavelengths in a material. This may be applied, for example, to determine the global components of a strain field. In addition, the 2D FFT is shown to be capable of retrieving those signals from noisy or fluctuating environments.

The focus of this paper is to establish an efficient method for implementing the distributed 2D FFT using a network of nodes embedded within a composite material. This requires that some primitive processing capability be introduced to each sensor node through the inclusion of a microprocessor. Assumptions regarding the low-power, low-bandwidth capabilities of the network are outlined that specifically apply to the technology involved in this project. The 2D FFT is shown to be a useful algorithm for such a network due to its hierarchical structure. This property allows for a convenient distribution of similar operations that can be performed independently and concurrently on separate microprocessors.

Two methods for implementing the 2D FFT are developed based on the radix-2 (Row-Column) and radix-(2x2) (Vector Radix) structures. When implemented on a single processor, the Vector-Radix algorithm is shown to require 25% fewer multiplications than the Row-Column algorithm. The distributed versions of both algorithms are then developed, and compared in terms of computational

requirements within the network of nodes. The orders of operations for calculations, and communications between network nodes, are outlined in detail. Due to their structural similarity, the distributed Row-Column and Vector-Radix algorithms are shown to require the same number of total data transfers. However, the Vector-Radix algorithm is shown to require 50% fewer multiplications than the Row-Column algorithm when performed in a distributed manner.

The 2D FFT can be a useful tool in revealing the relative strengths of periodic signals within a composite material. When looking for signals such as large pressure gradients or spikes, the most significant information can often be found in the low frequency components of the 2D FFT. Therefore, a significant amount of the output data can be ignored, allowing for modification of the 2D FFT algorithms to improve computational efficiency. Pruning techniques are developed for the distributed Row-Column and Vector-Radix algorithms to eliminate computation that is not necessary for the desired output points. It is shown that such techniques reduce communication requirements by 50% for both algorithms.

It is concluded that the pruned version of the distributed Vector-Radix 2D FFT is an efficient and useful algorithm for rapidly assessing the health of composite materials. Future work in this project includes the investigation of other applications of 2D FFT, such as identifying the location of failures in the material using the convolution of an anticipated failure mode pattern with the 2D FFT of the sampled data set.

5765-105, Session 22

High-precision photogrammetric technique for structural response measurement

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The past few years have seen unprecedented technological advancement in commercial digital cameras. The image resolution of these cameras has increased from below 1 million pixels a few years ago to over 10 million pixels today, with little increase in cost. These low cost high-resolution digital cameras have opened up new areas of application for various engineering disciplines, including civil engineering. The objective of this study is to investigate the application of close-range photogrammetric principle and digital image sequence analysis for measuring structural response. A general photogrammetric framework for high precision measurement of three-dimensional structural response is proposed using two commercial digital cameras. Some important issues such as camera calibration, feature point detection, image correspondence and synchronization are discussed. Preliminary test results indicate that the photogrammetric technique can provide sub-pixel measurement accuracy. In one of the tests, it is illustrated that the errors are as low as 0.1mm.

5765-106, Session 22

Metadata and network API aspects of a framework for storing and retrieving civil infrastructure monitoring data

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A framework has been defined for storing and retrieving civil infrastructure monitoring data over a network. The framework consists of two components. The metadata component provides the descriptions and data definitions necessary for cataloging and searching monitoring data. The communications component provides Java classes for remotely accessing the data. Packages of Enterprise JavaBeans and data handling utility classes are written to use the underlying metadata information to build real-time monitoring applications. The utility of the framework was evaluated using wireless accelerometers on a shaking table earthquake simulation test of a reinforced concrete bridge column. The NEESgrid data and metadata repository services were used as a test bed backend storage implementation.

Structural monitoring systems can collect large amounts of data over a period of several years. Unless there is an effective, automatable method to catalog, store, and retrieve the data, it is very difficult to develop modular and network-ready health monitoring applications that can operate near real-time. The metadata schema developed proposes a starting point for developing a data management solution for a smart civil system.

The metadata schema contains basic definitions for the information about the data collected by a monitoring sensor system. For example, the metadata classes for data collectors such as accelerometers and displacement meters provide slots for their calibration information, links to their location within the structure, links to collected data sets, and threshold values for damage detection. Metadata for observed data sets provide a link to the sensor that recorded the data, the time it was collected, and information about measurement units.

The data from health monitoring systems require special treatment, because damage-causing events can be sudden and occur over a very short duration compared to the life of a structure. For example, earthquake shaking might last only for a minute compared to the decades a building is in service. This poses a data mining problem because if the structure is continuously monitored over several years, the significant portion of that data is only a minute portion of the entire collected data set. The metadata system addresses this sparse data problem by grouping significant data by events, such as earthquakes. Events contain a description along with a defined beginning and end time. This allows more effective data mining by browsing significant events instead of the sifting through the entire data set. It also provides an interface for automatic damage detection algorithms to analyze the results.

In addition to the metadata component, a Java API has been developed to interact with the metadata on an object level. This API is a starting point for developing monitoring applications that execute over a network. Taking advantage of the Java 2, Enterprise Edition platform (J2EE) provides information technology services for health monitoring. The platform is designed to accommodate remote data management and data mining.

5765-107, Session 23

Development and implementation of a nondestructive monitoring system on a composite steel box-girder bridge in Connecticut

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The University Of Connecticut, with support and assistance from the Connecticut Department of Transportation, has been involved in monitoring bridges in the State for approximately two decades. These studies have provided information on how different bridges behave, have been used to develop monitoring techniques, both experimental and analytical, and have provided guidance on renovations in order to assist the State in the management of its bridge infrastructure. All studies have had a field-monitoring component.

Research now underway involves the design and implementation of long-term monitoring systems on a network of bridges critical to the State of Connecticut's highway infrastructure. Monitoring systems have been designed for a variety of bridges, with a variety of sensors. Data is collected continuously using normal traffic loads and temperature information. This paper will present a brief overview of the current program. This will be followed by a report on the development, implementation and evaluation of the monitoring of a steel box-girder bridge.

The bridge is a multi-span, continuous, box girder bridge made up of two steel box sections that are composite to the slab. The bridge is supported on a series of tall concrete columns, one per support. Field investigations have shown that the columns have been subject to torsion cracks. The bridge was included in the study to learn more about the long-term behavior, and to explore the cause of the column cracking.

Two spans in a three-span continuous segment are currently being monitored using 8 accelerometers, 8 temperature sensors and 6 tilt meters. An extensive analysis has been conducted to evaluate the test data. There have been large temperature gradients due to both climate changes and the position of the sun with respect to the bridge. The results have also been used to develop a basis for long-term NDE monitoring. This is based primarily on the development of a vibration signature. The results show that vibration signature has remained unchanged during the first 3 years of monitoring. Field results have also been compared to an extensive finite element analysis. The long-term goal of this project has been to characterize the bridge behavior and then to use this in the nondestructive evaluation of the performance over multi-year periods.

5765-108, Session 23

Structural health monitoring of bridges using effective two-step identification approaches

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Two-step identification approach for effective bridge health monitoring is proposed to alleviate the issues associated with many unknown parameters faced in the real structures and to improve the accuracy in the estimate results. It

is suitable for on-line monitoring scheme, since the rigorous damage assessment is not always needed to be performed whereas the alarming for potential damage occurrence is to be continuously carried out. In this study, two-step identification approach is incorporated. In the first step for screening potential damaged members, three different methods were utilized: (1) Damage Indicator Method based on the Modal Strain Energy (DIM-MSE), (2) Probabilistic Neural Networks (PNN), and (3) Neural Networks using Grouping technique (NN-Gr). Then, in the second step, the conventional neural networks technique is utilized for damage assessment on the screened members. The proposed methods are verified through a field test on the northern-most span of old Hannam Grand Bridge over Han River in Seoul, Korea. The issues on measurement noise, modeling errors and multiple damages are addressed.

5765-109, Session 23

Instrumentation for durability monitoring of a long-span cable-stayed bridge

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The Sutong Bridge over the Yangtze River in China has a total length of 8046 m and is comprised of a cable-stayed main bridge, a frame girder auxiliary bridge, and a series of approach span bridges. The cable-stayed main bridge has a total length of 2088m with two symmetry back spans and a central span of 1088m which creates a new world's record. To ensure the operational and structural safety and to facilitate the optimal maintenance during the service life, a comprehensive health monitoring system over 800 sensors has been devised by a joint venture between Hong Kong Polytechnic University and Jiangsu Transportation Research Institute.

As part of this long-term monitoring system, in-situ durability monitoring subsystem for reinforced concrete structures/components with embedded corrosion sensors is developed to provide timely information on the condition of concrete at different locations of the structure exposed to various micro-environments, especially for corrosion-prone zones. The corrosion sensors used in the Sutong Bridge include galvanic cells, resistivity probes, relative humidity sensors and temperature sensors covering both corrosion-environment monitoring and corrosion end-result monitoring. All the corrosion sensors are installed during the bridge construction stage, making it possible to trace the condition of concrete during the entire service life. The data from the corrosion sensors will be periodically collected with specifically developed acquisition systems and will be integrated with real-time monitoring data for durability analysis. Such a durability monitoring system allows the bridge owner to initiate timely remedial measures to avoid serious deterioration, to plan regular maintenance, and to check the effectiveness of maintenance activities, thus optimizing the life-cycle maintenance.

5765-110, Session 23

Intelligent health monitoring systems for cable-stayed bridges

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Recent years, with rapid economic development, a lot of huge civil infrastructures have been constructed or are being planned to be constructed in China. All government, scientists and engineers take care of the safety of the huge civil infrastructures in long-term service. Intelligent health monitoring systems provide an effective means to monitor safety condition and give the alarm of damage events and accidents. With the requirement of administrative authorities of transportation, authors have installed some intelligent health monitoring systems for cable-stayed bridges in mainland China.

In this paper, two types of intelligent health monitoring systems for two cable-stayed bridges are introduced. One of them is intelligent health monitoring system for Binzhou Yellow River Highway Bridge, which automatically runs in real time. The system includes 138 optical fiber Brag-grating strain and temperature sensors, embedded in deck, girders, towers, respectively; 38 accelerometers attached at cables, towers and decks respectively; 4 GPS receivers installed on the bank, tower and deck; and 2 anemoscopes fixed on the top of the tower and the deck. PCI bus mastering technique and Labview-based acquisition program are employed to collect data; Motorola wireless instrument is installed on the top of the tower for transferring data from the PC on the bridge site to the server at the toll station with 2 MB between 15kM; a SQL Server 2000 database in the server is employed to manage all measured data, and information of structures and sensors; a strain-mode-based damage detection method is employed to detect damage of the bridge; model updating and safety evaluation are also considered in the system. The system is integrated in Labview software and can automatically run in real time on Web by browser. Any modification, adding and delete can be done on Web. The finite element models of cables and towers are updated based on the data of the static and dynamic tests. The second is the intelligent health monitoring system for Harbin Songhua River Cable-stayed Bridge, which runs off-line. The system consists of 84 optical fiber Brag-grating strain and temperature sensors, strain sensors of which embedded between the deck and girders to measure the slip between concrete decks and steel girders. 32 accelerometers are attached at cables, towers and decks. 1 anemoscope is installed on the top of the tower. The system continuously runs twice times each year and for 7 days each time.

5765-111, Session 23

Structural health monitoring and risk alarming in plate-girder bridges under uncertain temperature condition

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For the critical structural systems such as long-span bridges, an accurate and timely capability of structural health monitoring (SHM) should be implemented in any affordable ways. Nonde-structive damage assessment is an important sub-task of structure health monitoring (SHM) and should form the basis of any decision for diagnosis and prognosis of a structure. During the past two decades, many researchers have attempted to detect and localize structural damage using changes in dynamic modal parameters. One of the most appealing features associated with us-ing modal information is that they are relatively simple to measure and utilize for a prompt diag-nosis. Despite these research efforts, however, a few key issues exist for the practical, vibration-based, damage detection in structures. The first issue is to assess the variability of modal proper-ties caused by temperature effects in the sensing and data acquiring levels of SHM. The second issue is to detect damage and alarm structural risk in these structures under uncertain temperature condition. Based on the previous reports, temperature differences are about 500C during a year in a real-life situation of a bridge, and these changes have an influence on the dynamic characteris-tics of the structure. Damage-induced frequency changes can be completely masked by changes due to normal varying temperatures.

In this paper, temperature-induced uncertainty in SHM is assessed to adjust modal data used for vibration-based damage detection in model plate-girder bridges. First, experiments on test structures are performed in the various temperature conditions. Controlled laboratory experi-ments were conducted on the structure to measure changes in modal parameters caused by tem-perature and structural degradation. Next, the uncertainty in modal properties is assessed statisti-cally. The relationship between temperature and modal properties is analyzed and a set of temperature-adjustment formula is formulated for the test structure. Finally, a vibration-based method is used to detect damage and alarm risk in the test structure.

5765-112, Session 23

A bridge structural health monitoring information system based on GIS technology

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This paper presents a research development on a bridge structural health monitoring and information management system (BSHM&IMS) by use of geographic information system (GIS) and other related technologies. Based on the dynamic monitored information from various sensors on a bridge, the status of its structural health can be monitored. One of the major issues in this process is to handle a huge amount of information – both real time and accumulated historical data. The traditional data process and management methods cannot fully meet the requirements on data process and management for bridge structural health monitoring.

Besides the attribute information, the bridge structural health status monitoring information is highly related to geospatial location. That is, the monitored information can be referenced to a spatial location, for examples, geospatial locations of bridges, geospatial layouts of various sensors on bridges, three dimensional models of bridges, and fault points of sensors on maps. GIS technology is therefore applied to manage the information in bridge structural health monitoring.

The general framework of BSHM&IMS will be introduced first in this paper, which is based on an integration of several information technologies, including GIS, database management system, network and others. As an implementation of the general design, a prototype BSHM&IMS is developed and the major solutions are

then described in details. These functions include, for example, geospatial database structure design of bridges, process of information from various sensors, management of a huge amount of monitoring data, visualization of bridges information, illustration of warning information of fault points of sensors on three dimensional models of bridges, backup and output of important data according to users' querying conditions.

The experimental results demonstrate that the BSHM&IMS is capable to manage huge amounts of bridge structural health monitoring data — both real time and accumulated historical data — effectively.

5765-113, Session 23

In-service inspection of deck beam bridge

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In-Service Inspection of Deck Beam Bridge

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ABSTRACT

Economic and effective evaluation of the actual condition of a bridge is an important issue for bridge maintenance and preservation. The current condition of the bridge is usually far more different from the construction design and also with the bridge being in service for few years, a quantitative evaluation is essential. Assimilating reviews and comparisons of traditional inspection and evaluation methods, this paper promotes the concept of application of wireless sensors developed at the Bridge Research Center for rapid installation and low power requirements for in-service real-time bridge inspection. The concept focuses on obtaining useful data such as strain, displacement, frequency for estimating the actual characteristics of the bridge while in service, thus avoid closing the traffic as compared to traditional load test which needs traffic closure causing inconvenience to public and indirectly affecting economy. Plans and procedures of the field inspection are detailed as well as the data processing and the analysis results are presented. The effectiveness and feasibility of the proposed real-time inspection based on wireless sensors approach are illustrated via the practical inspection of a deck beam bridge.

Keywords: in-service inspection, wireless sensors, bridge evaluation

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5766-24, Poster Session

Nondestructive testing of LIGA specimens utilizing laser doppler vibrometry

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Throughout the engineering community, nondestructive evaluation (NDE) of parts remains a powerful way of determining material characteristics and ensuring performance. It is no surprise that NDE methods have become pertinent in the realm of micro-devices. As IC chips must be tested and proved reliable through means of electrical testing, mechanical devices also made in the clean room must somehow be physically tested. A variety of NDE techniques are available, but the one discussed here will be based on laser Doppler vibrometry (LDV). The manufactured parts to be tested were created at Sandia National Laboratories using a LIGA process.

The reliability of these parts is of paramount importance and determining the material properties and the resulting performance is essential. Detection of surface flaws is possible through optical means, but interior defects or voids are more difficult to detect, the common means being X-ray radiography. This paper will discuss the merits of using LDV to not only help determine the material properties of a device, but also to detect defects by comparing the frequency response functions of parts.

It is the intention of this experiment to reveal the dynamic characteristics of a set of LIGA manufactured hurricane springs, display how those characteristics vary from batch to batch, and how they would shift with specimen damage. The PolyTec Micro-Motion Analyzer (MMA) will be used for this characterization, specifically, the Scanning Laser Doppler Vibrometer (SLDV). Dynamic characteristics will be determined for each arm of each spring leading to a statistical variation study of the specimens. Damage will then be induced on the specimens to prove the ability to detect flaws by monitoring shifts in resonant frequencies.

Four batches of parts, with several springs per batch, and two arms per spring made up the data set. Using the SLDV, each arm of each spring was analyzed by monitoring the velocity profile output induced by an impulse impact exciting all frequencies and a shaker excitation using a periodically chirping input ranging from 0 to 5000 Hz. Both in-plane and out-of-plane motion was examined. On each arm of the specimen, a single point was studied to generate a Frequency Response Function (FRF) with amplitude and phase information. A higher resolution scan was subsequently done to get a finer resolution on the frequency response and to garner images of the velocity profile. These FRFs were then utilized to help determine the elastic modulus of the material and were compared to the resulting FRFs found after the specimens are damaged.

The frequencies found using the LDV verified those found in Finite Element simulation using Abaqus. Thus, the models generated from the elastic modulus found from nano-indentation and micro-bending tests were honed by tuning the models to these results. By establishing a modulus through a combination of all these tests, any variation of the modulus in future part production can then be found by monitoring the shift in the resonant frequencies. Further, drastic changes in frequency for a part can point to interior defects not found through surface observation.

5766-25, Poster Session

Nondestructive characterization of micromachined ceramics

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The aerospace, automotive, and electronic industries are finding increasing need for components made from silicon carbide (SiC), silicon nitride (Si_3N_4), and aluminum nitride (AlN) ceramic materials. The development and use of miniaturized ceramic parts, in particular, is of significant interest in a variety of critical applications. As these application areas grow, manufacturers are being asked to find new and better solutions for machining and forming ceramic materials with microscopic precision. Recent advances in laser machining technologies are making precision micromachining of ceramics a reality. Questions regarding micromachining accuracy, residual melt region effects, induced strain, and laser-induced microcracking are of critical concern during the machining process. In this activity, a variety of nondestructive inspection methods have been used to investigate the microscopic features of laser-machined ceramic components. The primary goal was to assess the micromachined areas for machining accuracy, microcracking, and induced strain using laser ultrasound, Raman microprobe, and white-light interference microscopic imaging of the machined regions. Several different laser machining conditions were studied and adjusted using the nondestructive imaging techniques, which provide quality assurance, physical understanding, and optimization schemes for micromachined ceramic components.

5766-27, Poster Session

Statistical signal parameters of acoustic emission for process monitoring

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Many technological processes, e.g. in mechanical engineering, are causing acoustic emission. Acoustic emission (AE) consists of elastic waves, generated by stress changes in a solid. These waves can be detected at the surface of the solid by piezoelectric sensors. Classical methods to characterize acoustic emission signals include detecting and counting single events, describing their energy and frequency properties. The interference of a large number of AE sources leads to quasi-continuous signals from which no individual AE event can be extracted. This is typical for such technological processes as grinding, slicing, and lapping. If AE signals shall be used for online process monitoring, it is necessary to extract signal properties that are correlated with process changes. A common feature is the RMS value of the signal, which is correlated with the energy of AE and was found to be very sensitive to changes of process conditions. Other features used are the peak values of the signal and the number of zero crossings. To get more information about the actual state of the observed process,

parameters of the statistical distribution of short-time RMS like mean value, variation coefficient and excess have been tested and their sensitivity to process changes have been investigated. Online processing of broadband signals and long process duration demand for fast acquisition rates and signal processing. For these investigations, a monitor has been developed based on a hard- and software concept adapted to process continuous acoustic emission. The signal processing strategy, the monitor and some application examples are presented.

5766-28, Poster Session

X-ray fluorescence camera for high-resolution elemental mapping

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We present a novel approach to map characteristic x-ray fluorescence using an x-ray camera that can image selectively different x-ray energies. The camera employs a Fresnel zone plate as the x-ray imaging optic and achieves currently sub-100nm spatial resolution, ultimately limited by the quality of zone plates available.

The advantages of this camera compared to traditional EDS/WDS mapping techniques are: the spatial resolution is not limited by the excitation spot, a whole map of one element is collected simultaneously, the spatial resolution does not degrade with sampling depth, high efficiency and energy resolution for sub-2kV radiation, insensitivity to sample charging, and the ability to perform thin film measurements on small patterned structures.

The X-ray Fluorescence camera can be used for both x-ray and electron beam excitation. For example, it can easily be integrated into an existing scanning electron microscope, in a similar way to EDS and WDS equipment.

In contrast to EDS/WDS mapping, it is preferred for the x-ray fluorescence camera to excite a larger spot on the sample corresponding to the field of view of the fluorescence map. High spatial resolution is achieved by directly imaging the fluorescence x-rays on an array detector (CCD), rather than inferring the position by the excitation spot. The high spatial resolution of the x-ray imaging camera is also preserved with sampling depth, enabling high-resolution x-ray maps of buried structures and recovery of 3-d information. Since a whole map is collected simultaneously, x-ray fluorescence maps can be collected in a short amount of time compared to WDS/EDS maps.

X-ray fluorescence maps of backend copper integrated circuits are presented as an example of non-destructive imaging of sub-surface structures. The x-ray fluorescence camera enables the in-situ location of voids and defects in backend copper ICs without physical deprocessing or ion beam milling preparation and can be performed on whole silicon wafers.

Conference 5766: Testing, Reliability, and Application of Micro- and Nano-Material Systems III

5766-29, Poster Session

Integrated cantilever fabrication and system development for ultrasonic and acoustic scanning probe microscopy

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Although the conventional optical lever technology typically used for scanning probe microscope applications has proven highly sensitivity, accurate, and cost effective for most applications involving micromachined cantilever deflection measurements, the frequency limitations and space needs limit its applicability to emerging ultrasonic-based SPM applications. Recently, the fabrication of cantilevers integrated with actuation and sensing components has opened avenues for feedback-based driving of micromachined cantilevers at higher-order resonance frequencies while sensing average deflection without the need of an optical deflection pathway for average deflection sensing. The work presented here will review recent efforts by our group in fabricating micromachined cantilevers with integrated piezoresistive deflection-sensing components combined with integrated ZnO actuation layers to induce cantilever deflection. These cantilevers are being fabricated for use in a heterodyne force microscopy system (HFM) to enable SPM imaging contrast based on viscoelastic response of a surface in contact with a micromachined tip wherein active-feedback technology is being applied to maintain ultrasonic tip excitation at higher order cantilever resonances. The first and second-pass fabrication results will be presented and reviewed regarding cantilever release, piezoresistor formation, bridge-circuit fabrication and ZnO actuator (and electrode) fabrication. Dynamic response data from these structures, measured via laser Doppler vibrometery reveal the expected resonance structure for a cantilever of these dimensions. In addition, the design of a discrete-component feedback system will be presented for maintaining cantilever excitation at a higher-order resonance during scanning. A complementary design based on a Labview system driver for sub-1MHz resonance-based freedback will also be presented.

5766-01, Session 1

X-ray refraction topography and computed tomography for NDE of lightweight materials

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X-Ray Refraction Topography techniques are based on Ultra Small Angle Scattering by micro structural elements causing phase related effects like refraction and total reflection at a few minutes of arc as the refractive index of X-rays is nearly unity. The extraordinary contrast of inner surfaces is far beyond absorption effects. Scanning of samples results in 2D-imaging of closed and open pore surfaces of ceramics and foams, crack surface density and orientation in plastics and fiber/matrix debonding of polymer and ceramic composites after cyclic loading and hydro thermal aging. In most cases the investigated inner surface and interface structures correlate to mechanical properties. A commercial Refraction Scanner is available. Three-dimensional resolution is achieved by Synchrotron Refraction Computed Tomography.

For the exploration of Metal Matrix Composites (MMC) and other micro structured materials the refraction technique has been improved. A 3D Computed Tomography (CT) test station was combined with the X-ray refraction technique. Different from the set up for phase contrast CT, the sample is situated in an X-ray beam between two single crystals at the rocking curve centre while a 2D-detector is placed behind the second crystal. The first crystal acts as a monochromator and collimator while the second crystal refuses all scattered radiation beyond 2 seconds of arc. Therefore all sample scattering is strongly suppressed and interpreted as additional attenuation. Asymmetric cut second crystals magnify the image up to 50 times revealing nano meter resolution. The refraction contrast is several times higher than “true absorption” and results in images of cracks, pores and fibre debonding separations below the spatial resolution of the detector. The investigations have been performed at the materials research station of BAM “BAMline” at the Berlin Synchrotron Facility “BESSY”. The technique is an alternative to other attempts on raising the spatial resolution of CT machines, and is expected to solve many problems in understanding micro and sub micro structures in materials science. The given results yield a much better understanding of fatigue failure mechanisms under cyclic loading conditions.

5766-02, Session 1

X-ray diffraction topography images materials by molecular probe

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Crystallinity, composition, homogeneity and anisotropy determine the mechanical properties of materials significantly, but the performance of most non-destructive techniques is too poor for measuring these micro structures as they are optimised for finding individual flaws. X-ray (wide angle) Diffraction Topography by single beam scanning images molecular information at a spatial resolution of several ten micrometers even in three dimensions. Especially for the non-destructive characterization of composite materials, they provide additional capabilities by crystallographic contrast by the molecular/atomic probe. The different material phases of compounds and their molecular orientation can be imaged e.g. fibers or polymer chain orientation in composites: A sample is scanned or rotated, while only part of the scattering pattern is pointing at an X-ray detector area. Three different methods have been developed:

i)planar X-ray Scanning Topography at one or more pre-selected scattering angles provides high contrast of different phases of components.

ii)X-Ray Rotation Topography reveals the texture angle of composite fibres and chain polymers.

iii) X-ray Diffraction Microscopy images the texture and phase distribution of transversal sections of the material.

The principles of Wide Angle X-Ray Diffraction Topography are explained and examples of investigations will be presented. They combine the advantages of radiographic imaging and crystal structure information. The applied X-ray energies are much lower than in NDT radiography, which recommends preferably the application to light weight materials.

5766-03, Session 1

Micro-mechanical properties of fiber composites characterized by X-ray-refraction

V. Trappe, M. P. Hentschel, Bundesanstalt für Materialforschung und-prüfung (Germany)

Fibre Reinforced Plastics (FRP) are increasingly applied in transportation systems (aircraft, railway, automotive) and infrastructure industries due to the good specific properties of high strength at low weight. Advanced FRP structures have to endure high mechanical and environmental loading. There for the durability and reliability depends much more on the micro mechanical properties as on the global strength. For example pure intralaminar micro cracking – without any delaminations of layers and fibre fracture leads to a distinct strength reduction of carbon fibre reinforced plastics (CFRP). Micro cracking is non-detectable for conventional X-ray-radiography and ultra sonic measurements.

X-ray refraction topography is a powerful tool for the characterization of fibre matrix debonding and micro cracking. Strong correlations are found between the calculated stress state and the increase of inner surfaces due to fibre matrix debonding. Additionally a new method for a quantitative determination of transverse and shear strength in a complex laminate will be presented. There for the X-Ray refraction technique is applied on-line at a tensile loaded specimen. The combination of mechanical loading and non-destructive testing with the X-ray refraction technique yield a fundamentally new understanding of the micro mechanical properties of FRP.

5766-04, Session 1

Direct iterative reconstruction of computed tomography trajectories (DIRECTT)

M. P. Hentschel, A. Lange, J. Schors, Bundesanstalt für Materialforschung und-prüfung (Germany)

A new iterative algorithm performs the precise tomographic reconstruction of projection measurements without Fourier filtering. In case of parallel beam computed tomography the most predominant sinusoidal trajectories of sample elements are selected referring either to their contrast or their intensity. Each sinus path corresponds to exactly one element of the reconstruction matrix (image pixel). Fractions of their weight or contrast are added at the calculated image position. The preliminary reconstruction matrix is then projected into a sinogram, which is subtracted from the original one. The resulting residual sinogram is then iteratively treated like the original data set. As soon as the

residual sinogram has become weak enough after sufficient iterations nearly all the sample information is collected into the reconstruction.

The predominant advantage of the new algorithm is a sharp image at detector pixel size resolution, but considerable computing time is still needed. The capabilities for good reconstructions of incomplete data sets from projections at arbitrary angles or limited regions of interest are of further advantage. High noise projection data have no direct influence on edge resolution as the signals are averaged over the projection angles, not over the projection coordinate. Detector artifacts can be suppressed strongly. The reconstruction quality is documented during all stages of the iteration process and can be pre-selected by limiting the weight of the residual sinogram. The "direct iterative reconstruction of computed tomography trajectories" can be applied to all kind of projection measurements on moving and rotating objects. It is also suitable for additional image edge enhancing in conventional computed tomography. Examples of model calculations and reconstructions of experimental data are compared to conventional Fourier filtered back projections.

5766-05, Session 2

X-ray reflectometry and small-angle X-ray scattering

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Because their wavelengths are similar to the sizes found in nano-materials systems, X-ray probes are well suited to the non-destructive structural characterization of very small scale and/or thin film structures. The interactions of X-rays with atoms tend to be relatively weak (unlike, for instance, electron-solid interactions), so they can typically be described in terms of perturbations; this greatly simplifies the mathematical description of the X-ray scattering process and permits quantitative modeling of that process with relative ease. Even greater utility in nanomaterials characterization arises when the included angle between the incident and scattered X-ray beam directions is itself kept small. Because the distances probed in diffraction space (also known as "reciprocal space") are thus very reduced, the corresponding distances examined in "real" space are relatively large. X-ray scattering in the small-angle limit thus gives information on the large-scale features of a sample (when compared with interatomic spacings) and is thus insensitive to small-scale crystallography. It can thus be applied to materials irrespective of their physical state, whether that be amorphous, polycrystalline, or single crystal.

If the sample of interest happens to be a large, planar substrate such as those used in semiconductor manufacturing, then high resolution X-ray reflectometry (XRR) can be used to great advantage for characterizing thin film systems. Critical parameters such as layer thickness, chemical composition, and interfacial roughness can be obtained non-destructively using this method. On the other hand, if the sample does not permit specular reflection but can instead be observed in transmission (and, of course, if the scattered signal can be discriminated from the undeviated transmitted beam) then small-angle X-ray scattering (SAXS) can be used to characterize the structure of both simple and complex systems at length scales that are of importance to nanotechnology.

While the utility of both SAXS and XRR has been recognized for decades, the metrology needs for modern micro- and nano-materials systems have brought both techniques to a new-found level of prominence. This talk will discuss the theory that leads to the utility of XRR and SAXS for nanosystems metrology; specific technical problems that they have successfully addressed with the two approaches will be highlighted. Of course, the ultimate utility of any metrology tool depends on the factors that limit its accuracy and precision, and both XRR and SAXS are no different. Thus we will address several of the factors that limit the accuracy and precision of these tools, such as angle metrology, X-ray beam conditioning, alignment, the nature of the sample itself, and the noise that is an ever-present component of X-ray analyses. Within these limitations, however, we will argue that both X-ray reflectometry and small-angle X-ray scattering will serve important roles for non-destructive characterization and metrology in micro- and nano-materials systems for the foreseeable future.

5766-06, Session 2

Nondestructive characterization of nanoparticles in solid states by Raman spectroscopy and small angle x-ray scattering

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Nanotechnology offers different ways to create materials and devices of new amazing properties for very promising applications. Among them are nanoscale structuring of bulky substrates, composing of elemental nanoparticles, and the formation of nanoparticles in solid states by thermal treatment – here called nanodefect engineering. In this paper the characterization of nanoparticles of low concentration in dependence on the annealing history shall be discussed.

Transmission Electron Microscopy is the standard tool for characterization of nanoparticles in solid states. But this method is not non-destructive and as imaging technique limited with respect to revealing of particles and defects of very low concentration. Therefore, integrating methods as Raman spectroscopy (RS) and Small Angle Scattering of X-rays and Neutrons (SAXS and SANS, respectively) have proven to be very useful alternatives.

In this paper, the complementary determination of size distribution of arsenic precipitates in low-temperature grown GaAs layers and of CdS‹sub\›x‹/sub\›Se‹sub\›1-x‹/sub\› nanocrystallites in silicate glass filters by RS and SAXS shall be exemplarily presented.

5766-07, Session 2

High-resolution x-ray microscopy for NDE of micro- and nano-structrues

S. Wang, Xradia, Inc.

X-ray imaging offers a number of unique favorable properties for nondestructively characterizing micro- and nano-structures: (1) high energy x rays have very large penetration length to probe internal structures without the need of deprocessing; (2) x-ray absorption and fluorescence emission depends strongly on the elemental composition of the sample, thus allowing material analysis with extremely high sensitivity; (3) x-ray imaging has no charging effect and causes little structural damage. Furthermore, a sample's three-dimensional structures can also be obtained non-destructively with the computer tomography (CT) technique. While projection-type x-ray systems with a few um resolution have been widely deployed, recent advances in x-ray optics and detectors have resulted commercial lens-based x-ray microscopes with better than 60-nm resolution. Used independently or in combination with established techniques based on visible light and electron microscopy, these new high-resolution x-ray systems offer greatly enhanced NDE and material-specific imaging capabilities for studying structures at micrometer to tens-of-nm scale. We will provided a focused discussion on these systems and its applications.

5766-08, Session 3

Self-regulating charge control for ultra high-resolution scanning electron microscopy

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We describe a new tool that combines low vacuum charge control with ultra high resolution, immersion lens electron microscopy. Charging is controlled through self-regulating processes designed to yield consistent charge stabilization that is transparent to the operator, and independent of the tasks performed during imaging. This is illustrated by series of high resolution images of non-conductive samples such as chrome-on-quartz photomasks, acquired as a function of parameters like magnification and scan speed.

Conventionally, electron imaging of non-conductors entails tuning the primary beam landing energy to the so-called "E2 point" (typically around 1 keV) at which the net rates of charge injection and removal are equal and the sample surface potential is equal to zero. However, this approach is very impractical because the beam energy often requires re-tuning when performing routine operations such as a change in magnification or scan rate, and sample translation. This is a consequence of the fact that the E2 energy is, in reality, not a material constant, but a complex function of beam current density and the electronic properties of the region of sample irradiated by the electron beam.

In environmental scanning electron microscopy (ESEM), the specimen chamber contains a small amount of gas (typically, 20 – 700 Pa) and the beam energy is greater than E2. The resulting negative charging is stabilized by gas molecules ionized by electrons emitted from the sample and by the beam. Self-regulation (i.e., independence from beam current density and sample properties) is achieved by: (i) generation of an ion current greater than that needed for charge control, and (ii) employment of electrode structures that collect excess ions. In the latter, the ions are directed to a sink (i.e., a cathode) through a path on which the ion trajectories are susceptible to subtle variations in the electric field produced by charging. Any changes in the sample surface potential alter the flux of ions incident onto the surface so as to maintain the potential at a constant value. Fluctuations in the surface potential affect images far less than in the E2 method because the field strengths needed to re-direct the trajectories of low energy gaseous ions are much lower than those needed to alter the high energy electron beam.

However, combining ESEM-style charge control with state-of-the art ultra high resolution columns is not trivial. The latter operate at short working distances and utilize intense magnetic or electric fields in the lower column and the specimen chamber. Intense electric fields cause environmental gases to discharge, making them incompatible with low vacuum environments. Conversely, the field of a magnetic immersion lens does not affect the gaseous environment, and can be exploited in the design of ESEM detectors that provide self-regulating charge control and highly efficient electron detection at the short working distances required for high resolution imaging. The principles of operation of such devices will be discussed in terms of electron and ion generation and trajectories, and charge stabilization at the sample surface.

5766-09, Session 3

FIB based measurements for material characterization on MEMS structures

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Design, manufacturing and packaging of new MEMS/NEMS devices demands detailed know-how on mechanical material properties used. Because of size effects due to miniaturization as well as manufacturing and exploitation influences on material properties, classical methods of material testing often do not provide correct material data. Values published by different authors and determined on various devices can differ by ,e.g., a factor of three and more for the same material. Consequently, a strong need exists to measure material properties directly on MEMS devices or MEMS precursor structures.

Respectively, the authors present a new approach, fibDAC, which allows to measure and analyze deformation fields on stressed micro and nano components, which can be utilized for mechanical material characterization. The method bases on digital image correlation algorithms (DIC) applied locally to load state images captured in focused ion beam (fib) equipment. As a result, deformation fields are determined, which occur due to loading of MEMS structures inside the FIB station. Combining measured fields with finite element simulations relevant mechanical material properties can be evaluated. Corresponding object loading is accomplished either externally by testing modules designed for application inside the FIB equipment or by FIB specimen treatment in order to release inherent specimen stresses. A similar tool, called microDAC/nanoDAC, has been reported earlier [1,2] and applies DIC techniques to SEM or AFM images. The advantages of the new fibDAC approach occur in the incorporation of specimen preparation (ion milling, ion beam surface polishing and DIC patterning), specimen loading by ion milling and DIC deformation measurement in a single equipment.

The authors present several applications of fibDAC measurements on stressed micro components. Emphasis is made to the evaluation of residual stresses on micro component structures. “Smart” ion milling is used to cause local deformations resulting from inherent residual stresses. Their analysis gives access to quantified residual stresses. Although being not completely nondestructive the method possesses advantages against other approaches, like e.g. built-in stress sensing structures, because of its more general suitability with regard to quite different structures and residual stress states.

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5766-10, Session 3

3D reconstructive imaging of Cu/W/SiO2 integrated circuit interconnect structures through FIBSEM

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Although cross-sectional scanning electron microscope (CS-SEM) imaging of integrated circuit (IC) interconnect structures is a characterization technique that has proved critical in failure analysis and fabrication optimization of IC devices, the complexities of emerging device and interconnect structures will require three-dimensional (3D) information for necessary characterization. A case in point is the formation of voids in IC inter- and intra-level interconnects (so-called ‘vias’ and ‘lines’, respectively) where void formation during processing and burn-in may have serious implications for long-term IC reliability. One promising method for acquiring this 3D information employs a dual column Focused Ion Beam/Scanning Electron Microscope (FIBSEM) to serial section a structure in slices ~ 50nm thick using a conventional Ga-ion beam for ion-beam milling. This process has been carried out for interconnect structures incorporating W studs/lines and Cu vias/lines in a SiO2 dielectric matrix. A refinement procedure has been developed for low-damage imaging of the ‘tomographic’ Cu/W/SiO2 slice incorporating a conventional Pt ‘resist’ used for FIBSEM imaging. Utilizing this procedure serial ‘slicing’ of the test structure has been carried out in a LEO 1540 Crossbeam dual-beam FIBSEM system. After each slice is cut, secondary electron maps, backscattered electron maps, and x-ray maps of each exposed plane are recorded. The image series is stored and reconstituted using 3D reconstruction software similar to that employed for tomographic images. Once the interconnect structure is reconstituted, arbitrary slices through the model can be made in order to expose structures and defects therein from any viewing angle. This will be illustrated. In addition, a first-pass hyper-spectral imaging protocol has been investigated to incorporate x-ray microanalysis and textural mapping for similar tomographic reconstruction.

5766-11, Session 3

Application of photo and particle acoustic methods

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The paper summarizes several investigations on P(h)AM (photo and particle acoustic methods) carried out at the Fraunhofer Institute IZFP Dresden during the last years. They include modeling activities and experimental work.

In a scanning electron acoustic microscope (SEAM) the electron beam is modulated in its intensity. This leads to an elastic wave in the specimen which can be detected e.g. by piezoelectric transducers. Examples of SEAM images including the domain structure of ferroelectric BaTiO‹sub\›3‹/sub\› and the grain structure of martensitic steel are presented.

For modeling acoustic waves generated by photo or particle excitation, an efficient numerical code (CEFIT) has been developed. It allows calculation of wave propagation and scattering problems in heterogeneous and dissipative fluids and isotropic solids. The code has been verified against analytical solutions (Green´s function, integral transform solutions). For the case of laser excitation of a plate, modeling results were also compared with experimental results.

High energy ions provide a new method for cancer therapy. A beam of accelerated ions is shot into the body. The ions lose their energy mainly at the end of the path (Bragg peak). This effect is used to destroy cancer in inner parts of the body. In this application, ion acoustics represents an independent method for dose distribution monitoring. The ion acoustic effect has been proven for 200 MeV/amu carbon ions. Thereby the thermoelastic effect was identified as the main source contribution.

5766-12, Session 4

Elastic modulus of nanomaterials: resonant contact-AFM measurement and reduced-size effects

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Due to the development of nanomaterials (carbon nanotubes, ...) and of nanodevices (MEMS, NEMS, ...) the characterization of the properties of these nanostructures became a critical issue. In this communication, we present a new method called Resonant Contact Atomic Force Microscopy (Resonant C-AFM) that we developed to measure the elastic modulus of nanomaterials. This method was applied to the study of reduced-size effects on the elastic modulus of metallic nanowires and of polymer nanotubes. In Resonant C-AFM, the application of a normal load to the contact is obtained using a sinusoidal electric field applied between the sample holder and the microscope head, that induces the cantilever vibration. Varying the intensity and the frequency of the field enables the complete characterization of the resonance spectrum of cantilevers while the tip contacts the sample surface. The resonance frequencies of the cantilever-sample system shift to higher values relatively to the resonance frequencies of the free cantilever. This shift enabled the determination of the contact or nanomaterial stiffness. Here, the cantilever tip was located on the nanostructures suspended over pores of a membrane and the resonance spectrum was measured. The resonance frequencies for a model system of cantilevers with the tip in contact with a simple spring were calculated with the Rayleigh-Ritz method and compared to the experimental data for the different nanostructures. This comparison proved that, since the natural frequency of the suspended nanowires and nanotubes is much higher than that of the cantilever, these can be considered as simple springs. The method also enabled the determination of the boundary conditions of the nanostructures (clamping conditions) by measuring the resonance frequency distribution along the nanostructure suspended length. It is shown that

the correct model is that of beams clamped in deformable supports. Using the simple model of a cantilever with the tip in contact with a spring, the stiffness of the nanowires and the nanotubes was deduced from the measured resonance frequency and, hence, the tensile elastic modulus of the nanostructures. For both the polymer nanotubes and the metallic nanowires, the Young's modulus values measured on the bigger structure was in excellent agreement with the values reported in the literature for bulk materials. For the nanowires or nanotubes with smaller diameters, the measured elastic modulus increased continuously and differed significantly from that of bulk materials for the smaller diameters. To explain this behavior, the calculation of an apparent elastic modulus taking into account the surface tension effects was proposed. This model showed that below a critical size, the increase of surface during the deformation was responsible for the observed increase in the measured modulus. Moreover, this model allowed the calculation of the real elastic modulus and the surface tension of the probed material from the measurement of the apparent elastic modulus as a function of the diameter.

This study thus proves that the Resonant C-AFM is a reliable method to quantitatively measure the mechanical properties of nanomaterials and nanostructures: the Young's modulus and the surface tension.

5766-13, Session 4

Ultrasonic characterization of the mechanical properties of thin film coatings

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The development of structures and devices made of micro- and nano-structured materials has resulted in the need for advanced measurement techniques to characterize their properties. For instance, micron-thick diamond-like carbon (DLC) coatings are used on machining tools, rollers and gears etc because of their ultra-high hardness and good tribological properties. As another example, edge-supported thin film structures that are only a few hundred nanometers thick and a few hundred microns wide form an integral part of many MEMS devices such as mirror arrays, RF-switches, and pressure sensors. The elastic properties and residual stresses in such films affect their mechanical performance. Unfortunately, the properties of bulk materials are not necessarily indicative of those of the corresponding micro- and nano-structured materials since these are strongly affected not only by the material composition but also by the processing methods used. Therefore, convenient and precise characterization of the mechanical properties of thin films is important in order to provide valuable feedback during the thin film manufacturing process. In this work, two types of photoacoustic measurement methods - photoacoustic guided-wave technique and a picosecond ultrasonic pump-probe technique - are used for noncontact, nondestructive measurement of mechanical properties of free-standing thin films and coatings on substrates. The results are compared with those obtained using a quantitative line-focus contact acoustic microscope (LFAM), and also using destructive nanoindentation methods. It is shown that consistent and precise measurement of the mechanical properties of thin films and coatings is feasible using non-contact, nondestructive photoacoustic methods.

Results of measurements using photoacoustic guided waves, LFAM, and nanoindentation on several DLC hard coating specimens will be presented. In the photoacoustic guided-wave approach, dispersion curves for the pulsed laser generated surface acoustic waves (SAW) on various DLC hard coatings were measured optically with an acoustic bandwidth of 150 MHz. In order to derive the mechanical properties of the coatings, a multi-layer material model is developed and the transfer matrix method was used to theoretically analyze the wave motions in such multi-layer structures. The elastic parameters including Young's moduli and Poisson's ratios of the DLC thin films are derived by fitting the experimental SAW dispersion curves to the model. For comparison, LFAM was then used to measure the leaky SAW dispersion curves at 140-240 MHz range for the same set of DLC coatings. Independently obtained mechanical properties of DLC coatings from each approach were analyzed and then compared. The results from the ultrasonic methods were also compared with nano-indentation tests and these show excellent consistency of measurements for all the DLC samples tested.

In a second set of experiments, free-standing nanometer-sized two-layer thin film structures were tested using a femtosecond pump-probe method. A femtosecond laser launches bulk acoustic echoes at ultra-high frequencies (\>GHz), which propagate within the films and their reflections, are measured by a delayed femtosecond detection beam. Thus the bulk wave velocities are directly determined by the arrival time of the reflected waves, and these are related to the elastic properties of thin films. The measured results are compared with results obtained using the guided-wave photoacoustic technique.

5766-14, Session 4

Nondestructive mechanical imaging of carbon nanotubes

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Differential ultrasonic force microscopy (d-UFM) has been used to investigate the nanoscale mechanical response of multi-walled carbon nanotubes (MWNT) synthesized via arc-discharge (A-D) and chemical vapor deposition (CVD) techniques. Quantitative analysis of the MWNT d-UFM data utilized custom fabricated, single crystal diamond cantilevered tips, Si and sapphire substrates, and a high resolution laser vibrometer system for sample-to-sample calibration. Initial investigations of the A-D and CVD MWNTs through d-UFM reveal a surprisingly large radial indentation modulus compared to Si and sapphire. Nanoscale axial nonuniformities in the indentation modulus are also observed and correspond in size and conformation to variations in the MWNT wall thickness observed via TEM. UFM imaging was also carried out on MWNTs following prolonged exposure to a Ga-ion beam. Exposed areas of the nanotube exhibited modified mechanical properties resulting, presumably, from increased defects induced by the ion beam.

5766-15, Session 4

High-resolution imaging of ferroelectric domain structure by ultrasonic atomic force microscopy

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Miniaturized micro-electro-mechanical-systems actuator has motivated the development of ferroelectric materials capable of large strains. In order to improve the performance, the understanding of mechanical property at the ferroelectric domain level is important because the movement of the ferroelectric and ferroelastic domain boundary (DB) generates large strain, leading to high piezoelectric coefficient. Therefore, the elasticity of the DB as well as the domain may affect the piezoelectricity. However, the measurement of the DB itself is difficult because of the width in the range of 1 to 10 nm. Ultrasonic atomic force microscopy (UAFM) has been developed as an elasticity evaluation method with the resolution of an atomic force microscope, which enables the evaluation of stiff materials such as ceramics and alloys by the resonance vibration of the cantilever. In this study, ferroelectric domain structures in lead zirconate titanate (PZT) ceramics were investigated by high-resolution image of UAFM, combined with the observation by a piezoresponse force microscopy (PFM) that is widely used for visualizing the ferroelectric domain structure. We present the different elasticity by the differently oriented domain and the possibility of extremely low elasticity at the DB than that within the domain. In experiment, we used a resonance frequency tracking system in order to realize rapid measurement of the resonance frequency and obtain high spatial resolution image, which is essential for the evaluation of small structure such as the DB. Commercially available soft bulk PZT ceramics were investigated (sample 1: NEC Tokin Cooperation, N-21, sample 2: Fuji Ceramics Cooperation, C-82). They were annealed above Curie temperature to obtain a randomly oriented domain structure. These samples were lapped by diamond slurry. Sample 1 was polished by colloidal silica slurry. After the ferroelectric domain structure was visualized by the PFM, UAFM was applied. The periodic variation in elasticity due to the 90 degrees domain structure was visualized by the resonance frequency image at the 3rd deflection mode. For investigation of the DB, sample 2 was polished by alumina paste. The decrease of the elasticity along the ferroelectric DB was visualized by the resonance frequency image at the 2nd deflection mode. From an analysis using the cantilever vibration theory and the hertzian contact theory, the elasticity at the DB is approximately 55 GPa when the contact radius is 8.4 nm and the Young's modulus and the Poisson's ratio within the domain are 60 GPa and 0.39, respectively. Based on the mixture law of the Young's modulus under the identical strain, the elasticity at the DB is approximately 18 GPa when the half width of the domain is 1 nm. Because extremely low elasticity at the DB may be related to its higher mobility under stress or electric field, we are planning an in-situ observation method under electric field. We are going to fabricate a pair of surface electrodes on the sample using the photolithography technique and generate parallel electric field to the surface. This method will provide important information about a polarization fatigue in ferroelectric memories as well as unknown fundamental properties in ferroelectrics.

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5766-16, Session 4

Quantitative nanomechanical imaging with contact-resonance-frequency AFM

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As critical length scales in many applications shrink below one micrometer, new tools are needed to examine material properties on commensurate scales. In response, we are developing dynamic atomic force microscopy (AFM) methods to quantitatively image the nanoscale mechanical properties of surfaces, thin films, and nanostructures. We have previously demonstrated how elastic-property values can be obtained at a single point using atomic force acoustic microscopy (AFAM). In this talk, we will describe our work extending AFAM principles to achieve rapid, two-dimensional mapping of elastic properties. AFAM makes use of multiple resonant frequencies of an AFM cantilever in contact mode to calculate the tip-sample contact stiffness. Local elastic properties can be determined from the contact stiffness using the appropriate contact-mechanics models combined with information from a reference specimen of known properties. With this approach, elastic properties with a lateral spatial resolution of tens of nanometers can be obtained. However, fixed-position techniques are typically orders of magnitude too slow for practial application to two-dimensional mapping. Our approach uses a newly developed frequency-tracking circuit to locate the contact-resonance frequencies at each image position. The circuit is based on a digital signal processing architecture that enables rapid data acquisition (typically ‹ 30 minutes for a 256 x 256 image). With a range of operation from approximately 1 to 3000 kHz, the circuit can accommodate many different cantilever vibration modes. We will present imaging results obtained with both flexural and torsional modes on several nanostructured materials. By combining information from both vibrational modes, it may be possible to simultaneously determine both Young's modulus and Poisson's ratio for an isotropic material. Issues related to quantitative image interpretation will also be discussed, for example calibration methods, tip wear, and choice of contact-mechanics model. All of these elements play a role in achieving the objective of truly quantitative nanomechanical imaging.

5766-17, Session 4

Numerical time-domain simulation of wave propagation and scattering in acoustic microscopy for subsurface defect characterization

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The acoustic microscope is a well-established tool for studying internal microstructures of non-transparent solids and coatings. It is widely used in detection of cracks and subsurface defects in various materials. Image formation and interpretation strongly depend on frequency and material properties. For instance, in scanning acoustic microscopy (SAM) operating in the GHz frequency range, the images of subsurface defects in soft coatings can be easily interpreted by using acoustical ray theory since the wavelengths of longitudinal and shear waves are typically smaller than the film thickness. In stiffer materials or at lower frequencies, however, different problems arise. If the wavelength becomes comparable or larger than the film thickness, interpretation of the acoustical near-field images is very challenging. In this case ray theory no longer holds and Rayleigh surface waves cannot be neglected since they penetrate deeper than the focal points of longitudinal and shear waves.

A numerical model of an acoustic microscope based on the elastodynamic finite integration technique (EFIT) will be presented. It allows time-domain simulations of elastic wave propagation in both, fluids and solids, and includes focusing of the incident wave field as well as scattering at defects and the fluid-solid interface taking mode converted echoes and Rayleigh waves into account. The simulations can be performed for different frequencies and materials and can be used for continuous and time-resolved mode as well as for transmission and reflection microscopy. The simulation results can be represented by time-domain signals and wave front snapshots. Also formation of V(r,z) curves is possible. The simulations are applied to the problem of solid spherical inclusions in a solid half-space as well as subsurface characterization of thin coatings. The results are compared to theoretical and experimental data.

5766-18, Session 4

Damage detection in polymer composites with mechanochromatic nanoparticles

B. F. McCaughey, Beckman Institute

A simple and effective method of detecting damage and microcracks in structural polymer components would increase reliability and safety while decreasing overall system cost. Current methods to detect damage in polymers and polymer composites often utilize expensive and time consuming techniques such as ultrasound, electrical resistance, infra-red thermography, and low energy radiography. Our approach incorporates novel silica / polydiacetylene (PDA) nanoparticles within a structural polymer matrix to provide a simple and cost-effective method of detecting damage. Under mechanical stress, PDA undergoes an irreversible transition from blue to red due to changes in delocalization along the conjugated backbone. The red form of PDA is fluorescent, allowing both visible and fluorescent detection of damage. Both PDA nanoparticles and nanoparticle / epoxy composites were characterized with TEM, SEM, XRD, and UV-vis absorption. Materials were tested using a tapered double-cantilever beam test, impact tests from a drop tower mechanism, and fatigue tests. Visible adsorption and fluorescence measurements taken during and after these mechanical tests were compared with initial sample conditions. This damage detection system may find eventual application in industrial and commercial plastic components.

5766-19, Session 5

Shearographic technique for NDE analysis of high frequency bending vibrations of microstructures

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Investigation of dynamics of micro electromechanical systems (MEMS) is an important problem of engineering, technology and metrology. Specifically, recent interest in applying MEMS technology to miniaturization of relays, sensors, actuators for variety of applications requires design of appropriate testing and measurement tools for investigation of dynamic properties of those systems. Therefore, application of measurement technologies capable of detecting the dynamic properties of micro scale systems may help to understand and evaluate the functionality of those systems.

The shearographic technique for the detection of the tranverse displacements of micro-cantilevers with respect to the shearing direction is presented. The method is expanded upto a hybrid numerical-experimental approach and includes the generation of shearographic images of the microstructures using finite element methods. The presented analysis is based on modeling NDE shearographic method and microstructures behavior.

5766-20, Session 6

Near-field Raman microscopy and spectroscopy

L. Novotny, N. Anderson, Univ. of Rochester

Progress in science and technology was often triggered by the invention of new instrumentation. Due to the availability of new kinds of microscopes and spectroscopic techniques we have developed a thorough understanding of physical phenomena, ranging from the atomic structure to the structure of biological cells. The rapid advance of nanoscience is also largely due to new instrumentation that allows us to manipulate and measure structures on the nanometer scale. Optical spectroscopy provides a wealth of information on structural and dynamical properties of materials. The chemical specificity attained through optical spectroscopy (IR absorption, Raman scattering, etc.) is remarkable. We will demonstrate that near-field optics makes it possible to extend resolution of optical spectroscopy down to 10nm, - the length scale of biological proteins and the length scale of quantum confinement in semiconductor nanostructures. Our technique, called near-field Raman microscopy, makes use of the highly localized electromagnetic field at a laser-irradiated metal tip. This localized field acts as a secondary light source that can be raster-scanned over a sample surface at close proximity. For every sample pixel, an entire Raman scattering spectrum is recorded and evaluated. We have applied near-field Raman microscopy to the characterization of single-walled carbon nanotubes. We find that the technique is able to localize defects and dopants. The technique holds also promise for the nanoscale analysis of local stress in silicon nanostructures. A better understanding of induced stress will help the trend of miniaturization and provide important feedback for improved device performance.

5766-21, Session 6

Direct observation of molecular vibrations by tip-enhanced near-field scanning optical microscopy

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A light microscope capable to show images of molecules in nanometer scale has been a dream of scientists, which, however, is difficult due to the strict limitation of spatial resolution due to the wave nature of light. While there have been attempts to overcome the diffraction limit by using nonlinear response of materials, near-field scanning optical microscopy could provide better detecting accuracy. Near-field spectroscopy, such as fluorescence, infrared absorption, and Raman scattering, is a very powerful tool for the in-vivo chemical analysis of organic molecules in nanometer scale. Raman scattering and infrared absorption spectroscopy allow for direct observation of molecular vibrations without necessarily photobleaching of the sample as well as quenching. While conventional Raman spectroscopy is relatively straightforward to carry out with well-established light sources and instruments in the visible region, the Raman scattering cross-sections (~10-30cm2) are much smaller than that of fluorescence (~10-16cm2) and infrared absorption (~10-20cm2). Moreover, in a near-field scanning optical microscope setup, the observed volume of the sample must be confined in the nanometer scale that corresponds to very small number of molecules. Therefore, it becomes difficult to realize near-field nano-Raman spectroscopy. In this presentation, we present molecular nano-imaging colored by Raman-scattering spectral shifts, which is probed with a metallic tip. The metallic probe tip has been used to enhance the optical field only in the vicinity of the probe tip. The effect is similar to the one seen in the detection of molecules on the metal-island film, known as surface-enhanced Raman spectroscopy (SERS), while in this case a single metallic tip works for the field enhancement in nanometer scale. We also apply this tip-enhanced field to the excitation of 3rdorder nonlinear vibrational spectroscopy, coherent anti-Stokes Raman scattering (CARS), for the higher sensitivity and spatial resolution. Owing to the 3rdorder nonlinearity, the excitation of the CARS polarization is extremely confined to the end of the tip apex, resulting in a spatial resolution far beyond the diffraction limit of light. Our tip-enhanced CARS microscope visualized the DNA network structure at a specific vibrational frequency (1337 cm -1) corresponding to the ring-breathing mode of diazole of adenine molecules and achieved 15 nm spatial resolution.

5766-22, Session 6

Antenna-based near-field scanning optical microscopy

H. F. Hamann, IBM Thomas J. Watson Research Ctr.

A powerful extension of apertureless near-field scanning optical microscopy exploits antenna and localized near-field enhancement effects, where a scanning probe tip is utilized as a highly localized light source. Specifically, an antenna-based optical scanning near-field microscope is presented, which monitors the optical interactions between a sample and an atomic force microscope tip under evanescent field laser illumination. The presented microscope has the essential requirements to exploit efficiently antenna effects. First of all, the excitation laser is correctly polarized along the probe axis providing an antenna-like field enhancement due to the elongated shape of the probe tip. Secondly, the evanescent field generated via total internal reflection only illuminates the very end of the probe tip (~150 nm), which avoids dephasing of the dipolar field contributions along the tip. Finally, the resulting signal is monitored in a direction of the incident evanescent wave, which most efficiently detects the dipolar radiation pattern of the probe-sample system.

First, the excess scattering due to the mutual near-field interaction between a Si-probe and a metallic nanoparticle is investigated as a function of lateral scan position. Very high sensitivity down to single molecule level is achieved with this method, while high spatial resolution is accomplished by virtue of the short-ranged near-field effects. The wavelength dependence of the scattering signal is investigated revealing a first-order near-field spectrum of a single Au-nanoparticle.

Second, we monitor the extinction of the reflected beam for probe-sample interactions illuminated by the evanescent fields. The scheme exploits shot-noise limited detection of changes in reflected light intensity due to near-field interactions between the sample and a sharp AFM tip as a function of probe-sample geometry, providing both high sensitivity (‹0.1 ppm Hz0.5) and absolute cross-section data for comparison with near-field model predictions.

Finally, we investigate the luminescence from dye-doped polystyrene nanospheres. In the near-field region a strong near-field enhancement is observed, which results in both high spatial resolution (‹ 10 nm) and excellent sensitivity (~ 2 Ao2 in 1 Hz bandwidth). This fluorescence enhancement is further investigated as a function of probe-sample distance.

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b.) Part of this work has been done at JILA / University of Colorado at Boulder

5766-23, Session 6

Near-field nano-Raman imaging of Si device structures

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Aperture-based and apertureless-based near-field Raman imaging holds the potential for nanoscale stress metrology in emerging Si devices. Although preliminary application of near-field Raman imaging on Si device structures has demonstrated the potential for stress measurements it is necessary to increase the signal-to-noise ratio of the measurement before it can be widely applied. To that end, we present near-field nano-Raman imaging of Si device structures using a modified near-field optical microscope (NSOM). The nano-Raman system utilizes an off-axis (45 degree) backscattering NSOM geometry with free-space collection optics. The spectroscopic configuration utilizes a single-bounce spectrometer incorporating a holographic notch filter assembly utilized as a secondary beam-splitter for an apertureless backscattering collection geometry. Initial aperture and apertureless-based implementation on Si wafers agree with previous results and are compared to theoretical models for off-axis scattered power. Application to Si/SiN strip test structures reveals a spatial modulation in Raman scattering as expected. These data are compared to the same measurements using an apertureless approach.

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5767-01, Session 1

In-situ ultrasonic monitoring of crack growth under static and dynamic loading conditions

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Successful in-situ monitoring of crack initiation and growth is a necessary prerequisite for applying ultrasonic methods to structural health monitoring. For conventional ultrasonic testing methods, a focused beam may be used to directly image the crack tip; however, this method is difficult to apply during fatigue testing because of access limitations and couplant contamination issues. However, ultrasonic sensors can be permanently attached to a specimen to detect signal changes due to crack initiation and growth if the wave path is properly directed through the area of critical defect formation. The dynamics of cracks opening and closing during the fatigue process modulate the amplitude of ultrasonic waves propagating across these crack interfaces. Thus, even very small cracks can be reliably detected using permanently mounted sensors if the ultrasonic response can be measured as a function of load. A methodology is presented here that uses this behavior to detect and monitor crack formation and growth. This methodology may also be applied to structures subjected to unknown dynamic loads by using the ultrasonic signal to both estimate the instantaneous dynamic load and interrogate the integrity of the structure. Essential to the success of this method is an initial calibration on the undamaged structure where ultrasonic response is measured as a function of known static load. Results are presented from several aluminum specimens undergoing low cycle fatigue tests, and the dynamic loading results are shown to be comparable to the static ones in terms of the response of the ultrasonic signal to crack progression.

5767-02, Session 1

Evaluation of impact-induced damage of CF/AF hybrid fabric composites with scanned image microscopy

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An experimental investigation was conducted to evaluate the interior damage of CF/AF hybrid fabric reinforced plastic composites induced by impact loading. Experiments were undertaken on a series of the hybrid specimens with different stacking sequences of carbon fiber and aramid fiber reinforced prepregs. The specimens were damaged by 5mm and 10mm diameter steel ball projectiles propelled through an air-gun type of impact apparatus. The impact velocities were 40m/s and 113m/s for the 5mm projectile, and 40m/s for the 10mm one. The scanning acoustic microscope (SAM) was used to visualize the delamination located within the specimen. Based on the interior images formed by SAM, the damage areas are calculated for damage evaluation. In addition, a scanning electron microscope(SEM) was used to see some matrix crackings and debondings at the cross-sectional area of the specimens for confirming the results.

5767-03, Session 1

Composite structures with pre-stress subject to low velocity impact damage

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The effect of an initial prestress on the response of Carbon-Fibre/Epoxy laminated plates subjected to low velocity impact is investigated. The material used for this study was 8 ply quasi-isotropic carbon fibre – epoxy resin “HYE 970/STD 12K (RH) 13”composite panels [0,+45,-45,90]s. Four 1 m x 1 m panels were manufactured to aerospace standards using an autoclave, from which 84 test specimens (215 x 215 mm) were machined. The geometry of the specimen was to chosen to allow an “impact area” of 140 mm x 140 mm unaffected by end restraint conditions.

Prior to being impacted, the samples are loaded either uniaxially or biaxially using a specially designed test rig which enables tension or compression loading, independent on each axis. Impact tests were carried out for two impact energies for uniaxial and biaxial tension, pure shear and the zero prestress cases. It was necessary to determine a relationship between the applied load and the strain in the centre of the plate. Several specimens were strain gauged, and data was recorded for loading of the specimen under all configurations of prestress. Values of ram pressure corresponding to a specific central uniaxial or biaxial strain were determined.

The effect of the prestress on the permanent indentation depth, absorbed energy and peak impact loads was experimentally quantified and was the subject of a previous paper. Prestress was shown to not significantly affect the dynamic response of the samples. This paper presents the results on the effect of the prestress on the internal damage area, residual tensile strength and stiffness. Flash thermography and ultrasonic c-scanning NDI methods were carried out to inspect the impact damage.

The results indicate that prestress influences the size of the internal damage area. Biaxial tension presents the most severe loading case as it produces the largest internal damage area. The residual tensile strength and stiffness are essentially independent of the nature and magnitude of the pre-stress at low levels of impact energy (6J), and at higher levels of impact energy (10J).

5767-04, Session 1

Identification of failure modes in composite materials using AET and neural network

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Introduction

The inherently higher level of uncertainty in the structural properties of advanced composite materials is an impediment to the acceptance of these materials by users. Structural members fabricated from fiber composite materials exhibit several different modes of damage growth. In laminated unidirectional composite materials, the failure modes include fiber breaks, delamination, and transverse matrix cracks.

The present study is an attempt to use the various parameters related to the AE signal for identifying the sources of AE signals. AE signals from mode I fatigue crack growth normal to the direction of load axis in fabric composite materials as well as mode I and II delamination growths are considered in this study. In addition different types of noise signals are also considered.

Experiment

The coupons were 1 inch wide, 0.125 inch thick and 16 inches long. In the fatigue specimen a 0.125-inch long edge notch was used to initiate a fatigue crack. The growth of this mode I crack was monitored under constant amplitude cyclic load. In the mode II delamination specimen a delamination was created between the plies approximately at mid thickness. This delamination specimen was also subjected to axial cyclic load and the growth of this mode II crack in the matrix/interphase was monitored. The sensor arrangement is as shown in the fig 1.

The material used in this study was glass fabric/epoxy composite laminate. The AE signals were recorded using a digital oscilloscope. These waveforms were further processed to extract the various AE parameters. These parameters included the AE amplitudes, frequency contents, rise time, and duration. Typical AE waveforms arising from mode I fatigue crack growth normal to the direction of load axis and mode II delamination growths are shown in fig 2.

There exists a very clear distinction in the three waveforms, and this is very clearly established visually. In a real time environment, the maintenance crew usually has to come to a decision very quickly, and they do not usually have the time or expertise to do it. An application which can identify the failure modes automatically and efficiently in real time would be ideal in such a situation. Neural networks have been in vogue [3, 4], for quiet sometime and easily become the apt choice for such an application.

Neural Network

Neural networks can be trained broadly in two different ways supervised and unsupervised. In supervised training, the network has a target output for a given input, whereas in unsupervised training, the target output is not known, the network is given certain number of inputs during training and the network

intuitively puts them into different classes. After the training, the neural net outputs the target output or the target class for a given input, as per the training given.

In our current study we are going to use a feed forward multi layer neural net. The training algorithm used was back propagation. The input layer has the inputs from the different variables obtained from the waveforms like amplitude duration and frequency. The output layer has just one neuron because we need only output for classification irrespective of the number of inputs. The transfer functions used are tan sigmoid and the output layer has a pure linear transfer function.

Current Status

We have developed a neural net using the Neural Network toolbox of MATLAB. A considerable amount of data has been classified with considerable accuracy, and we are currently working on developing a GUI application where the data extraction and input to the neural network can be completely automated. More experiments are also being done and different other parameters are also being investigated to serve as inputs to the network. We are also experimenting with other topologies of a neural network, to find out the optimal one suited for the job.

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5767-05, Session 1

Evaluation of stress-induced martensite phase in ferromagnetic shape memory alloy Fe-30.2at%Pd by non-destructive Barkhausen noise

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Barkhausen noise (BHN) method seems a useful technique to non-destructive evaluation of martensite phase transformation of ferromagnetic shape memory alloy, which is used as the filler of our proposing " Smart Composite Board". The concept of design for "Smart Composite Board" which can combine the non - destructive magnetic inspection and shape recovery function in the material itself was formerly proposed. BHN is caused by pinning the movements of magnetic domain walls on coarse grain boundaries and/or on microstructure boundaries during magnetization of ferromagnetic alloy.

We have studied BHN caused by the irregular interaction between magnetic domains and thermally activated martensite twins during magnetization of ferromagnetic shape memory alloy Fe-29.6at%Pd, which is in stable martensite phase(fct structure) at room temperature.

  In the present study, we survey the possibility of Barkhausen noise (BHN) method to detect the transformation of microscopic martensite phase caused by stress-loading in Fe-30.2at%Pd thin foil, which has a stable austenite phase (fcc structure) at room temperature. The BHN voltage was measured at loading stress up to 100 MPa in temperature range of 300K to 373K. Stress-induced martensite twin was observed by laser microscope above loading stress of 25 MPa. A phase transformation caused by loading stress were analyzed also by X-ray diffraction. The signals of BHN are analyzed by the time of magnetization and the noise frequency. BHN caused by grain boundaries appears in the lower frequency range (1kHz–3kHz) and BHN by martensite twin in the higher frequency range(8kHz – 10kHz). The envelope of the BHN voltage as a function of time of magnetization shows a peak due to austenite phase at weak magnetic field. The BHN envelope due to martensite twins creates additional two peaks at intermediate magnetic field. BHN method turns out to be a powerful technique for non-destructive evaluation of the phase transformation of ferromagnetic shape memory alloy.

5767-06, Session 1

Comparison of normal and phase stepping shearographic NDE

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The paper presents results of non-destructive testing of composite main rotor helicopter blade calibration specimens using the laser based optical NDE technique known as Shearography. The tests were performed initially using the already well established near real time non-destructive technique of Shearography, with the specimens perturbed during testing for a few seconds using the hot air from a domestic hair dryer. Subsequent to modification of the shearing device utilized in the shearographic setup, phase stepping of one of the sheared images to be captured by the CCD camera was enabled and identical tests were performed on the composite main rotor helicopter blade specimens. Considerable enhancement of the images manifesting or depicting the defects on the specimens is noted suggesting that phase stepping is a desirable enhancement technique to the traditional Shearographic setup.

5767-07, Session 1

Use of high frequency dielectric measurements in the NDE of adhesively bonded aluminium joints

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This paper presents evidence of how high frequency dielectric measurements can be made on adhesively bonded aluminium joints, the ways in which such measurements can reveal information on the long term health of such joints and discusses the developments in the theory of non-uniform transmission lines necessary to realise the practicality of measurements on realistic mechanical test coupons.

The high frequency region (100 kHz to 6 GHz) has the potential of being used as a Non Destructive Examination technique for bonded structures. It has the advantage of not requiring any modifications or insertions into the bond to allow the measurements to be performed and is totally non invasive.

The principle change in dielectric behaviour on long term exposure of adhesive bonded joints to the environment is seen both in the contribution of absorbed water itself and its effect on the dielectric spectrum of the adhesive. There is also secondary contribution to the high frequency response which can be interpreted as due to a change in the interfacial region between the adhesive and the metal adherend.

The measurements reported here are on a clad aircraft grade aluminium with chromic acid anodisation bonded with a commercial epoxy adhesive. Test coupons designed for shear and cleavage tests were exposed in water baths at elevated temperatures for periods up to 700 days and periodically subjected to dielectric measurements over a frequency range of 100kHz to 6GHz. Some test coupons were destructively mechanically tested to monitor directly the changes mechanical properties of the joints. In addition plaques of the adhesive alone were subjected to similar environment and their dielectric spectrum recorded periodically over a large frequency range 1Hz to 20GHz.

A major limitation to date in the application of high frequency dielectric measurements to real structures is the modification of the Transverse Electro-Magnetic (TEM) wave propagation by non-uniformities of practical structures. We present the development of an analysis that significantly improves the interpretation of data that is collected.

Results are presented that show how dielectric measurements can reveal evidence of adhesive plasticisation, morphological changes and degradation during long term water exposure.

Evidence is also presented of how the high frequency Transverse Electro-Magnetic wave propagation is influenced by degradation of the adhered/ adhesive interface.

This paper indicates the significant potential for non destructive examination of ageing in adhesive bonded structures by the application of the high frequency dielectric method.

5767-09, Session 2

Novel guided-wave based damage detection method for arbitrary defects

M. Yang, P. Qiao, Univ. of Akron

Based on the phenomenon of elastic wave propagation, a novel approach is presented to effectively analyze wave scattering and assess damage. First, a new

time-domain wave scattering theory is proposed by using mode superposition, and the governing equations are solved by direct numeric time integration. Then, the detection problem is treated as an optimization problem, of which a combination of patch locations making up the feed back signals from sensors is found, thus minimizing the difference of the measured sensor signals and the output signals from the wave scattering results. These sensor patch locations actually indicate the locations and sizes of damages. By combining the above two aspects, a systematic health monitoring methodology is formed, which can perform the following two functions: (1) Using the sensor signals (usually more than two sensors should be used in order to increase the reliability of finding the locations and sizes of damages), a material characterization is performed based on the signals from the healthy sample, and (2) Further, an optimization module is used to approximate the signals from the sensors on damaged samples and assess the location and size of damage. Wave scattering process is an important aspect in understanding the wave propagation and detecting the damage in thin wall structures. The excitation signal considered in this study is a five-count Hanning window smoothed tone burst, which is obtained from a pure tone burst of frequency f filtered through a Hanning window. It indicated that the Hanning window smoothed tone burst enhanced the reliability of damage detection and increased the feedback signal from both the experimental and analytical studies as observed by the authors (Yang and Qiao 2004). An analytical wave propagation and scattering model is then accordingly developed for active wave propagation in a plate due to the surface bonded PZT patches. In this study, the wave scattering phenomena with arbitrary defects are demonstrated using the proposed time domain wave scattering analysis, and the results are then compared with the existing theoretical solution for a simple case of a thin plate containing a circular hole. Here is an example of wave propagation process in an aluminum plate actuated by an actuator at the center location. The plate has a dimension of 0.88 x 1.21 x 0.0032 m and the actuator has a dimension of 25.0 x 50.0 x 0.25 mm. The first 100 vibration modes are used, and compared with the published results (Ghoshal and Kim 2003), the validity of the model is demonstrated. The application of wave propagation technique in damage detection is shown in another example of an aluminum beam (916x14x1.6mm) with damage close to the right end. In summary, the proposed time domain wave scattering theory and optimization scheme demonstrate their effectiveness and accuracy in damage assessment using PZT sensors and actuators, and they can be used as a effective and robust tool in structural health monitoring systems.

5767-10, Session 2

Traverse and longitudinal crack detection in the head of rail tracks using Rayleigh wave-like wideband guided ultrasonic waves

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We have developed a 'pitch-catch' low frequency-wideband Rayleigh wave EMAT system with a centre frequency of approximately 200 kHz. On the head of a rail the generated waves are strictly speaking a type of guided wave mode as the propagation surface is not a flat halfspace. These waves are Rayleigh wave-like in behaviour and propagate surface is not a flat along the surface of the rail penetrating down to a depth of several millimetres. We have used this approach to demonstrate detection of gauge corner and longitudinal cracking in the rail head. On samples containing machined slots we have shown that crack depth can be estimated by measuring the relative amount of the ultrasonic wave at a particular frequency that passes underneath the crack. The EMAT system also has the potential to assess the condition of the combined microstructure and stress state around the rail head by measuring accurately the velocity of the surface waves. The approach that we have used is fundamentally different to and has several advantages over conventional ultrasonic contact methods that should ultimately facilitate testing the rail head more thoroughly at higher speeds.

5767-11, Session 2

Experimental investigation of damage detection on composite plates using wave analysis

W. Lestari, P. Qiao, Univ. of Akron

Early detection or monitoring is the key to prevent a catastrophic failure of structures, which in most cases are expected to perform well near their limit conditions. Such a monitoring system will provide information concerning the development of structural damages, which can be used to implement timely action for maintenance or repair to ensure the safety and integrity of structures. Damage monitoring and detection in composite structures is especially more difficult compared to the metallic structures, due to the anisotropy of the material, the conductivity of the fiber (e.g., carbon fiber) and the fact that much of the damage often occur beneath the surface, and are hence hardly detectable or visible. Wave propagation-based techniques offer appealing ability to inspect wide area of structures, owing to their unique potential for long-range, in-plane propagation. The challenge is to develop the ability to identify the changes and interpret them in relationships with the changes of physical properties of the structures, including the ability to differentiate the type of damage in the structure as well. Wave propagation characteristics in anisotropic composite materials depend on directions, and attenuation of the wave modes varies due to material damping. Due to inherent difference in damage characteristics, changes of the wave signal resulting from different types of damages are quite distinguishable. Examination of the wave propagation can be used to establish essential knowledge for damage type recognition.

This paper presents an experimental investigation to detect damage in composite plates using a damage identification candidate based on Lamb wave propagation analysis. From the measured time history data of the propagated wave, the traveling time, speed reduction and wave attenuation parameters are extracted and used as the damage identification variables. Plates made of carbon/epoxy laminates or honeycomb sandwich are used. Two damage configurations, i.e., delamination and impact damage, are evaluated in this study. Piezoelectric transducers (PZTs) are used as the wave transmitters and receivers. Post-processing of the recorded signals using wavelet transform, which allows better isolation of the interested propagation mode and extraction of the traveling time and thus enhances the accuracy of damage localization, is performed. Further, the wave propagation profiles after interaction with damages are examined, from which the classifications of damage types in the composite structures are deduced. This study provides the location and experimental propagation profiles of two different damages (i.e., delamination and impact damage) in two different types of composite plates.

5767-12, Session 2

Response of FBG sensors to Lamb wave propagation and its application to active sensing

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An ultrasonic sensing system using fiber Bragg gratings (FBGs) was constructed. The system utilizes wavelength-optical intensity modulation technique and includes a broadband light source, FBGs for sensing and filtering, as well as a photodetector. Broadband light travels to the FBG sensor via an optical circulator and light reflected from the sensor passes filtering FBG whose Bragg wavelength is very close to that of the sensor. This optical filtering process converts the change in the Bragg wavelength of the sensor induced by ultrasonic wave into the change in light intensity. Light transmitted through the filter enters the photodetector where the intensity of light is converted into voltage signal. The photodetector output signal corresponds to the ultrasound signal.

Ultrasonic inspection was performed using the FBG ultrasonic sensing system. Ultrasonic Lamb wave generated by a piezoelectric ultrasonic transducer was propagated through a thin cross-ply CFRP with visible impact damage. The ultrasonic transducer has a central frequency of 250 kHz and generates fundamental symmetrical Lamb (So) wave in the monitored specimen. The monitored CFRP has a stacking sequence of [0/90]2s and a dimension of 290 X 190 X 1 mm3. The CFRP was damaged by ball dropping with an impact energy of 7.35J and the size of damaged area was 65 X 15 mm2 where delamination and splitting overlapped. In order to determine the optimal transducer drive signal for impact damage detection the ultrasonic transducer was driven by four kinds of signals: spike, 1-cycle toneburst, Gaussian-windowed 5-cycle toneburst and 7-cycle toneburst signals. Response to So wave propagated through the damaged area was compared with the reference response in intact area.

Response to So wave propagated through the damaged area had narrower frequency bandwidth and lower frequency characteristics than response in the intact area. A spike pulse proved to be optimal for the transducer drive signal in active sensing diagnosis. The experiments demonstrated that the FBG ultrasonic sensing system was effective to detect impact damage of CFRP.

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5767-13, Session 2

Estimation of corrosion damage in steel reinforced concrete using wave guides

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Corrosion in reinforced concrete is a chronic infrastructure problem. To assure structure integrity and to allow for proper rehabilitation efforts, a testing method must be used to identify the location, accumulation rate, and extent of damage. Currently used methodologies lack the breadth to ascertain all of the needed information and are quite ambiguous regarding reinforcement deterioration. Thus, there is a need for a new testing procedure.

Towards the development of a wireless embedded sensor system to monitor and assess corrosion damage in prestressed concrete girders, two sets of reinforced concrete specimens were manufactured. The first set of specimens was manufactured with seeded defects to simulate corrosion damage in the reinforcing steel bars. Accelerated corrosion methods were used to induce corrosion damage in the second set of specimens.

By taking advantage of wave guide effects of the reinforcing steel bars, these specimens were tested using an ultrasonic approach. To accommodate long beams, transducers were mounted on the side (i.e., perpendicular to the steel bar) with a transducer separation distance of about 107 cm. Using lower frequencies (<250 kHz), both transducers were used as the sender and the receiver of the ultrasonic pulses. The dispersion and attenuation characteristics of the different guided wave modes were used to illustrate the correlation between corrosion damage and the observed characteristics of the received waveforms. Experiments show that because of their wave guide structure the lower frequency longitudinal modes can detect loss of bond, i.e., delaminations, due to corrosion.

5767-14, Session 3

Damage detection on a steel-free bridge deck using random vibration

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Previous studies at the University of Saskatchewan demonstrated that small scale damage on a bridge deck can be reliably detected and located using vibration-based damage detection (VBDD) methods in conjunction with well controlled, harmonic forced vibrations. With full-scale structures, however, purely harmonic vibration may be difficult to achieve, leaving the consideration of vibration due to random excitation sources such as wind and traffic as a more practical option. The statistical uncertainty associated with random excitation, though, inevitably decreases the reliability of measured dynamic characteristics, making it more difficult to apply VBDD techniques successfully.

In the current study, the application of VBDD methods to detect and locate small scale damage in a steel-free bridge deck subjected to random excitation was investigated numerically. Transient dynamic analyses of a finite element model of the bridge deck were undertaken using applied load time histories that were artificially generated to resemble “white noise”. Simulated damage states were induced into the model by removing selected elements of the bridge deck. Experimental verification of the numerical results was carried out using laboratory tests on a physical model featuring similar damage states.

The numerical investigation enabled the uncertainty introduced by the random excitation to be isolated from the experimental random noise caused by instrumentation error and ambient interference. Numerical results were considered both with and without typical levels of simulated experimental noise that was superimposed on computed displacement time histories at the post-processing stage. The influence of the experimental noise on the reliability of the VBDD results, though, was found to be relatively minor compared to the effects of the random excitation.

Results indicated that damage could be reliably detected and located only if the uncertainty in the vibration mode shape definition was reduced by averaging modal analysis results from repeated trials. In this averaging process, statistical theory implies that the standard deviation of mode shape value at any location is inversely proportional to the square root of the number of trials that are averaged. It was found that the standard deviation of the measured mode shapes had to be less than half of the maximum change of the mode shape caused by damage in order for the VBDD techniques to be successful.

The required number of repeated tests was seen to depend on the scale of the damage, the longitudinal and transverse location of damage relative to the nearest sensor, and the distance between the damage and the support. For a given number of repeated tests, the scale of the minimum detectable damage was found to depend on the location of damage relative to the nearest sensor, and the distance between the damage and the support.

Both experimental and numerical tests indicated that the level of uncertainty in the measurement of higher mode shapes was significant, regardless of whether harmonic or random excitation was used. Fortunately, use of the fundamental mode shape alone was found to be sufficient for the VBDD analyses in the studies described above.

5767-15, Session 3

Application of artificial neural networks in vibration based damage detection

H. Xu, J. M. Humar, Carleton Univ. (Canada)

A technique of structural health monitoring of civil engineering infrastructure that has attracted considerable attention during the last few decades is vibration based damage identification (VBDI), which relies on the fact that damage in a structure reduces its stiffness and alters its global vibration characteristics. Measurement of changes in the vibration characteristics can therefore be used to determine the location and extent of damage in the structure. VBDI offers several advantages, however, most of the available damage identification algorithms fail when applied to practical structures due to the effect of measurement errors, need to use incomplete mode shapes, mode truncation, and the non-unique nature of the solutions.

Damage detection based on changes in modal characteristics can be treated as a pattern recognition problem, and neural networks provide an ideal means of obtaining a solution to such a problem. In addition, neural networks can effectively deal with uncertainty and are quite tolerant of errors in the input data. This study presents a new robust two-step algorithm that uses the artificial neural network technique for detecting the location and magnitude of damage. Because of its sensitivity to damage a modal energy based vibration property, known as the damage index vector, is used as the input to the network. The proposed algorithm is applied to detect simulated damage in a finite element girder model of the Crowchild Bridge, an innovative three-span continuous bridge with steel-free deck built under the advice of ISIS Canada. The properties of the girder model are derived from the geometry of the bridge and then fine-tuned so that its first three flexural frequencies match the corresponding frequencies measured in the field. The first step of damage detection employs a perceptron neural network designed to localize the damage. The hard-limit transfer function of the perceptron outputs either 0 or 1, denoting undamaged and damaged status of each element, respectively. The network is trained incrementally, so that the weights and biases are updated after each input has been presented. Next, the damage magnitude is evaluated by a feedforward neural network that has one hidden layer consisting of 30 neurons. A tangent sigmoid transfer function is used in the hidden layer while a pure linear transfer function is used in the output layer. The scaled conjugate gradient algorithm is employed in the training of network with the input vectors presented in batch.

The paper describes the network architecture and details of the training process. It also presents the results related to the identification of simulated damage in the girder. The result shows that the proposed algorithm is quite effective in identifying the location and magnitude of damage, even in the presence of measurement errors in the input data.

5767-16, Session 3

Improved iterative regularization for vibration-based damage detection

B. Weber, P. Paultre, J. Proulx, Univ. of Sherbrooke (Canada)

A nondestructive damage detection method that has become an active research topic is vibration-based damage detection. Based on measured eigenfrequencies and mode shapes, a finite element model is updated, and loss in stiffness is interpreted as damage. It has been recognized by many researchers that finite element updating from vibration measurements is an ill-posed problem and some regularization is therefore needed. The most popular algorithms are the truncated singular value decomposition and the Tikhonov regularization. If the update is based on the sensitivity matrix, the problem is nonlinear and has to be solved iteratively. When applying the Tikhonov regularization iteratively, some additional problems occur that are well known in the mathematical literature but have not been recognized in the engineering community. The regularization depends not only on the regularization parameter but also on the number of

iterations. In fact, it has been observed that the effect of regularization can be annihilated when the number of iterations is too high. This problem can be overcome by an appropriate stopping criterion or by using a modified version of the iteration algorithm. First numerical calculations show that the modified version is practically independent of the number of iterations and that less iterations are needed. The modified algorithm also seems to give more useful indications for the choice of the regularization parameter from L-curves and generalized cross validation. Numerical examples show results for a frame with simulated eigenfrequencies and mode shapes with random noise. Parametric studies show the influence of the regularization parameter, the number of iterations, and the noise level. The method is also applied to a real frame recently tested in the lab at the University of Sherbrooke.

5767-17, Session 3

Characterization of system sensitivity in SHM event-detection systems

L. Card, D. K. McNeill, Univ. of Manitoba (Canada)

Practical structural health monitoring (SHM) systems rely upon effective pre-processing of sensor data in order to isolate those measurements which are of significance from the myriad of raw measurements collected. To be of use in a commercial environment, this filtering or data compression task must be performed in an automated fashion and in real-time. In achieving this goal, an artificial neural computing approach has been taken to the characterization of a structures normal response in order to provide a relative measure of novelty resulting from unusual excitations or changes to the structure over time.

Neural computation has previously been demonstrated to isolate novel sensor events from the sensor record and thereby provide a means to intelligently decimate the measurements for storage and further analysis. In this article we examine the sensitivity of the novel event detection system in order to characterize the types of excitations which are detectable. This investigation explores the sensitivity of event identification systems trained on actual SHM measurements from three in-service structures (two bridges and a statue). Results show the system to be responsive to atypical excitations with resolution on the order of one microstrain or below over the range of inputs to which the system is subjected. In the case of the system discussed in this article, network inputs take the form of a power spectrum over the range of 0.5-16Hz.

5767-18, Session 3

Developing an SHM system for FRP-strengthened beams

J. P. Newhook, Dalhousie Univ. (Canada)

Fibre reinforced polymer (CFRP) laminates are used to rehabilitate concrete beams that do not possess the required ultimate flexural capacity. Because this is a new technology, there is a need to use structural health monitoring techniques in many of the field projects to verify their field performance and increase user confidence. This paper discusses the process of developing an SHM system for concrete beams with FRP flexural strengthening laminates. While the precise methodology is specific to this application, the process of SHM system development discussed in the paper is adaptable to a wide range of field structures.

SHM is used to assess the structure's performance under service load conditions and to detect damage or deterioration by collecting in-situ response information about the structure. In the specific case of FRP laminates, debonding or delamination is a damage mechanism of specific concern. For a SHM system to be effectively implemented, knowledge of the behaviour of the structure complemented by laboratory testing is required to determine how the damaged structure behaves. Specifically for FRP laminates, it needs to be established how a delamination of the FRP laminate influences the readings collected by the SHM sensors. It is extremely important that this assessment be conducted with appropriate levels of damage and under conditions representing realistic service load conditions.

Once the change in mechanical response due to damage has been established, the sensitivity and hence feasible of various detection technique can be assessed. Appropriate sensor types and spatial resolution can then be established. Data management and interpretation protocol can then be developed thereby completed the SHM system.

This paper will specifically discuss the use of continuous strain sensing and modal analysis techniques, with the former being the prime focus. An experimental program using concrete beams strengthened with FRP laminates with controlled debonding zones was implemented to investigate the mechanical response of the components to the specified damage. This was complemented by the development of a finite element model for use in a parametric study of response and damage detection parameters. From the results of this investigation, a SHM system based on strain sensing is proposed. Due to the need for a dense spatial resolution of sensors with low noise, Brillouin scatter or multi-Bragg grating style fibre optic sensors are suggested as the most appropriate for this application. Finally a damage assessment methodology is discussed and the criteria for data management system identified.

5767-19, Session 3

Rugged and affordable wireless micromachined sensors for civil infrastructure

M. Saafi, P. Shansez, P. Romie, Alabama A&M Univ.

Critical civil infrastructure systems such as bridges, high rises, dams, nuclear power plants and pipelines present a major investment and the health of the United States' economy and the lifestyle of its citizens both depend on their safety and security. The challenge for engineers is to maintain the safety and security of these large structures in the face of terrorism threats, natural disasters and long-term deterioration, as well as to meet the demands of emergency response times. With the significant negative impact that these threats can have on the structural environment, health monitoring of civil infrastructure holds promise as a way to provide information for near real-time condition assessment of the structure's safety and security. This information can be used to assess the integrity of the structure for post-earthquake and terrorist attacks, rescue and recovery, and to safely and rapidly remove the debris and to temporary shore specific structural elements. This information can also be used for identification of incipient damage in structures experiencing long-term deterioration. However, one of the major obstacles preventing current sensor-based monitoring is the lack of reliable, easy-to-install, cost-effective and harsh environment resistant sensors that can be densely embedded or surface mounted on large-scale civil infrastructure systems. To overcome the shortcomings of the current sensing technologies, the research community explored the feasibility of using MEMS-based devices for structural health monitoring. Work conducted by the authors on embedded MEMS indicated that although MEMS can be embedded into concrete for environmental and mechanical damage detection, they have serious limitations. One main issue is the powering system for the embedded MEMS. Using an embedded battery to power the MEMS is not practical due to its limited life span. The battery will also increase the size of the embedded sensing node which in return will act as a defect in the structure thereby changing the mechanical properties of the material. The use of inductive powering technique has serious problems, where the embedded sensing required different ICs to transform electromagnetic signals into DC voltage leading to a large size node, low SNR and high cost. Moreover, inductive powering has limited distance range communication (few inches) and large distance range communication will require high power. Another issue is related to the long-term durability of MEMS in civil engineering environment. Silicon-based MEMS sensors have limited environmental resistance and are susceptible to damage when embedded into concrete thereby requiring complex and expensive packaging systems.

The authors developed new rugged and extremely cheap micromachined sensors to monitor the long-term structural performance of civil infrastructure systems such as high rises, bridges, dams, nuclear powers plants, pipelines and underground nuclear waste containers and to evaluate their condition after overloading caused by natural hazards or other extreme events. The proposed new micromachined sensors can be embedded or surface mounted into concrete or composites to detect crack propagation and to measure displacement/strain as well as to measure key parameters affecting the long-term durability and safety of structures such as chloride (Cl-) concentration, carbon dioxide (CO_2) concentration, concrete pH and temperature and relative humidity (RH). These parameters can be used to assess the progress of different damage mechanisms mainly steel corrosion, concrete carbonation, alkali-silicate reaction (ASR) as well as can be used to monitor the concrete strength gain and shrinkage stresses during construction. In addition to their high sensitivity, thermal stability, linear response, high SNR and wide dynamic range, the proposed micromachined sensors are capable of withstanding high moisture conditions, strong electro-magnetic interference and temperatures exceeding 10000C without affecting the sensor signal, and can be interrogated without power on board and wirelessly from a large distance. Moreover, each sensor has a self-identification capability in order to identify its data and its location amongst other sensors. In this paper, the proposed micromachined sensors will be presented and their durability, wireless sensing capability will be discussed.

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5767-20, Session 3

Comparison of strain measurements using polyimide and acrylate recoated FBG sensors

D. J. Thomson, E. Rivera, A. A. Mufti, Univ. of Manitoba (Canada)

No abstract available

5767-48, Poster Session

Damage detection in engineering structures using spectral finite element method

W. M. Ostachowicz, Gdynia Maritime Univ. (Poland) and Polish Academy of Sciences (Poland)

This paper presents the use of a wave propagation approach for damage detection in structures. The investigated damage detection system is based on the known fact that material discontinuities affect the propagation of elastic waves in solids. The change in material characteristics, such as a local change in stiffness or inertia caused by a crack or material damage, will affect the propagation of elastic waves and will modify the received signals. The change of the wave propagation process due to a damage appearance is examined by comparing the differences between the responses from damaged and undamaged structures. The influence of the damage growth for the wave propagation is also analysed. The differences in the propagating waves allow indicating the damage location and size in a very precise way.

Efficient numerical tools allowing proper modelling of wave propagation require special elements, that provide correct numerical analysis of that process in damaged structures. Among many techniques of modelling the wave propagation spectral finite element method (SFEM) specifically with regard to monitoring damages in highly stressed structures has become a major issue, specifically in the aerospace environment but also elsewhere. SFEM has led to developing structural health monitoring systems which are able to sense and locate damages in structures.

The SFEM approach is based on exact solution to governing Partial Differential Equations (PDE) in the frequency domain. This exact solution is used as interpolating function for spectral element formulation. As a consequence, relatively small number of elements can be used for modelling without loosing the accuracy. The solution is obtained in terms of generalised displacements, subsequent calculations for velocity, acceleration, strain and stress for any applied load can then be found with relatively inexpensive postprocessing calculations. The spectral element method directly computes a structure's frequency response function and in this manner gives additional information that bridges the gap between modal methods based on free vibrations and time reconstruction based on direct integration. This is particularly useful for wave propagation modelling.

In this study a wide variety of elements have been developed which can be used to detect small failures in rod, beam–like and plate structures. The author has discussed the dynamics of a cracked rod, a cracked Timoshenko beam, a delaminated multilayer composite beam, and cracked plate spectral finite elements. The way of modelling the stiffness loss due to the crack appearance and the excitation force has also been presented. Damage detection is formulated as an optimisation problem which is then solved by using a genetic algorithm.

The results obtained indicate that the current approach is capable of detecting cracks and delaminations of very small size, even in the presence of considerable measurement errors. Only from the differences between the signals measured from undamaged and damaged structures can there be information about the location of the crack. The influence of the growth of the damage for wave propagation in the damaged structure has been shown.

The approach presented is very promising as a fatigue damage detection method. As concluded spectral analysis is very sensitive and allows one to detect damage in its very early state of growth. This fact is extremely important from the practical and economical point of view.

5767-49, Poster Session

Magnetization changes induced by low cycle fatigue both in the geomagnetic field and the magnetic-free environment

E. Yang, L. Li, Tsinghua Univ. (China)

Abstract—"Magnetic memory" is a kind of change in magnetic properties of ferromagnetic materials, in particular magnetic field aberration in stress concentration region, which resulting from the applying of stress in the earth's magnetic field. This phenomenon has attracted attention because of it's relevance to important nondestructive evaluation method. In the presence of earth's magnetic field, stresses in ferromagnetic materials can be evaluated and lifetime of ferromagnetic materials can be predicted by measuring changes in magnetic properties without additional applied magnetic field.

To study the mechanism of magnetic memory, several samples including 1045# steel, Q235A steel, and pure steel were examined by measuring magnetic fields on their surface. All samples had been annealed and demagnetized to remove the residual stresses and residual magnetization. The stresses were applied to those samples in a form of low cycle fatigue both in the earth's field and in the magnetic-free environment. The procedure was repeated till samples were destroyed. After the test, obtained magnetic fields were compared. It was found that there were glaring discrepancies between the results got from those two different environmental conditions. Similar magnetization effects were found in presence of earth's magnetic field, while the equivalent demagnetization effects were occurred in magnetic-free environment. Besides this, there were many other important features, including the differences of magnetic field aberration in stress concentration region of those two environments, and the influence of chemical composition on magnetic memory. It was found that for similar heat treatment the magnetic field aberration in stress concentration region increases with carbon content in both two environmental conditions.

An explanation is suggested based on the theory proposed by Jiles in 1995, in which the magneto-mechanical effect had been explained in terms of "law of approach", which has been found to be valid for low cycle fatigue as well as for elastic range. The earth's magnetic field was found to be very important for magnetic memory. There is no magnetic memory phenomenon without the earth's magnetic field. The higher carbon levels for the same heat treatment, the more sensitive magnetic memory was to applied stress. This can be explained by increased carbon content leading to an increase in the amount of pinning sites for domain walls. Application of stress will conversely lead to unpinning of domain walls.

This paper reports the technology details and observation results of the experiment, and discusses the mechanism of magnetic memory as well.

I will appreciate to be considered for the ward of "2005 NDE Best student Paper Award". I feel honored to participate in this competition.

5767-50, Poster Session

Nondestructive and contactless determination of layer and coating thickness

C. Sklarczyk, U. Netzelmann, W. Gebhardt, Fraunhofer-Instituts für Zerstörungsfreie Prüfverfahren (Germany)

The paper describes some new developments in the field of contactless and nondestructive determination of the layer and coating thickness on different substrates. The first method is based on millimeterwaves which are emitted and received by a compact integrated radar sensor. It is the aim to online measure the thickness of the plastics coat on big steel pipelines in production process. By combining phase and amplitude sensitive measuring quantities and with the help of a pattern recognition algorithm the ambiguities concerning phase can be eliminated. An axial accuracy of 0.1 mm or better is reachable. To take into account the variations in distance between the sensor and the pipe the distance is measured with a laser triangulation sensor.

Another approach is based on thermal effects induced in the coating by flash heating or laser light heating. The temperature response of the test object is monitored by an infrared sensor. While commercial systems for spot measurements are already on the market, an infrared camera can generate a coating thickness map in a short testing time. The problem of optically partly transparent coatings will be discussed in the contribution. An important application are zirconia thermal barrier coatings on steel.

With the help of an airborne ultrasonic transducer the thickness of powder coating, e.g. ceramics-coating on steel, can be determined contactlessly with an accuracy of better than 10 μm.

5767-51, Poster Session

High energy x-ray refraction system to characterize inner surfaces or interfaces in materials

X. Ding, J. N. Gray, T. Jensen, Iowa State Univ.

X-Ray refraction is a relatively new technology for the characterization of inner surfaces or interfaces in structures. When X-rays cross an interface in a structure, X-ray refraction occurs. The index of refraction, n=1-delta, where delta ~1x10^-6

for typical X-ray energies, leads to refraction angles of several minutes of arc. As the X-ray energy increases, the refraction angle decreases, making it more difficult to separate the refraction beam from the main X-Ray beam. During the last decade, most X-ray refraction work has used low energies, typically under 30 keV. The penetration of x-ray beams with energies below 30 keV is poor, limiting the method to low density objects or very small samples. It is desired to apply this method to larger samples of aerospace materials such as aluminum and titanium alloys and composite structures. The ability to nondestructively detect micro-porosity and crack initiation at length scales of 0.1 to 100 microns would greatly advance the understanding of the properties of these materials. In particular, this will enable the detection of very small cracks generated in the early stages of fatigue during a specimen life cycle.

In our current work, we are evaluating the use of high energy polychromatic x-ray beams to generate refraction signals from material discontinuities. This paper includes the design and preliminary results for our high energy refraction system. We have demonstrated a refraction signal at boundaries using a filtered 120 kVp beam. At these energies we can penetrate larger samples of materials with higher density. In this paper, we will discuss the limits to refraction analysis, and describe our plans for further development of our X-Ray refraction system.

5767-53, Poster Session

Probabilistic model for bridge structural evaluation using nondestructive inspection data

F. J. Carrion, J. A. Lopez, Instituto Mexicano del Transporte (Mexico); A. Balankin, Instituto Politecnico Nacional (Mexico)

A bridge management system developed for the Mexican toll highway network applies a probabilistic-reliability model to estimate load capacity and structural residual life. Basic inputs for the system are the global inspection data (visual inspections and vibration testing), and the information from the environment conditions (weather, traffic, loads, earthquakes); although, the model takes account for additional non-destructive testing or permanent monitoring data. Main outputs are the periodic maintenance, rehabilitation and replacement program, and the updated inspection program. Both programs are custom-made to available funds and scheduled according to a priority assignation criterion.

The probabilistic model, tailored to typical bridges, accounts for the size, age, material and structure type. Special bridges in size or type may be included, while in these cases finite element deterministic models are also possible. Key feature is that structural qualification is given in terms of the probability of failure, calculated considering fundamental degradation mechanisms and from actual direct observations and measurements, such as crack distribution and size, materials properties, bridge dimensions, load deflections, and parameters for corrosion evaluation. Vibration measurements are basically used to infer structural resistance and to monitor long term degradation.

5767-54, Poster Session

A technique for damage diagnosis of bridge structure based on information fusion

Z. Liang, W. Chen, Chongqing Univ. (China)

The information fusion technology has caught people's attention significantly in the field of damage diagnosis and state assessment of bridge structural in recent years. By information fusion technology, several data channels are integrated to enhance system performance. In this paper, the theory of information fusion applied in damage diagnosis for bridge structure is stated firstly, then the decision methods for data fusion based on Dampster-Shafer(D-S) theory of evidence are discussed, and the basic functions of probability distribution for diagnosis and fusion are constructed according to real conditions and the demand of D-S theory of evidence. Finally, the calculation of a real example is completed.

In this article, we use three signals acquired from a cable-stained bridge named Masangxi Yangze River bridge in Chongqing. The three signals are the static displacement, strain and the mode shape of girder, which are combined to determine the damage of bridge structure by a fusion algorithm based on D-S theory of evidence.

The result indicates that information fusion can reduce the uncertainty of system output and improve the veracity of damage diagnosis greatly. And this paper will provide a considered guidance for the algorithm development of damage diagnosis for bridge structures.

5767-55, Poster Session

Data fusion technique and its application in structural health monitoring

S. Jiang, Shenyang Jianzhu Univ. (China)

As an integrated information processing technique, data fusion was originally developed for military purpose. Due to its inherent capacity in extracting information from different source and integrating them into a consistent, accurate and intelligible data set, multi-sensors data fusion technique attracted increasing attentions in structural health monitorin.

In this paper, it first introduced the basic concepts and principals of multi-sensors data fusion; Secondly the feasibility of the multi-sensors data fusion technique applied to the structural health monitoring was discussed; Thirdly, the method of data fusion-based structural health monitoring was studied, its application in structural health monitoring and diagnosis, the concrete measuring strength rebound curves based data fusion were investigated. The result shows that the method of data fusion-based structural health monitoring is feasible and effective.

5767-56, Poster Session

Regulatory issues and utility of ultrawideband ground penetrating radar

D. R. Huston, Univ. of Vermont; B. Esser, Univ of Vermont

Ultrawideband (UWB) is a pulse-type electromagnetic wave technology that is gaining currency in ground penetrating radar (GPR) and communications systems. As a result of the increased interest in using UWB technology for commercial applications in the U.S., the FCC has recently opened and regulated unlicensed UWB bands for GPR, wall imaging and other applications. Similar regulatory moves are anticipated elsewhere. These regulations (FCC 02-48) put both a constraint on the use of GPR for pavement and concrete NDE applications, as well as open up opportunities for the development of newer more advanced and capable instruments. This paper will discuss the implications of the regulations on the operation and performance of GPR instruments. Results from efforts at measuring air-filled delaminations in reinforced concrete slabs will be presented along with proposed designs of novel multipulse test systems.

5767-57, Poster Session

Ultrasonic measurement of the elastic properties of ultra-high performance concrete (UHPC)

G. A. Washer, Univ. of Missouri/Columbia; P. A. Fuchs, Fuchs Consulting, Inc.; A. Rezai, Wiss, Janney Elstner, Inc.; H. Ghasemi, Federal Highway Administration

This paper discusses research to develop ultrasonic methods for materials characterization of an innovative new material known as Reactive Powder Concrete (RPC). Also known as Ultra-high performance concrete (UHPC), this relatively new material has been proposed for the construction of civil structures. UHPC mix designs typically include no aggregates larger than sand, and include steel fibers 0.2 mm in diameter and 12 mm in length. These steel fibers increase the strength and toughness of the UHPC significantly relative to more traditional concretes. Compressive strengths of 200 to 800 MPa have been achieved with UHPC, compared with maximum compressive strength of 50 to 100 MPa for more traditional concrete materials. Young's modulus of 50 to 60 GPa are common for UHPC. However, the curing methods employed have a significant influence on the strength and modulus of UHPC. This paper reports on the development of ultrasonic methods for monitoring the elastic properties of UHPC under a series of curing scenarios. Ultrasonic velocity measurements are used to estimate the bulk elastic modulus of UHPC and results are compared with traditional, destructive methods. Measurements of shear moduli and Poisson's ratio based on ultrasonic velocity are also reported. The potential for the development of quality control techniques for the future implementation of UHPC is discussed.

5767-21, Session 4

Some practical issues in remote structural health monitoring

L. Han, Univ. of Manitoba (Canada) and ISIS Canada (Canada); J. P. Newhook, Dalhousie Univ. (Canada) and ISIS Canada (Canada); A. Mufti, Univ. of Manitoba (Canada) and ISIS Canada (Canada)

ABSTRACT

Structural health monitoring (SHM) activities in civil engineering grow at a rapid pace and mature in both research and field applications. The internet technology

was successfully incorporated into a structural health monitoring program in 2004 which makes it possible to manage the real-time sensing data and centralize the remote structural monitoring systems. With the increase in size and complexity of the monitored structures, more sensors and data acquisition equipments are involved. This paper addresses some specific issues related to the long distance low-level signal transmission and Ethernet IP sharing between different devices. The issue of data volume versus communication bandwidth is discussed especially in the application of a web camera image transferring and recording. The approach is illustrated through reference to two current case studies which include a bridge and a statue. It is seen that these practical solutions employed by ISIS Canada are easy to implement and reduce the cost for the maintenance of SHM systems. The paper also discusses future activities and research needs related to the reliability and security of the SHM system.

5767-22, Session 4

The implementation of civionics in a second generation steel free bridge deck

C. Klowak, Univ. of Manitoba (Canada) and ISIS Canada (Canada); E. Rivera, Univ. of Manitoba (Canada); A. A. Mufti, Univ. of Manitoba (Canada) and ISIS Canada (Canada)

As the design and construction of civil structures continue to evolve, it is becoming imperative that these structures be monitored for their health. In order to meet this need, the discipline of Civionics has emerged. Civionics is a new term coined from Civil-Electronics, which is derived from the application of electronics to civil structures. It is similar to the term Avionics, which is used in the aerospace industry. Therefore, for structural health monitoring to become part of civil structural engineering, it should include Civionics.

It involves the application of electronics to civil structures and aims to assist engineers in realizing the full benefits of structural health monitoring (SHM). In past SHM field applications, the main reason for the failure of a sensor was not the installation of the sensor itself but the egress of the sensor cables. Often, the cables were not handled and protected correctly. Therefore, for SHM to be successful and useful, specifications must be written on the entire process, beginning with system design and concluding with data collection, interpretation, and management. The Civionics specifications include the technical requirements for the SHM system including fibre optic sensors, cables, conduits, junction boxes and the control room. A specification for data collection and storage is currently being developed as well. In the spring of 2004 research engineers at the University of Manitoba constructed a full-scale second generation steel free bridge deck. The bridge deck is the first of its kind to fully incorporate a complete civionics structural health monitoring system to monitor the deck's behaviour during destructive testing. Throughout the construction of the bridge deck the entire installation of the civionics system was carried out by research engineers to simulate an actual implementation of such a system in a large scale construction environment. One major concern that consulting engineers have raised is the impact that a civionics system that uses conduit, junction boxes, and other electrical ancillary protection, will have when embedded and installed externally on full-scale infrastructure. The full-scale destructive testing of the second generation steel free bridge deck that uses a civionics system designed and implemented using a civioncs specification manual at the University of Manitoba will provide engineers with the information necessary to address the constructability and structural integrity issues. Civioncs combined with structural health monitoring will provide engineers with feedback necessary to aid in optimizing design techniques and understanding our infrastructures performance, behaviour and state of condition.

5767-23, Session 4

Impact resonance method for fatigue damage detection in RC beams strengthened with CFRPs

C. Gheorghiu, Univ. of Manitoba (Canada); P. Labossiere, J. E. Rhazi, Univ. de Sherbrooke (Canada)

As the extent of publications in the field shows, there are numerous successful applications of FRPs for rehabilitating the civil engineering structures. Most of these repairs are being continuously or intermittently monitored for assessing their effectiveness and safety. Since the cost of the installation, maintenance and data interrogation for these monitoring systems is prohibitive for many applications, it would be interesting to find new ways for monitoring and assessing the structural health of an FRP repair. The impact resonance method (IRM), a non-destructive technique, utilized in civil engineering exclusively for determining the dynamic concrete properties, could be a valuable and viable damage detection technique for structural elements. The IRM gives useful information about the dynamic characteristics of rectangular and circular concrete members such as beams and columns. In this experimental program, a 1.2 m-long reinforced concrete beam strengthened with a CFRP plate has been employed. The CFRP strengthened-beam has been loaded in fatigue for two million cycles at 3 Hz. The load amplitude was from 15 to 35% of the yielding moment of the beam. Throughout fatigue testing the cycling was stopped for IRM measurements to be taken. The obtained data provided information about changes in modal properties such as natural frequencies and damping. These results have shown the successful use of the IRM technique for detecting fatigue damage in concrete members strengthened with FRPs. The conference paper will provide full details on the test set-up and an extensive analysis of all the data obtained experimentally.

5767-24, Session 4

SHM data interpretation and structural condition assessment of the Manitoba Golden Boy

B. A. Bogdabovic, A. A. Mufti, Univ. of Manitoba (Canada); A. Bagchi, Concordia Univ. (Canada)

The Golden Boy statue was placed on top of the Manitoba Legislature building in 1919 and it served as a source of inspiration to Manitobans since then. During inspection in 2001, it was found that steel shaft connecting the statue to the top of the dome of the building deteriorated significantly. While replacing the existing shaft with a stronger stainless steel shaft, a number of sensors including electrical strain gauges, accelerometers, fibre optic sensors and thermocouples were installed. A web camera, and wind meter were also installed. Although some of the sensors were damaged during positioning of the statue at its location, the data from the remaining sensors are made available through the internet to facilitate web based structural health monitoring (SHM) in real time. There is a facility to monitor the statue visually through a video feed from an on-site web camera. The connecting shaft of the statue can be idealized as a single degree of freedom cantilever structure. Despite the simple nature of the structure, interpretation of its SHM data presented some challenges. Wind is the predominant exciting force to the structure. Wind velocities are recorded by a wind meter placed near the statue, while the acceleration, strain and temperature are recorded by the respective sensors installed in the shaft. The wind and acceleration data could be used to estimate the strains experienced by the shaft near the fixity, which can then be correlated with the actual strain recorded by the strain sensors. However, this correlation has proved to be difficult as the sensor data contains various levels of measurement errors or noise, and the strain data needs to be isolated from thermal strain. Detailed diagnostic analysis of sensor data has been performed for correlating the strains obtained from the wind meter, and the accelerometer data, with the strain gauge measurements. The advantage of such analysis is that, it is still possible to get a good estimate of strains from the wind meter and the accelerometer data if the electrical strain gauges ever malfunction. Finally, the observed strain has been correlated with the hourly peak wind velocities reported by Environment Canada and a relationship between these quantities has been established empirically. The empirical relationship would be a useful tool to the owner of the structure to get a ball-park estimate of the strain in the shaft based on the wind velocity and detect possible malfunction of the sensors or deterioration of the structure.

5767-25, Session 4

Application of vibration-based damage detection to an integral abutment bridge

A. B. Siddique, L. D. Wegner, B. Sparling, Univ. of Saskatchewan (Canada)

Vibration-based damage detection (VBDD) methods use changes to the dynamic characteristics of a structure (i.e. its natural frequencies, mode shapes, and damping properties) to detect the presence of damage and determine its location. The application of these methods to constructed civil engineering facilities is complicated by the large size of these structures, inherent uncertainties in material properties, support conditions, and connectivity of components, and variability in loading and environmental conditions. Despite these challenges, the development of reliable VBDD methods for constructed facilities has the potential for great benefit and cost savings to infrastructure owners. It is therefore important that their capabilities and limits be fully explored.

This paper focuses on the application of VBDD techniques to a two-span, slab-on-girder, integral abutment bridge in Saskatoon, Canada. The dynamic response of the bridge under ambient traffic loading has been measured periodically using temporarily installed accelerometers. A detailed finite element

(FE) model has been developed and calibrated to match the natural frequencies and mode shapes acquired from measured data. This model is being used to simulate the dynamic response of the bridge as various states of small-scale damage are induced, and VBDD techniques are being applied to detect and locate the damage. The paper will discuss the performance of the VBDD techniques as well as issues related to the feasibility of using such techniques as a practical health monitoring tool, the effect of seasonal temperature variations, and the calibration of the FE model to field measurements.

5767-26, Session 4

Electromagnetic and elastic wave scattering and imaging for multi-mode nondestructive testing of concrete

K. J. Langenberg, Univ. Kassel (Germany)

Nondestructive testing of concrete is a safety relevant task in civil engineering. Therefore, particular attention must be given to a quantitative analysis of measured data, and a combination of different wave modes, i.e. electromagnetic and elastic waves, is often required. A typical problem is the location of metallic tendon ducts in concrete below the metallic reinforcement grid and their subsequent check against corrosion; to achieve this goal the physical scattering properties of electromagnetic and ealstic waves may be exploited to complement each other.

To locate metallic objects embedded in concrete we apply diffraction tomographic imaging schemes either in reflection and transmission. Applications to synthetic data obtained with a Finite Difference Time Domain code reveals the resolution of the respective algorithms with the reinforcement grid size as a parameter; yet the application to experimental Ground Penetrating Radar data still exhibits a better performance on synthetic data. Grouting holes in the tendon duct are perfect targets for elastic waves because they act as scattering voids. Yet for the ultrasonic frequency regime under concern, concrete is a very heterogeneous propagation medium. Therefore, detailed investigations were performed with the numerical EFIT code (Elastodynamic Finite Integration Technique) to understand elastic wave scattering in concrete; this is demonstrated with wave propagation animation. We confirm on synthetic as well as on experimental data that diffraction tomographic imaging techniques can be equally applied to ultrasonic data even in a highly random scattering environment.

5767-27, Session 4

Distributed cable sensors with memory feature for post-disaster damage assessment

G. Chen, R. McDaniel, S. Sun, D. J. Pommerenke, Univ. of Missouri/Rolla

A new design of distributed crack sensors based on the topological change of transmission line cables is presented for the condition assessment of reinforced concrete (RC) structures during and immediately after an earthquake event. This study is primarily focused on the performance of cable sensors under dynamic loading, particularly a feature that allows for some “memory” of the crack history of an RC member. This feature enables the post-earthquake condition assessment of structural members such as RC columns, in which the earthquake-induced cracks are closed immediately after an earthquake event due to gravity loads, and are visually undetectable. Factors affecting the onset of the feature were investigated experimentally with small-scale RC beams under cyclic loading. Test results indicated that both crack width and the number of loading cycles were instrumental in the onset of the memory feature of cable sensors. Practical issues related to dynamic acquisition with the sensors are discussed. The sensors were proven to be fatigue resistant from shake table tests of RC columns. The sensors continued to show useful performance after the columns can no longer support additional loads.

5767-28, Session 4

Characterization of dented pipelines utilizing ultrasonic velocity measurements

P. D. Panetta, Pacific Northwest National Lab.; G. Alers, EMAT Consulting

Maintaining the integrity of the nation’s aging infrastructure is of primary importance. Specifically there is a desire to characterize degradation to the civil infrastructure to monitor its integrity. Of particular importance is the accurate prediction of the lifetime of damaged natural gas pipelines due to outside force. In order to accurately predict the remaining life it is essential to accurately determine the degree stress and strain in damaged regions for input into fracture mechanics models. Currently, determination of the degree of stress and strain in damaged regions utilizing ultrasonic velocity measurements is complicated by the inherent texture variations in the alloys and the difficulty in separating these effects from the stress and strain contributions. We will report ultrasonic velocity measurements on plastically deformed steel specimens and natural gas pipelines to elucidate the state of damage in dented and bent regions. Specifically, we have found the shear wave birefringence is directly related to the degree of plastic strain and residual stress. Ultrasonic results will be compared with finite element modeling calculations of the stress and strain distributions and analytic theories of the effects of stress and strain on the ultrasonic measurements.

5767-29, Session 5

Modeling of active fiber composite for delamination sensing

K. T. Ajay, P. J. Guruprasad, D. Harursampath, Indian Institute of Science (India)

Flexbeams, made of composites, are being used in bearingless helicopter rotor as well as tailrotor blades because of theinherent advantages they offer in terms of mechanical simplicity. These rotor blades made of flexbeams rotating at high speeds are susceptible to damages which degenerate their flapwise and lagwise performance leading to catastrophic accidents. Hence, there is a strong need and requirement for online damage detection and health monitoring of rotor flexbeams.

A significant amount of research work has been expended to detect damage/delamination in composite structures using various methodologies, notable among them being vibration based methods. These vibration based methods can be further sub-divided into model-dependent and model-independent methods. In general, these vibration based methodologies suffer from certain disadvantages like: complicated mathematical manipulations and the size of the mathematical model used for real-time detection and slow convergence of the currently available training methods to detect damage. The above mentioned issues act as liabilities in the realization of a real-time damage detection model using vibration based methods. Also, since the degradation in stiffness is very less due to the presence of delamination in flexbeams, which are predominantly made of o deg plies, classical approach is not viable for the development of a damage model. This forms the primary motivation for the development of a novel approach using AFC’s as sensors to detect damage. In order to demonstrate the feasibility of AFCs as sensors, a pretwisted strip with symmetric free-edge delamination is considered in this paper. AFCs are placed on the top and bottom of the strip to measure the strain developed. Variational Asymptotic Method (VAM) is used in the development of a non-classical non-linear cross sectional model. The original three dimensional (3D) problem is simplified by the decomposition into two simpler problems: a two-dimensional (2D) problem, which provides in a compact form the cross-sectional properties using VAM, and a non-linear one-dimensional (1D) problem along the length of the beam. This procedure gives the non-linear stiffness, which is very sensitive to damage, at any given cross-section of the strip. The developed model is used to study a special case of cantilevered laminated strip with antisymmetric layup, loaded only by an axial force at the tip. The charge generated in the AFC lamina is derived in closed form in terms of the 1D strain measures. It is observed that delamination length and location have a definite influence on the charge developed in the AFC lamina. Also, sensor voltage output distribution along the length of the beam is obtained using evenly distributed electrode strip. These data could in turn be used to detect the presence of damage.

5767-30, Session 5

Structural assessment of metal foam

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Cellular foams are an interesting class of materials that appear widely in nature. Their mechanical and thermal properties encompassing low density, low thermal conductivity and high energy absorption capability have intrigued researchers for centuries. Recently, manmade cellular foams are being produced from polymers, ceramics and metals to be used in many applications ranging from filters, thermal insulation, packaging, and even structural. Metal foams are expected to find use in structural applications where weight is of particular concern, such as space vehicles, rotorcraft blades, car bodies or portable electronic devices. Although methods to produce metal foams are not new, the difficult process control and high costs have prevented the spread of their use. However, advances in production techniques and cost reduction have created a new interest in the metal foam technology. The obvious structural application of metal foam is for light weight sandwich panels, made up of thin solid face sheets

and a metallic foam core. The stiffness of the sandwich structure is increased by separating the two face sheets by a light weight foam core. The resulting high-stiffness structure is lighter than that constructed only out of the solid metal material. Since the face sheets carry the applied in-plane and bending loads, the sandwich architecture is a viable engineering concept. However, the metal foam core must resist transverse shear loads while remaining integral with the face sheets. Challenges relating to the fabrication and testing of these metal foam panels remain due to some mechanical properties falling short of their theoretical potential. The theoretical mechanical properties are based on an idealized foam microstructure. But the actual testing is performed on as fabricated microstructure. Hence in this study, a high fidelity finite element analysis is conducted on as fabricated metal foam microstructures, to compare the calculated mechanical properties with the idealized theory. The metal foam material is an aerospace grade precipitation hardened 17-4 PH stainless steel with high strength and high toughness. The mechanical properties such as the compressive and shear moduli, plastic collapse and shear strength deduced from the FEA model will be compared with the experimental measured values. The high fidelity geometric models for the FEA are generated using ScanFE software developed by Simpleware, LTD [1] via multiple 2D CT scans of the foam structure. The combined NDE/FEA will provide insight in the variability of the mechanical properties compared to idealized theory and the results will be communicated back to the metal foam manufacturer to improve the foam processing.

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5767-31, Session 5

Application of finite element modelling to predicting the effects of short-term post-weld heat treatments on residual stresses in flashbutt welds

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Welding is commonly used in the manufacture of complex aerospace components. The finished welds typically exhibit high levels of tensile residual stresses in the web region. In addition, the surface condition of the weld may contain shear drag or other defects resulting from the shearing process or other treatment. When combined with torsional loading under service loading (particularly at high loads), these conditions may contribute to fatigue failure of the weld. The risk of weld failure may be alleviated by reducing the magnitude of the residual stresses.

The residual stress distribution in flashbutt welds is influenced by a range of factors; these include preheating and post-weld cooling conditions, and the characteristics of the material. These factors will also determine the resultant hardness distribution across the weld, which in turn affects the behaviour of the weld under high load conditions. For high load operations, achieving the required weld performance may therefore involve achieving a satisfactory balance between the hardness distribution and the residual stress levels.

A thermo-mechanical finite element (FE) model, incorporating the transformation characteristics of the material and temperature-dependent mechanical property data, has been used to examine the effects of various localised short-term post-weld heat treatment residual stresses. The results have indicated that the (tensile) residual stress levels in both vertical and longitudinal directions of the web can be reduced by either reheating the base of the foot directly after welding, or air quenching the web. Both treatments have no effect on the microstructure or mechanical properties of the finished weld.

An experimental program is currently being undertaken to validate the predicted results. Thereafter, both modelling and experimental approaches will be used to develop modifications to the flashbutt welding procedure that should result in improved weld performance under high axle load conditions.

5767-32, Session 5

Finite element calibration of pulse phase IR thermography for the NDE of composite structures

M. Krishnapillai, Monash Univ. (Australia)

The use of IRT as a nondestructive evaluation technique is becoming increasingly attractive in the detection of sub-surface defects in composite structures. Extensive in-field damage data acquisition studies have been performed to date that provide qualitative results. Yet given this establishment a restriction to damage prediction applies when considering a more complex geometry upon which experimental data has not been collected or in collection would lead prediction redundant. This study reports on the use of numerical FE models as a flexible tool to create and simulate the thermographic process. It looks at the response of an FE model to predict damage parameters with the intention of determining numerical relationships and modeling methods that may be used upon more complex non-axisymmetric geometry. As a result of this study a suitably calibrated finite element simulation has been generated and validated, in demonstration of the fact that the process can be done efficiently and productively, with the potential for application upon more intricate composite structures.

5767-33, Session 5

Detection of micro scale changes in structures from vibration data

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The spectral data i.e. eigenvalues (natural frequencies) and eigenvectors (mode-shapes), characterizes the dynamics of the system. Recent experimental modal analysis techniques have potential to obtain the spectral data of microstructures such as cantilever beams, resonators and oscillators. The mathematical formulation of such dynamic behavior of the system deals with certain direct and inverse eigenvalue problems. The direct eigenvalue problem deals in evaluating the spectral behavior of microstructures for various distributions of physical parameters such as mass, area, stiffness etc. whereas, the estimation of these physical parameters form the spectral data is commonly known as inverse eigenvalue problem. The detection of micro and nano scale changes in the stiffness and mass of the microstructure, by solving certain inverse eigenvalue problems, is considered here. Such identification may be useful in various MEMS and NEMS applications such as structural health monitoring and reliability of MEMS sensors and actuators, detection of single and multiple cells by using Bio-MEMS sensors (micro-cantilever beams, resonators and oscillators) etc.

We have considered two types of eigenvalue problem in solving the proposed problem: (i) the conventional algebraic eigenvalue problems in which the structure is approximated by the finite element and finite difference methods and (ii) recently developed transcendental eigenvalue problems corresponding to the associated distributed parameter system. For simplicity, a cantilever micro beam structure is considered and the associated direct and inverse eigenvalue problems are solved by extending the existing numerical methods that are used for solving algebraic and transcendental eigenvalue problems. In conclusion, we have (a) identified a suitable mathematical model for addressing such problems, (b) analyzed the behavior of the spectral data due to micro and nano scale change in the physical parameters, (c) determined the different type of spectral data corresponding to various boundary conditions that are required for such detection, and (d) suggested the conditions on the spectral data for the unique solution of the continuous system. It is demonstrated here that by solving inverse transcendental eigenvalue problems, the severity and location of the changes in physical parameters can be detected accurately compared to those identified solutions that are obtained by solving associated inverse algebraic eigenvalue problems. Several numerical examples are solved here demonstrating the feasibility and accuracy of the identification technique. The results obtained here can also be used in future engineering applications for establishing and optimizing the design parameters of the MEMS sensors and actuators that are based on vibration measurement.

5767-34, Session 6

Fatigue and damage tolerance evaluation of an aircraft spoiler

S. Hurlebaus, L. Gaul, Univ. Stuttgart (Germany)

The spoilers of an aircraft are responsible for several tasks like the support of the rolling maneuver or increasing of the braking action. The spoiler examined consists of carbon fiber reinforced composite material and is attached to the wing by four bearings and one actuator fitting. A new design of a spoiler requires an updated interpretation of which includes considering the loads, calculating of stresses and strains and examining of possible failures. The fatigue and damage tolerance evaluation of such a spoiler has to follow the certification rule JAR/FAR 25.571.

This paper deals with the definition of the most relevant parameters such as the aero load, mass load and wing bending of each duty cycle of the spoiler. Then a finite element model is built in order to calculate the reaction forces at the actuator and bearings using unit loads dependent on the deflection of the

spoiler. Together with the previous defined load spectra the fatigue life calculation of the hinges and the CFRP spoiler is performed using Miner's rule. Finally, the damage tolerance evaluation is performed assuming that different hinges such as the actuator hinge or the bearing hinges are failed. The results are discussed and a certification test scenario is proposed.

5767-35, Session 6

Evaluation of modal-based damage detection techniques for composite aircraft sandwich structures

J. B. Kosmatka, J. Oliver, Univ. of California/San Diego

Abstract:

Composite sandwich structures are becoming more and more important as structural components in aircraft, but are susceptible to catastrophic failure without obvious forewarning. Internal damage, such as disbonding between skin and core, is detrimental to the structures' strength and integrity and thus must be detected before reaching critical levels. However, highly directional low density cores, such as Nomex honeycomb, make the task of damage detection and health monitoring very difficult. One possible method for detecting damage in composite sandwich structures, which seems to have received very little research attention, is analysis of global modal parameters. This study will investigate the viability of modal analysis techniques for detecting skin-core disbonds in carbon fiber-Nomex honeycomb sandwich panels through laboratory testing. A series of carbon fiber prepreg and Nomex honeycomb sandwich panels—representative of structural components used in lightweight composite airframe were fabricated by means of autoclave co-cure. All panels were of equal dimensions and all but two control panels were made with predetermined sizes of disbonded areas, created by substituting areas of Teflon release film in place of epoxy film adhesive during the cure. The resulting panels were clamped at all boundaries to simulate structural components in an actual aircraft. A laser vibrometer was used to capture frequency response functions (FRF) of all panels. These FRF functions were processed to determine their modal parameters (frequencies, modes, damping levels). Both the FRF functions and the determined modal properties were used, along with a variety of published damage detection algorithms to try and locate the known internal disbands. Criteria used to evaluate the algorithms include: effectiveness of the procedure for detecting changes resulting from damage, repeatability of results, amount of time and computing power required to get results, and potential for eventual practical application. These studies show that modal methods can be used to locate core disbands as long as accurate baseline (undamaged) data is known.

5767-36, Session 6

Application of modal analysis with Hilbert-Huang transforms for spar-skin disbond detection in a lightweight composite aircraft wings

J. B. Kosmatka, J. Oliver, Univ. of California/San Diego

Abstract:

Carbon-fiber-reinforced-polymer (CFRP) composites represent the future for advanced lightweight aerospace structures. However, a tendency for non-yield, non-visible damage modes leading eventually to catastrophic failure is impeding their widespread acceptance. Reliable and cheap techniques for health monitoring and damage detection must therefore be developed and implemented. Modal analysis offers one promising method, offering global information on structural stiffness as well as more specific information about particular damage cases. In this way, it can play an important role in a fully functioning Structural Health Monitoring (SHM) system—which would provide details of damage presence, type, location, and severity, and estimates of life remaining—or even form the base of a stand-alone system.

In the case of lightweight composite Unmanned Aerial Vehicles (UAVs), one of the most common and potentially destructive examples of structural damage are internal disbonds between the wing-skin and the internal spar. This study concentrates on the development of techniques for detecting the presence of such disbonds and estimating the overall severity of damage through monitoring minute changes in the modal signature of the structures. Four UAV wing sections were fabricated—two undamaged wings, one with small level of internal disbond damage, and one with a larger level of internal disband damage. Each wing comprises two CFRP prepreg and Nomex honeycomb co-cured skins bonded around a CFRP prepreg box-tube spar. The disbonds are introduced during bonding via the addition of Teflon patches. With each wing clamped in a cantilever position to simulate attachment to the fuselage, and excited from a pseudo-random shaker source, a laser vibrometer is used to capture modal signatures of the outer wing skins. An analysis procedure making use of Hilbert-Huang Transforms (HHT) is then developed to correlate changes to presence and severity of damage. The results are compared to analytical predictions using finite element analysis. Correlation with the physical experiments provides validation of results and a powerful model for use in prediction and data interpretation in a further developed damage detection system.

5767-37, Session 6

Impact damage detection in composite structures using Lamb waves and scanning laser vibrometry

W. J. Staszewski, F. L. Scarpa, Univ. of Sheffield (United Kingdom)

A number of NDT approaches have been developed for structural damage detection over the last fifty years. Damage detection methods based on guided ultrasonic waves can utilise non-contact approaches such as optical/laser techniques and dry coupling transducers. Classical laser-based methods usually involve different types of interferometers. The paper shows that commercial laser vibrometers, designed for modal/vibration analysis, can be used for impact damage detection based on guided ultrasonic waves. A single Lamb wave mode is generated using a piezoceramic actuator bonded on a composite plate. Lamb wave responses are sensed using a multi-point laser vibrometer working in a scanning mode. The results show the potential of the method for rapid and reliable detection of impact damage in composite structures.

5767-38, Session 6

Application of nonlinear dynamic analysis for diagnosis of cracked rotor vibration signatures

J. T. Sawicki, X. Wu, Cleveland State Univ.; A. L. Gyekenyesi, G. Y. Baaklini, NASA Glenn Research Ctr.

The nonlinear model of the cracked Jeffcott rotor is investigated, with the particular focus on the study of the rotor's vibrational response using tools of nonlinear dynamics. The considered model accounts for nonlinear behavior of the crack and coupling between lateral and torsional modes of vibrations. Load torque is applied to the rotor which is laterally loaded with a constant radial force (gravity force) and unbalance excitation. The co-existence of frequencies of lateral modes in the frequency spectra of torsional mode are characteristics of the coupling response of lateral and torsional vibrations. When only the lateral excitations are applied, vibration amplitude bifurcation plot with the shaft speed as a control parameter, demonstrates some speed ranges for which vibrations of the rotor dramatically increase. Furthermore, the vibration of torsional response at the same speed ranges also increases and chaotic behavior can be observed due to the lateral excitations. These phenomena cannot be observed for pure lateral vibration response with the torsionally rigid rotor assumption.

5767-39, Session 6

Finite element design study of a bladed, flat rotating disk to simulate cracking in a typical turbine disk

A. Abdul-Aziz, J. J. Trudell, G. Y. Baaklini, NASA Glenn Research Ctr.

Developing health management and ultrasafe engine technologies are the primary goals of NASA's Aviation Safety Program. Besides from improving safety, health monitoring can also reduce maintenance costs. For instance, health monitoring of rotating components in aircraft engines continues to generate high interest among the engine companies and government institutions to improve safety and to lower maintenance costs. In general, a health monitoring system requires that: 1) the sensor system to withstand normal function in a severe environment; 2) to transmit a signal upon detecting a crack in the component that is above a predetermined length, but below a critical length that would lead to failure; and 3) to act neutrally upon the overall performance of the engine system and not interfere with engine maintenance operations. Currently, Non Destructive Evaluation (NDE) techniques are used to perform periodic inspections and during major overhauls to discover any cracks that may have formed in an attempt to avert catastrophic failure (burst) of the engine. The lowest cost NDE technique is Fluorescent Penetrant Inspection (FPI). However, FPI often fails to disclose cracks that are tightly closed during rest or that are below the surface. The NDE eddy current system is more effective at detecting both crack types, but requires careful setup and operation, while allowing only a small portion of the disk to be practically inspected. Therefore, the need for more reliable diagnostic tools and high level techniques for damage detection and health monitoring of

rotating components are essential elements in maintaining engine safety, reliability and life assessment.

The above concerns are high priorities of the NASA Aviation Safety Program (AvSP), which intends to develop and demonstrate technologies that will contribute to a reduction in the aviation fatal accident rate by a factor of 5 by 2007. Thus and In support of the program activities, the NDE Group here at NASA Glenn Research Center at Lewis Field is actively involved in developing combined experimental and analytical capabilities to address the development of specific health monitoring technologies to detect rotor damage prior to any catastrophic events [2].

This paper is focused on presenting finite element results of a 25.4 cm (10 in.) diameter flat turbine-like disk test article used to evaluate crack detection techniques by simulating cracks that are typical in turbine disks. The results emphasize on finding the changes in maximum radial deflections and changes in the center of mass as a function of rotational speed and crack characteristics (crack size and location) to make detection feasible in the subscale flat test article. Furthermore, the ultimate goal is to utilize this design study to induce changes in radial tip displacement without disk yielding in order to test the instrumentation, and to then initiate and grow cracks by machining and/or increasing rotational speed.

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5767-40, Session 7

Quadrupole resonance as a nondestructive evaluation technique for aerospace materials

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Techniques for nondestructive evaluation (NDE) of structural aerospace materials must be reliable, efficient, cost-effective, and easily integrated. Quantum Magnetics has developed an effective NDE technique for various types of composites using quadrupole resonance (QR). Applications for this innovative approach include structural health monitoring and quality control.

In QR a single-sided coil is used to send radio frequency (RF) pulses into a part with QR-active additive. Since strain in the part is transferred to the QR-active crystals embedded in the resin matrix, these tiny crystals give rise to a strain-dependent QR response.

This paper will discuss the two primary methods of implementing a QR NDE system. The first method involves application of a thin film containing our proprietary QR additive to a composite surface. Tensile strain in carbon composites has been successfully observed using this technique. In the second method, small amounts of the tiny crystals are homogeneously mixed throughout the resin in composite parts during the manufacturing process. We have demonstrated 99% or greater probability of distinction between faulty and acceptable composite beams, thereby demonstrating that QR is a feasible method for quality control.

One advantage of QR over other NDE technologies is that strain can be detected within a composite part before significant or visible damage occurs. A second advantage is that the sensors and QR equipment are portable. Properties of the parts with and without embedded QR-active additive are virtually the same. Furthermore, the crystalline additive can withstand temperatures used in all common composite materials processes, including pultrusion and compression molding.

5767-41, Session 7

Inspecting multilayered air space structures using ultrasonic narrowband spectroscopy

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Recently, an increased demand for effective NDE tools for layered structures has been observed with the increased use of bonded structures (e.g. GLARE) and carbon fiber reinforced panels (CFRP) in modern aircraft constructions.

NDE of multilayered airspace structures can be performed using ultrasonic spectroscopy which makes use of the information in the frequency domain generated due to the constructive and destructive interference of elastic waves.

The paper presents novel narrowband ultrasonic spectroscopy (NBUS) technique which utilizes specially designed resonance transducers with carefully selected narrow frequency bands. The NBUS is based on sensing electrical impedance of the piezoelectric transducer in the vicinity of its resonance. The theoretical model which enables predicting the resonance frequencies and modal shapes of the thickness mode resonances occurring in multi-layered structures is presented in the first part of the paper. The model includes the KLM equivalent circuit of a piezoelectric transducer used for sensing the resonances. Theoretical and experimental results are presented showing the relation of the impedance plane indications to the parameters of adhesive in aluminium sandwich structures. Results of the mechanized inspection of GLARE and CFRP specimens are presented in the second part of the paper.

5767-42, Session 7

Phased array transducers for damage detection in aircraft structures

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This paper will present the results of applying low-frequency phased array transducers for damage detection in structures made of composite materials and in structures with bonded repairs.

Composite materials become increasingly important in aircraft structures. The content of these materials in modern aircraft steadily grows. Although this phenomenon brings many advantages, such as weight reduction, it also exposes aircraft structures to new hazards, such as barely visible damage. The fact that the integrity of an aircraft part made of composite material may be severely compromised by a defect undetectable by visual inspection calls for the development of new damage detection methods. One of the most promising techniques is the phased array approach.

Ultrasonic phased array systems play an important role in the field of non-destructive evaluation. The currently available phased array transducers are quite expensive, mainly because the MHz-order frequencies imply tight tolerances and high manufacturing precision. That is why several programs dedicated to develop cheaper, low frequency phased array systems have been started recently. However, most of these research projects have been limited to defect detection in metallic materials.

Application of phased array systems in parts made of composite materials presents a significant challenge, mainly due to the directional nature of laminae the structure is built of. Phased array systems offer a promise to overcome these problems due to the ability to send and receive focused interrogation signals.

Another important application of phased array systems is monitoring of damage under bonded repairs. Ageing metallic structures often develop cracks and other defects, principally due to fatigue phenomena. Composite patches surface-bonded to the damaged zone have been shown to be an effective remedy. However, full benefits of these repairs – particularly in terms of relaxed maintenance schedules - cannot be achieved, because it is very difficult to control bonding quality and the behavior of the damage under the repair patch using currently available methods.

The work presented in this paper is based on previous studies and aimed at the development of a built-in, low-cost and low-frequency phased array transducer for damage detection in composite panels and in metallic panels with bonded repairs. The presented system has been designed to be permanently installed at critical locations in an aircraft structure, in order to monitor its condition in real time. This paper is divided into two main portions: the component dedicated to the introductory study done for composite panels and the part describing the investigation of damage monitoring under simulated composite repairs. The data acquisition system is also described.

The results of damage detection tests are presented. Basic limitations of the proposed system, such as range and resolution as well as problems related to the peculiarities of wave propagation in composite materials are described. The potential of automatic beam steering and the accuracy of damage size and location estimation are also presented. Recommendations for system industrialization are given.

5767-43, Session 7

Impedance based detection of corrosion

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Corrosion begins as moisture penetrates the protective barrier of a surface, starting an electrochemical process which leads to surface pitting. Structural integrity is reduced as the pits enlarge to form nucleation sites for surface cracks, which propagate into through-the-thickness cracks. Precise structural health monitoring of pre-crack surface corrosion is paramount to understanding and predicting the effect corrosion has on the fatigue life and integrity of a structure. Initially, corrosion induced damage and impedance shifts are small relative to the induced damage and impedance shifts of most traditional damage detection experiments. Therefore, resolving the corrosion induced damage from the random variation, noise, and error within the experiment requires additional corrosion specific experimental procedures to ensure detection. In this study, the procedural variations required to detect corrosion with the impedance method are presented. The impedance method was experimentally tested to detect and quantify the onset and growth of pre-crack surface corrosion in 1-D and 2-D structures. Experimental results indicate the method is an effective detection and tracking tool for corrosion induced structural damage. Additionally, the impedance method was evaluated as a damage location tool for 1-D and 2-D structures.

5767-44, Session 7

Recent developments in absolute optical fiber sensors for static and dynamic performance evaluation of ceramic matrix composites at elevated temperature

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Advanced ceramic-matrix (CMC) composite materials offer the primary advantages of increased strength-to-weight ratio and superior mechanical performance over conventional metallic structural materials. The development of new CMC materials is critical for the implementation of advanced military and dual-use civilian aerospace, hydrospace and land-based vehicles, civil infrastructure systems, power generation and transmission systems, biomedical instrumentation and other applications. In particular for NASA/Air Force applications, the development and performance evaluation of new carbon/silicon-carbide (C/SiC) composite structural components has been hampered by the lack of reliable strain sensors that can survive up to the exceedingly high temperatures (3000°F) at which these materials must be tested.

Existing off-the-shelf high-temperature strain sensors, including free filament electrical strain gages and optical fiber based strain sensors, currently do not have the necessary performance characteristics to tackle the next generation of high-temperature CMC testing programs. Free filament electrical strain gages cannot be used reliably over 1800 °F (1000 °C) and are further hampered by exceedingly large thermal apparent strains which requires the use of complex thermal compensation techniques. Conventional optical fiber strain sensors with the appropriate protective metal coatings can operate reliably only up to close to the melting point of the silica (2000 °F/1100 °C) from which they are fabricated. To meet the growing needs for strain sensors that can withstand future high temperature testing regimes, we will present recent developments of absolute optical fiber sensors with the necessary high temperature, high-frequency response required for the static and dynamic characterization of emerging SiC/C aerospace structural materials.

5767-45, Session 7

A smart composite patch for aircraft structure repair

C. K. Wakha, D. J. Pines, P. D. Samuel, Univ. of Maryland/College Park

This paper details the development of a stiffness/energy sensor for monitoring the integrity of a composite patch used to repair an aluminum structural component. The sensor and damage detection methodology are being developed for the AFRL/VASM under PO 4600-32-077 Invoice Number 32508-1.

One method commonly used to repair damaged structural components is the composite patch repair.

The basic principle of this method is to adhesively bond a composite patch over the damaged area in order to restore the load carrying capacity of the structure. The primary advantages of the bonded composite patch repair over traditional bolted or riveted metallic patch include the fact that no fastener holes are required, and therefore the potential for the development of micro cracks is minimized. Other advantages of the bonded composite patch, as compared to the conventional bolted metallic repair include:

- More uniform and efficient load transfer to the patch
- Bonded repairs produce a sealed interface and therefore reduce the danger of corrosion and fretting under the repair
- The composite patch exhibits excellent fatigue characteristics and corrosion resistance
- Bonded composite repairs are more aerodynamically smooth
- A reduction in the time and cost for the repair can be realized

However, there exist certain shortcomings regarding this method. The first uncertainty regards the ability to determine the quality of the bond. Non-destructive evaluation (NDE) methods can detect a disbond or delamination, but if the surfaces are in contact, the NDE cannot quantitatively assess the quality of the bond between the composite patch and the metallic parent material. Secondly, there are certain reservations regarding the long-term durability of the bond and composite material patch. Even if there exists a superior repair at the time of application, significant degradation may occur due to a combination of repeated loads and environmental exposure.

In the present work, a mechanical multi-functional dual-stiffness sensor for in-situ real-time stiffness and energy density measurements developed at the University of Maryland is used to monitor the condition of the repair patch. The sensor has the ability to predict the elastic field of the composite patch based on the strain state of two strain sensors of different stiffnesses integrated into the structure. It has been shown that this sensor can be used to predict the local instantaneous host stiffness and the strain energy density.

The detection of the onset of any damage, the subsequent monitoring of its growth and help in predicting the remaining life of the repair patch structure constitute the important goals of this project.

Current Accomplishments

At this point, FEM models have been developed and the sensors have been mounted on the specimens. The sensor integrity has been validated.

Quasi-static testing of the specimens has been performed. The results indicate that the various damage cases can be detected using the dual stiffness/energy sensor. Based on the results, a damage metric is being developed.

Dynamic fatigue testing was performed in conjunction with the second set of quasi-static tests since testing to failure was deemed unnecessary. Unfortunately, these tests were inconclusive. A different experimental test setup is deemed necessary. Development of this setup is nearly complete and the results will be included in the paper.

5767-46, Session 7

Application of Hilbert-Huang transform for improved defect detection in terahertz NDE of shuttle tiles

R. F. Anastasi, E. I. Madaras, NASA Langley Research Ctr.

Terahertz NDE is being examined as a method to inspect the adhesive bond-line of Space Shuttle tiles for defects. The terahertz frequency regime is between 100 GHz and 10 THz with free space wavelength between 30 mm and 3 mm. Terahertz signals are generated and detected using optical excitation of biased semiconductors with femtosecond laser pulses. Shuttle tile samples were manufactured with defects that included repair regions unbond regions, and other conditions that occur in Shuttle structures. These samples were inspected with a commercial terahertz NDE system that scanned a tile and generated a data set of RF signals. The portion of the signal recorded corresponded to a region that included the back of the thermal tile, the adhesive region, and the aluminum plate used to simulate the Shuttle skin. The signals were post processed to generate C-scan type images that are typically seen in Ultrasonic NDE. To improve defect visualization, typical signal processing methods were investigated and included signal smoothing, signal averaging and background signal subtraction, and gradient operations to enhance signal changes. These signal processing operations only slightly improved imaging of the defects. In another attempt to

improve defect visualization the Hilbert-Huang Transform, a transform that decomposes a signal into oscillating components called intrinsic mode functions, was applied to test signals identified as being in and out of the defect regions and then on a complete data set. As expected with this transform, the results showed that the decomposed low-order modes correspond to signal noise while the high-order modes correspond to low frequency oscillations in the signal and mid-order modes correspond to local signal oscillations. The local oscillations compare well with various reflection interfaces and the defect locations in the original signal.

5767-47, Session 7

Thermographic characterization of impact damage in SiC/SiC composite materials

L. M. Cosgriff, Cleveland State Univ. and NASA Glenn Research Ctr.; R. T. Bhatt, S. R. Choi, D. S. Fox, NASA Glenn Research Ctr.

SiC/SiC composite materials targeted as turbine components for high temperature environments are being investigated under the Ultra-Efficient Engine Technology program at NASA Glenn Research Center. In order to examine damage mechanisms in these materials SiC/SiC coupons were impacted at increasing velocities from 115 m/s to 400 m/s. Pulsed thermography, a nondestructive evaluation technique that monitors the thermal response of a sample over time, was utilized to characterize damage in these samples after impact. Relationships between impact velocity and scope of damage were investigated. In addition, width and depth of damage due to impact as detected by thermography were examined.

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5768-01, Session 1

The pressure and temperature fields generated by focused ultrasound in biological materials

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This paper is motivated by possible medical applications of focused ultrasound in minimally invasive treatment of a variety of musculoskeletal disorders that are responsive to thermal treatment. A model based analysis of the interaction of high intensity focused ultrasound with biological materials is carried out in an effort to predict the path of the sound waves and the temperature field in the focal region. A finite element based general purpose code called PZFlex is used to determine the effects of nonlinearity and geometrical complexity of biological structures. It was found that the nonlinear effects can be ignored in many therapeutic applications, and at the frequencies of interest, the geometrical complexities can be handled through the application of sub-structuring. An approximate analytical method with high accuracy is developed here as an alternative to the purely numerical approach used in PZFlex. The mechanical and thermal effects in two-layered fluid material systems induced by high-frequency focused ultrasound are calculated through this analytical method. The results are compared with those obtained using PZFlex as a benchmark.

5768-02, Session 1

The elastic properties of hamster kidney cells evaluated by ultrasonic atomic force microscopy

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Abstract—Ultrasonic atomic force microscopy (U-AFM) was used to image the elastic properties of hamster kidney (BHK) cells. Force-distance curves and finite element analysis were also used in this work assist in the description of the U-AFM images. These tools helped explain the differences in contrast seen from the center to the edge of the cell. The explanation of the U-AFM image contrast will lead to more analytical tools to investigate both nonviable and viable materials.

5768-03, Session 1

In-vivo investigation of protein absorption on implant surfaces

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A decisive problem in biomedical or biomaterial research of the post-genomic era is the determination of protein structure and function. Common techniques that can give full structural information do not permit in-vivo measurements. Vibrational Proteomics – an innovative combination of biochemical techniques and infrared or Raman spectroscopy - can provide information which will help substantially to fill this gap. Infrared and Raman spectroscopy are well established as methods for qualitative and quantitative analysis of protein secondary structure, in solution and even when adsorbed to implant surfaces. Their singular advantage over other techniques is that spectra can be obtained for proteins in a wide range of environments, in solutions and on surfaces including polymers, metals and bioceramics. Here we report on structural changes in fibrinogen from the dissolved to the adsorbed state on implant material of different hydrophobicity. FTIR imaging permits the identification of coagulation spots on the implant.

5768-04, Session 1

Acoustic phase micrographs in mesoscale materials characterization

W. Ngwa, W. Luo, Univ. of Central Florida; W. Grill, Univ. Leipzig (Germany); T. Kundu, Univ. of Arizona

Acoustic techniques are widely employed in health monitoring and nondestructive evaluation of materials. Phase micrographs obtained by phase-sensitive acoustic techniques often contain useful information complementary to the information acquirable from amplitude micrographs alone. Most of this information remains relatively unexploited due to the difficulties encountered in unwrapping and processing of the raw phase data. In this study, a review of the derivable information from the phase images of a scanning acoustic microscope with phase contrast (PSAM) is presented. Different perspectives and novel insights from theoretical and experimental analysis of sample structural and biological mesocale systems are discussed, predicated on phase information obtained by simulations and three dimensional imaging.

5768-05, Session 1

Biosystem damage using thermal infrared imagery

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When dynamically loaded over the fatigue limit, mechanical elements increase its temperature as much as the applied load. A large number of papers demonstrated the correlation between the rate of temperature, measured with termography, and the presence of damages induced by dynamic loads. Starting by that consideration, a new methodology was developed (Risitano's method), to allow defining the fatigue limit and then, the whole fatigue curve.

Aim of this work is to transfer the same methodology to the bio-system in order to establish a relationship between the normal state (undamaged) and damaged (stress or traumas) conditions in bio-systems. The final purpose of the research is to define a methodology for the check of the bio-system, when injured or subjected to high stresses conditions by a Thermo-Bio-Mechanical Characterization (T.B.M.C.). Also in the case of biomechanical system, the temperature variations can be considered as a parameter of the physical state. Then, the surface thermal variations of a bio-system dynamically loaded in presence of a damage can be used to monitor the damage increasing as a function of the time.

Fatigue damage for high load or traumas or simple motion is a continuous process that can bring system to failure, both for low and high fatigue cycles. In the first case, the system is loaded with high stress values, inducing the damage growth until the failure. For high cycle fatigue also physiological movements, instead, can induce an incremental phenomenon growing the damage cycle by cycle until failure.

The main purpose of this paper is using thermography to measure surface temperature during the loaded of the bio-system. For mechanical system, Risitano's Methods is based on the assumption that there is a correlation between the stress and the superficial temperature increase on the component loaded. In a bio-system like, for instance a knee, the variation of the temperature under stress can be used to a thermo bio-mechanical characterization (T.B.M.C.). In the first part of the programme the T.B.M.C. of the bio-system (knee) was defined. Fatigue tests were carried out under load control with a bike or a leg extensor testing system. The knee was subjected to stress amplitudes always increasing, and the T.B.M.C. of the knee was performed. The same procedure, used for the same patient by comparing the thermal curves in different periods, could put in evidence if a damage was produced.

5768-06, Session 2

Polymer grating micro pressure sensor

C. Huang, W. Wang, Univ. of Washington

In this paper, we propose a flexible polymer-based distributed pressure/force sensor using microfabricated Bragg grating array. The gratings will be constructed along a waveguide that is distributed over an area. With the high refractive index compared to the air, we can still have a great output power after propagating a long waveguide and by that we can build relatively large sensors. Each grating with slightly different periods made by electron beam lithography will serve as a sensing point. By monitoring the shift of the reflected spectral response from the grating, we can measure the corresponding period change and with that we can characterize the applied force. Because the reflected spectral response is highly sensitive to grating period, we can achieve a distributed sensing over a large area with slightly different periods on Bragg grating array. With the high resolution of spectral analyzer, a very sensitive micro force sensor can be built.

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5768-07, Session 2

Determination of biological cell properties using acoustic microscope

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Among the methods for the determination of mechanical properties of living cells acoustic microscopy provides some extraordinary advantages. It is relatively fast, of excellent spatial resolution and of minimal invasiveness. Sound velocity is a measure of the stiffness or Young´s modulus of the cell. Attenuation of cytoplasm is a measure of supramolecular interactions. These parameters are of crucial interest for studies of cell motility, volume regulations and to establish the functional role of the various elements of the cytoskeleton.

Using a phase and amplitude sensitive scanning acoustic microscope longitudinal wave speed, attenuation and thickness profile of a biological cell have been measured by the authors from the voltage versus frequency or V(f) curves in an earlier study. A series of images, for instance in the frequency range 980-1100 MHz allows the experimental generation of V(f) curves for each pixel while keeping the lens-specimen distance unchanged.

Two limitations of the earlier study are overcome in this paper. In that study it was assumed that the cell properties did not change through the cell thickness; however, these properties could vary in the lateral direction. Secondly, the acoustic microscope generated ultrasonic signal was modeled in that study as a plane wave striking the cell and the substrate at normal incidence. Such assumption ignores the contribution of the surface skimming Rayleigh waves. Improved and more generalized analysis that is presented here avoids such restrictive assumptions. The inverse problem is solved to study the effect of a drug on skin cells.

5768-08, Session 2

Diagnostic method in photonic mechanics

T. C. Fan, Univ. of Washington

Photonic mechanics is defined as the application of quantum and engineering mechanics coupled with optics. It is to be used as one of diagnostic methods in bio-medical field. Well known are the techniques by imaging of MRI, and PET and acoustic energy for ultrasonography etc. They may detect the presence of particles and their sizes in an organ normally free of any particles besides locating the tissues of vessel wall with changed density.. The methodology is based upon wave propagations which lead to critical dynamic strain in solids induced by either elastic and/or quantized elastic waves. When there is inhomogeneity in solids the influence of diffraction, refraction and dispersion etc. are present. Thus, an inclusion, a loose particle or a void could increase the value of local strain at the location of study. A MRI photo may show the quantity and the sizes of subject particles. This class of analysis belongs to waves mechanics associated with theories by Lamb, Love, Stoneley, Maxwell and Schrodinger in composites materials and structures.(Fan 2003).

By making use of Fourier's heat conduction the temperature profile at the affected region then is available to complete the study with optical source as proposed..If the inflammation of tissue is to be examined in this case, a constitutive modeling of [3x3] is considered.

The tissue is postulated to have three layers with uniform cells in local isotropy and homogeneity but is anisotropic and nonuniform grossly as stated in a generalized Hooke's. (Fan 1990). In bio-engineering the strain matrix for tissue is given below:

Thus, fever = (equilibrium potential) (virus)
+ (collision of electrons & photons)(contamination)
+ (lower energy by losing electrons & ATP)(induced problem in bio- radicals)

As expected the inbance of ion gradients across the plasma membrane of cells by virus interrupts the function of equilibrium potential., and leads a lower energy in ATP and the reducing power in acquiring electrons. Collision of photons and electrons tends to some irregularity in conduction of heat as evidenced in a fever with high temperature.

Swelling = (action potential)(virus) + (gradient, Na,K)(contamination)
+ (unavailability of metal ions)(induced)

The action potential may ineffectively transmit signals in a neuron system.affected by viruses The battle between the viruses and the white cells results in an energy loss as heat dissipation and change of local tissue density by excreta . In a dynamic wave evaluation the inclusion (density change) magnifies the local strain. With thermo-couples the released heat can be recorded...The Na (sodium), K (potassium) pump which transports oxygen in blood can be affected unfavorably, if there is ionic- chemical inbalance. The consequence may lead to the malfunction of cardic muscle and sensory system. In porphyria the undistributed compound on any layer in their bio-chemical process without oxygen and metal ions creates radicals that can erode the tissues.

Pain = (resting membrane potential)(virus) + (clots)(contamination)

+ (photo and non-photosynthesis)(induced)

The virus can create an inbalance in ionic and electrical gradient across the cell membrance. The postulated consequences are the ineffective delivery of oxygen in blood. A clot can happen at the region of contamination. Any asymmetrical or rotationally asymmetrical deformation of tissues and cells developed by unequal pressure on a body of nonuniform thickness leads to a blockage of body fluids thus, a clot. The presence of such a object tends to squeeze the sensory system of tissue. A pain is anticipated then Respiration problem may follow. By radiation the neutrinos of sun gives energy in ATP and reducing power to humans by making use of photosynthesis. For organism of nonphotosynthesis the cited process provides support of growth with synthesis of sugar and starch for life The proposed diagnostic method can complement the cited procedures with photonic waves to determine the critical strains at different laminate of tissues as composites (Fan 1998)

5768-09, Session 2

Sizing of microbubbles in blood stream based on ultrasound velocity

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Microbubbles are produced inside the human body by several mechanisms and these bubbles may cause many serious problems or even death. The ability of a gas bubble to scatter ultrasound waves has led to the testing of various ultrasonic devices to monitor microbubble formation in the blood stream. These have included pulsed echo, acoustic-optical imaging, Doppler technique and the through-transmission technique. In this work, a pulse through transmission method for measuring ultrasound velocity in bubbly gel phantoms was used. The bubble size has been assessed by measurement of the pulse-wave velocity. A specially designed pressure chamber ensures the measured velocity is directly related to the volume of microbubble by Boyle's law. This velocity is an average indicator of the bubble size between transmitting and receiving transducers. The average bubble radius is 0.1 mm. For best results the measurement were carried out around 1-3 MHz frequency range. It is shown that a large change in velocity of ultrasound occurs as a result of small changes in the volume of microbubble. When the fraction by volume of gas in gel is changed from 0.6 percent to 1 percent the velocity changed from 1500 to 500 m/s respectively. This large change in velocity should provide a good base for detecting and more importantly, sizing microbubbles in the blood stream. The measured results were compared with theoretical prediction with good agreement between theory and experiment. This technique can be used as a simple real time method to monitor and measure the volume of the microbubles in the blood stream. This technique has many application in medical field such as; open heart surgery, blood dialysis and deep sea diving (Decompression Sickness).

5768-10, Session 2

Non-destructive testing (NDT) of Sree Chitra heart valves by using holographic interferometry

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Artificial heart vaive is one of the important life saving implant organs that require reliability of the highest order. It should cross over a minimum of 380 million cycles, without a mechanical failure in an accelerated wear tester. This corresponds to 10 years of durability in a patient. The above implies that even a microscopic flaw in the valve structure or nonuniformity of its materials becomes decisive and affects the life of the patient. The Sree Chitra heart valve is the first indigenous heart valve developed in India. The valve has a cage of Haynes alloy and a disc of single crystal sapphire. This valve has undergone several rigorous material analysis, failure analysis and life testing. However, it was not subjected to holographic non-destructive testing (HNDT). HNDT of Sree Chitra heart valve has been attempted for the first time. The valve was held properly in various positions and was subjected to thermal and mechanical loding. A set of holographic interferograms of the valve was recorded. The paper describes about the experiment and the results obtained.

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5768-11, Session 3

Design of a low-power wireless structural monitoring system for collaborative computational algorithms

Y. Wang, Stanford Univ.; J. P. Lynch, Univ. of Michigan; K. H. Law, Stanford Univ.

In this study, a newly designed wireless sensing unit prototype is presented for structural monitoring applications. The design of the sensing unit is intended to ensure it is low-power for long-term field deployment in civil structures. A relatively long communication range of the selected wireless radio enables near-synchronized dynamic data acquisition for large-span structures. A multi-channel high-resolution analog-to-digital converter is included within each sensing unit to provide flexibility for high-fidelity data collection. A key feature of the wireless sensing unit design is the inclusion of a sophisticated computing core that is capable of locally executing engineering algorithms in real-time. A collaborative computational framework is proposed that exploits the merits of wireless peer-to-peer communications to optimally distribute the computational tasks of a global data interrogation algorithm (e.g. damage detection, modal

analysis) to the grid of wireless sensing nodes. To illustrate the capabilities of the wireless monitoring platform, including the execution of collaborative computational tasks, a lumped-mass laboratory test structure exposed to seismic excitations is employed. The modal properties of the test structure are determined in real-time by the wireless monitoring system installed.

5768-12, Session 3

Wireless sensor seismic response monitoring system implemented on top of NEESgrid

J. Wong, B. Stojadinovic, J. Goethals, Univ. of California/Berkeley

Emerging wireless sensor technology presents a tremendous opportunity for developing low-cost monitoring systems for civil infrastructure. A set of wireless Mica2 mote accelerometers were deployed on a reinforced concrete bridge column to collect data during a shaking table earthquake simulation test. The data from the test were ingested into a data and metadata system for testing the usability of the metadata description for data mining and visualization. The metadata system used the NEESgrid metadata services interface for backend storage. The results of the data acquisition and ingestion were used to determine the feasibility of using a comprehensive sensor, data storage, and data retrieval system for health monitoring.

The Mica2 platform was chosen for evaluation because of its low-cost and low-power consumption components. The sensors use MEMS accelerometers manufactured by Crossbow Technology, Inc. The sensors are equipped with an onboard microprocessor running the TinyOS operating system. The processor allows the user to program intelligence into the sensor. The sensors use a self-organizing ad-hoc network to communicate data back to the base station.

A special application was written for the TinyOS platform specifically for acquiring data in a laboratory testing environment. This control program was uploaded into the flash memory of each sensor. A base station mote was connected directly to the data acquisition computer to communicate with the accelerometers. Commands to start and stop data recording, increase and decrease radio transmission power, and to stream buffered data to the base station were sent to the motes for testing control.

Six different tests were run on the test specimen. An elastic range test, a yield level test, a maximum level test, a 7% test and a 70% test were performed. Failure of the specimen occurred after the 70% test. White noise tests were performed before each test in all three directions.

The results of the experiment showed that the radio interference and subsequent packet loss were the largest sources of error in the acquisition system. Resolution problems also posed a significant source of error. With one mote, the amount of packet loss is negligible. However, with two different motes streaming data to the base station simultaneously, packet loss increased to 25%. Packet loss with three motes increased to nearly 40%. Because of the high amount of packet loss, the data storage and retrieval system could not be used effectively for all the sensors in real time. However, near real-time data might be collected accurately if each sensor's data is transmitted individually to the base station from the on-board buffer, or if better transmission methods are developed.

5768-13, Session 3

Wireless structural health monitoring of cyclically loaded bridge piers

J. P. Lynch, T. Hou, G. Parra-Montesinos, Univ. of Michigan

High-performance fiber reinforced cementitious composites (HPFRCC) are a new class of building material for civil structures that have the potential to provide structural systems with ultra ductility and high damage tolerance. To monitor the behavior of this new class of material, promising wireless monitoring technologies can be adopted to provide HPFRCC structural elements capabilities to accurately monitor their performance to highly demanding loading conditions, such as those posed by seismic events. In particular, the computational core of a wireless sensing unit can be harnessed to screen HPFRCC components for damage in real-time. A seismic damage index initially proposed for flexure dominated reinforced concrete elements is modified to serve as an algorithmic tool that can rapidly assess the extent of damage in shear-dominated HPFRCC components. Embedded in the core of a wireless sensor prototype, damage index models are used to interrogate the deformation history of a circular HPFRCC bridge pier cyclically loaded in the laboratory. Traditional and non-traditional sensor strategies are proposed to optimize the correlation between the proposed damage index model and damage (micro- and macro-cracking) witnessed in the bridge pier. Empirical observations are also described by formulization of fiber-matrix mechanistic models that fully depict the damage mechanism.

5768-14, Session 3

Methodologies for quantifying changes in diffuse ultrasonic signals with applications to structural health monitoring

J. E. Michaels, Y. Lu, T. E. Michaels, Georgia Institute of Technology

Changes in diffuse ultrasonic signals recorded from permanently mounted sensors can be correlated to structural damage, offering hope that sparse sensor arrays can be utilized for monitoring large areas. It is well-known that both temperature and surface condition changes also have significant effects on diffuse ultrasonic signals that are of comparable magnitude to the effects of damage. Several methodologies are investigated for quantifying differences in diffuse ultrasonic signals and computing parameters that can be used to discriminate damage from environmental changes. The methodologies considered are waveform differencing, spectrogram comparisons, local temporal coherence, and computation of temperature compensated residuals. Experimental data from several aluminum plate specimens with different artificial defects are analyzed. Results show that the local coherence method is able to successfully discriminate moderate damage from both temperature changes and modest surface condition changes, and that the method of temperature compensated residuals is able to detect very small flaws in the presence of large temperature changes.

5768-15, Session 3

Real-time seismic monitoring and functionality assesment of a building

M. Celebi, U.S. Geological Survey

Seismic monitoring of structures must fulfill a need – that is, during and after a strong-shaking event, the monitoring system should yield data to meet installation objectives. In particular, objectives of the owner concerning functionality of the building, during and following an event, must be met. The purpose of this paper is to report on a recently implemented building seismic monitoring system that relates to such needs and uses IP technology to facilitate local and remote and local monitoring.

The 24-story building structure is a "pre-Northridge" perimeter welded steel moment frame and its construction was completed in 1982. The building is part of the recently initiated Building Occupancy Resumption Program (BORP) by the City of San Francisco. This program allows building owners to pre-certify private post-earthquake inspection of their buildings by qualified licensed engineers. The owner's engineers post the red/yellow/green placards in lieu of the city inspectors who would typically be unfamiliar with the building and may not be available for several days following the earthquake.

Unique performance specification requirements of this IP-based monitoring systems are:

·rapid assessment of the state of health of the building following an earthquake,

·rapid correlation of recorded data with known and building specific engineering parameters (e.g. drift ratio) and damage condition of the building, and

·data recovery in near real-time if not in real-time.

Performance characteristics of this PC-based monitoring system are centered around defining the thresholds of drift ratio, to be selected by engineers, as indicator of damage condition, at selected locations. The lateral deformation in this case will be drift ratios at selected pairs of floors. The performance-based theme is compatible with Figure C2-3 of FEMA Report 274. The threshold levels are selected by engineers in consultation with the owners. Performance limits of the welded beam-column connections are to be established using FEMA351 Steel Moment Frames: Evaluation and Upgrade Criteria for Existing Buildings. This will allow the various drift thresholds to be matched to a probability of connection fractures in different areas of the building. Such a health monitoring system can have applications not only for seismic events but also for man-made threats.

5768-16, Session 3

Investigation of data quality in a wireless sensing unit composed of off-the-shelf components

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This study examines the data and system identification results (derived from these data) in a wireless sensing environment. The focus is to understand how various hardware design choices and operating conditions would affect the quality of the data and accuracy of the identified results. A series of experimental investigation is carried out using a laboratory shaking table and a linear building model instrumented with off-the-shelf MEMS accelerometers. A wireless unit is developed to interface with these wired analog accelerometers to enable wireless data transmission. To reduce the overall design variance and aid convenient applications in civil infrastructure health monitoring, this wireless unit is built upon an off-the-shelf microcontroller and radio development board. The anti-aliasing filter and analog-to-digital convectors (ADC) are the only customized designed components in the hardware. By varying critical hardware configurations including using analog accelerometers of different commercial brands, taking various designs for the anti-aliasing filter and adopting ADCs with different resolutions, shaking table tests are repeated, the collected data are processed, and the results are compared. Operating conditions such as sampling rate and wireless data transmitting range are also altered separately in the repeated testing. In all the cases, the data collected directly, i.e., through the wires, from the analog MEMS sensors are used as datum to evaluate the impact due to wireless data transmission. Based on this study, design and operating recommendations are made by taking advantage of the off-the-shelf products to achieve satisfactory data qualify for the need of wireless sensing based structural health monitoring.

5768-17, Session 3

Monitoring of bolt preload using piezoelectric active devices

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It is estimated that 70% of all mechanical failures are related to fastener failure. One important mode of fastener failure is self-loosening of bolted joints. Self-loosening is especially problematic when the bolted joint is in an inaccessible location, a hostile environment, or a part of a machine whose shutdown would be costly. In this study, a piezoelectric (PZT) active-sensing device was used to detect self-loosening mode in joint connections. A PZT stack actuator or a PZT enhanced washer and nut were used to continuously monitor the condition of the joint by monitoring its dynamic characteristics. A study was performed to correlate the changes in the preload with the dynamic response changes measured from PZT. The dynamic response was readily measured using electro-mechanical coupling property of the PZT patch, in which its electrical impedance is coupled with the mechanical impedance of the structure. The mechanical impedance matching between the PZT enhanced devices and the joint connections were used as a key feature to monitor the preload changes and prevent further failure. This paper summarizes the considerations needed in experimental procedures and design, while outlining some assumptions made, and several issues that can be used as a guideline for future investigation.

5768-18, Session 3

Bio-inspired design of sensor system for damage prognosis

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Damage prognosis of structures and systems can be significantly improved by developing intelligent sensors with adaptive sensitivity to the ambient signals via self-tuned criticality. Active amplification of weak signals using an inherent dynamical sensory mechanism which is maintained at the threshold of an oscillatory instability is proposed in this paper as a general framework for designing and developing sensors for damage detection and prognosis for civil and mechanical systems. This idea is inspired by the sensing mechanism of mammalian cochlea to develop a new sensing system paradigm with applications to damage detection and prognosis. The mechanism of detecting sounds imposes stringent demands on the design of the inner ear, where the transduction of acoustic stimuli to electrical signal takes place. The inner ear and its associated dynamics has been investigated by various researchers from various perspectives. The hair cells with in the cochlea act as mechanical sensors and are responsive to a particular frequency component of the auditory input. In addition to this each of these hair cells have adaptive sensitivity because the weakest sound imparts energy, per cycle of oscillation, close to thermal noise. However, cochlea can accommodate a wide range of volume, responding to and adapting to volume which could vary by orders of magnitudes. The resonant gain of a passive elastic system is not sufficient due to the heavy viscous damping at the microscopic scales. In response to this cochlea has an active amplificatory process, whose precise nature remains to be discovered. There is strong evidence that the cochlea contains a dynamical system which generates forces capable of executing oscillations characteristic of a Hopf bifurcation . Some of the important features of this active dynamical process in cochlea are:

•It is fast since the hearing range in mammals is close to 100 kHz .

•It generates forces to counter viscous damping effects and essentially provides negative damping.

•It is robustly stable against thermal noise.

The amplification mechanism of the cochlea can be further illustrated by the amplification process resulting due to the fine tuning of bifurcation parameter in the proximity of a bifurcation to its critical value without prior knowledge of this critical value, with a high degree of precision. One approach proposed by other researchers is to develop adaptation laws which steer the bifurcation parameter to its critical value. The adaptation mechanism may depend on state but not on the critical parameter value. Any such adaptation mechanism needs to be robust with respect to the perturbations in its parameters. Understanding of such dynamical systems with adaptation laws will provide mathematical background for developing a new class of bio-inspired active sensor systems and is the focus of this paper. Based on this background design of a sensor system is proposed in this paper. The proposed design is demonstrated via simulation studies to have enhanced input sensitivity. Selected examples are provided for demonstrating the self tuned criticality and adaptive sensitivity properties of this class of sensor system design. Analog implementation of the proposed sensor system design is essential for validation of this sensor system design and is a significant direction of future research for the author.

5768-19, Session 4

Identification of damage in a standoff metallic thermal protection system panel subjected to combined thermo-acoustic excitation

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The thermal protection system is an essential part of any aerospace vehicle. Standoff metallic thermal protection system (TPS) panels protect the vehicle from the hostile environment on the panel exterior; consequently, the panels are exposed to a variety of loads including high temperature thermal stresses, thermal shock, acoustic pressure, and foreign object impact. These loads can cause degradation in the health of mechanically attached metallic TPS panels in the form of, for example, face sheet buckling, deformation/cracking of standoff bolts and standoffs or wrinkling to thermal seals. In this work, two sets of experiments were performed. The first experiment aimed to partially recreate the acoustic environment that the TPS experiences during service by subjecting the panel to broadband noise broadcast from a loudspeaker. In this set of experiments, “damage” was introduced into the TPS by loosening standoff fasteners to represent cracked or warped bolts and a transmissibility-based damage index

was implemented to detect and locate damage. The second experiment was designed to examine the variation in damage indices when the panel is subjected to combined thermo-acoustic loading. In this set of experiments, the panel was not subjected to any "damage"; instead, the exterior of the panel was heated with an infrared heat lamp while being excited by acoustic noise. It is demonstrated that the transmissibility-based damage indicator is a viable method for detecting and locating damage in the TPS panel. It is also shown that damage present in the panel may become more or less identifiable while the system is subjected to thermal loading.

5768-20, Session 4

Fusion of visual and eddy current inspection results for the evaluation of corrosion damage in aircraft lap joints

Z. Liu, D. S. Forsyth, S. Safizadeh, A. Marincak, National Research Council Canada (Canada)

An enhanced visual inspection named Edge of Light (EOL) was invented at the Institute for Aerospace Research of the National Research Council Canada. This technique provides a fast inspection and generates an intuitive result of the pillowing deformation caused by corroded products in aircraft fuselage joints. Using previously developed models, the pillowing deformation can be related to the total material loss in a fuselage joint structure. Eddy current techniques, e.g. multi-frequency eddy current testing and pulsed eddy current testing, can provide depth-sensitive inspections of fuselage joints. The objective of this study is to investigate how the testing results obtained from the two heterogeneous methods correspond to each other and what kind of complementary information is available in each result.

The fusion of the data from the EOL and eddy current inspections is investigated in this work. This work contains two aspects. First, the EOL inspection is used to estimate the total material loss while the eddy current or pulsed eddy current testing is employed to provide the complementary information on the remaining thickness. The results are compared; the fusion process is applied and the accuracy is determined. The accuracy of the results is improved by the combination of multiple measurements and the extent of corrosion by layer is estimated. Secondly, the EOL inspection that provides a higher resolution scanning than eddy current testing is used and the corroded regions on the specimen are identified from the EOL images according to the pillowing deformation. The corrosion damages in these regions are further characterized by eddy current or pulsed eddy current testing. The results of this two-stage approach will be compared with the previous results.

5768-56, Session 4

Feature selection for partial discharge diagnosis

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In design of partial discharge (PD) diagnostic systems, finding a set of features corresponding to an optimal classification performance (accuracy and reliability) is critical. A diagnostic system designer typically does not have much difficulty to obtain a decent number of features by applying different feature extraction methods on PD measurements. However, the designer often faces challenges in finding a set of features that give optimal classification performance for the given PD diagnosis problem. The primary reasons for that are: a) features cannot be evaluated individually since feature interaction affects classification performance more significantly than features themselves; and b) optimal features cannot be obtained by simply combining all features from different feature extraction methods since there exist redundant and irrelevant features. This paper attempts to address the challenge by introducing feature selection to PD diagnosis. Through an example this paper demonstrates that feature selection can be an effective and efficient approach for systematically finding a small set of features that correspond to an optimal classification performance of PD diagnostic systems.

5768-22, Session 5

Modular dry-coupled ultrasonic probes for field inspections of multi-layered aircraft structures

I. N. Komsky, Northwestern Univ.

Most of the multi-layered aircraft structures are still inspected primarily through various visual methods that require removal of multiple structural components to detect flaws in the internal layers of the structure. Some aircraft operators utilize for the multi-layered inspections more advanced NDI techniques such as X-ray. However, application of the X-ray technique still requires access to the bottom layers of the multi-layered structures for proper positioning of films or digital sensors. Additional time is also needed to comply with the safety rules for the X-ray inspection procedures. Hence, current inspection procedures for the multi-layered aircraft structures are fairly cumbersome, time-consuming and costly.

Application of the dry-coupled ultrasonic modules makes it possible to detect and characterize cracks in the internal layers from outside aircraft skin without disassembly. The inspection technique is easy to use, and, at the same time, is sensitive enough to identify critical structural degradation caused by cracking. The dry-coupled inspection technique is also sufficiently rapid so that aircraft downtime is minimized. The modules are also suitable for concurrent crack detection and sealant quality monitoring in the multi-layer aircraft structures. The concept of the dry-coupled transducer modules has already been tested on the DC-10 horizontal stabilizer (crack detection around fasteners).

Several current inspection procedures for aircraft multi-layered wing structures were reviewed to identify the areas for effective implementation of the dry-coupled ultrasonic techniques. Ultrasonic inspection techniques are being developed including flaw detection and characterization protocols for internal cracks in bottom layers of the multi-layered structures. Modular dry-coupled ultrasonic transducers with exchangeable elements and digital encoding systems are being modified for application on the multi-layered wing structures.

5768-23, Session 5

Scanning-laser-source and microcantilever receiver for detection of surface flaws in microdevices

Y. Sohn, S. Krishnaswamy, Northwestern Univ.

In recent work at Northwestern University, we have shown that near-field scattering of ultrasound generated by a Scanning Laser Source (SLS) can be used to effectively identify surface flaws in macroscale structure. In past work, the laser ultrasound source was in the near-field of a scatterer and a piezoelectric detector was used to measure the ultrasound in the far field. It was observed that distinct variations are observed in the far-field signals as the SLS scans past surface-breaking flaws. These changes were attributed to the near-field scatterer redirecting parts of the ultrasonic beam (which might otherwise have gone into the bulk of the object) towards the far-field detector.

We now propose an extension of the SLS approach to map defects in microdevices by bringing both the generator and the receiver to the near-field scattering region of the defects. For the purpose of near-field ultrasound measurement, the receiving transducer has to be made very small as well. To facilitate this, silicon microcantilever probes are fabricated and their acoustical characteristics are first investigated. Silicon cantilevers with tip and handling part are fabricated using anisotropic reactive ion etching and isotropic KOH etching. To characterize the free cantilever vibration, the chip with the microcantilever is excited by an ultrasonic transducer and an optical Michelson interferometer (or optical vibrometer) is used to monitor the cantilever motion. The fundamental frequencies of the microcantilever are measured and compared with analytically calculated fundamental frequencies assuming the cross sections of the cantilevers are rectangular. Next, the performance of the fabricated microcantilevers as ultrasound detectors is investigated. The microcantilever is used essentially as a profilometer by contacting it to the specimen surface. Surface and bulk acoustic waves are generated with specific narrowband frequencies and the surface ultrasonic displacements are detected using the microcantilever probe. Next, broadband ultrasound is generated by a laser source and the resulting surface acoustic displacements are monitored using the microcantilever probe in the near field of the source. Finally, both the laser-generated ultrasonic source and the microcantilever probe are used to monitor near-field scattering by a surface-breaking crack microfabricated in a thin silicon wafer.

5768-24, Session 5

Quantitative magneto-optic imager for non destructive evaluation

M. B. Lemistre, ONERA (France) and ENS-Cachan (France); P. Joubert, J. Pinassaud, ENS-Cachan (France)

Magneto-Optical Imagers (MOI) appear to be good alternatives to conventional eddy currents sensors for defect detection in large metallic structures. Indeed, they allow short time inspection of large structures such as airplanes fuselage or wings, thanks to the visualization of "real time" images relative to the presence of defects [1]. The basic principle of the MOI is to combine a magnetic inductor,

used to induce the circulation of eddy currents into the structure under test, with an optical set–up used to image the resultant magnetic field, thanks to the Faraday effect occurring in a magneto-optical garnet. The MOI designed by G. L. Fitzpatrick and Physical Research Instrumentation [2] provides binary images relative to the presence of defects, with an adjustable detection threshold. These so-called qualitative images, although highly contrasted, are rather poor and limited in terms of defect characterisation possibilities, even with the help of dedicated signal processing algorithms [3].

In, this paper, the authors present a new kind of MOI, called Quantitative-Magneto Optical Imager (Q-MOI), which provides images allowing a full defect characterisation, such as 3-D inversion [4], since the intensity of the provided images is linearly related to the magnetic field due to the defects [5]. First, the Q-MOI prototype, based on the use of a dedicated "linear" magneto-optical garnet associated with a specific instrumentation, will be described. Then first images obtained on various calibrated defects will be presented and first evaluations of the device will be given. Finally, further improvements of the presented Q-MOI prototype will be discussed.

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5768-25, Session 5

NDT of wafer direct bonding by non-confocal transmission phase sensitive acoustic microscopy

E. Twerdowski, R. Wannemacher, W. Grill, Univ. Leipzig (Germany)

Acoustic Micro Imaging (AMI) has long been established as a method of NDT of the wafer-to-wafer bonding quality in directly bonded wafers. In conventional imaging systems the C-Mode Scanning Acoustic Microscope operating in reflection is utilized. In this paper a non-confocally adjusted Phase Sensitive Acoustic Microscope (PSAM) operating in transmission at a frequency of 100 MHz is employed for imaging. This mode of operation results in a line-shaped point spread function of the system, which relaxes the constraint of keeping the lens-wafer distance stable when scanning at high ultrasonic frequencies. The full temporal transients acquired during a spatial 2D scan of the sample are stored for later analysis. Both the completely disbanded and the weak bonding regions in the wafer-to-wafer interface are identified. These latter areas are present, e.g., at the rim of the entirely disbanded regions as an intermediate interface condition between fully bonded and completely disbanded states. Reflection of mode-converted transversal waves from the wafer interface is exploited as a basis of weak bond detection in Si and GaAs bonded wafers. A short burst ultrasound excitation and time-selective post-processing of the acquired data is employed to prevent overlap with the direct transmission signal or its echo sequences and in this way making visible the amplitude variation induced by the interface bond degradation.

5768-26, Session 5

Hybrid electromagnetic method for NDE of GFRP and CFRP composite materials

M. B. Lemistre, ONERA (France) and ENS-Cachan (France)

The currently used methods for NDE of composite materials can be classified in two categories, the eddy currents methods and the ultrasonic methods. Concerning methods using eddy currents, one can obtain good results but this kind of investigation is uniquely usable with conductive structures (i.e. metallic structures or CFRP materials). The ultrasonic methods have a great sensitivity as regards to damages having a mechanical origin (i.e. delaminations, fiber breaking and cracks) but weakest sensitivity as regards to other kind of damages such as light burns or liquid ingress. The proposed method, called HEM (Hybrid Electromagnetic Method) allows to localize and to characterise main damages inside composites GFRP (Glass Fiber Reinforced Plastic) and CFRP (Carbon Fiber Reinforced Plastic). This method is based on the measurement of the local electrical characteristics of the material (i.e. dielectric permittivity and/or electrical conductivity), all damages inside composite materials inducing a local variation of dielectric permittivity (GFRP) and/or a local variation of electrical conductivity (CFRP). This measurement is performed by analysis of the local electric field induced by electrical excitation (GFRP) or magnetic induction (CFRP). From this concept, an electromagnetic probe has been designed. This probe allows to detect and to estimate the extension of main damages such as: delaminations, fiber breaking, cracks, burns and liquid ingress.

In this paper, one gives the principle of the electromagnetic method called HEM (i.e. magnetic and electric). One describes the probe designed and the data reduction algorithm used. One shows several examples of damages detected in GFRP and CFRP materials that one compares with ultrasonic C-scan investigations. This comparison allows determining the sensitivity, for each kind of damages, of the HEM concept as regards to ultrasonic C-scan analysis, these two methods being complementary.

5768-27, Session 6

Analysis of chaotic vibrations for damage detection in structures

L. M. Pecora, L. Moniz, J. M. Nichols, S. T. Trickey, M. E. Seaver, Naval Research Lab.

We employ chaotic forcing to vibrate linear structures to determine when parameters of the structure change, i.e. damage has ocurred, during the lifetime of the structure. We explain the procedure and show proof of concept first using a circuit simulation of a structure and a metal plate with varying size cuts in place. We will cover several data analysis techniques for these experiments ranging from SVD/empirical mode extraction, attractor construction, continuity statistics, and Holder continuity statistics. For all these tests the chaotic forcing approach equaled or bettered the standard modal approach to damage detection. A further advantage is that the method is model free. The data itself is the model.

5768-28, Session 6

Exploring damage sensitivity of state-space-based prediction error methods for structural health monitoring

L. Overbey, C. C. Olson, M. D. Todd, Univ. of California/San Diego

One paradigm within the structural health monitoring field involves analyzing the vibration response of structures as a method of detecting damage. Recent work has focused on extracting damage-sensitive features from the state-space representation of the structural response. One class of these features involves using attractors reconstructed from measured time series to predict themselves consistently over time. Loss of predictability is hypothesized to be due to damage-induced dynamical changes. Such methods are sensitive to a number of variables, including attractor reconstruction parameters, computation of the prediction error, and statistical accuracy. This work couples a numerical model with experimental data to optimize the method for maximum sensitivity to damage.

5768-29, Session 6

Sensitivity and computational comparison of state-space methods for structural health monitoring

C. C. Olson, L. A. Overbey, M. D. Todd, Univ. of California/San Diego

Detection of the change in the vibration response of a structure as a means of damage detection has long been explored in the structural health monitoring field. Recently, damage detection metrics based on state-space attractor comparisons have been presented in the literature. This work compares various state-space attractor methods within both numerical and experimental contexts to maximize detection sensitivity and statistical robustness, while minimizing computational effort.

5768-30, Session 6

Piezoelectric active sensing using chaotic excitations and state space reconstruction

T. R. Fasel, M. D. Todd, Univ. of California/San Diego; G. Park, Los Alamos National Lab.; H. Sohn, Carnegie-Mellon Univ.; C. R. Farrar, Los Alamos National Lab.

Recent research has shown that chaotic structural excitation and state space reconstruction may be used beneficially in structural health monitoring (SHM). The focus of this study is to apply a chaotic waveform to a piezoelectric (PZT)

patch that is bonded to a test structure. The use of high frequency chaotic excitation (~ 40 kHz) combined with PZT active sensing allows the location of incipient damage in the structure to be easily identified. The generation of high frequency chaos from a low frequency process necessitates bandwidth up-conversion that will be shown to be dimension preserving. We investigate the use of this method in conjunction with a novel prediction error algorithm to determine the damage state of a frame structure.

5768-31, Session 6

Detecting nonlinearity in a frame experiment with measures of information flow and interdependence

M. D. Todd, Univ. of California/San Diego; J. M. Nichols, Naval Research Lab.; L. Overbey, C. C. Olson, Univ. of California/San Diego

Structural system identification, historically, has largely consisted of seeking linear relationships among vibration time series data, e.g., auto/cross-correlations, modal analysis, ARMA models, etc. This work considers how dynamical relationships may be viewed in terms of 'information flow' between different points on a structure. Information or interdependence metrics (e.g., time-delayed mutual information) are able to capture both linear and nonlinear aspects of the dynamics, including subtle correlations. This work computes information-based metrics on a frame experiment where nonlinearity is introduced by the loosening of a bolt. The results detect the subtle nonlinearity that subsequently arises, which is failed to be captured by standard linear techniques. Such a result implies utility in structural health monitoring, where increasing nonlinearity typically correlates with damage to the structure.

5768-32, Session 7

High-speed defect detection in rails by non-contact guided ultrasonic testing

F. Lanza di Scalea, I. Bartoli, P. Rizzo, Univ. of California/San Diego; M. A. Fateh, Federal Railroad Administration

Recent train accidents and associated direct and indirect costs including cost of repair of equipment and infrastructure as well as delay and death/injury costs, have reaffirmed the need for developing rail defect detection systems more effective than those used today. In fact, rail defect detection has been identified as a priority area in the U.S. Federal Railroad Administration 5-year R&D plan. This paper proposes new inspection systems that are targeted to the detection of transverse-type cracks in the rail head, notoriously the most dangerous flaws in rails. The proposed technology uses ultrasonic guided waves that are detected by remote sensors positioned as far away as 76 mm (3") from the top of rail head. An impulse hammer is used to generate waves below 50 kHz that can successfully detect cracks larger than 15% of the head cross-sectional area. For smaller cracks, as shallow as 1 mm in depth, a pulsed laser is used for generating waves above 100 kHz. The inspection ranges are at least 10 m (32') for cracks larger than 15% head area, and at least 500 mm (20") for surface head cracks as shallow as 1 mm. Hence the potential exists for extremely high inspection speeds. Fast data output is achieved by processing the ultrasonic defect signatures by Wavelet Transform algorithms. The defect detection reliability is improved by using both reflection measurements and transmission measurements. Automatic defect classification capabilities are added to the system based on supervised learning methods.

5768-33, Session 7

Underground pipe inspection by guided waves using wavelet analysis

R. Ahmad, S. Banerjee, T. Kundu, Univ. of Arizona

Exposure to aggressive soil condition and deleterious reactions lead to significant deterioration of the integrity of underground water transmission pipelines. Ultrasonic guided wave techniques are widely used for obtaining information about material discontinuity and defect geometry. In this research work multimode cylindrical guided wave modes, generated by piezo-electric transducers, are used to identify defects in underground water pipelines in service. A Continuous Wavelet Transform (CWT) based algorithm is applied to analyze the signals received from the damaged and undamaged pipes to detect and predict the extent of the defect. Investigations have also been carried out to observe how the leaky cylindrical guided waves attenuate due to the presence of pipe defects while water is flowing through the buried pipeline in service condition. The experiment is carried out in a laboratory model.

5768-34, Session 7

Health monitoring of composite structures using Lamb waves

A. K. Mal, Univ. of California/Los Angeles; F. Shih, Seattle Univ.; S. Banerjee, Univ. of California/Los Angeles

This paper is concerned with the detection of low velocity impact and the associated internal damage in composite structural components using the Lamb waves generated by these events. Impact tests are carried out on graphite epoxy cross-ply composite plates using an instrumented impact testing system. The contact force and the surface motion caused by the impact load are recorded at several points on the plate surface away from the impact location and are analyzed based on theoretical simulations. Post-impact nondestructive, as well as destructive evaluations are also preformed to determine the internal damage caused by the impact load. Further research on the detection method can lead to the development of a viable impact monitoring system for composite aircraft and aerospace structures using distributed broadband sensors.

5768-35, Session 7

Improved attenuation calculation algorithm for multi-mode, transient leaky Lamb waves and its use in material characterization

K. Luangvilai, L. J. Jacobs, Georgia Institute of Technology; J. Qu, Goergia Institute of Technology

This research presents the improvement of the attenuation calculation algorithm for multi-mode, transient Lamb waves (presented at the 2004 SPIE NDE Conference). The previously developed algorithm suffers when the modes of a Lamb wave cannot be well separated in time-frequency space. The proposed modification is to make the algorithm adaptive. The filter and its parameters are chosen based on the level of dispersion and the arrival time of the individual modes. The most appropriate filter (varied with frequency) is applied to obtain the decay of magnitude of a specific Lamb wave mode at a specific frequency and slowness, and the attenuation corresponding to that point follows. This research then presents the use of this attenuation information in material characterization. In an isotropic plate loaded with a fluid half-space, multi-mode, transient leaky Lamb waves are generated and detected using broadband laser ultrasonic techniques. Both the unmodified and modified algorithms are applied to the resulting time-domain signals. The improved attenuation dispersion curves are developed, and then used to characterize the fluid half-space (provided that properties of the isotropic plate are known). The accuracy of attenuation is the key to success in the inversion. The combined attenuation calculation and inversion techniques proposed here establish a robust technique for material characterization using leaky Lamb waves.

5768-36, Session 7

Novel methods of Lamb wave detection for material damage detection and location

G. J. Thursby, B. Sorazu, Univ. of Strathclyde (United Kingdom); D. C. Betz, DaimlerChrysler AG (Germany); B. Culshaw, Univ. of Strathclyde (United Kingdom)

We describe and compare two novel methods of detecting ultrasonic Lamb waves used for damage detection and location, and then go on to compare their characteristics with those of more conventional PZT transducers. The two methods are measurements of the change in polarisation state of the light in an optical fibre and the change in reflected power from a fibre Bragg grating.

The polarimetric sensor operates on the principle that the pressure field of the acoustic wave changes the birefringence of a fibre bonded to the sample plate. This varying birefringence change in turn alters the polarisation state of light propagating through the fibre, which in turn can be detected by an analyser positioned at the fibre output. The sensor is directional, and is at its most sensitive when the direction of the acoustic wave is normal to that of the axis of the fibre. The length of sensing element of the fibre can be altered according to application requirements, though the response will be an integrated measurement of the pressure field it is subjected to. This can be complex integral if the axis of the fibre is not parallel to the wavefront.

Fibre Bragg gratings work by measuring the in-plane strains produced by the acoustic waves. The use of Bragg gratings to measure strain is a well established technique, however the strains produced by an acoustic wave are so small that an extremely sensitive measurement technique is required to detect them. The bonding between the grating and the sample plate is also critical if efficient

strain coupling between them is to be achieved at ultrasonic frequencies. As is the case for the polarimetric sensor, the Bragg grating is also directionally sensitive, though in this case the sensitivity is greatest when the direction of the acoustic wave is along the fibre axis. Three or more gratings may be configured to produce a rosette that can be used to determine the direction of the acoustic wave through the relative amplitude response of the gratings. This can be in turn be used to determine the location of damage, as will be demonstrated by practical results.

PZT transducers provide the most well established method of detecting Lamb waves and, like the Bragg grating do so mainly by detecting in-plane strain. When they are circular in shape (which they frequently are), their response does not vary with the change in direction of the acoustic wave. This makes it difficult to use them for directional or location measurements.

Since different transducers measure different properties of Lamb waves by different methods, their relative sensitivities to the So and Ao modes can also vary. This can be of interest because, for instance, the Ao mode is more sensitive to the presence of delaminations in a sheet due to the larger shear strain component that this mode contains. We will describe these different sensitivities in our presentation.

5768-37, Session 7

Elastic wave propagation in corrugated plates

S. Banerjee, T. Kundu, Univ. of Arizona

Analysis of Wave propagation in plates with sinusoidal boundaries has been considered for this paper. Guided elastic waves in periodically corrugated plates are studied analytically. The plate material is considered as homogeneous, isotropic and linearly elastic. In a periodically corrugated wave-guide all possible spectral order of wave numbers are considered. The dispersion equation is obtained by applying the traction free boundary conditions. Solution of the dispersion equation includes both symmetric and anti-symmetric modes. Non-propagating 'stop bands' and propagating 'pass bands' are investigated. The 'stop bands' are verified with the experimental results by performing the experiments over a wide range of frequencies.

5768-38, Session 7

Three-dimensional guided waves in laminated composite plates excited from a point source

P. Banerji, S. Nayak, Indian Institute of Technology Bombay (India)

Wave propagation in layered media is subject of considerable importance to a number of areas ranging from geophysics to nondestructive evaluation of laminated composite plate. One of the main objects to study the guided wave characteristics is to use it for ultrasonic non-destructive testing of structures. It is well established ultrasonic waves attenuate in laminated composite material. This is caused by the viscoelastic behavior of the resins ad scattering due to the fiber. The material here is, therefore, numerically modeled using complex elastic modulii to incorporate the material and frequency dependent damping for each layer of the laminated plate. In this paper 3-dimensional wave propagation characteristics in laminated plates are studied considering this anisotropic and viscoelastic properties of fiber reinforced composite material. A Rayleigh-Ritz based stiffness method is used to discretize the plate in the vertical direction to determine dispersion characteristic (wave number, phase velocity, group velocity) and mode shapes for a plane wave. For 3-dimesional cases, wave propagation problem is decomposed into a series of two-dimensional plane wave problems with three displacements coupled. Double Fourier transform integral transformations are used to get the governing equation in a transformed wave number domain. Steady state Green's functions for the laminated composite plates are constructed through summing the contribution of all two dimensional problem and the application of modal summation technique. Numerical integration of double infinite integrals is performed by summations over a finite range. To study the attenuation behaviors dispersion characteristics (wave number, phase velocity, group velocity) and Green functions for a particular frequency are studied for different viscoelastic condition. Due to presence of viscoelasticity, all wave numbers, including those for propagating modes, are complex irrespective of the direction of wave front. However, the relative value of the imaginary part of the wave number of the propagating modes are small, and it is seen that incorporation of damping has an insignificant effect on dispersion characteristics, irrespective of the excitation frequency. It is also found that attenuation in laminated composite plate largely depends on modes of the wave and direction of plane wave front as well. Viscoelasticity significantly affects both displacement and stress fields, especially as the distance from the transmitter increases. This effect is dependent on the excitation frequency. At relative low frequencies, the attenuation of the displacement and stress fields is small, although significantly more than in the 2D plane strain case. Furthermore, transient response of the plate to a point source is also studied using elastodynamic Green's functions for different damping states. Here also we see that decaying of response at far field region, without any time shift.

5768-52, Poster Session

Human movement tracking based on Kalman filter

Y. Zhang, H. Hu, Sr., Univ. of Essex (United Kingdom)

During the rehabilitation process of the post-stroke patients is conducted, their movements need to be localized and learned so that incorrect movement can be instantly modified or tuned. Therefore, tracking these movement becomes vital and necessary for the rehabilitative course. In the technologies of human movement tracking, the position prediction of human movement is very important .In this paper, we first analyze the configuration of the human movement system and choice of sensors. Then, The Kalman filter algorithm and its modified algorithm are proposed and to be used to predict the position of human movement. In the end ,on the basis of analyzing the performance of the method, it is clear that the method described can be used to the system of human movement tracking.

5768-53, Poster Session

Neural networks for delamination flaw detection in FRP laminated composite plates

P. Banerji, A. A. Bage, Indian Institute of Technology Bombay (India)

Non-destructive evaluation (NDE) techniques are useful in the damage detection and continuous monitoring of the structures. The flaws in the structure may adversely affect the performance of the structure and the resulting consequences may be catastrophic. Laminated composites are being increasingly used in making different parts of important structures such as aircrafts and satellites. Delamination is one of the important types of flaws often encountered in parts made of laminated composite plates. Thus there is need to evolve a suitable non-destructive evaluation technique for detecting delamination in laminated composite plates.

Artificial neural networks (ANN) are inspired by the neuronal architecture of the brain. Due to their capability to learn and generalize from examples, they are used in a wide range of applications involving association, clustering, classifications, pattern recognition, regression, and generalization and optimization. They are increasingly used in the field of damage detection.

In this study, the delamination detection in the laminated composite plate is carried out using artificial neural networks (ANN) in a two level cascading manner. The three damage parameters detected using ANN are the size of the delamination crack, its vertical location (across the plate thickness) and horizontal location (along the plate surface). The numerical data in the form of the frequency domain Green's function for the displacement response on the surface of the plate with delamination crack is generated first using an available numerical method. The numerical data is generated for different locations of the actuator from the crack and for different size and location (vertical as well as horizontal) of delamination crack, each time keeping the distance between the actuator and receiver at a constant value. Pseudo-experimental data are generated by adding artificial random noise into this numerical data.

At the first level, a counter-propagation neural network is trained for classifying each of the damage parameters using the numerical data generated above. The damage parameters are qualitatively classified by the first level network. Next, a second level back-propagation network is used for each class to quantify each of the damage parameters. This network is also trained using the numerical data generated above. The overlapping data set is used for the training of each class of the second level network. As a result it is found such that, any pattern misclassified in the first level network due to its closeness to the boundary of any two classes is still quantified correctly.

By feeding the pseudo-experimental data to the trained networks, it is seen that the classification success rate and noise tolerance level of counter-propagation networks is excellent. The quantification of damage parameters by the second level back-propagation networks is also quite good. It is possible to stop after the first level if only a qualitative assessment of the damage and its approximate location is required. These cascaded networks show promise in providing a fairly successful delamination damage detection algorithm for plates.

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5768-54, Poster Session

Can damage be detected without any baseline data?

H. Sohn, H. Park, Carnegie Mellon Univ.

For the development of a robust structural health monitoring (SHM) system, signal changes due to damage need to be distinguished from those caused by ambient operational and environmental variation of a structure. It has been reported that dynamic characteristics of an in-service structure could be influenced by ambient operational and environmental variation of the structure, and the ambient variation could often mask changes caused by damage. To address this issue, a damage detection technique, which does not rely on any past baseline signals, is proposed to assess damage in composite plates by using an time reversal process. First, a feature sensitive to delamination in composite plates is extracted based on a time reversal concept of modern acoustics. According to the time reversal concept, an input signal can be reconstructed at an excitation point if an output signal recorded at another point is reemitted to the original source point after being reversed in a time domain. This time reversibility is based on the spatial reciprocity and time-reversal invariance of linear wave equations. However, this time reversibility of Lamb waves is violated when wave distortion due to wave scattering is caused by a defect along the wave propagation path. Examining the deviation of the reconstructed signal from the known initial input signal allows instantaneous identification of damage without requiring the baseline signal for comparison. In addition, a decision boundary for damage identification is established based on a consequent outlier analysis but again without using any prior knowledge.

5768-55, Poster Session

Design of a 2-D actuator for an SU-8 based waveguide endoscope

R. R. Panergo, W. Wang, Univ. of Washington

Recent developments in alternative methods to current endoscopy devices include a vibrating single optical fiber as well as a microfabricated cantilever beam. The purpose for the aforementioned changes is to reduce the overall size of the device while still maintaining the resolution for high quality imaging. Discussed here in this report is the design of a 2-D MEMS based actuator for a microfabricated SU-8 based cantilever beam. The design utilizes comb drive actuation with fabrication done using an inductively coupled plasma deep reactive ion etch as well as a wet chemical etch. Actuation achievable for the vertical direction is 800Hz with the horizontal at 20kHz. The waveguide is also redesigned using a ribbed structure for improved confinement. Coupling efficiency through the waveguide was calculated to be 82%. However, absorption from the film caused a considerable amount of light loss. The overall power output of the waveguide with coupling and absorption loss was 2%.

5768-39, Session 8

Study of embedded wireless sensors network for application to SHM of bridges

S. Haran, J. Cole, B. Hampton, Arkansas State Univ.

The basic goal of structural health monitoring (SHM) is to determine the condition of the monitored structure and identify potential problems at an early stage. Several SHM strategies have been developed by many researchers in support of efficient monitoring of civil infrastructure. This may involve measuring several different parameters; vibration and strain are two of the important parameters used to gauge the health of a structure. Simultaneous measurement of both acceleration and strain would provide a better indication of the health of a structure. In addition, multiple measurements taken from different points on the structure, and used together in a wireless sensor network will prove to be lot more effective, with the potential to improve SHM. Such a strategy also represents future uses of wireless sensors for advanced SHM. In this paper, we study the performance of a distributed sensing system using accelerometer and strain gage sensor measurements. To being with, the measurements are simultaneously collected on a reinforced concrete beam, which have accelerometers as well as strain gauges embedded in the beam at different points. The Mica family based wireless system (Crossbow, Inc.) is used to network the sensors. The objective is to demonstrate the viability of this kind of a system for real-world SHM applications such as monitoring of a concrete bridge. Networked sensor nodes with wireless communication capabilities offer many opportunities. It is hoped that the use of embedded sensors for such a combination of parameters can help in combining data from their own measurement and from neighboring sensors, and process these data to extract important information about the structural system. Some results will be presented from the embedded sensors beam tests and its application to a concrete bridge.

5768-40, Session 8

Noise reduction in wireless strain sensors

D. J. Thomson, J. Chuang, G. E. Bridges, Univ. of Manitoba (Canada)

Existing sensing technologies for civil structural health monitoring have a serious deficiency in that they require some type of permanent connection to the outside world. This causes significant problems in the installation and ongoing use of these sensors. Recent cases have shown that the cost of installation and preparation of site for monitoring equipment can easily equal the cost of sensors and interrogation equipment. Therefore, not all sites will justify the cost of installation and maintenance of a permanent site. Wireless technology could make the monitoring of many more sites feasible and therefore significantly increase the utility of civil structural health monitoring. We have developed a wireless strain requires no battery or electrical power. This strain sensor is a passive device that can be easily embedded in concrete civil structures. The sensor has recently been installed in a full scale concrete bridge deck. The strain sensor is a metal cavity that changes dimension in response to an applied force. A short length of wire from the inside to the outside couples RF signals from the cavity inside to an antenna. The sensor can then be interrogated via the antenna. Such a system has the advantage of requiring no permanent physical connection between the sensor and the data acquisition system. Changes in the structure's dimensions will be reflected in changes in the resonant frequency, which is then used to calculate the strain on the structure. One serious issue with this type of sensor are RF signals coming from sources other than the sensor. Using a sensor that has been embedded in concrete test cylinders and interrogated using an external antenna we will show how time domain signal processing can be used to largely eliminate these sources of error. Experimental results show a strain resolution of better than 1 microstrain with a bandwidth of 30 Hz on this sensor. We will present results of interrogation schemes including a simple switched detector circuit, a gated detector circuit, peak fitting and also using lock in techniques. Since this sensor scheme can be very compact it may also have applications in other fields, such as biological systems.

5768-41, Session 8

FBG sensors for the measurement of the dynamic response of offshore storage tank platform model

S. Li, H. N. Li, Dalian Univ. of Technology (China)

Abstract: The dynamic response of offshore storage tank platform under seismic excitation is the coupling of liquid and solid vibration. In recent years, the computation of dynamic responses and design of offshore platform attract the attention of many researchers. This paper presents a shake table test of offshore storage tank platform model. The model is scaled down actual offshore storage tank platform. Fiber Bragg grating is a new measurement technology with their superior ability of explosion proof, immunity to electromagnetic interference and high accuracy. In this paper, FBG sensors are used to monitor the dynamic response of offshore storage tank platform on line. Nine FBG sensors are installed, two FBG sensors of which are acceleration sensors and the others are strain sensors. One acceleration sensor is placed on the surface of the shake table; the other accelerator sensor is placed on the top surface of the offshore storage tank platform model. Strain sensors are placed on the key parts of the platform model. Some traditional strain gages are installed at same parts with FBG strain sensors. The date obtained by strain gages must be filtered, because electromagnetic interference of strain gage used in shake table test is very big, while the data gained by FBG strain sensors need not be filtered. Based on the experiments results, FBG sensor is superior to strain gage. The measurements of model tests was compared with the response of computer simulation, and reached consistent results. Then, this paper gives the dynamic response of offshore platform under different earthquake inputs, which gives required parameters and good advices for design.

5768-42, Session 9

Structural health monitoring and life prediction system for fatigue damaged components

L. Sun, S. S. Kulkarni, S. Krishnaswamy, B. J. Moran, J. D. Achenbach, Northwestern Univ.

A structural health monitoring system which tracks the state of damage due to fatigue and then provides a probabilistic forecast of the remaining lifetime of a

component is discussed. The state of damage is monitored by ultrasonic SAW sensors and a probabilistic damage analysis procedure estimates the remaining life of the component.

The state of damage due to fatigue is estimated by measuring the acoustic nonlinearity. The nonlinearity measurement system uses a pair of ultrasonic sensors to monitor the variations in the fundamental and second harmonic SAW signal as a function of loading and damage development. The sensor data is then used in a probabilistic fatigue damage analysis.

The probabilistic fatigue damage analysis procedure consists of a suitably chosen phenomenological model to represent damage evolution. Based on the sensor data, the free parameters in the model are estimated. The uncertainty in the random quantities viz. nonlinearity measurements, material properties, etc. is incorporated in the model by choosing appropriate probability distributions for the random quantities. Probabilistic fatigue lives are then evaluated using a combination of reliability methods, such as First Order Reliability Method (FORM) and its variants, and the Monte Carlo Method with Importance Sampling.

Using the structural health monitoring system approach presented above, changes in the acoustic nonlinearity as a function of damage are monitored for steel specimens undergoing fatigue. Probabilistic lifetimes are then calculated, and the results are compared with the actual lifetimes. A method to mitigate the couplant effects in nonlinearity measurements is discussed. The effect of different phenomenological models on the estimated lifetimes is also investigated.

5768-43, Session 9

Important factors of input excitation in vibration based damage detection

S. T. Trickey, J. M. Nichols, M. E. Seaver, Naval Research Lab.

The research effort of our group over the past several years has been focused on vibration based structural health monitoring. In particular we have been investigating how the consideration of nonlinear processes can be used to increase the fidelity of the assessment of a structure's health over methods that are based on linear assumptions. Our consideration has included a number of analysis metrics calculated from the response of a structure such as a local variance ratio, prediction error, continuity of a functionalrelationship and differentiability of a functional relationship. In all cases the metric can be calculated from an input output relationship, from the relationship of one output location to another, or from the relationship between the same output location across different damage levels.

Input excitation has been another area we have explored in our study of structural health monitoring. The principal method we have used for including nonlinearity in our work to date has been to drive linear systems with a nonlinear input. Additionally we have considered several forms of stochastic processes including broad band noise, shaped noise, and naturally occurring processes such as ocean waves and wind gust loadings. In the present work, we turn our attention to an investigation of what aspects of the input play important roles in terms of improving the damage detection sensitivity in a structural health monitoring approach. A nonlinear input will be compared with various shaped noise bands.

5768-44, Session 9

Examining coupling in structural dynamics using information flow

J. M. Nichols, Naval Research Lab.

An information-theoretic approach is described for examining coupling mechanisms in structures. Both the time delayed mutual information and time delayed transfer entropy are presented as methods for computing the amount of information transported between points on a structure. By examining this "information flow" the presence and degree of nonlinearity in a system may be deduced. For a linear, two-degree-of-freedom system both mutual information and transfer entropy are derived. An algorithm is then described for computing both quantities from time-series data and is shown to be in agreement with theory. Potential applications of this approach include structural health monitoring where the presence of nonlinearity is often associated with structural degradation.

5768-45, Session 9

On a bifurcation theory based prognosis methodology for characterizing multiple damage mechanisms

P. Mejia, A. Shukla, Miami Univ.

Structural owners, civil or military, constantly strive to reduce the costs associated with pushing their equipment beyond conservative design envelopes while maintaining the safe reliable operation readiness. Research in smart damage detection and prognosis has largely taken a vibration-based approach where by the structural dynamic response to either ambient or applied excitation is analyzed for changes in characteristics 'features' that serve as indicators. Performance and life limits for structural and other complex systems are often limited by the fear of failure. Damage prognosis is a proposed methodology to better utilize these systems in a safe and reliable operation. Prognosis integrates physics based models of damage, noninvasive real time interrogation techniques and data/signature analysis to predict future performance. One of the significant capabilities essential for the prognosis methodology to work is to develop analysis methods for multiple and interacting damage and failure mechanisms. This paper proposes a novel bifurcation theory based methodology to characterize damage for tracking, evaluation and prediction. Using this methodology, a system with multiple possible damage mechanisms can be tracked to predict the mode of failure. In this paper the proposed methodology has been demonstrated with the help of a nonlinear multi-degree-of-freedom system which exhibits various types of phenomenological damage phenomenon. The damage phenomenons included in this study are sudden damage with arresting plasticity, damage resulting in limit cycle oscillations, and catastrophic damage events.

5768-46, Session 9

Damage assessment of an isolation system

L. W. Salvino, Naval Surface Warfare Ctr.

A new method of structural damage detection, aimed to monitoring the state of the structure based on measured time series data, is presented for the analysis and interpretation of underwater explosion (UNDEX) test data. This method extracts sets of simple basis function components, known as Intrinsic Mode Functions, and tracks structural damage based on a fundamental relationship connecting the instantaneous phases of measured structural waveforms to the structural mass and stiffness parameters.

The data was obtained during a recently conducted test series in which shock isolators, mounted on the adjustable deck fixture, are used to mitigate the shock impact for equipment cabinets. Shock input and deck fixture response are extracted and analyzed separately in order to better understand the particular support environment. The state of the isolation system is then evaluated, and possible structural damage is identified based on the instantaneous phase features. The studies presented here show that this novel method, intrinsically suited to non-linear systems and non-stationary processes, produces valuable insight into the state of a structure directly using UNDEX data as well as a more thorough understanding of shock effects on structural system behavior.

5768-47, Session 10

Effect of geometric non-linearity on acoustic modulation

H. Wu, Wayne State Univ.

Non-destructive testing for constructed facilities has been attracting researcher's attention in recent decades because that our infrastructure system is deteriorating at an alarming rate. Acoustics is considered to be one of the most promising methods. Non-linear nondestructive testing is different from linear acoustic in that it correlates the presence and characteristics of a defect with acoustical signals whose frequencies differ from the frequencies of the emitted probe signal. The difference in frequencies between the probe signal and the resulting frequencies is due to a nonlinear transformation of the probe signal as it passes through a defect. Under acoustic interrogation due to longitudinal waves, as the compression phase passes the defect the two sides of the interface are in direct contact and the contact area increases. Similarly, the tensile phase passes through the defect, the two sides separate and the contact area decreases, thereby modulating the signal amplitude. The contact area depends on the roughness of the surface and on the magnitude of the cohesive forces that arise from the small crack openings. Such cohesive forces may be attributed to aggregate interlock (in plain concrete), fiber bridging (in fiber reinforced concrete) or both. In this paper, the frequency shifts of the probe elastic wave will be analytically related to the roughness and varying cohesive forces of the crack-like defect.

Conference 5768: Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems IV

5768-48, Session 10

Multi-damage detection with embedded ultrasonic structural radar algorithm using piezoelectric wafer active sensors through advanced signal processing

L. Yu, V. Giurgiutiu, Univ. of South Carolina

The embedded ultrasonic structural radar (EUSR) algorithm was developed by using piezoelectric wafer active sensor (PWAS) array to detect defects within a large area of a thin-plate specimen. EUSR has been verified to be effective for detecting a single crack either at a broadside or at an offside position. In this research, advanced signal processing techniques were included to enhance inspection image quality and detect multiple damage. The signal processing methods include, discrete wavelet transform for signal denoising, short-time Fourier transform and continuous wavelet transform for time-frequency analysis, continuous wavelet transform for frequency filtering, cross-correlation for time-of-flight detection, and Hilbert transform for envelope extraction. All these signal processing was implemented by developing a graphical user-friendly interface program in LabView.

The paper starts with an introduction of embedded ultrasonic structural radar algorithm. Then the mathematical aspects of the signal processing methods are introduced briefly. Several multi-damage experiments results are presented to verify how the improved EUSR works. The results are discussed and EUSR is concluded being improved by using the advanced signal processing techniques. The improvement includes: 1) EUSR is able to provide better image of the specimen under monitoring; 2) it is able to detect multi-damage such as several cracks and different types of damage; 3) it is also able to identify different damage types.

5768-49, Session 10

Thermo-acoustic emission method of failure prediction of composites

E. G. Nesvijski, Univ. of Minnesota

This paper describes a novel nondestructive method for composite material and structures testing and failure prediction. This method are recovering all types of composites includeing cement based material, rocks, other earth substances and structures from them. under critical level of stresses or less. This new method can estimate current state of composites for failure prediction by thermal acoustic emission which called “Thermo-Acoustic Emission” (TAE) method and could be applied for evaluation of testing materials for stability state or cracking development under local, short term or low-cycle thermal loads. Thermal loads could be applied as heating, cooling or their combination. Registration and analysis of the TAE data, their signatures and patterns, as well as control data of thermal loads, allows predict failure of composites. The paper is describing an algorithm which uses heating-cooling device, acoustic emission sensor, acoustic emission data acquisition equipment and special evaluating parameters and analysis software for TAE pattern recognition and automatic decision making. Experimental results of TAE application is demonstrated and discussing their interpretation for composite analysis with smart sensors imbedding to structures in services and other future applications.

5768-50, Session 10

Dynamics-based model-independent local inspection method for damage detection of large structures

P. F. Pai, L. Huang, Univ. of Missouri/Columbia

The Boundary Effect Evaluation Method (BEEM) is a newly developed method for locating and estimating small structural defects (e.g., service-induced damage and manufacturing defects) using Operational Deflection Shapes (ODSs) measured by a scanning laser vibrometer. The BEEM works without using any structural model or historical data; it uses a sliding-window least-squares curve-fitting method to decompose an experimental ODS into central and boundary solutions. Because defects introduce small localized boundaries to a structure, boundary solutions exist around defects and actual structural boundaries. Moreover, because defect-induced boundary solutions show characters different from those of actual boundaries, defects can be easily located by examining the boundary solutions. The BEEM is non-destructive because a structure only needs to be harmonically excited to have a transverse vibration amplitude less than 1% of the structure’s thickness. Furthermore, the BEEM works without knowing the actual boundary conditions of the structure, and it actually estimates the boundary conditions. The BEEM only requires in-situ ODSs of the local area under examination, and hence a large structure (e.g., aircraft structures) can be examined area by area without disassembling.

Experiments have been performed to verify the capabilities of the BEEM in locating surface slots, edge slots, surface holes, internal holes, fatigue cracks, internal cracks, internal delamination, stiffened sections, and non-uniform material distributions. Numerical and experimental results show that the BEEM is more accurate and efficient than other dynamics- or deformation-based methods, including shearography, curvature methods, and strain energy methods. For example, the BEEM can locate a 2% (crack depth/beam thickness) backside crack in a beam and a 0.18% (attached mass/plate mass) mass attached to the backside of a plate.

In this paper we improve the BEEM by combining the use of boundary effects, the equality of elastic and dynamic energy densities of 1D structures at any point away from boundaries, the equality of elastic and dynamic energy densities in each mode cell of an ODS of a 2D structure, the differences of damage-induced boundary solutions and boundary solutions due to actual boundaries and/or non-uniform material distribution, and the Gibbs’ phenomenon caused by the use of continuous functions in curve-fitting a discontinuous function. Moreover, we show how to combine the use of a scanning laser vibrometer and an 8-camera motion analysis system to make small localized high-frequency excitations and area-by-area vibration measurements feasible for damage inspection of large structures. Numerical and experimental results obtained from several structures (including three beams, one 30”x22.8”x0.2” aluminum plate, and two actual aircraft panels) will be shown to confirm this newly developed technique.

(This work is supported by the NSF under Grants CMS-0120798 and CMS-0319853.)

5768-51, Session 10

Vision system using linear CCD cameras in fluorescent magnetic particle inspection of axles of railway wheelsets

H. Hao, L. Li, Tsinghua Univ. (China)

Axles of wheelsets are important parts in the traffic security of railway vehicles, and the continuous expansion of fatigue cracks will affect the health and life of axles extremely. Although fluorescent magnetic particle has been widely used to inspect the fatigue cracks, the identification of cracks still depends on people’s observation under UV light in dark room so far. The machine vision technology has been applied in NDT&E more and more these years, however, few investigations were developed on the fluorescent magnetic particle inspection for axles of railway wheelsets due to its large size and complex inspection conditions. The vision system in fluorescent magnetic particle inspection of axles of railway wheelset was presented and its design and algorithms were discussed in this paper.

The vision system includes four linear CCD cameras that have much higher resolution than area CCD cameras (two cameras for axle body and two cameras for two journals respectively), a 4-chanel 8-bit image acquisition card and an industrial PC. The linear CCD cameras kept scanning the magnetic particle indications on axle surface during the rotation of wheelset, the acquired data was transferred into computer by image acquisition card, and the two-dimensional developed images of axle body and journals were acquired by image mosaic. The longitudinal and circumferential resolutions of 5 pixels per millimeter have been proved enough for inspecting fatigue cracks, so the dada will be about 30 M bytes (3000 scanning line per rotation and 10000 pixels per line) for a typical axle of railway wheelset.

The rapid algorithms of image processing and crack identification based on mathematical morphology are the cores of the vision system. According to the image characteristics of magnetic particle indications on the axles of railway wheelsets, the algorithms of tangential filtering, edge detection, and adaptive fuzzy threshold segmentation were developed, so the effects of pseudo magnetic particle indications caused by corrosion, pit, oxide scale and nick were eliminated and the magnetic particle indications of fatigue cracks were distinct in the image. Based on the collected representative scanning images of magnetic particle indications induced by actual fatigue cracks, the knowledge database for the intelligent pattern recognition of cracks was established, so the fatigue cracks on axles of railway wheelsets can be diagnosed more accurately and more rapidly by the intelligent vision system in fluorescent magnetic particle inspection.

Conference 5769: Nondestructive Detection and Measurement for Homeland Security III

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5769-01, Session 1

Creating a trusted information network for homeland security

Z. Baird, Markle Task Force on National Security; T. Lemmey, LENS Ventures

The Markle Task Force on National Security in the Information Age, comprised of leading national security experts from four administrations, as well as widely recognized experts on technology and civil liberties, was created to focus on the question of how best to mobilize information and intelligence to improve security while protecting established civil liberties.

In our second and most recent report, Creating a Trusted Information Network for Homeland Security, the Task Force noted that the government has not yet taken advantage of America's technology expertise to combat terrorism, which we believe is the best way to gain a competitive edge against terrorism.

Our presentation by Task Force members would illustrate our recommendations for a "virtual reorganization" of government through the immediate creation of a Systemwide Homeland Analysis and Resource Exchange (SHARE) Network, which could be built with existing technology and would fundamentally alter how information is used to facilitate better, faster decision-making at all levels of government.

5769-02, Session 1

A new vacuum insulated tandem accelerator for detection of explosives and special nuclear materials

J. P. Farrell, M. V. Murzina, J. R. Powell, Brookhaven Technology Group, Inc.

Photon Resonance Imaging unambiguously identifies explosives, nuclear and other materials. The accelerator based system produces a penetrating beam of high energy photons that can "see" inside a sealed container. If chemical explosives or special nuclear materials are present, they will emit a characteristic signal that can be detected and interpreted by electronic sensors. To achieve a photon beam with the required characteristics, a low energy tandem accelerator similar to those used by the semiconductor industry to make computer chips, accelerates protons and projects them onto a target made of a carbon isotope. The target converts the energy of the ion beam into a high energy highly penetrating photon beam. The photon beam is made to pass through the container. If explosives or special nuclear materials are present, the beam together with suitable a detection system, uniquely identifies the location, amount and density of material. This system is based on entirely new ion source and accelerator designs that were not available in the 1990's when the nuclear resonance absorption method was first studied. The system and its estimated performance specifications are discussed.

5769-03, Session 1

Visual identification system for homeland security and law enforcement operations support

T. J. Samuel, D. Edwards, Pacific Northwest National Lab.

To support the operations and meet the needs of law enforcement and Homeland Security efforts, the Battelle Memorial Institute (Battelle) has developed an optics based Visual Identification System (VIS) using commercial off-the-shelf technology (COTS) that has been adapted to meet law enforcement requirements.

This paper discusses the unique functions and requirements associated with law enforcement visual identification systems and describes the ability and related limitations for utilizing and adapting COTS for law enforcement needs.

Topics covered in this paper include:

·Basic Law Enforcement and Homeland Security Functions & Requirements

·Digital vs Analog Systems

·Challenges Associated with Lighting

·Camera Triggering and Remote Control

·Wireless Communication

·Optical Character Recognition

Off the shelf technologies can be adapted in many cases to meet and or exceed law enforcement requirements. These technologies can have a significant impact on staffing requirements as well as significantly aiding in the identification of vehicles that are to be targeted for further investigation.

5769-04, Session 1

Functional optical brain sensor to monitor deception

S. C. Bunce, A. Devaraj, M. A. Izzetoglu, B. K. Onaral, K. Pourrezaei, Drexel Univ.

Near-infrared based functional optical brain imaging (a.k.a., fNIR) is a noninvasive technique that uses the reflection of infrared light pulses to monitor changes in the concentration of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in the blood, comparable to that of fMRI. Importantly, this technology also allows the design of safe, portable, wearable (i.e., wireless), affordable, and negligibly intrusive monitoring systems. Our current fNIR system lends itself to wireless designs and to non-contact methods for monitoring brain functions. These qualities, along with the fact that deception or "guilty knowledge" has been associated with local changes in blood oxygenation in the cortex, make fNIR an excellent candidate for the evaluation of brain activity during functional tasks, including the detection of deception. Conventional polygraphy relies on psychophysiological measures of autonomic nervous system response to detect anxiety associated with guilt or lying. These autonomic measures suffer, in particular, from a lack of specificity differentiating "guilt" from "anxiety," resulting in an unacceptably high level of false positives. Recent efforts to detect deception have turned to more direct measures of the neural circuitry underlying deception.

Concurrent EEG-fNIR measurements were conducted using a modified Guilty Knowledge Task designed to detect an individual's attempt to conceal information (approved by the Drexel University IRB). The paradigm capitalizes on a socially acceptable form of deception (the game of poker). Our results indicate the involvement of bilateral prefrontal cortex in this form of deception. To date, we have achieved 91.7% correct classification of lies versus telling the truth (89% sensitivity, 94.4% specificity). These data suggest that fNIR, alone or in conjunction with other methods of determining deception, could greatly increase our capacity to reliably detect deception.

5769-05, Session 1

Straddle carrier portal

E. S. Andersen, T. J. Samuel, O. D. Mullen, Pacific Northwest National Lab.

U.S. Customs and Border Protection (CBP) is the primary enforcement agency protecting the nation's ports of entry. CBP is enhancing its capability to interdict the illicit import of nuclear and radiological materials and devices that may be used by terrorists. Pacific Northwest National Laboratory (PNNL) is providing scientific and technical support to CBP in their goal to enable rapid deployment of nuclear and radiation detection systems at U. S. ports of entry to monitor 100% of the incoming international traffic and cargo while not adversely impacting the operations or throughput of the ports. The U.S. ports of entry include the following vectors: land border crossings, seaports, airports, rail crossings, and mail and express consignment courier facilities.

U.S. Customs and Border Protection (CBP) determined that a screening solution was needed for Seaport cargo containers being transported by Straddle Carriers (SCs). A stationary Radiation Portal Monitor (RPM) for Straddle Carriers (SCRPM) is needed so that cargo containers can be scanned while in transit under a Straddle Carrier. The Straddle Carrier Portal operational impacts were minimized by conducting a time-motion study at the Port, and adaptation of a Remotely Operated RPM (RO-RPM) booth concept that uses logical lighting schemes for traffic control, cameras, Optical Character Recognition, and wireless technology.

This paper presents a complete, generic design that could be put in place at any Port with a minimum impact to the Port Operations. This paper will describe the key functions and requirements of a Straddle Carrier Portal, design challenges and how they were met, and the knowledge obtained from the mockup testing.

Conference 5769: Nondestructive Detection and Measurement for Homeland Security III

5769-06, Session 1

Advanced ultrasonic measurement methodology for on-invasive interrogation and identification of fluids in sealed containers

B. J. Tucker, A. A. Diaz, T. J. Samuel, Pacific Northwest National Lab.

The Hazardous Materials Response Unit (HMRU) and the Counterterrorism and Forensic Science Research Unit (CTFSRU), Laboratory Division, Federal Bureau of Investigation (FBI) have been mandated to develop and establish a wide range of unprecedented capabilities for providing scientific and technical forensic services to investigations involving hazardous chemical, biological, and radiological materials, including extremely dangerous chemical and biological warfare agents. Pacific Northwest National Laboratory (PNNL) has developed a portable, hand-held, hazardous materials acoustic inspection device (HAZAID) that provides noninvasive container interrogation and material identification capabilities using nondestructive ultrasonic velocity and attenuation measurements. Due to the wide variety of fluids as well as container sizes and materials, the need for increased measurement sensitivity and more advanced ultrasonic measurement techniques were identified. The HAZAID technology platform is being developed using signal processing techniques including cross correlation, pulse compression, and cross spectral density. Advantages of the new techniques and their incorporation into the new portable unit will be presented.

5769-07, Session 1

Portable source identification device

E. S. Andersen, T. J. Samuel, K. Gervais, Pacific Northwest National Lab.

U.S. Customs and Border Protection (CBP) is the primary enforcement agency protecting the nation's ports of entry. CBP is enhancing its capability to interdict the illicit import of nuclear and radiological materials and devices that may be used by terrorists. Pacific Northwest National Laboratory (PNNL) is providing scientific and technical support to CBP in their goal to enable rapid deployment of nuclear and radiation detection systems at U. S. ports of entry to monitor 100% of the incoming international traffic and cargo while not adversely impacting the operations or throughput of the ports. The U.S. ports of entry include the following vectors: land border crossings, seaports, airports, rail crossings, and mail and express consignment courier facilities.

As the deployment of radiation detection systems proceeds, there is a need to adapt the baseline radiation portal monitor (RPM) system technology to operations at these diverse ports of entry. When screening produces an alarm in the primary inspection RPM, the alarming vehicle is removed from the flow of commerce and the alarm is typically confirmed in a secondary inspection RPM. Currently, CBP then uses a hand-held radioisotope identifier device (RIID) to try to identify that material (radioisotope) responsible for the alarm. All currently available RIIDs have limited capability to identify alarming material in an operational environment. Consequently, given the operational and throughput requirements for seaports and rail vectors, these deployment teams have identified a significant need for an improved portable source identification device (PSID) that would rapidly scan alarming cargo containers on trailers and rail cars with 1) adequate sensitivity to accurately identify the source of the alarm and 2) only minimal disruption to commerce.

The PSID is a portable device consisting of a scissor lift on a small truck. The lift supports a box containing a commercial off-the-shelf (COTS) sodium iodide detector that provides real-time isotopic identification, including neutron detectors to interdict Weapons of Mass Destruction (WMD) and radiation dispersion devices (RDD). The scissor lift will lower the detectors to within a foot off the ground and raise them to approximately 24 feet in the air, allowing a wide vertical scanning range. The mobility of the PSID would allow it to travel efficiently to the location of the alarming cargo.

This paper identifies the design features for a mobile, portable source identification device (PSID) that incorporates a radiation sensor panel (RSP) based on thallium-doped sodium iodide (NaI(Tl)) scintillation detectors and gamma spectroscopic analysis hardware and software.

5769-08, Session 2

Wireless structural monitoring for homeland security applications

A. Kiremijdian, Stanford Univ.; G. K. Kiremidjian, B. Benco, Sensametrics, Inc.; E. Caryer, Stanford Univ.

This paper will describe the development of a robust, low-cost, low power, and high performance autonomous wireless monitoring system for civil assets such as large facilities, new construction, bridges, dams, commercial buildings, etc. The conceptual design of the system was presented during a previous conference. In this paper, recent advances in the design and implementation of the system will be presented. The focus will be on the development and a test mode implementation of a prototype system for bridge monitoring.

The system concept is based on dense networks of "intelligent" wireless sensing units. The fundamental properties of a wireless sensing unit include: (a) interfaces to multiple sensors for measuring structural and environmental data (such as acceleration, displacements, pressure, strain, material degradation, temperature, gas agents, biological agents, humidity, corrosion, etc.); (b) processing of sensor data with embedded algorithms for assessing damage and environmental conditions; (c) peer-to-peer wireless communications for information exchange among units (thus enabling joint "intelligent processing coordination) and storage of data and processed information in servers for information fusion; (d) ultra low power operation; (e) cost-effectiveness and compact size through the use of low-cost small-size off-the-shelf components. An integral component of the overall system concept is a decision support environment for interpretation and dissemination of information to various decision makers.

5769-10, Session 2

Detection of chemical, biological, and radiological hazard materials on highway transportation systems using nanotechnology-based wireless sensors

M. Saafi, P. Shansez, P. Romine, Alabama A&M Univ.

Recent anxiety on the potential use of transportation systems such as trucks, cargo containers and other vehicles to transport weapons of mass destruction for possible terrorist attacks is causing great concern to federal and local governments to improve information, inspection, tracking and monitoring technologies. Movement of hazardous materials and the potential of sabotage is also causing increased concern among law enforcement agencies and resulting in increasing demands for detection of vehicles transporting chemical, biological and radiological hazardous materials. A new monitoring and detection system currently under development at the Center for Transportation Infrastructure Safety and Security to detect and locate trucks and other vehicles carrying chemical, biological and radiological hazardous materials over a wide geographical area where nanotechnology-based sensors are being designed to form a "homeland security" chip to detect the above hazardous materials. The homeland security chip will be installed at critical locations on the highway to wirelessly detect and locate vehicles carrying hazardous materials then notifies the authorities through wireless communication networks to undertake urgent measures. The proposed technique will allow authorities to detect threats at an early age without causing major traffic congestions. In this paper, the wireless monitoring and detection system will be presented; this will include the design of micro-nano chemical, biological and radiological sensors, monitoring systems and wireless communication networks.

5769-11, Session 2

Managed traffic evacuation using distributed sensor processing

S. Biswas, P. Ramuhalli, Michigan State Univ.

This paper will present an integrated sensor network and distributed event processing architecture for managed in-building traffic evacuation during natural and human-caused disasters, including earthquakes, fire and biological/chemical terrorist attacks. The contributions of this paper will be twofold. First, it will provide low-latency and energy-efficient communication protocols for connecting wireless sensor devices with disaster specific data prioritization. Second, the paper will develop a set of signal and event processing mechanisms that can be used for detecting and monitoring in-building disaster propagation and human traffic movement, and for making disaster management decisions including optimal traffic evacuation strategies.

The majority of traditional building evacuation systems are based on centralized disaster management servers that collect, store and process periodic data samples from wired sensors distributed around a building and its supporting structures. These systems have the following shortcomings. While being dependable during smoke and some biological attacks, wired sensors cannot be relied on during fire and similar disasters that can produce extreme temperature and other environmental conditions. Wireless sensors will be needed to make the system dependable in such situations. Although an evacuation system based on centralized servers can be made somewhat reliable using server redundancy, it is still vulnerable to server failures which are very likely during a disaster. This concern can be addressed by distributing disaster detection and evacuation decision-making functions at the level of sensor nodes which can be deployed

with a much larger degree of redundancy compared to traditional evacuation servers.

The proposed wireless sensor network protocols and distributed event processing mechanisms in this paper offer a new distributed paradigm for improving reliability in building evacuation and disaster management. The networking component of the system is constructed using distributed wireless sensors for measuring environmental parameters such as temperature, humidity, and detecting unusual events such as smoke, structural failures, vibration, biological/chemical or nuclear agents. Low-latency and energy-efficient networking protocols will be designed for these sensors to communicate wirelessly for inferring impending or present disasters within the building. Distributed event processing algorithms will be executed by these sensor nodes to detect the propagation pattern of the disaster and to measure the concentration and activity of human traffic in different parts of the building (e.g. hallway, exits, basement etc.). Based on this information, dynamic evacuation decisions will be taken for maximizing the evacuation speed and minimizing unwanted incidents such as human exposure to harmful agents and stampedes near exits. A set of passive audio-visual indicators (e.g. direction towards exits) and active actuators (e.g. water and foam sprinklers) will be used for aiding the automated evacuation process.

In this paper we develop integrated protocols, algorithms and their simulation models for the proposed sensor networking and the distributed event processing framework. A notable networking feature is to provide cross-layer protocol syntax in which sensor Medium Access Control (MAC) and routing protocols are energy and delay optimized based on the distributed event processing requirements for this specific application framework. Also, efficient harnessing of the individually low, but collectively massive, processing abilities of the sensor nodes is a powerful concept behind our proposed distributed event processing algorithms. Results obtained through simulation in this paper will be used for a detailed characterization of the proposed evacuation management system and its associated algorithmic components in terms of their networking performance, fault tolerance, energy efficiency, processing requirements and implementation feasibility.

5769-12, Session 2

CREM monitoring: a wireless RF application

J. D. Valencia, B. J. Burghard, J. R. Skorpik, K. L. Silvers, Pacific Northwest National Lab.

Recent security lapses within the Department of Energy prompted the establishment and implementation of additional procedures and training for all operations involving classified removable electronic media (CREM) storage. In addition, the definition of CREM has been expanded and the number of pieces of CREM has increased significantly. The new procedures require that all CREM be inventoried on a weekly basis. Weekly inventories consist of a physical comparison of each item against the inventory listing and thorough documentation.

Securing and accounting for CREM is a continuous challenge for existing security systems. An innovative Automated Removable Media Observation and Reporting System (ARMOR) has been developed by PNNL to monitor, track, and locate CREM in safes, vaults, and storage areas. This is an extension of an existing PNNL program, SecureSafe, which monitors safe lock/unlock status with central alarm station reporting. The key attributes of the ARMOR system include improved accountability, reduced risk of human error, improved accuracy and timeliness of inventory data, and reduced costs as a result of man-hour reductions. The ARMOR solution is to tag the CREM with an electronically readable unique RF identification code and use a combination of local fixed and mobile readers to regularly collect data on the inventory in each security container. This eliminates the need for hand-written inventory sheets and allows automated transfer of the collected inventory data to an electronic reporting system. Using access event time and date stamps along with individual staff identification provides enhanced accountability for daily or weekly checks, routine audits, and follow-up investigations in the event of a security incident.

5769-13, Session 2

DuraNode: wireless network sensor for structural safety monitoring

H. Chung, ImageCat, Inc.; C. Park, Q. Xie, P. H. Chou, M. Shinozuka, Univ. of California/Irvine

DuraNode is designed for structural health monitoring and the safety of civil structure systems by detecting damage of structural integrity. The system is comprised of two MEMS-type acceleration sensors, namely ADXL202E and SD1221, wirless-LAN communication adapter (802.11b), and alternative power supply modules such as solar power panel and wind power generation devices. The system is also designed with adaptive power management circuit that makes it durable for long term service without battery replacement and device maintenance. The system is integrated with wireless LAN connection enabling longer distance and sufficient band width for an ad hoc networking in a more energy efficient way. The efficacy of this system for structural monitoring is demonstrated in a case study of measuring the acceleration of a pedestrian bridge caused by man-made excitation force. The result is compared with that from traditional cabled sensors. The DuroNode system is shown to be cost-effective for carrying out robust analysis functions elaborated with digital computers in the real time monitoring mission.

5769-14, Session 3

The role of uncertainty in evaluating condition and vulnerability of constructed systems

K. Ciloglu, Q. Pan, K. A. Grimmelsman, Drexel Univ.; F. N. Catbas, Univ. of Central Florida; A. E. Aktan, Drexel Univ.

Condition evaluation of large structures has been widely researched over the last decade. In numerous studies dynamic testing has been used as a primary experimentation tool for extracting indicators on structural condition. Despite the efforts, dynamic testing on constructed systems has not fully evolved to a point that it can be standardized and presented as a tool for condition evaluation to civil engineering community. Writers believe that two major sources of uncertainty in dynamic test based condition evaluation cause keeping the gap between concepts and real-life applications wide open. Dynamic test methods are built on principles of linearity and stationarity. First major source of uncertainty is initiated from the violation of those principles because of structure's inherent complexity and inhomogeneity. The second one is related to the data acquisition and processing procedures for different dynamic test methods. For example, ambient vibration and impact tests are two different tools aiming to identify same parameters. Comparative evaluation of different test methods at the presence of different levels of uncertainty will enable us to assess the reliability of dynamic testing tools for condition evaluation. Writers designed a matrix of experiments on a laboratory physical model to investigate the effects of these two groups of uncertainties on modal parameter identification. Results will be discussed along with mitigation measures of uncertainties in dynamic testing of constructed systems.

5769-15, Session 3

Fatigue crack propagation of magnesium alloy in biaxial stress fields

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The density of the magnesium alloy is about 2/3 of that of aluminum and a quarter of that of steel. Magnesium alloy, among metal materials for structural use, is the lightest in weight and excellent not only in specific strength and specific rigidity but castability, vibration absorption, and machinability. Recently, for its lower cost of fuel, the magnesium alloy is used more and more widely in the manufactory of automobile. In order to perform the design in consideration of the reliability and the safety, especially in long-distance run, the fatigue characteristics data of a magnesium alloy are indispensable. Machines and structures, such as automobiles, ships, and aircrafts, are usually subjected to biaxial or three-axial stresses instead of uniaxial stress. However, research on the fatigue failure under multi-axial stresses has not been fully presented because such experiments are difficult. To solve this problem, we developed the servo biaxial fatigue-testing machine. In this research, in order to clarify the effect of biaxial stress condition on fatigue properties of magnesium alloy, we performed the biaxial fatigue tests of a magnesium alloy. The Magnesium alloys AZ31B-O used for this research are 2.5mm thickness plates. In any cases, a static tensile test, a uniaxial fatigue test, or a biaxial fatigue test, we defined the Y-axis as the rolling direction, and extracted the results on the basis of the Y-axis. The pre-crack with a length of 30.0mm was put into the central part of a fatigue testing specimen. Fatigue crack growth tests were conducted by the servo biaxial fatigue-testing machine under uniaxial and biaxial stresses. In this research, the load shape is sinusoidal, the load ratio (R=Pmin/Pmax) is 0.1, the maximum load (Pmax) is 8kN, and the cycle speed is 10Hz. As a result of the fatigue test, when load of the biaxial stress was carried out, it was confirmed that crack progress velocity becomes slow. In the case of inequality biaxial stresses load, the tendency was more remarkable than that in the case of equal biaxial stresses load. As a result of observing the fatigue fracture surface of a magnesium alloy by SEM, the striation-like striped pattern was observed. However, the micro-

scopic crack progress direction guessed from striation-like striped patterns differed from the macroscopic crack progress direction greatly. Then, the crack progress behavior was considered from the shape of the metal structure of AZ31B which was observed by the optical microscope.

5769-16, Session 3

Some issues in condition assessment of large structures using dynamic measurements

F. N. Catbas, Univ. of Central Florida; A. E. Aktan, Drexel Univ.

Assessment of damage and objective condition evaluation of existing civil infrastructure systems (CIS) are important needs for making decisions during regular operation as well as before and after disasters. Objective condition assessment is also a fundamental knowledge need for successful health monitoring of CIS. Condition indices or metrics for health and performance must be established for the selection and use of the available technologies such as the Internet, remote data acquisition and wireless sensors. However, due to the size and complexity of large structures, it is difficult to conceptualize them completely, accurately and uniquely, also difficult to extract and use mechanical properties directly as objective condition and damage indices. In this study, the writers present the displacement coefficients as promising kernel condition and damage. Displacement coefficients are very conceptual and can be applied to a variety of structures. Dynamic tests, which do not require stationary reference measurement locations such as direct-displacement measurements, can also be used to generate data for the displacement coefficients. Previously, the writers have shown how the displacement coefficients can be obtained from the modal flexibility using modal tests data. In this paper, the writers further discuss critical issues such as the spatial and temporal resolution requirements to determine the modal parameters, and the use of incomplete modal flexibility matrices for condition assessment when dynamic methods are applied on large structures.

5769-17, Session 3

Global structural condition assessment of highway bridges

M. Q. Feng, Y. Chen, Univ. of California/Irvine; C. Tan, Wayne State Univ.

Structural condition assessment of highway bridges has long been relying on visual inspection, which, however, involves subjective judgment of the inspector and detects only local flaws. Local flaws might not affect the global performance of the bridge. By instrumenting bridges with accelerometers and other sensors, one is enabled to monitor ambient or forced vibration of the bridge and assess its global structural condition. Ambient vibration measurement outwits forced vibration measurement in that it requires no special test arrangement, such as traffic control or a heavy shaker, so that it can be continuously executed while the bridge is under its normal serving condition. For short- to mid-span highway bridges, ambient vibration is predominantly due to traffic excitation, inducing the bridge to vibrate mainly in vertical direction. Based on its physical nature, traffic excitation is modeled in this study as moving loads from the passing vehicles whose arrivals and speeds are extracted from digital video. Traffic-induced vibration provides valuable information for assessing the super-structure health, but is less sensitive to possible seismic damage in the sub-structure. During earthquakes, bridges are excited in all directions by short-duration un-stationary ground motion, and are expected to better reveal their sub-structure integrity. Therefore, traffic-induced and ground-motion-induced ambient vibration data are treated separately in this paper for different assessment objectives, because of the different characteristics and measurability of the excitation. By continuously monitoring the ambient vibration of the instrumented bridge, its global structural condition of both super- and sub-structures can be evaluated with possible damage locations identified, which will aid local non-destructive evaluation or visual inspection to further localize and access the damage.

5769-18, Session 3

Acoustic emission monitoring of structural perturbations with serially multiplexed optical fiber sensors

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Development of a serially multiplexed fiber optic acoustic emission sensor is described. The sensor detects acoustic emission events in real time at two different points along the length of an optical fiber. The time domain waveform contains signals from both sensors, and a method is introduced for identification of the signals. Detection and identification of signals along a single data stream reduces the data acquisition rigor and provides for rapid real time detection of perturbation, i.e. damage, fracture and their locations in structural elements. The sensor consists of two optical fiber coils along an arbitrary length in a Michelson interferometer arrangement. The formulations involve the methodology for tagging of the time domain signals. The process leads to matching of the arrival times in the waveform to the individual coils along the length of the optical fiber. The waveform is detected at the Quadrature point for maximum sensitivity. A bias is created through differentiation and superposition of the waveform to accomplish signal identification. The experimental program involved proof of concept tests by way of damage location detection along the lengths of individual composite rods. Conventional PZT transducers were also employed for comparison of results.

5769-20, Session 4

Dynamic hyperspectral imaging

M. V. Murzina IV, J. P. Farrell, Brookhaven Technology Group, Inc.

Bad things often happen fast.

This means that we need to react fast. In this work, we develop the technology that allows one to identify and characterize fast events. In real time, we dynamically process hyperspectral information of a scene, specifically analyzing its temporal behavior. The goal is to detect fast and super-fast events like explosions, fast-moving objects and instant changes in chemical composition of the air and other materials.

Until recently, the enormous amounts of hyperspectral information confined us to static hyperspectral data processing. Hyperspectral techniques were used for finding certain objects, chemicals, or anomalies in a picture, frame by frame, statically. Dynamic (temporal) analysis was developed primarily for astrophysical applications performed a long time after the frames had been captured.

In this work, we take advantage of emerging hardware technologies that allow one to look at hyperspectral information dynamically: by characterizing temporal changes as they occur. We apply methods from astrophysics (supernova observations) and present our unique algorithms for contemporaneous dynamical analysis of hyperspectral data.

The first application addresses the question: have there been any sudden changes in the hyperspectral pattern of a scene? If there were sudden changes, were those changes related to a substantial energy release? These questions do not depend on assumptions about specific spectral patterns, chemical composition, or shapes : we look for any changes in a scene. Such dynamical analysis can therefore offer a unique opportunity to react promptly to fast events without prior knowledge about what was to occur.

The talk addresses the issues of dynamic hyperspectral imaging (based on Physics and Chemistry), algorithmic approaches to dynamic hyperspectral data processing and its hardware-implementation issues.

5769-21, Session 4

Hyperspectral characterization of adjustable nano-coating systems

M. V. Murzina IV, J. P. Farrell, O. A. Aksipetrov, T. V. Murzina, Brookhaven Technology Group, Inc.

Nano-coating with adjustable features is one of the most revolutionary technologies of today. In this work, we consider how adjustable nano-surfaces are seen by an external observer. In particular, how a hyper-spectral imaging device characterizes such nano-coatings. The “least adjustable” parts of the spectrum are discussed, and methods of utilizing this hyperspectral information for recognizing the nano-coated surfaces are explored. The research applies to both recognizing the camouflaged objects and to developing techniques of building unrecognizable camouflage objects.

5769-22, Session 4

Detection of gas leaks in the subsurface environment

M. Ghandehari, Polytechnic Univ.; G. Khalil, Univ. of Washington

A vast network of natural gas pipeline supply residential and industrial customers around the globe. Leaking valves, connections and distribution pipelines are significant sources of fugitive gas and volatile chemical emissions in chemical manufacturing, gas production, transmission, and oil refineries. A gas leak detection method has been developed based on continuous monitoring of the oxygen concentration surrounding a natural gas pipeline. The method utilizes optical fibers coated with an oxygen permeable polymeric film containing

a luminescent sensor molecule. When the specialty fiber is illuminated by a light source that excites the luminophor, the functional cladding compound has the ability to detect and quantify leaks by measuring small changes in oxygen concentrations in the surrounding environment. Key features of the technology include long-term performance based on well understood platinum porphyrin chemistry, in addition to the capability of distributed sensing using fiber optic evanescent field spectroscopy. Results of leak detection in various environments namely atmospheric conditions, dry sand as well as saturated sand is reported, along with test results on long term system performance.

5769-23, Session 4

SMART sensing solutions for homeland security

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The role of smart sensing is of paramount importance in the enabling technologies for homeland security. Emphasis had been placed over the years to adding intelligence to transportation structures and infrastructures so as to provide information on the surrounding environment in the event of a disaster caused by terrorist elements. This intelligence can be improved and integrated into structures through the use of Acellent's SMART Layer®. Over the last few years, Acellent has demonstrated in numerous applications the viability of having an integrated network of sensing elements incorporated with a variety of structures coming from the automobile, aerospace to pipeline.

Another area is the use of SMART Layer® in building infrastructures to determine the location of and magnitude of a crash or impact by a large object onto a building or bridge infrastructure. The sensors could at the same time be used to monitor the integrity of a structure after an impact and assess its structural integrity. This information would be valuable to the rescue workers during a disaster crisis. It would help, for instance, firefighters, provide a map showing the locations of impacted and damaged areas, which are either safe or dangerous. This can then be used to evaluate risks to rescue operations and also victims entrapped in a collapsed structure. The information could also be used by designers to shed light on the performance of their designs and offer information on structural weaknesses

5769-24, Session 4

A conceptual framework for intelligent monitoring systems: a response to terrorist attack or catastrophic accidents in critical infrastructure

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There are several hundred thousand miles of pipelines stretching across the US carrying essential fluids such as natural gas, chemical and petroleum products, and drinking water. Terrorist threats include, but not limited to, the forceful destruction of distribution system and introduction of foreign fluids to the system. These pipelines are not typically monitored against terrorist threats or catastrophic accidents. These threats can cause damage to pipelines and fluids delivered resulting in loss of product, contamination of fluids delivered, release of hazardous materials, and stoppage of essential fluid delivery. In addition, and more importantly, ensuing explosions and fires may cause collateral damage including loss of life and property. We propose the development of a comprehensive intelligent system with feedback capabilities to monitor critical pipelines. Proposed research is an extension of the scope of current research listed below and will enhance the activities of USEPA under the Presidential Executive Order 37347 issued in 1996 requesting the evaluation and upgrading Critical Infrastructure, especially the pipeline systems.

This monitoring system will consist of an array of sensing technologies including, but not limited to, pressure sensors, impact/acoustic sensors, and material thickness sensors based on resistance. The proposed monitoring system will complement existing control systems currently utilized by the pipeline owners. The information from these sensing devices will be relayed through a remotely controllable telemetry system based on wireless communication, which will be an active system, in that it will have the ability to independently excite the sensors. The system will continuously gather data from the sensors and identify unusual events for evaluation through intelligent software. The proposed software will be based upon pattern recognition algorithms that analyze combined signals from all sensors and compare their patterns to historical data. Once the system identifies an atypical event, it will send a feedback control initiated signal to the sensors to generate controlled responses, which will also be monitored to confirm the occurrence of the event and to rule out false alarms. The system will then alert the control room of the occurrence, report the location of the event and whether or not it has been a confirmed response, thus allowing the decision for immediate shut down if necessary.

Conference 5770: Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring

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5770-01, Session 1

Magnetoresistive sensors for nondestructive evaluation

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New high-sensitivity solid-state magnetoresistive (MR) sensor technologies offer significant advantages in nondestructive evaluation (NDE) systems. A key advantage of MR sensors is a flat frequency response extending from dc to hundreds of MHz, making them particularly attractive for low-frequency and multi-frequency eddy current detection for deep-flaw detection and depth profiling. Other advantages include small size permitting manufacture of arrays of sensors including on-chip arrays and the on-chip integration with standard IC components.

MR sensors are mass produced by thin film processing techniques similar to integrated circuit manufacturing, dramatically reducing the cost per sensor. The fabrication process is compatible with silicon circuit technology, allowing integration of sensors with on-chip signal processing. MR sensors can easily be produced in dense arrays for rapid, single-pass scanning of large areas. The small size and low power consumption of these solid-state magnetic sensors enable the fabrication of compact arrays of sensors on a variety of substrates as well as on-chip sensor arrays. Arrays have been fabricated with sensor spacing as small as 5 micrometers.

This paper presents a review of the state of the art in MR sensors and applications in NDE. The physical principles, manufacturing process, and performance characteristics of the three main types of MR devices, anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) are discussed. The characteristics of these MR devices is discussed, and their performance is compared to other magnetic sensor technologies for NDE applications. Finally, some NDE applications of MR sensors and arrays to crack and corrosion detection will be discussed.

5770-02, Session 1

Health monitoring using MWM®-Array and IDED-Array sensor networks

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This paper describes the use of MWM eddy current array sensor networks and IDED (Interdigitated Electrode Dielectrometer) dielectrometer array sensor networks as well as hybrid MWM-IDED sensor networks for monitoring of absolute electrical properties for the purposes of detecting and monitoring damage, usage and precursor states within an Adaptive Damage Tolerance (ADT) framework. We present specific results from MWM-Array fatigue monitoring demonstrations, temperature measurement and new IDED methods for age degradation monitoring. We also describe the use of such sensor networks as part of an ADT framework, for generation of real damage standards (e.g., real cracks without starter notches), and for prognostics model validation.

5770-03, Session 1

Transient magnetic flux leakage NDT technique for ferromagnetic materials inspection

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The MFL technique has shown excellent potentials for NDE detection of corrosion, fractures and fatigue-induced stress defects, for inspection of in-service oil and gas pipelines. It consists on magnetising the ferromagnetic specimen, typically pipeline walls, to near saturation. In many cases, if material anomalies or flaws exist along the path of the magnetic flux lines, a perturbation in the field distribution will be generated and results in flux being forced out of the sample. The profile of the generated MFL signal is closely related to the size and geometry of the detected defects. In order to separate and identify the types of the flaws involved, without recourse to calibration tests, analytical and FEM modelling are very useful methods for this purpose.

Most of the theoretical studies related to MFL techniques, are based on the static analytical simulation of dipolar magnetic charge (DMC) distributions. MFL signal simulations in terms of cracks, corrosion pits, and mechanically induced stress, have been studied both through finite element modelling, and analytical methods based on DMC approach.

The success of Pulsed Eddy Current (PEC) technique for inspection of deeply buried flaws in conductive materials, and the group's experience in this arena has inspired as to study the pulsed Magnetic Flux Leakage (MFL) in application for NDT of ferromagnetic materials such as iron and magnetic steel. Therefore, this paper introduces the application of the MFL by using pulsed excitation currents instead of static or AC signals. The advantage of this technique over the DC mode includes less energy dissipation, and better localisation of hidden flaws from the signal's time domain features. Pulsed excitation also implies a better field penetration capability than single frequency signals, due to its wide band characteristic. Therefore, the time and spatial domains characteristics of transient signals allow better localisation of buried defects while assuring in-depth readability of buried flaws properties.

Transient FEM simulations based on time stepping approach will be investigated against different material defects, in both time and spatial domains. A newly refined pulsed MFL 3D analytical model, based on the DMC approach and Laplace transform, will be also presented. This model could predict transient MFL signals due to different emulated flaws shapes and cross-section, by appropriately modifying the DMC distribution. Different types of flaws will be investigated using this analytical model. The simulation results of magnetic flux leakage spatial distributions will be compared with the experimental MFL profiles. A calibration of MFL signals vs. various flaws types in term of aspect ratios (width/depth) formulation will be given, and the corresponding charts will be determined from the introduced analytical paradigm. Thereby, an inverse evaluation of the defects sizes will be directly predicted from the established charts.

5770-04, Session 1

Radar sensor for monitoring the injection moulding processes

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A compact and high integrated radar sensor working in the millimeterwave range can be applied for monitoring the injection moulding processes with and without gas assistance. The millimeterwaves are introduced into the cavity by a hollow waveguide and by a window transparent to millimeterwaves. In the frame of injection moulding experiments the process has been recorded simultaneously optically and by radar signal data. When the melted plastics or the gas bubble are passing over the position of the sensor window the signal of the sensor is abruptly changing both with regard to amplitude and phase thus indicating if the process is running correctly or not. The experimental investigations have been complemented by simulation calculations.

5770-05, Session 2

Using magnetoresistive sensors for a sensitivity quantum leap in aircraft nondestructive evaluation (NDE)

R. D. Rempt, Boeing Phantom Works

Magnetoresistive sensors offer a significant increase in sensitivity for inspection of subsurface features and flaws in metallic aicraft structure. This is especially true for deeper inspections with depths between 10 and 20 mm below the accessible surface. I show C-scan images of deep flaws, with dimensions down to one-tenth of the thickness of the covering metal. Issues involved in developing and operating an imaging scanner using these sensors are discussed.

5770-06, Session 2

Hollow shaft integrated health monitoring system for railroad wheels

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The economic efficiency and competitiveness of environment-friendly rail transportation depends on safety, availability and maintenance of single highly loaded structure components. Until now these components have been replaced in fixed maintenance intervals irrespective of any usage related conditions. With

the knowledge and evaluation of the component conditions, life cycle costs can be reduced by means of optimized maintenance and/or "fit for purpose" design. For example, rail-bound vehicle wheel sets are among the most highly stressed traveling gear components of the bogie. If such a component fails, a serious accident may occur.

For this reason, a health monitoring system based on the interpretation of ultrasonic sound signatures has been developed. First, the ultrasonic waves generated by an artificial defect on the outer wheel tread of a railroad wheel towards an acoustical sensor, placed inside the hollow shaft of the railroad axis, were simulated with EFIT (Elastodynamic Finite Integration Technique). The results achieved proved that relevant signals can be found in a frequency range up to 300 kHz. Based on this a diagnostic unit was designed and built for application under rotation conditions, which consists of a piezo-electric sensor, primary electronics (filters, preamplifiers), an analog-to-digital converter, a digital signal processor, a trigger unit, and a telemetric transmitter. This diagnostic unit was integrated in the hollow shaft of a railroad wheel axis. This railroad wheel is part of the special laboratory test rig which was established at Fraunhofer IZFP to test the diagnostic unit.

Algorithms which allow for the rotation-synchronized processing of acoustical signals were implemented into the rotating diagnostic unit. After successfully completing a test campaign for this unit inside the laboratory test rig, a second test was performed inside the wheel/railroad simulation test rig of the Deutsche Bahn AG under railroad-like conditions.

The data generated inside the hollow shaft of the railroad wheel axis by the diagnostic unit were telemetrically transmitted to an industrial computer. The detection of artificial defects of different sizes will be shown in correlation with theoretical assumptions.

5770-07, Session 2

Development of acoustic health monitoring for railroad tank cars

R. Finlayson, V. Godinez, R. Gostautas, Jr., A. Pollock, Physical Acoustics Corp.; J. Pena, Federal Railroad Association

This paper presents the research and development of an Acoustic Health Monitoring (AHM) program that uses new Guided Lamb Wave (GLW) technology to determine the thickness of railroad tank car shells, for identification of wall loss due to corrosion.

Traditionally, tank car inspection and recertification are performed at fixed time intervals, the interval being mandated according to the car type and commodity involved. This would be an excellent approach if the operating conditions were the same for all tank cars of the same type carrying the same commodity. In reality however, the rate of deterioration is very variable due to variations in utilization, handling, service loadings and even geographical factors (e.g. coastal environments, temperature and humidity environments). Structural deterioration contributes to the accidental releases of hazardous material from tank cars that are reported each year, resulting sometimes in injuries and always in economic loss. In recent regulatory changes, the emphasis has shifted from the traditional hydrotest to more modern methods for assuring tank car integrity. The new generation of maintenance programs will rely heavily on nondestructive testing, and will use damage tolerance concepts and risk analysis to establish inspection frequencies and items to inspect. Instead of following prescriptive cover-all regulations, owners are to set up experience-based maintenance programs that are suitable for the working conditions of their own particular fleets.

An ideal Acoustic Health Monitoring (AHM) system for railroad cars would be an instrument that incorporates Acoustic Emission (AE) and Guided Lamb Wave (GLW) technology. The combination of active and passive acoustic technologies integrated into a single system would be a highly efficient means of determining the structural integrity of a tank. The passive AE method monitors the tank shell and associated load-bearing structure, during pressurizations and jacking, twist and lift tests, to detect weld flaws and fatigue cracks and local corrosion. Active methods, such as acousto-ultrasonics (AU) in the form of GLW technology, allow identification of wall loss and calculation of average thicknesses, along paths between pairs of sensors.

The integration of new GLW technology with current-generation AE instrumentation can assist in improving the economy of fleet management. The GLW system will identify corrosion wall loss in a zone between two sensors, rather than at a single point as is done with current ultrasonic thickness gauging techniques. Thus, a much larger area of the structure can be inspected for approximately the same inspection cost. By inspecting a greater area in this way, the risk of missing major corrosion can be reduced. With a suitable integration of this new technology into the overall inspection and corrosion management program, the fleet can be more efficiently maintained and the risk of accidental release through progressive corrosion damage can be significantly reduced.

5770-08, Session 2

Characterization of sensor performance and durability for structural health monitoring systems

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A key question that needs to be addressed and answered with regard to successfully implementing Structural Health Monitoring technologies in Air Force systems involves the long-term operability, durability, and survivability of integrated sensor systems and their associated hardware. Whether a sensor system is fully integrated within a structural material, or surface-bonded to the structure, a number of environmental and system level influences will tend to degrade the sensor system's performance and durability over time. In this activity, an initial sensor durability study was undertaken to better understand the performance and degradation of piezo wafer active sensor (PWAS) systems under adverse mechanical, temperature, and moisture conditions. A novel displacement-field imaging approach was utilized to understand the vibration characteristics of PWAS transducers placed in accelerated vibration, temperature-cycling, and moisture-cycling conditions. The results showed damage in the form of PWAS sensor cracking events, bond degradation and failure, as well as indications of performance variation and reduction due to the accelerated exposure levels. Future activities will focus on identifying critical durability and survivability issues through advanced sensor modeling and additional accelerated testing efforts, with the ultimate goal of improving the robustness of health monitoring systems through improved sensor system design and packaging.

5770-09, Session 2

The use of embedded sensors for the monitoring of adhesive joints in marine environments

S. T. McGovern, G. M. Spinks, G. G. Wallace, Univ. of Wollongong (Australia)

Polyaniline emeraldine salt (PAn ES) has been well documented to show conductivity increases with water ingress. Miniature humidity sensors were constructed using a blend of Polyaniline (PAn) and Poly(butyl acrylate -co- vinyl acetate) (poly BuA/VAc) copolymer as a sensing medium. Aniline monomer was polymerised in the presence of poly BuA/VAc and camphor sulphonic acid. A portion of the PAn emeraldine salt residue was de-doped to the emeraldine base (EB) form by washing with a dilute ammonia solution. Two processable polymer blends were then developed by separately redissolving 1-2 w/w% of the PAn ES and PAn EB residue in dichloromethane.

The final sensor design utilised 125μm polyester insulated platinum wire as conducting electrodes that were first dip coated in the PAn ES solution, dried and then dip coated in the PAn EB solution as a protective barrier layer. The sensors had an overall final thickness of less than 150μm and showed high sensitivity to humidity, low resistance, and good reversibility without hysteresis.

These sensors were embedded in Aluminium 5083 Araldite 2015 adhesive joints joined in a lap-shear configuration for the monitoring of salt water ingress during service. Both static and fatigue loads were applied separately to adhesive joints and joint strengths at failure were monitored and correlated against salt water ingress. Conclusions on the effect of salt water ingress on joint strength have been made.

5770-10, Session 3

Smart coatings for health monitoring and nondestructive evaluation

T. J. Bencic, NASA Glenn Research Ctr.; J. I. Eldridge, NASA Glenn Research Ctr

The use of luminescent coatings has been increasing dramatically over the last decade as imaging capacities have increased. These coatings have been used to monitor surface temperature, air pressure and strain in testing facilities around the world. Through the commercial suppliers of these coatings, custom assembled hardware systems and especially data reduction and analysis software, the use of smart luminescent coatings are starting to find their way in to inspection monitoring and nondestructive evaluation testing. The use of a temperature sensitive paint for example, can be a potential replacement for

infrared imaging where changing emissivity and multiple materials are involved. Detection of the luminescent signal can use simple intensity ratio methods to synchronized pulsing systems to capture frequency responses in imaging applications. Time or frequency methods allow signals to be detected in the presence of high background noise that allow measurements that were previously unobtainable.

This paper will describe detection methods and examples of coatings that are applied over test examples or embedded in materials to measure or monitor the health of a specimen. The sensors include but not limited to, phosphors for high temperature and extreme environments, oxygen sensors for measuring air pressure and strain sensitive coatings.

5770-11, Session 3

Materials investigations of gallium arsenide for direct converting energy sensitive x-ray detectors

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For the last decade a tremendous development in the field of imaging radiation detectors has taken place. Conventional X-ray film has been replaced by digital X-ray imaging systems in a number of ways. Such systems mainly consist of silicon charge coupled devices (CCDs). Incident photons create electron-hole pairs in the thin silicon absorption layer near to the surface of the device. In contrast to visible light, which is absorbed within a 2 μm layer of silicon, the penetration of X-ray is much deeper due to higher photon energy. This disadvantage is often circumvented by the use of a scintillator as absorption layer. Due to scattering of the low energy fluorescence photons, resolution and contrast of the X-ray image decrease. In order to eliminate these disadvantages hybrid detectors consisting of a direct converting semiconductor part and a readout electronics part are fabricated.

For this configuration, it is advantageous that both parts can be optimized separately and different materials can be used. Because of the well developed technology the readout chip is fabricated out of silicon. As absorbing material silicon is less suited. In a silicon substrate of 500 μm thickness only 15% of a 30 keV radiation is absorbed and converted into charges. In order to increase the absorption, materials with a higher atomic mass have to be used. Several compound semiconductors can be used for this purpose. One of them is GaAs, which is available as high quality semi-insulating wafer material.

For detector optimization, GaAs wafers from several manufacturers with different properties were investigated. Test structures with Schottky and PIN diodes were fabricated. The I/V curves of the diodes, the spectral response from 5 up to 150 keV, the carrier concentration, and the carrier mobility were measured and compared. A survey of the results and the criteria for material selection resulting from these measurements will be given in the full paper.

5770-12, Session 4

Structural damage assessment of propulsion system components by impedance based health monitoring

R. E. Martin, Cleveland State Univ. and NASA Glenn Research Ctr.; J. T. Sawicki, Cleveland State Univ.; A. L. Gyekneyesi, NASA Glenn Research Ctr. and Ohio Aerospace Institute; G. Y. Baaklini, NASA Glenn Research Ctr.

Critical components of propulsion systems frequently operate at high stress levels for long periods of time. The integrity of these parts must be proven by non-destructive evaluation (NDE) during various manufacturing steps and also during the systematic overhaul inspections. Conventional NDE methods, however, have unacceptable limits. Some of these techniques are time-consuming and inconvenient for service aircraft testing. Impedance-based structural-health-monitoring (SHM) uses piezoelectric (PZT) patches that are bonded onto or embedded in a structure; each individual patch both actuates the surrounding structural area and senses the resulting structural response. The size of the excited area varies with the geometry and material composition of the structure. A series of experiments on simple geometry specimens (thin-gage aluminum square plates) was conducted for assessing the potential of E/M impedance method for structural damage detection. Based on the generated results it can be concluded that the E/M impedance method has the potential to be used for damage detection of structures. The experimental method, signal processing, and damage detection algorithm should be tuned to the specific method used for structural interrogation.

5770-13, Session 4

Air-coupled ultrasonic NDE of automotive tires

B. R. Tittmann, J. Du, I. Lucas, The Pennsylvania State Univ.

Tires usually consist of rubber and reinforced metal wires. Understanding the elastic properties of the rubber material and evaluating the bond condition between the rubber and wires are important. In our work, rubber material properties were first studied. A sample set consisting of generic elastomeric compounds was analyzed using non-destructive air-coupled ultrasonic techniques. The longitudinal sound wave velocities in the sample and wave amplitude attenuation in the sample were measured using the Second Wave Inc. Non-Contact Analyzer 1000 (NCA1000). The results show that polymer type of rubber and the loading level of carbon black fillers in rubber can cause attenuation difference, this suggests the potential of amplitude attenuation measurement for the rubber properties evaluation. Then samples cut from used good and failed tires are imaged with the ultrasonic C-Scan technique. The tire attenuation images show that the attenuation of good and failed tires are almost the same, which means the rubber material is not the reason for the failure. However, rubber/wire interface images show that the interface disbonds caused the failure of the tire.

5770-14, Session 4

Non-uniformity correction and dynamic range extension for acoustography

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Acoustography is a full-field ultrasonic imaging process where a high resolution 2D Acousto-Optic (AO) sensor is employed to directly convert the ultrasound into a visual image in real time. This study shows initial results of a methodology developed to correct for image non-uniformity and extend the dynamic range of acoustography images. Unprocessed acoustography images typically suffer from non-uniformity due to non-linearity of the (AO) sensor field, non-uniformity of the sound source, and / or the lighting conditions. Additionally, dynamic range is limited due to the sinusoidal nature of the brightness versus time response of the acousto-optic sensor. The nonuniformity and dynamic range limitation can result in difficulty in acoustography image interpretation and impracticality for large field application. The approach of this study is to apply algorithms to obtain characteristic voltage versus time curves of pixels of the acousto-optic sensor so that corrections to the pixels can be employed after sample inspection. The algorithms also effectively “unwrap” the sinusoidal response of the AO sensor to extend the dynamic range of the acoustography method. Images scaled in terms of dB loss are recorded. The ultimate vision for this project, once characteristic curves are recorded prior to sample inspection, is to perform corrections in near real-time so that the end user obtains a more uniform and dynamic range-extended live image.

5770-15, Session 4

Advancement of wave generation and signal transmission in wire waveguides for structural health monitoring applications

M. Kropf, M. Pedrick, G. Facco, B. R. Tittmann, The Pennsylvania State Univ.

As per the recent advances in remote in situ monitoring of industrial equipment using long wire waveguides (~10m), novel applications of existing wave generation techniques and new acoustic modeling software have been used to advance waveguide technology. The amount of attainable information from an acoustic signal in such a system is limited by transmission through the waveguide along with frequency content of the generated waves. Magnetostricitve, Piezoelectric, and Electromagnetic generation techniques were investigated in order to maximize acoustic transmission along the waveguide and broaden the range of usable frequencies. Commercial EMAT, Magnetostrictive and piezoelectric disc transducers (through the innovative use of an acoustic horn) were utilized to generate waves in the wire waveguide. Insertion loss, frequency bandwidth and frequency range were examined for each technique. Both piezoelectric and electromagnetic techniques allow for higher frequency wave generation. This increased accessibility of dispersion curves provides further versatility in the selection of guided wave modes, thus increasing the sensitivity to physical characteristics of the specimen. Both electromagnetic and magnetostrictive transducers require the use of a ferromagnetic waveguide, typically coupled to a steel wire when considering long transmission lines (\>2m). The interface between these wires introduces an acoustic transmission loss. Coupling designs were examined with acoustic finite element software (Coupled-

Acoustic Piezoelectric Analysis). Simulations along with experimental results aided in the design of a novel joint which minimizes transmission loss. These advances result in the increased capability of remote sensing using wire waveguides.

5770-16, Session 4

Acoustic emission (AE) health monitoring of diaphragm type couplings using neural network analysis

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This paper presents the latest results obtained from Acoustic Emission (AE) monitoring and detection of cracks and/or damage in diaphragm couplings, which are used in some aircraft and engine drive systems.

Early detection of mechanical failure in aircraft drive train components is a key safety and economic issue in both sectors of aviation, military and civil. One of these components is the diaphragm-type coupling, which has been evaluated as the ideal drive coupling for many applications that include requirements such as high speed, high torque, and no lubrication. Its flexible axial and angular displacement capabilities have made it indispensable for aircraft drive systems. However, diaphragm-type couplings may develop cracks during their operation. The ability to monitor, detect, identify, and isolate coupling cracks on an operational aircraft system is required in order to provide sufficient advance warning to preclude catastrophic failure. The monitoring methodology discussed in this paper is based on using Acoustic Emission (AE) for crack detection using neural network analysis, and is intended to provide suitable advance warning to indicate the presence of cracks and to preclude catastrophic failure.

It is known that metallic structures generate characteristic Acoustic Emission (AE) during crack growth/propagation cycles. The AE generated by this crack growth can be detected using externally mounted piezoelectric sensors. This phenomenon makes AE very attractive among various monitoring techniques for fault detection in diaphragm-type couplings. However, commercially available systems that are capable of automatically discriminating between signals from crack growth and normal mechanical noise are not readily available. In most cases, positive classification of signals requires experienced personnel and post-test data analysis, which tend to be a time-consuming, laborious, and expensive process. The solution is to use automated classification methods. With further development of automated classifiers AE can become a fully autonomous fault detection technique requiring no human intervention after implementation. AE has the potential to be fully integrated with automated query and response mechanisms for system/process monitoring and control. In this paper we will discuss the details of this approach and results obtained from testing of diaphragm couplings installed in a full-scale test frame.

5770-17, Session 5

Sensor modules for structural health monitoring and reliability of components

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Safety and availability of ageing infrastructure require the periodic or continuous monitoring of the structure integrity.

New design criteria for new components might allow reducing material and energy consumption if the components are continuously monitored by advanced sensor systems. This concept for periodic Structural Health Monitoring will replace a significant part of conventional NDE in state-of-the-art maintenance concepts.

The desire are sensor networks based on advanced principles of testing physics with integrated signal and data processing and data communication. NDE modeling is required for quantification of the measurement results. Finally the decision about the integrity of the structure based on sensor results requires detailed knowledge about the material behavior as well as modeling capacity for materials and components.

The IZFP has developed sensor concepts for complex solutions of Structural Health Monitoring for different applications. These applications include railroad inspection, aircraft inspection, the inspection of wind energy systems, power electric switches, and micro gas valves.

The basic concepts and applications of the sensor networks will be presented.

5770-18, Session 5

Microsystem for signal processing applications

B. Frankenstein, K. Froehlich, D. Hentschel, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); G. Reppe, RHe Microsystems (Germany)

Acoustic monitoring of technological processes requires methods that eliminate noise as much as possible. To achieve this goal, sensor near evaluation of the signals can contribute substantially. Frequently, the necessity exists to integrate the measuring technique into the structure which has to be monitored.

The solution contains components for analog preprocessing of acoustic signals, their digitization, algorithms for data reduction, and digital communication. The core component is a digital signal processor (DSP).

Digital signal processors can perform the basis algorithms necessary for filtering, down sampling, FFT computation and correlation of spectral components particularly effective.

Therefore, a compact signal processing structure has to be realized as sensor-near as possible, which integrates both analog electronics and a DSP with peripheral components. For the standardized development of components for microsystem engineering, the German Association for Mechanical and Plant Engineering (VDMA) has specified the Match-X standard. It refers to micro-technical modules, which can be combined to application specific systems.

The solution is based on AL‹sub\›2‹/sub\›O‹sub\›3‹/sub\› ceramic components which include different signal processing modules. One of them includes a 12 Bit, 16.5 MSamples/s ADC and a 1MWord memory. It runs with 150MHz clock frequency. A second module supplies power on the basis of a standard 24V voltage source. Beside the signal processor module an arbitrary waveform generator with 128kWords waveform memory, 14Bit DAC and an output frequency of 20MHz has been developed. This waveform generator is combined with a power amplifier for piezoelectric transducers in a special module.

Another module interfaces piezoelectric sensors. It contains a multi-channel preamplifier, some highpass and lowpass filters for analog signal processing and an ADC-Driver. A bluetooth communication chip for wireless data transmission and a disc on chip module with a capacity of 128Mbytes are under construction.

As a first application, the combustion behavior of safety-relevant contactor is monitored. A special waveform up to 5MHz is produced and sent to the monitored object. The resulting signal form is evaluated. With special signal processing algorithms significant parameters of the signal are extracted and transmitted via CAN-bus.

5770-19, Session 5

Nanoscale deformation measurements for reliability analysis of sensors

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With ongoing miniaturization from micro electronic mechanical systems (MEMS) towards nano electronic mechanical systems (NEMS), there is a need for new reliability concepts making use of meso-type (micro to nano) or fully nanomechanical approaches. For the development of theoretical descriptions and their numerical implementation on the basis of simulation tools experimental verification will be of major interest. Therefore, there is a need for measurement techniques with capabilities of determination and evaluation of strain fields with very local (nanoscale) resolution.

Following this challenge the authors developed the nanoDAC method (nano Deformation Analysis by Correlation) which enables the extraction of nanoscale displacement fields from scanning probe microscopy (SPM) images. The tested components are thermomechanically loaded under the SPM and images are taken at specific load states. The obtained images are analyzed by digital image correlation resulting into full-field displacement and strain fields. The method was successfully applied for the extraction of fracture mechanical properties of micro materials.

In combination with finite element simulations the application of the described experimental method to sensor elements is a promising approach for reliability analysis of newly designed sensor architectures. Examples will be presented at the conference.

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5770-20, Session 5

Smart measurement transducer and information technologies through task of NDE for HMAD

G. A. Abramchuk, K. Abramchuk, Measurements & Metrologies (Canada)

A class of problems of nondestructive evaluation (NDE) for health monitoring and diagnostics based on understanding of functional peculiarities of information transform in measuring channel and tied with complicated functioning structure or mechanical system is examined. For such solutions when an measurement equation can be changed in result of relationship between a distributed parameter measuring process (DPMP) and a measuring transducer (MT) in conditions when mechanical system or structure functions chaotically, and as a result of the structure differential nonlinearly changing like a time function problem is uncovered. What does a correlation or a "weight" in functional transform measurement channel's components like a functional transform "DPMP – MT", an adaptive transformation "MT- Information Processing", and an information processing algorithmisation change in time domain? It is shown, that a changing of dynamic component of measurement equation leads to appearance of dependence ε = ψ (t), where ε – a "momentary" dynamic error of transformation, and t- time, which requires of new principles of information processing or a changing of known principles for problem of control. A redistribution of correlation between the functional transformation "process-MT" and "MT- Information Processing" is described on the example of NDE for health monitoring and diagnostic procedures. What would technologies of the diagnostics be used in the system for optimal control? An extracted information about some process may be essentially different in dependence from: the measuring method, a dynamics of structure and processes, a signal and information processing methods, and their interaction. Investigators already begin to process of information by a measuring transducer till an information become basis for signal-information analysis. And they do not suspect it. Information processing may include as a transformation in time-frequency domain as joint time-frequency transforms, and spacious transforms of signals and information or special transforms. Feather usage of information processing technique cannot be effective without an understanding feature of transformation of measuring information in system "Distributed parameter measuring process – measuring transducer", where MT can be by a measuring transformer with distributive parameters. Frequently, this problem remains without a proper attention. The measurement/registration method of developing dynamics of abnormal processes in the structure or its elements is described. A completely integrated solution to an object for life and/or health condition monitoring is written. A multi-parameter process-solving approach to detecting and diagnosing of the dynamics of object's troubles using information about acoustic and vibration processes in structure is presented as an example. An anomaly detection scheme for examined structure is written. How does a "momentary" component of dynamic error change? What must an algorithm practice be used in order to increase a reliabless and permitting possibility of measurement technique. Measurement Technique permits: to realize "equal in strength" measurements in large loading rates; to distinguish vibrations, other comparatively quickly proceeding processes; to extract of optimal information about anomalies with different combination between components of process; to increase of failure resolution of structure elements to create active measurement procedures with new functional capabilities. Problem of acoustic and vibration measurement channel is analyzed. It is a general aim to be tied with growing in time of variations of informative flow in considered structure or mechanic system. It is shown how a measurement technique makes it possible to receive optimal information about anomalies or damages for different levels of correlation between components of dynamic process. The ways of optimization of information about anomalies of mechanical system or structure are determined. What must a measurement technique be to satisfy main demands in described problem? What can we do and how to distinguish and evaluate such deflection into a function of structure that this information was enough (for making decision)? What should we do and how in order to distinguish anomalies or a damage in a functioning structure from different results reflecting the origin and the development of future troubles? (We need to see things as in case when a structure functions normally as if). What does aims allow reaching of optimal results? These and other attendant problems are analyzed in this paper.

5770-21, Session 5

Calibration of GPS for dynamic displacement measurement of long span cable-supported bridges in vertical direction

W. Chan, Y. Xu, X. Ding, Y. Xiong, W. Dai, The Hong Kong Polytechnic Univ. (Hong Kong China)

For a long span cable-supported bridge, its structural displacement is a key element to assess its safety condition. Accelerometers and displacement transducers are two commonly-used sensors for the measurement of long span bridge displacement. The major drawback of the two sensors is that they are unable to measure the static deflection of the bridge which is an important component of the structural displacement of the bridge under wind. Therefore, Global Positioning System (GPS) has recently become an important tool for monitoring both static and dynamic displacement responses of long span cable-supported bridges. Typical examples include Akashi Kaikyo Bridge in Japan, Humber Bridge in England, and Tsing Ma Bridge in Hong Kong. However, the error in GPS-based position measurement in the vertical direction is often larger than that in the horizontal direction by a factor of 2 to 3, but under strong wind the vertical vibration of a long span bridge is more important than the lateral vibration. Therefore, this study focuses on the assessment of dynamic displacement measurement accuracy of GPS in the vertical direction and the evaluation of the performance of GPS in both static and dynamic displacement measurement in the vertical direction using a newly-developed motion simulation table.

The motion simulation table developed can simulate various types of motion of a long span cable-supported bridge deck in the vertical direction with a frequency range from 0.025 Hz to 2 Hz and an amplitude range from 2 mm to 40 mm. With a function of manual home position, the table can start any dynamic motions in the pre-defined static position. Total displacement generated by the table can thus be used as a test bed to assess the performance of the GPS whose rover station is installed on the table. This is an important step to understand the accuracy of GPS in both static and dynamic displacement measurements of a long span cable-supported bridge deck.

In order to identify the best performance of GPS (two Leica GX1230 GPS receivers with a sampling rate of 20 Hz), an open area in Hong Kong was selected to carry out a series of calibration tests. The static tests with stationary antennae were first performed to assess the background noise of the GPS. The dynamic tests were then carried out to assess the amplitude and frequency sensitivities of the GPS in the vertical direction using sinusoidal waves. A band-pass filtering scheme was then applied to these dynamic data recorded by the GPS. The static and dynamic displacement measurement accuracy of the GPS in vertical direction was finally assessed using complex signals including white noise random wave with frequencies range from 0.025 Hz to 1.8 Hz and wind-induced bridge deck motions measured from Tsing Ma Bridge during Typhoon Victor. It was found that the multipath disturbance has a certain correlation in both static and dynamic displacement responses measured. An adaptive filtering scheme using the Recursive Least Squares (RLS) algorithm was then applied to the GPS data to enhance the accuracy of the measured bridge response in the vertical direction.

5770-22, Session 6

Real-time nondestructive structural health monitoring using support vector machines and wavelets

A. Bulut, A. K. Singh, Univ. of California/Santa Barbara; P. Shin, T. Fountain, H. Jasso, San Diego Supercomputer Ctr.; L. Yan, A. Elgamal, Univ. of California/San Diego

In this paper, we present an alternative to visual inspection for detecting damage to civil infrastructure. We describe a real-time decision support system for nondestructive health monitoring. The system is instrumented by an integrated network of wireless sensors mounted on civil infrastructures such as bridges, highways, and commercial and industrial facilities. To address scalability and power consumption issues related to sensor networks, we propose a three-tier system that uses wavelets to adaptively reduce the streaming data spatially and temporally. At the sensor level, measurement data is temporally compressed before being sent upstream to intermediate communication nodes. There, correlated data from multiple sensors is combined and sent to the operation center for further reduction and interpretation. At each level, the compression ratio can be adaptively changed via wavelets. This multi-resolution approach is useful in optimizing total resources in the system. At the operation center, Support Vector Machines (SVMs) are used to detect the location of potential damage from the reduced data. We demonstrate that the SVM is a robust classifier in the presence of noise and that wavelet-based compression gracefully

degrades its classification accuracy. We validate the effectiveness of our approach using a finite element model of the Humboldt Bay Bridge. We envision that our approach will prove novel and useful in the design of scalable nondestructive health monitoring systems.

5770-24, Session 6

Tunable infrared filter based on elastic polymer springs

W. Zhang, Univ. of California/Irvine; M. Almasri, Georgia Institute of Technology; A. Kine, J. LaRue, R. D. Nelson, Univ. of California/Irvine

This paper describes the design, fabrication and testing of tunable fabry-perot filters. The goal of this research is to develop novel tunable filter that will be used in infrared gas sensors. This exploits the fact that most gases have unique infrared absorption signatures in the 2-14 um wavelength region. The filter consists of two thin silicon wafers coated with thin dielectric layers and separated by an air gap with a height of 3 um and 6 um. The mirrors are supported by four elastic polymer posts with an area of 100x100 um2 made by using homemade photodefinable elastomer springs. An electrostatic voltage is used to compress the springs, change the air gap height and hence shift the transmission peaks to a shorter wavelength. A finesse of 12 with full width at half maximum (FWHM) of 70 nm and a peak transmission of 63 % were achieved by applying a voltage of 80 volt on the 125 um thick devices with 6 um posts height. In addition, the measured tunability before and after hard baking the devices were 210 nm and 120 nm, respectively. The tunability stayed constant after hard baking the devices and did not show any changes with time. The tunability was also measured on a thinner silicon mirror with 3 um posts height. In this case, the filter was tuned 200 nm by a voltage less than 20 volt. However, the filter finesse was 3, transmission peak was 40% and FWHM over 200 nm. A new mask set was designed and fabricated to build the filter with 3-segment electrodes and anti-reflection coating to correct the slight difference in the posts heights and to enhance the transmission peaks respectively. Due to reproducibility problem and oxygen poisoning effect during patterning the posts, thermally-cured elastomer replaced the photodefinable one. A cavity filling deposition method was used to apply the material and post dimensions were under good control.

5770-25, Session 6

Optical fiber gas sensor for remote detection of CH_4 gas in underground mines

S. Li, Z. Yin, H. Cui, Stevens Institute of Technology

Methane, as one of the major components of the natural gas, is an inflammable and explosive gas. Due to this intrinsic property, its measurements and monitoring are safety major issues in plants, mines, and residential areas. Furthermore, methane detection is critical for environmental monitoring, because the accumulation of CH_4 causes the temperature rise in the atmosphere.

Fiber based optical spectroscopy technology with frequency modulation of laser diode had been applied in the gas sensor development and significantly improved the sensitivity of the detection system. Comparing with the conventional ionization and electrochemical gas sensors, the advantages of fiber sensors include their remote detection capability, high sensitivity and safety in hazardous environment, long term reliability and immunity to electromagnetic field.

This paper will demonstrate a particular optical-fiber-based gas sensor for the CH_4 gas real-time monitoring in the mining complexes and residential area. A long-distance silica fiber link with compact open single-path or multi-path gas cells has been employed in conjunction with a wavelength-tunable InGaAsP DFB laser diode at 1.64μm (at the R(6) absorption peak of methane) to achieve highly sensitive remote interrogation of CH_4 in the mining complexes.

It is well known that the absorption spectra of CH_4 molecules cover the mid-infrared (3-μm) region and near-infrared region (1.33-μm and 1.66-μm). Though we found that the absorption of CH_4 in mid-infrared region is even stronger than that in the near-infrared region, we choose the wavelength of 1.64 μm in our remote gas monitoring system for its easy implementation with the low-loss commercial communication optical fibers. Furthermore, it was found that the 1.66-μm band of CH_4 absorption is more suitable for the extremely low-loss optical-fiber-based remote sensing, since the absorption coefficients are larger and the spectral widths are broader than those in the 1.33-μm band, whilst there is no disturbance of water absorption in this band which will definitely enhance the sensitivity of the gas sensor system.

To deal with the particularly challenging environment of underground mines, which are full of dust and water vapor, a special optical sensor cell is designed to satisfy the real-time detection under the rough condition without the contamination of the optical component inside the cell which will significantly reduce the sensitivity of the system. By wavelength modulation with the DFB laser diode, multi-path gas cell and a synchronous detection technique, sensitivities down to less than 1% of lower explosive limit (LEL) had been achieved in the laboratory and the preliminary field test data will be collected and demonstrated in this paper.

In addition, while a single-cell system has a higher cost comparing with the conventional catalytic-based sensor, a multiplexed array of low-cost fiber sensors with multiple-point distribution sharing the same DFB laser diode and signal processing system is scheduled and discussed which will greatly reduce the cost the entire sensor system. On the other hand, this system can also monitor several gas species simultaneously by incorporating several laser sources.

Because of the distinct characteristics and performance, the distributed optical-fiber-based CH_4 sensor system will have promising potential in large area low-level gas real-time health monitoring and detection application.

5770-26, Session 6

Development of tube-packaged FBG strain sensor and application in the vibration experiment of submarine pipeline model

L. Ren, Dalian Univ. of Technology (China); H. Li, Dalian Univ.of Technology (China); S. Li, D. Li, Dalian Univ. of Technology (China)

Abstract: Optical fiber sensors have received increasing attention in the fields of aeronautic and civil engineering for their superior ability of explosion proof, immunity to electromagnetic interference and high accuracy, especially fitting for measurement applications in harsh environment. In this paper, a novel FBG (fiber Bragg grating) strain sensor, which was packaged in a 1.2mm stainless steel tube by epoxy resin, was developed. The relationship between the strains measured by an FBG strain sensor and the actual structural strains is deduced, then the average strain transfer rate computed by the formulation developed in this paper is compared with available experimental data. Experiments were conducted on the universal material testing machine to calibrate its strain transferring characteristics. The strain measurements by the packaged FBG strain sensor developed in our laboratory agree with the analytical results. The sensor has the advantages of small size, high precision and flexible use, and demonstrates promising potentials. Ten of tube-packaged strain FBG sensors were applied in the vibration experiment of submarine pipeline model. The strain measured by FBG sensor agrees well with the electric resistance strain sensor.

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Elsewhere $30 USD for 1st item; $15 USD each addl item [1 week delivery]

SUBTOTAL

$_____

Method of Payment

☐ **Check enclosed.**
Payment in U.S. dollars (by draft on a U.S. bank or international money order) is required.
Do not send currency. Wire transfers from banks must include a copy of the transfer order.

TOTAL

$_____

☐ **Charge to my:** ☐ VISA ☐ MasterCard ☐ Discover ☐ American Express ☐ Diners Club

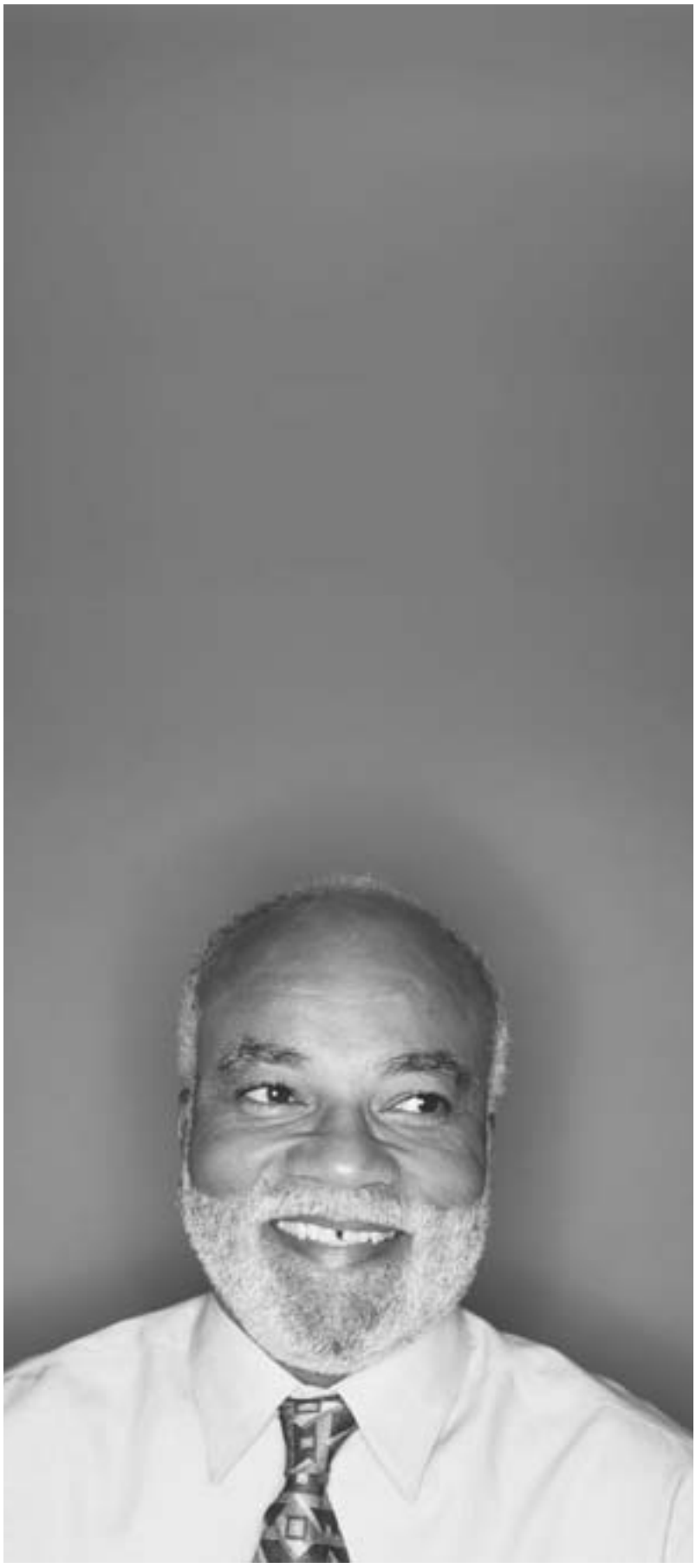
Card Number _____

Expiration date _____

Signature _____

☐ **Purchase order enclosed** *(Purchase orders must be preapproved).*

All orders must be PREPAID in U.S. dollars. Prices subject to change without notice. No returns without written authorization of SPIE. **ITEMS WILL NOT BE SHIPPED UNLESS PAYMENT IS RECEIVED.**



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