Sensor Modalities for Structural Health Monitoring

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The First Engineering Institute Workshop:
Energy Harvesting

Outline

- Sensing role in structural health monitoring (SHM) process

- Primary sensing approaches
    - conventional accelerometers
    - conventional strain gages
    - fiber optic systems (strain and acceleration)
    - piezoelectric patches (strain, impedance, actuation)

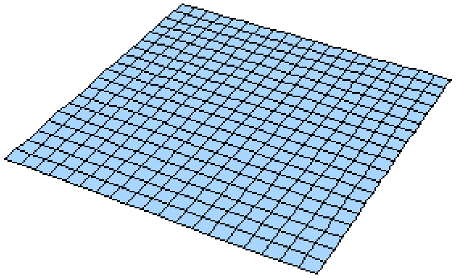
- Some current trends in sensing

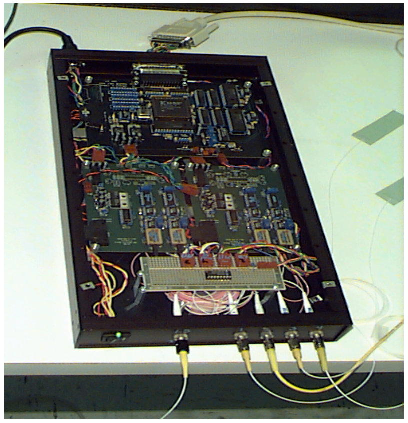
- Primary overall approaches to data interrogation for SHM
    - modal analysis, ‘linear’ time series analysis
    - state space methods
    - impedance method
    - guided waves

- Needs/requirements/challenges in energy harvesting for SHM

Structural Health Monitoring Process

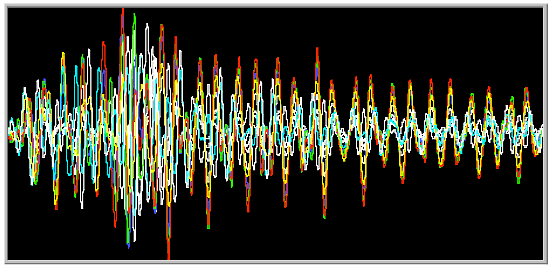
structural
response to
excitation



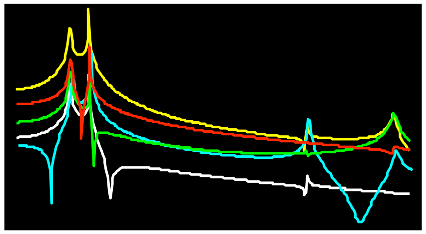


sensing system

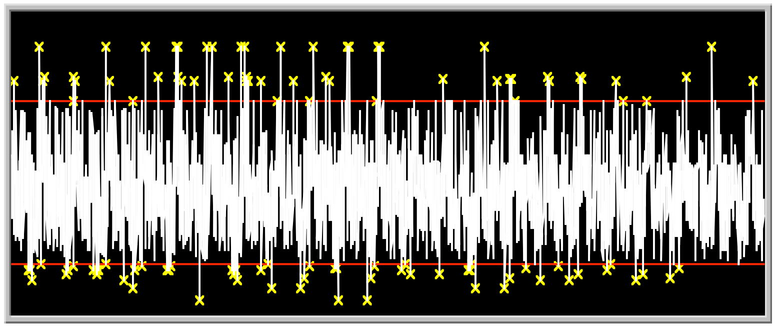
measured
time series

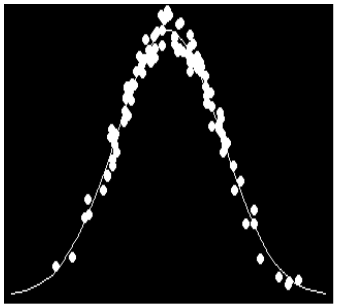


feature extraction

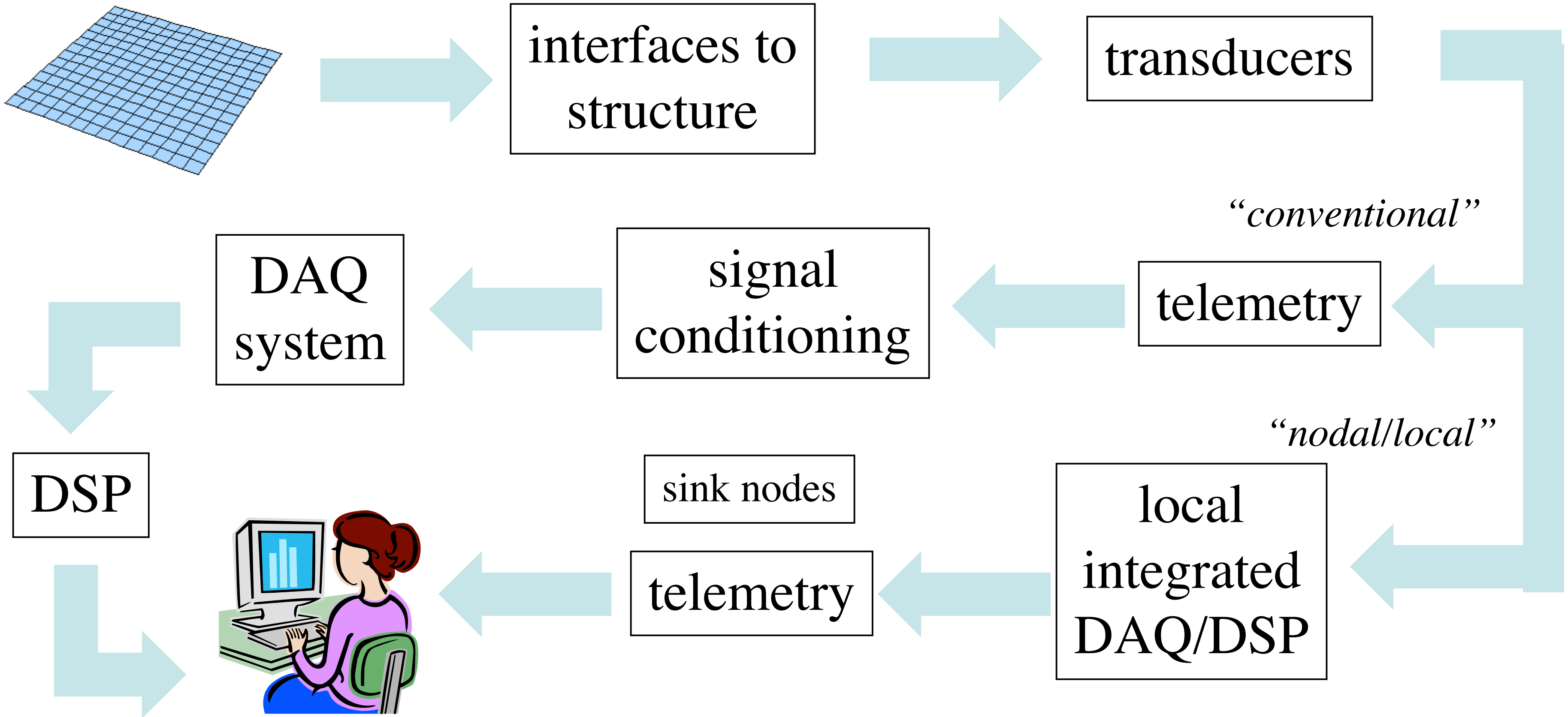


statistical
modeling





The Process of Getting and Processing Measurements



interfaces to structure

transducers

"conventional"

telemetry

signal conditioning

DAQ system

DSP

"nodal/local"

local integrated DAQ/DSP

telemetry

sink nodes

- All elements in this diagram usually have a power requirement
- In 'nodal' configurations, where sensing and data interrogation (SDI) are increasingly fused with localization, power management is key
- This presentation will consider primary SHM SDI methods

Sensor System Modalities

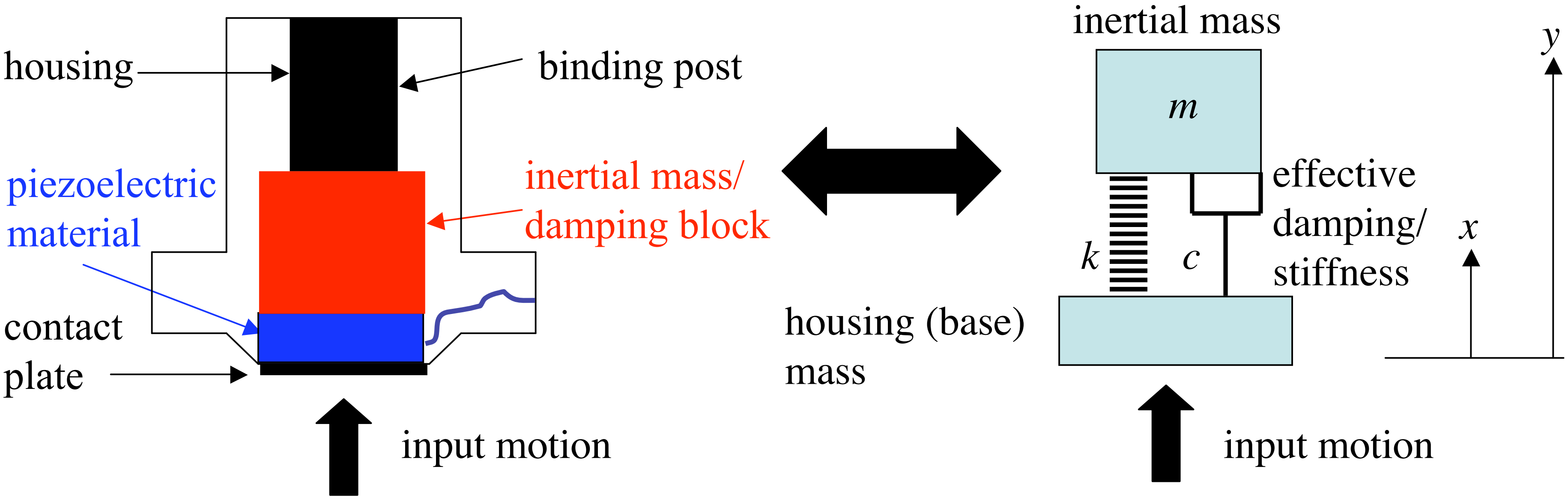
SHM starts with the sensing system; the **most common** measurements made for SHM applications are:

- acceleration (piezoelectric, piezoceramic, fiber optic accelerometers)
- strain (resistive foil, fiber optic, piezoelectric patches)
- impedance (piezoelectric patches)

In addition, we must distinguish between *active sensing*, where measurements are combined with local or global excitation of the structure through actuation, and *passive sensing*, where the measurements alone (usually a response to ambient conditions) are made

A large number of specific sensor and sensor network configurations exist for each of these modalities, resulting in a wide range of power requirements for the systems (mW to several W)

Conventional Accelerometers



- the piezoelectric crystal produces a charge under a change in mechanical loading (inertial coupling of rigid base motion to mass)

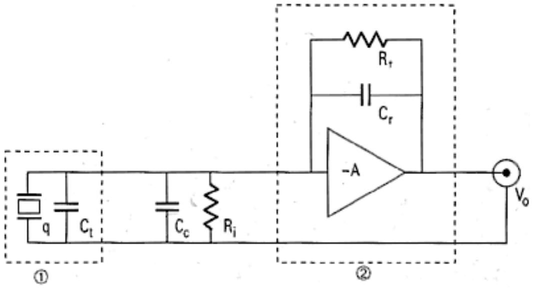
- two general types
    - high □: require external charge amplifier or impedance converter
    - low □: require built-in charge-to-voltage converter and an external power supply for electronics energization and remove DC biases

Single-Channel Conventional Accelerometer System

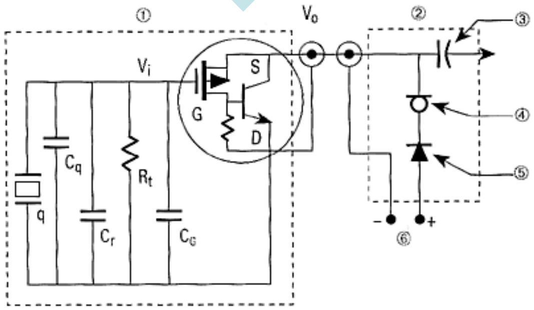
high impedance

individual transducer

low impedance



external charge amplifier



internal charge-to-voltage converter

power supply

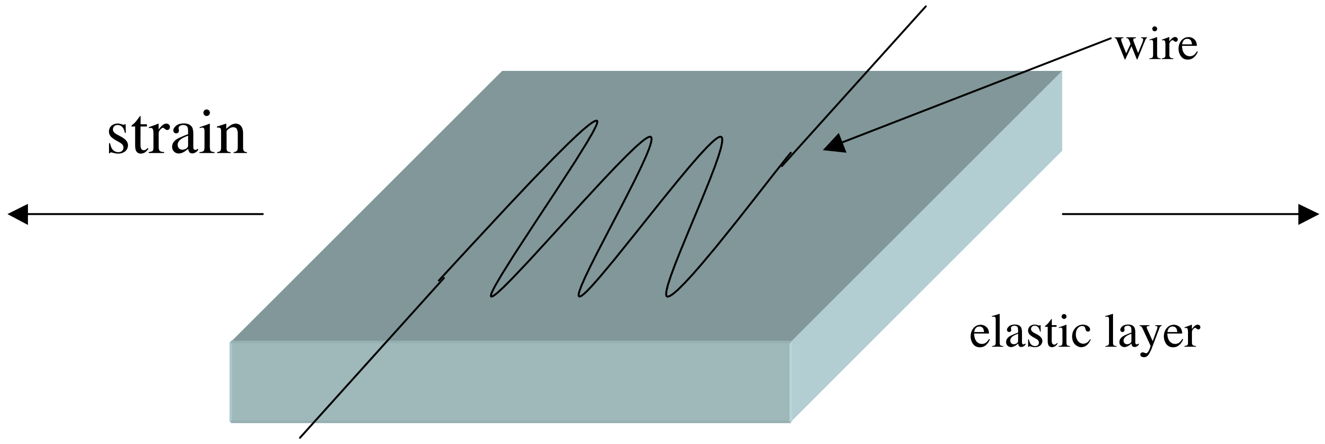
bias decoupling

multiplexer, conditioner, A/D

coaxial cable

coaxial cable

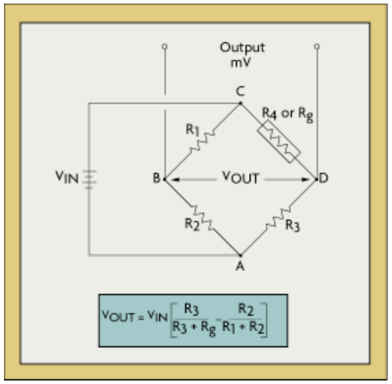
Conventional Strain Gages



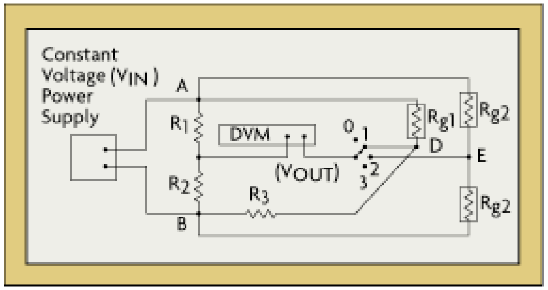
- a uniform, conductive wire is bonded to an elastic substrate
- the elastic substrate is then attached, with adhesive, to the structure of interest
- as the structure (and the elastic substrate, so thus the wire) displaces, the change in length and area of the wire causes a resistivity change
- a simple DC voltage may be applied across the wire to effectively measure the change in resistivity

Single-Channel Conventional Strain Gage System

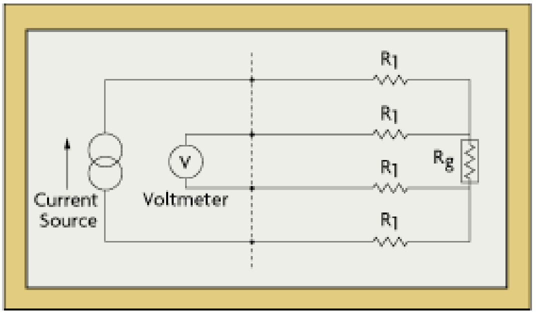
typical foil gage



Wheatstone bridge



Chevron bridge



4-wire Ohm circuit

four wire leads
(per channel)

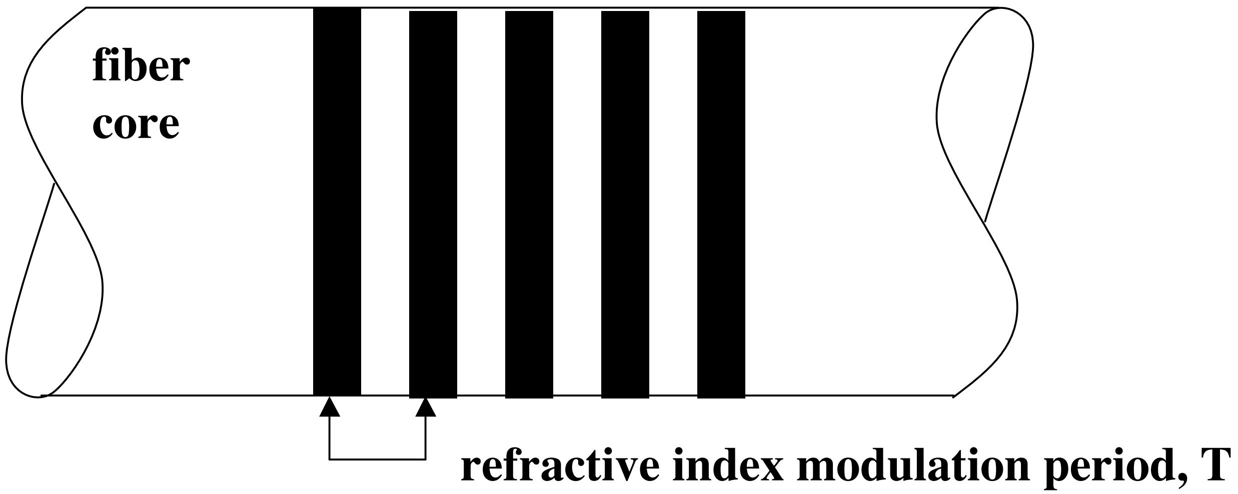
multiplexer, conditioner, A/D,
temperature compensation

power supply

Multiple element circuits used to extract tiny voltage (resistance) changes due to strain (mV/V)

Fiber Optic Sensing: Bragg Grating

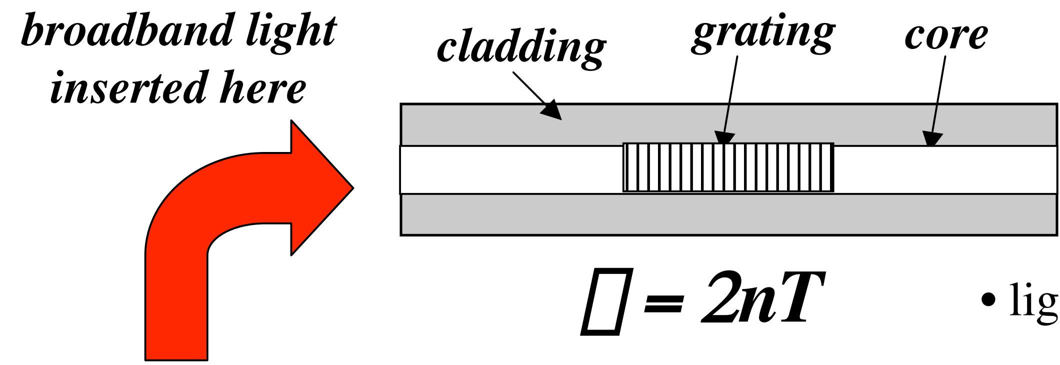
- A fiber Bragg grating is region of periodic refractive index perturbation inscribed in the core of an optical fiber such that it diffracts the propagating optical signal at specific wavelengths.



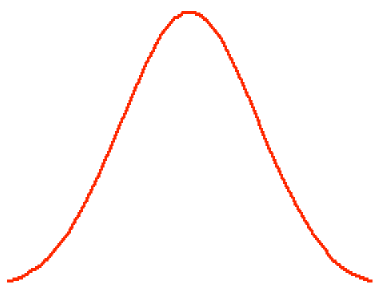
- Each time the forward-propagating light encounters a stripe (index mismatch), some is scattered (diffracted)

- Scattered light accrues in certain directions if a phase-matching condition is satisfied: in particular, at the resonant wavelength given by $\lambda_r=2nT$, light is reflected backward in phase with previous back-reflections such that a strong reflection mode at wavelength λ_r is generated

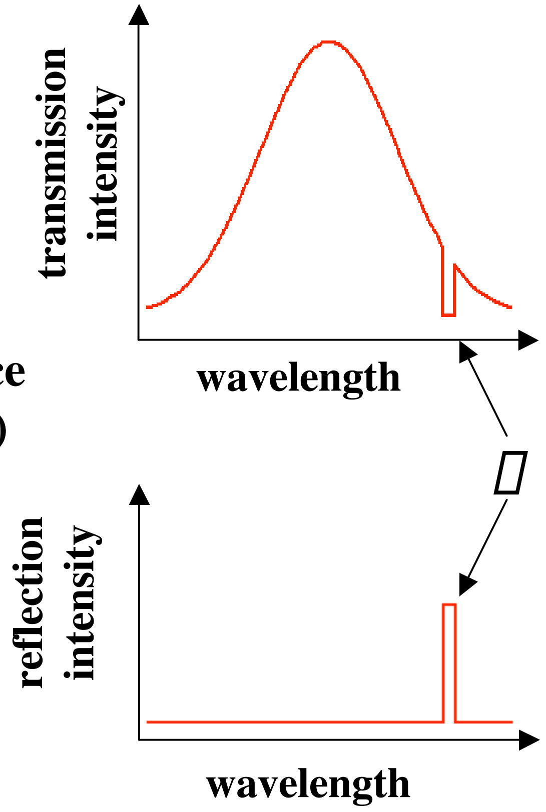
Bragg Gratings Act as Optical Notch Filters



$$\lambda = 2nT$$

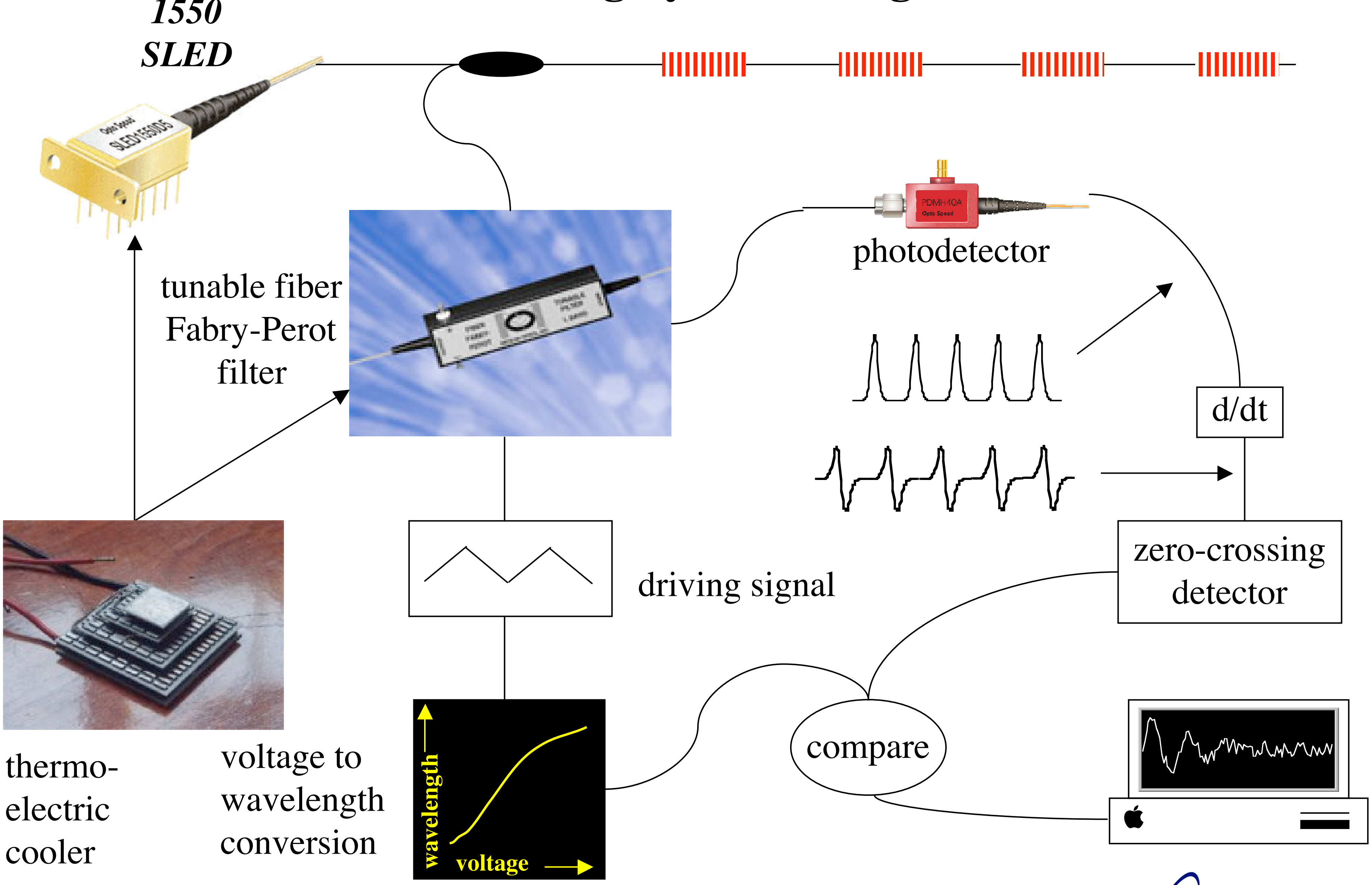


typical LED source spectrum (input)



- light at wavelength λ is reflected
- FWHM of the reflection peak is typically 0.1-0.3 nm
- if the fiber is locally stretched or compressed, T changes, meaning λ changes
- gratings may be multiplexed in the wavelength domain by initially writing each grating to reflect at a unique wavelength
- sensor system must track individual wavelength shifts

Multi-Channel Grating System Using Tunable Filters



1550
SLED

tunable fiber
Fabry-Perot
filter

photodetector

d/dt

driving signal

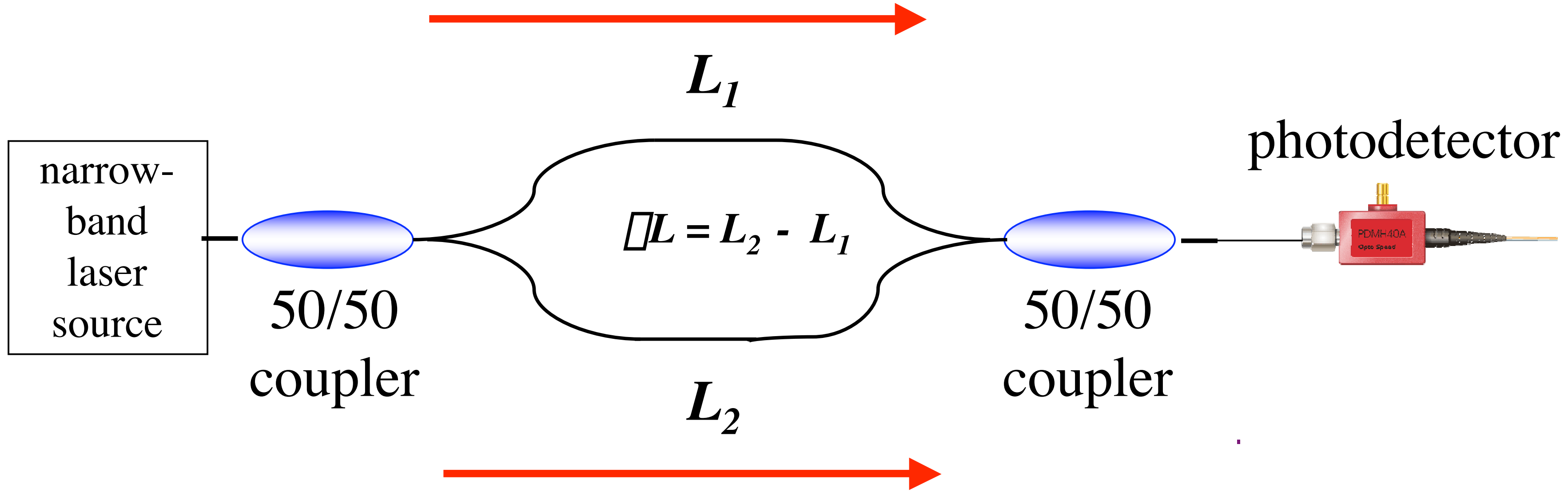
zero-crossing
detector

thermo-
electric
cooler

voltage to
wavelength
conversion

compare

Fiber Optic Sensing: Interferometry



L_1

narrow-band laser source

50/50 coupler

$\Delta L = L_2 - L_1$

50/50 coupler

photodetector

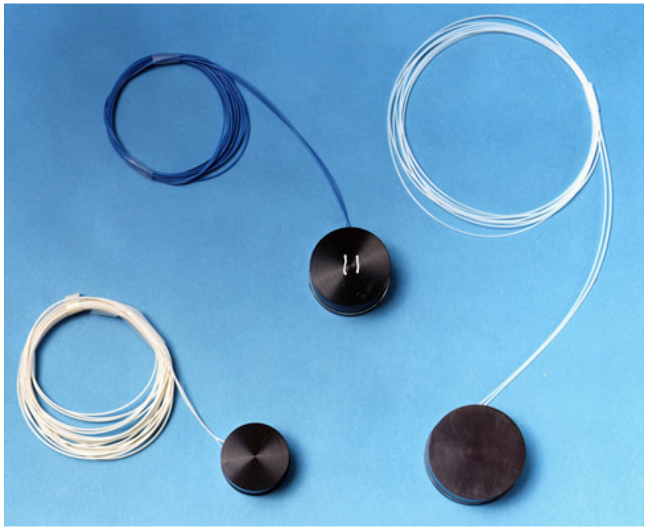
L_2

$$\Delta\phi = \frac{2\pi n \Delta L}{\lambda}$$

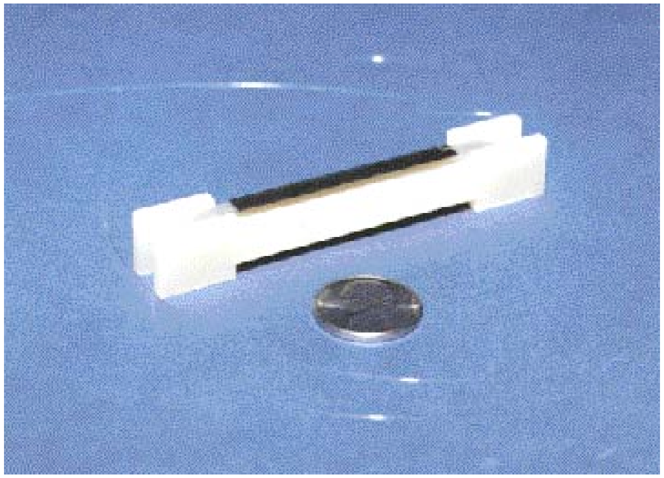
← Changes in pathlength of the light get converted to phase shifts by the interferometer when measured with a square-law detector

Fiber Optic Transducers

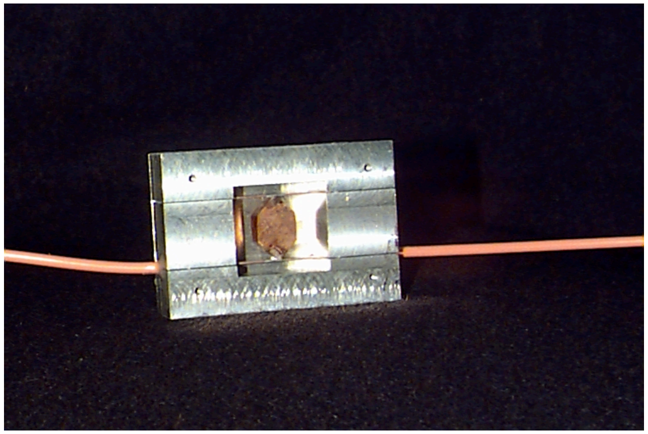
Fiber interferometers and Bragg gratings may be coupled with mechanical transducers to detect other measurands besides strain:



interferometric accelerometers



interferometric magnetic field sensor

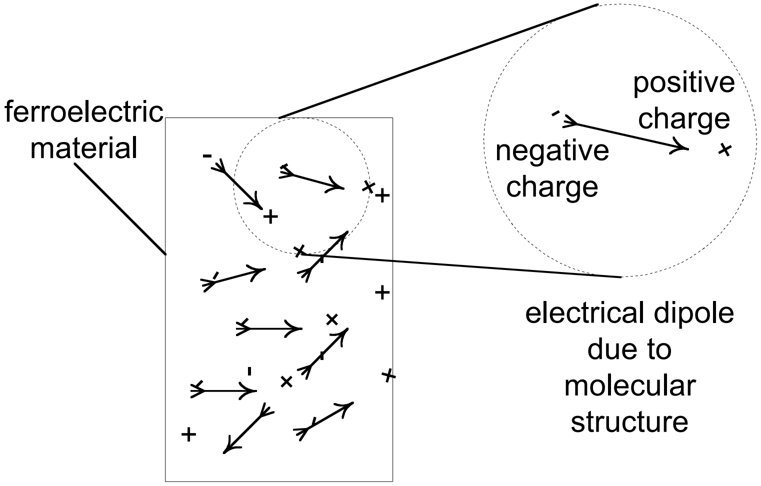


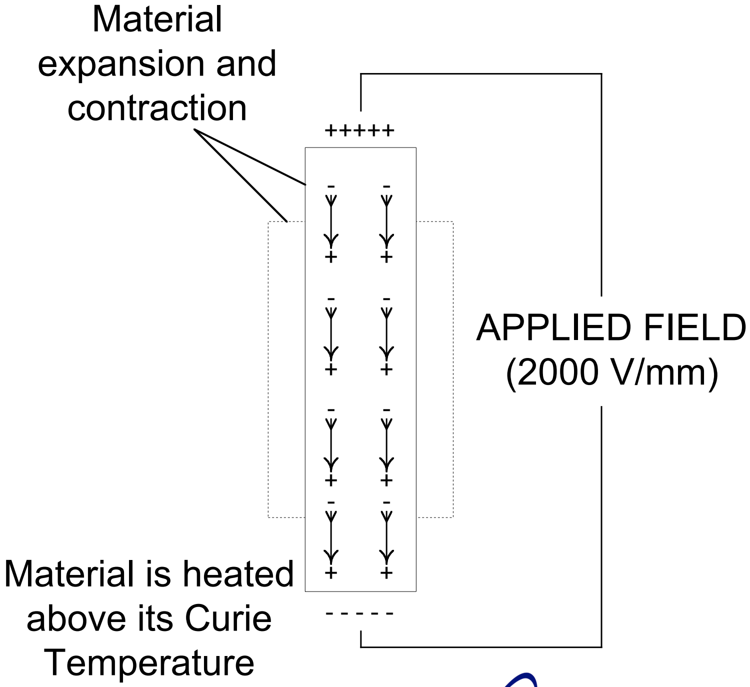
Bragg grating accelerometer

biological agent detection sensor

Piezoelectric Devices

- Materials produce a voltage when mechanically strained (direct effect).
- These materials also deform when a voltage is applied to them (converse effect).
- This effect is practically linear as the electric field and the mechanical strain are proportional.

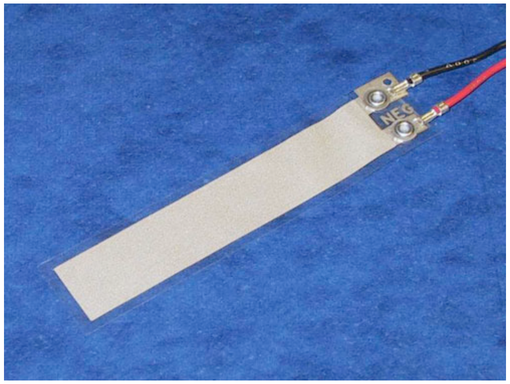




Piezoelectric Devices

- Comes in both ceramics and polymers
- Natural fix for SHM applications → Capabilities in both sensing and actuation
- Higher operating frequency (> 30 kHz)
- Local excitation requires relatively low power
- Can also be used as a power generation source

www.piezo.com



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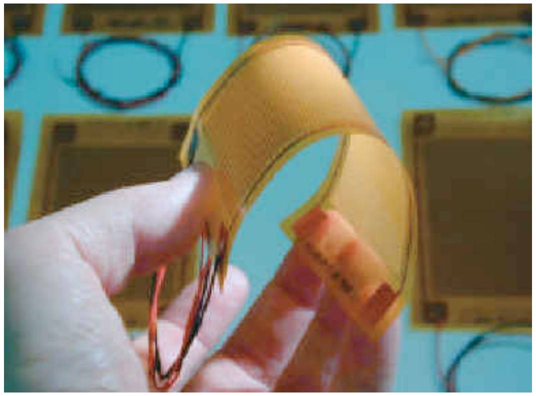


NASA Langley

Some Current Trends in Sensing

- SMALLER, SMALLER, SMALLER, SMALLER

✓ Microelectromechanical systems (MEMs) have been and continue to be developed to measure fields such as force, acceleration, and strain
✓ These sensors work on same principles mentioned, just on much smaller scale
✓ The challenges are in engineering parts to required tolerances at these scales (and dealing with significant static electricity build-up problems due to Coulomb interactions)

- Ride the light (with apologies to Qwest, Inc.)

✓ Utilizing fiber optics for various sensing applications began in the 1970s and exploded in the 1990s during the telecom boom
✓ Fiber optic accelerometers and force gages still have to utilize seismic design principles
✓ Electronics more complex and generally more power-demanding than conventional sensors
✓ Huge performance gains in many applications due to electromagnetic insensitivity

- Think globally, act locally (taking a cue from environmentalists' 1960s bumper stickers)

  ✓ Distribute data interrogation procedures at a sensor or nodal level, rather than at a global 'centralized' level
  ✓ Power requirements generally smaller, more manageable
  ✓ More adaptable and reconfigurable

Integrating Sensing and Data Interrogation for SHM

- Miniaturization, networking advances, and improvements in wireless telemetry and embedded computing architectures are stimulating the integration of sensing and local data interrogation

- It is increasingly important to consider local computing power requirements as well as sensing power requirements when budgeting a sensor system for SHM

- In the next few slides, we will summarize some of the PRIMARY methods of data interrogation being used to process measurements for SHM-related information
    - linear signal processing (modal analysis, ARMA, FRF, etc.)
    - state space methods
    - impedance method
    - guided wave methods

Time Series Linear Processing Methods

1. Make discrete measurements of vibration response

input (ambient
or applied)
$\mathbf{u}(t)$

state
response
$\mathbf{x}(t)$

sensor
network

$x_1(\mathrm{n})$
$x_2(\mathrm{n})$

2. Compute features from measured time series or frequency domain transformations thereof and compare metrics computed on under baseline conditions to test conditions

Auto/cross correlation:

$$R_{ij}(\tau) = E\left[x_i(n)x_j(n+\tau)\right]$$

Autoregressive/moving average models:

$$x_i(n) = \sum_{m=n-1}^{n-M} a_i x_i(m) + \sum_{m=n-1}^{n-M} b_i u(m)$$

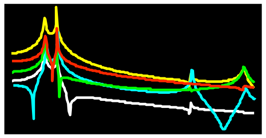
Frequency response:

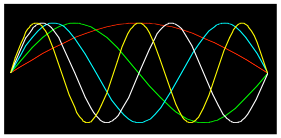
$$H_j(\omega) = \frac{G_{x_j x_j}}{G_{uu}}$$

Transmissibility:

$$T_{ij}(\omega) = \frac{G_{x_j x_j}}{G_{x_i x_i}}$$

Modal parameters:

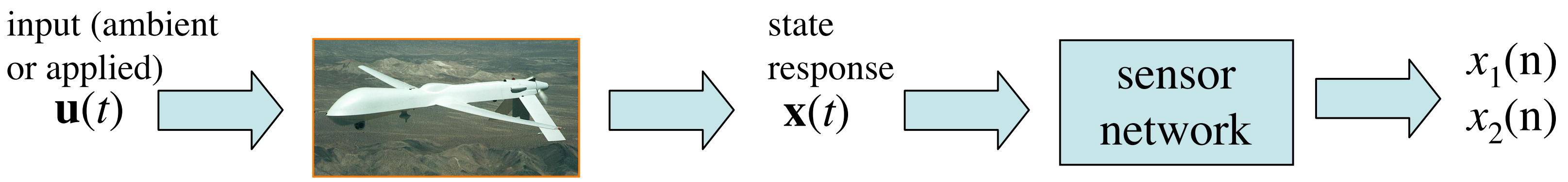




DSP computations fairly inexpensive (well-established linear techniques)

State Space Methods

1. Make discrete measurements of vibration response



input (ambient or applied) $\mathbf{u}(t)$

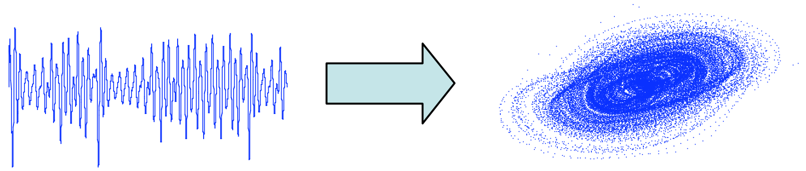
state response $\mathbf{x}(t)$

sensor network

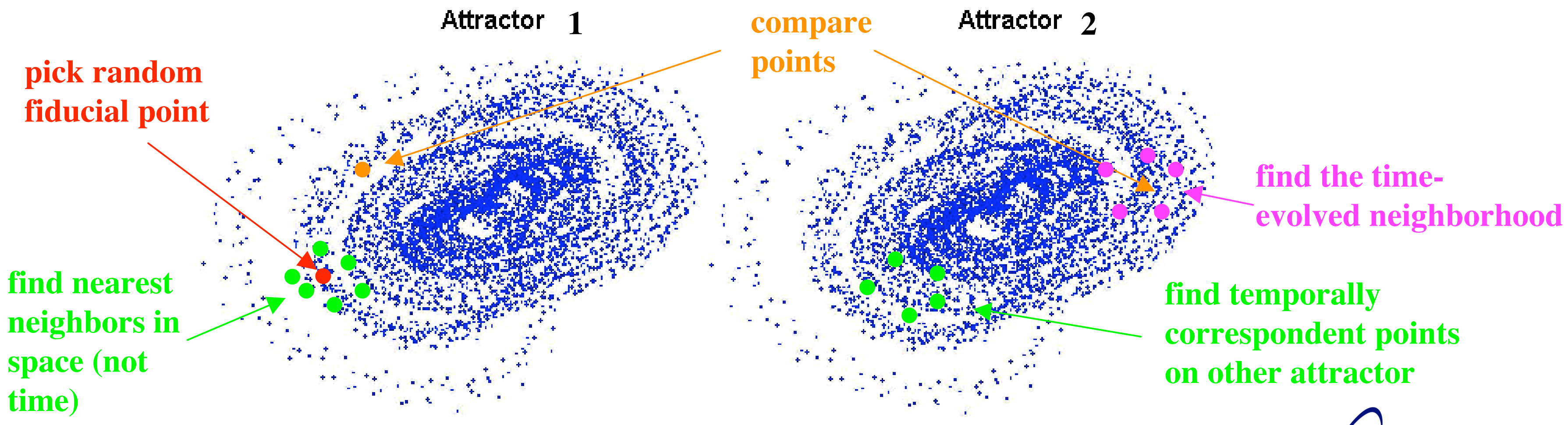
$x_1(\mathrm{n})$
$x_2(\mathrm{n})$

2. Reconstruct state space using embedding theorem prescriptions

$$y_1(n) = [x_1(n), x_1(n+D), \ldots, x_1(n+(d-1)D)]$$
$$y_2(n) = [x_2(n), x_2(n+D), \ldots, x_2(n+(d-1)D)]$$



3. Compute various metrics from state space representations and compare baseline to test



Attractor 1

compare points

Attractor 2

pick random fiducial point

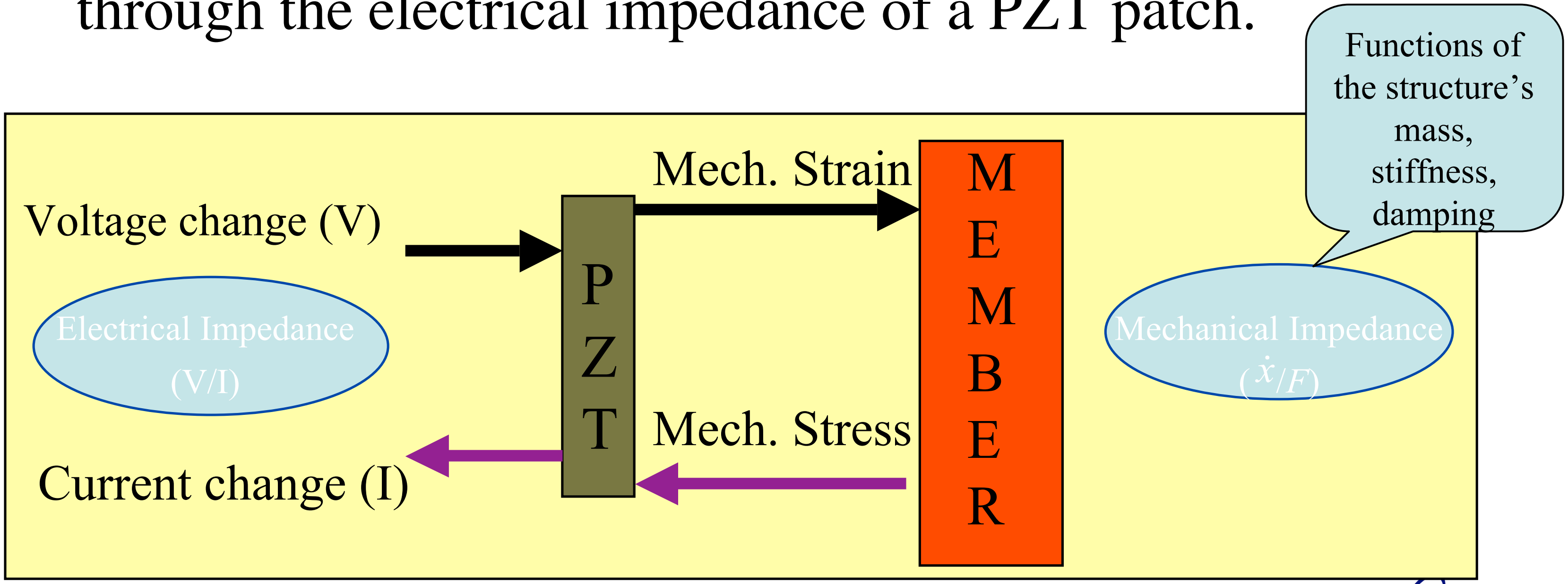
find nearest neighbors in space (not time)

find the time-evolved neighborhood

find temporally correspondent points on other attractor

Impedance Method

- Piezoelectric (PZT) patches are used to couple the electrical impedance and mechanical impedance of structures.
- The mechanical impedance of a structure is a function of the structure's mass, stiffness, and damping.
- Therefore, if any of these quantities changes, it can be seen through the electrical impedance of a PZT patch.



Voltage change (V)

Electrical Impedance (V/I)

Current change (I)

PZT

Mech. Strain

Mech. Stress

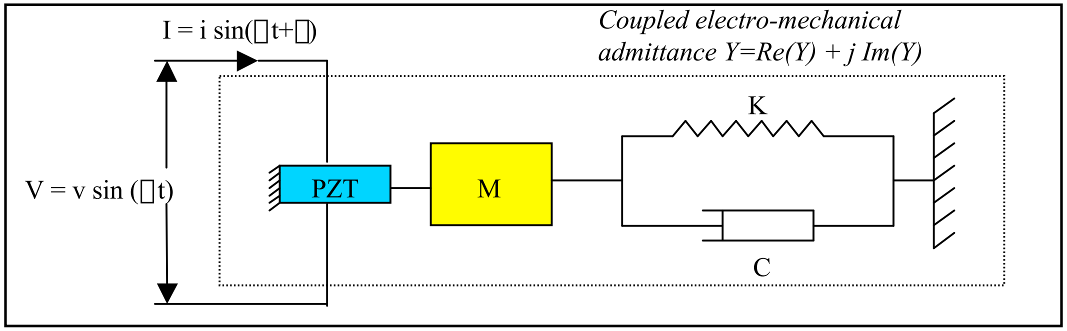
MEMBER

Mechanical Impedance $(\dot{x}/F)$

Functions of the structure's mass, stiffness, damping

Impedance Method

- Excite structures with PZT and measure mechanical impedance changes (>30 kHz)

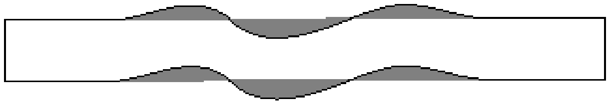


  - Qualitative approach to damage detection
  - Uses small PZTs as co-located actuators and sensors
  - Detect incipient structural fault, such as cracks or loosening of bolts
  - Can be remotely controlled, and then, automated
  - Localized sensing area. Unaffected by changes in boundary conditions, loading, or operational variations
  - Low excitation forces + high frequencies produce “low” power requirements (<10 mW)
  - Sensors are small, unobtrusive and inexpensive

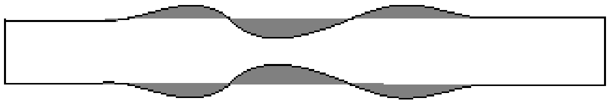
Guided Waves: Lamb Wave Propagation

- PZT Actuators are used to generate elastic waves through material; response is measured at an array of PZT sensors.
- Identifies damage from wave attenuation/reflections and changes in transmission velocit
- Used for large area damage detection

Asymmetric mode (Ao)

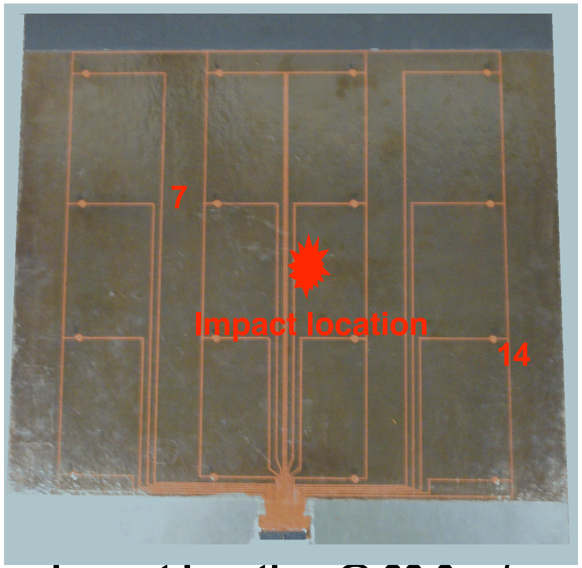


Symmetric mode (So)

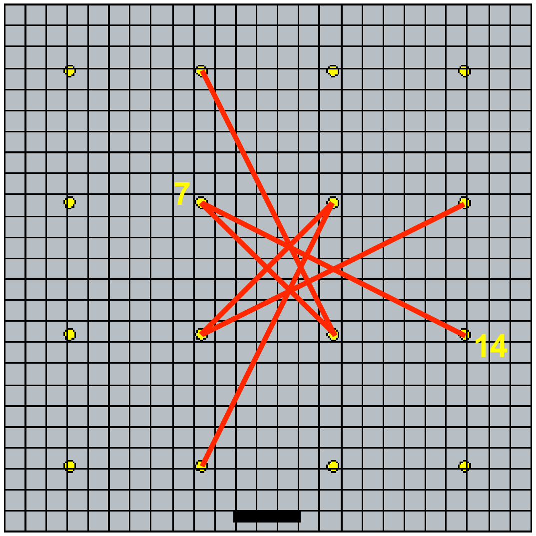


- Very efficient in SHM
- Requires significant amount of electric power to generate Lamb waves

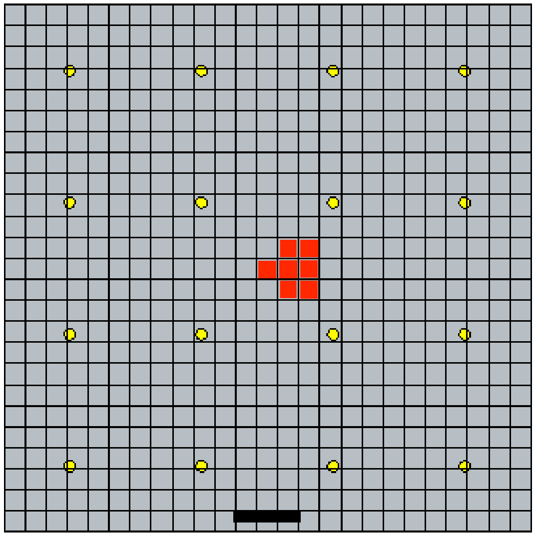
Lamb Wave Method Applied to a Composite Plate



Impact location @ 33.0 m/s

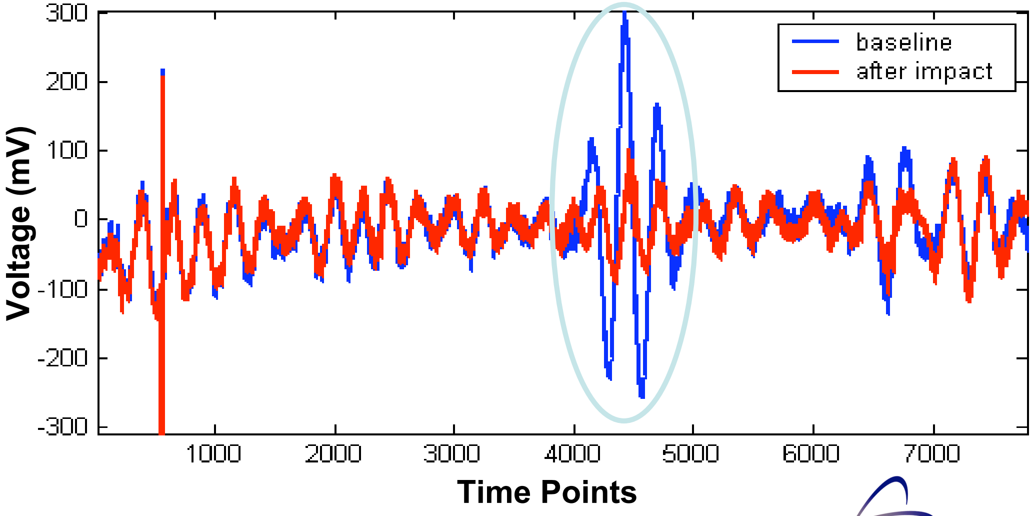


Selected damaged paths



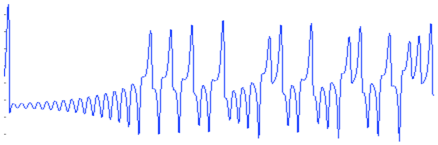
Estimated Delamination area

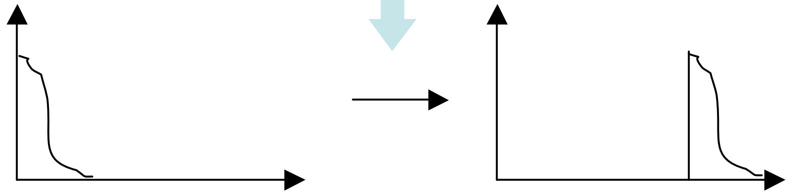
Response time signals corresponding to a damaged path (from PZT 7 to PZT 14)



Guided Waves: Chaotic Waves and State Space Method

digitally generate Lorenz waveform at slow time

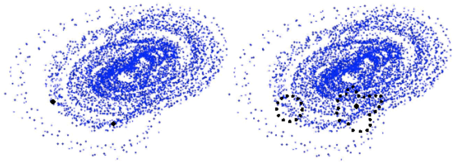


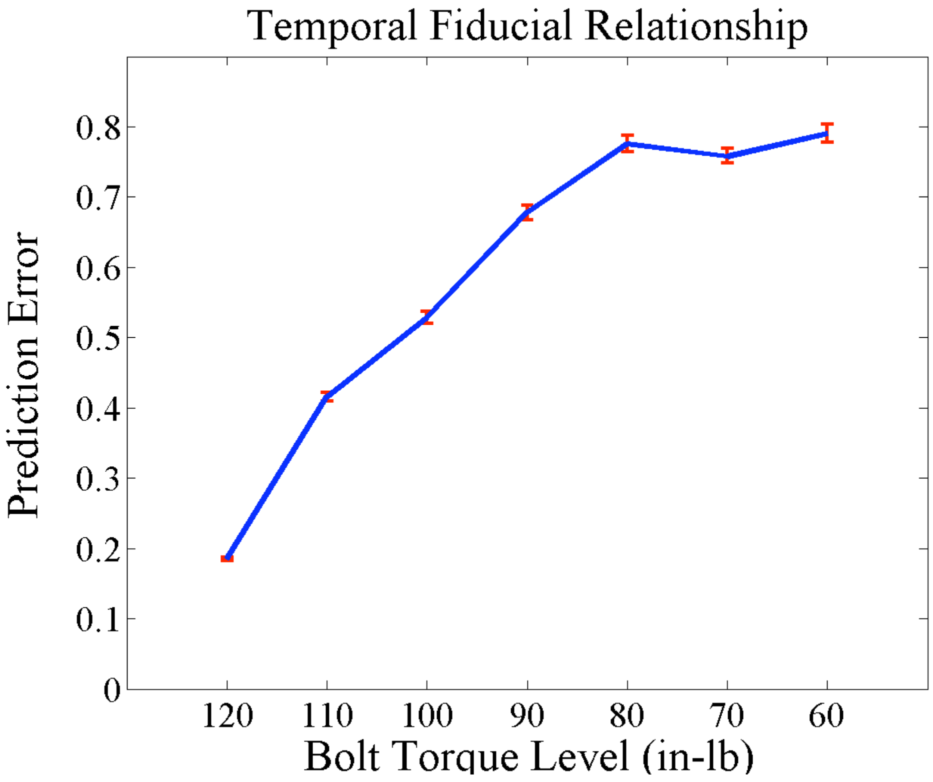


frequency domain shift to high frequency

Excite structure with shifted waveform using PZTs

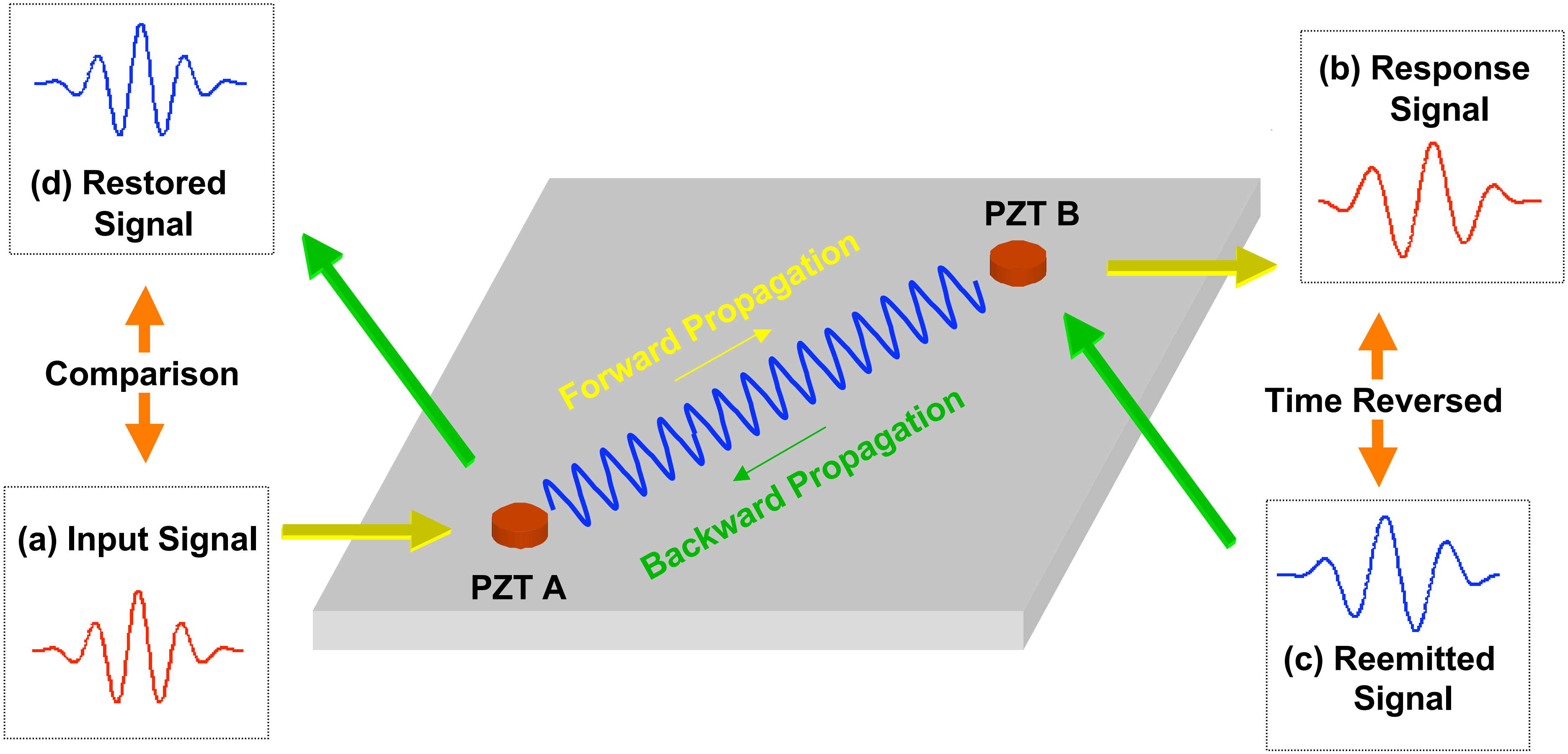
build attractors and compute metrics





- combines the advantages of high-frequency guided waves with state space methods
- DSP-intensive
    - create waveform
    - frequency domain shifting/smoothing
    - attractor reconstruction

Guided Waves: Time Reversibility



- Nonlinearities in the structure (i.e. damage) cause the restored signal to significantly differ from the input signal
- A measure of reciprocity

Where Does SHM Need to Go?

- The following elements are required
  - An embedded system with SHM and/or Prognosis algorithms
  - A sensing device
  - An actuating device (for active sensing)
  - A power source
  - A telemetry method

- This system would provide a completely self contained sensor patch for structural Health Monitoring
  - Computing is needed because it is cheaper in energy to compute than transmit.

So, how are we currently limited?

Current SHM System Limitations

- Most current SHM systems have required significant wire lengths to implement
- Wireless technology developments hold promise for moving from conventional single central-node sensor network to local distributed sensing/processing networks, but the advantages of such networks still bring key power requirements
  - power for telemetry/transmission (may be significant)
  - power for local computing (not as significant, mostly)
  - significant power demand from doing active sensing, where actuation is required

Is wireless technology for SHM applications really feasible without efficient energy harvesting techniques?

Towards Energy Harvesting for Integration into SHM

- Since 2003, "Self-powered SHM Sensing System" has been a recurrent topic of DoD SBIRs and other funding agencies.
- Several prototypes of passive self-powered strain monitoring systems have been reported in papers, but not in practice.
- Most likely, solutions are application-specific, as they depend upon
    - Total power budget
    - SHM algorithm/sensing duty cycle
    - Power generation capability and storage
    - Low-power electronics