Fundamental Aeronautics
Subsonic – Rotary Wing
Reference Document

Submitted May 26, 2006

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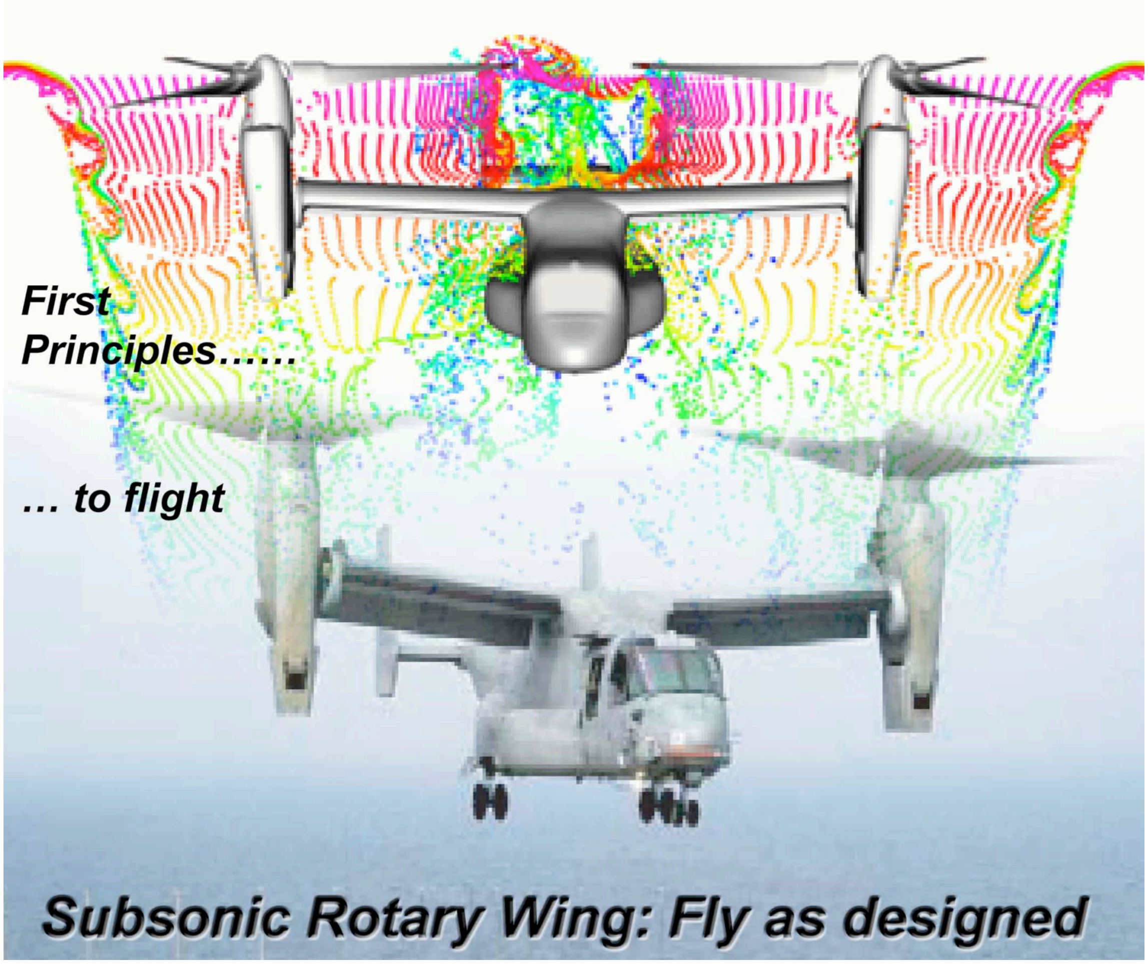

This document was developed over the past several months by NASA to define the rationale, scope and detailed content of a comprehensive Fundamental Aeronautics Subsonic Rotary Wing research project. It contains reference to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The document also references potential opportunities for cooperation with external organizations in areas that are currently considered to be of common interest or benefit to NASA. This document should be considered a reference document and not a completed research plan.

1.0 Technical Plan

1.1 Relevance

Helicopters today provide many crucial services to society, including emergency medical and rescue services, security patrols, off-shore oil platform access, logging and heavy-lift activities, and even sightseeing operations. Recent natural disasters such as the tsunami in Southern Asia, hurricanes Rita and Katrina in the Gulf Coast states, and the earthquake in Pakistan have demonstrated the need for vertical takeoff and landing and hovering capability to cope with stranded survivors, to transport the injured, and to deliver food and medical supplies when no roads are accessible. The civil benefits of the helicopter are very visible during times of natural disaster, and the importance of military helicopters to the defense of our country is well established. Yet the tremendous potential for rotorcraft to transform air transportation is still to be realized. The vertical takeoff and landing capability of rotary wing aircraft can ease congestion at airports and in cities, and even make air transportation available to rural and unimproved areas — but only if technology can provide an efficient, quiet, and competitive vehicle.

The focus of the Subsonic Rotary Wing project of the Fundamental Aeronautics program is civil competitiveness of rotorcraft. Several facets of competitiveness will be attacked: efficiency, including aerodynamic performance and structural weight; productivity, which requires high speed, large payload, long range, and good maneuverability; and environmental acceptance, particularly noise and handling qualities. Without intending to predict where the design process will lead when truly effective design and analysis tools are available, some very promising (and very challenging) configurations can be identified to drive the required fundamental research. A recent NASA investigation[1] showed the tremendous potential of a large, fast, civil tiltrotor, a potential based on achieving significant advances in aerodynamic and structural efficiency, including slowing the proprotor in cruise to about 50% of hover tip speed. Alternatively, the slowed-rotor compound configuration uses the rotor for lift and control in hover and low speed flight, and wings and auxiliary propulsion for efficient cruise, with the unloaded edgewise-flying rotor slowed to minimize its drag. The potential of this configuration has long been acknowledged, but only now are aerodynamic and structures technologies appearing that may make it a competitive vehicle. Such rotorcraft configurations offer revolutionary capability that substantiates as well as requires investment in the technology. The unique and interesting aspect of rotorcraft technology is its inherent multi-disciplinary nature. The application of slowed rotors (whether axial or edgewise) for efficient, high-speed cruise flight in particular requires significant advances in all disciplines.

The rotary wing community is expanding and growing, with over 6500 civil helicopters operating in the United States today.[2] NASA's investment in solving the fundamental civil barrier issues such as aerodynamic and structural efficiency, and vibration and noise, will enable tremendous progress in the use and acceptance of civil rotorcraft.

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[1] Johnson, W.; Yamauchi, G.K.; and Watts, M.E. "NASA Heavy Lift Rotorcraft Systems Investigation." NASA/TP-2005-213467, December 2005.

[2] FAA, *Administrator's Fact Book*, December 2003. (http://www.atctraining.faa.gov/factbook/)

It is necessary for the United States, through NASA, to invest in technology research that will benefit the U.S. civil market and re-establish the technical pre-eminence of the U.S. rotorcraft industry.[3] NASA must be the national focal point for long-term, fundamental research that fosters innovation through development and reporting of promising new technologies for which industry determines applications. NASA has accepted the responsibility to maintain the core technical competencies of Aeronautics for the nation[4], including rotary wing capabilities. NASA's role is to define and execute long-term, fundamental research, provide exceptional quality data using NASA's unique facilities, and foster the outstanding technical skills of the NASA research staff to provide a national asset for the rotary wing community.

This document proposes a new Subsonic Rotary Wing project in the Fundamental Aeronautics program. This project provides fundamental and far-reaching research in technologies that will pull the industry forward and point the way to a bright, new future for civil rotorcraft configurations that are commercially competitive. The challenges faced in rotary wing aviation are among the most complex and demanding of any configuration: highly complex, three-dimensional rotor and fuselage structures, unsteady flows in speed regimes from low subsonic to high transonic, dynamically-stalled components, harsh operating environments, highly-loaded propulsion systems, and a vehicle that is statically unstable. To solve these extremely difficult problems and pave the way for the future, a sustained and concentrated effort involving innovative and revolutionary methods must be made. Nothing could be more challenging or more exciting, and that is the heart of the NASA charter.

The Subsonic Rotary Wing (SRW) project proposes to focus its research effort in the most persistent technical challenge areas, in order to produce advances in prediction tool capability and technology. Figure 1 presents the building block approach of the SRW project. There are four levels in this approach, with the most fundamental research elements found at Level 1. Discipline research topics are collected at Level 2, integration of disciplines into components or subsystems are represented at Level 3, and the overarching goal of the thrust for multi-disciplinary, physics-based design tools is located at Level 4. The connections between the blocks in Figure 1 are illustrative and are meant to show the foundational technology development flowing upward and supporting the higher levels. This document addresses critical research at each of these levels that will advance the state-of-the-art (SOA) in the design and characterization of rotary wing vehicles.

With the goal of validated, physics-based design tools and advances in technology in mind, the SRW planning team developed a strategy that focuses on key technologies that will maximize the use of NASA resources and highly leverage partnerships with other Government Agencies, industry consortia, and industry partners. The SRW document is centered on several technology demonstrations at the component integration level (Level 3). These Level 3 research areas were selected for their relevance to a broad range of industry and government programs, for their inherent requirement to force integration of multiple disciplines to accomplish the tasks, and for their challenging technical issues that are beyond the reach of current prediction tools.

Each of the Level 3 milestones brings together the analytical methods and experimental validation data that are required to advance the state-of-the-art in a multi-discipline environment. The ability to demonstrate each of these Level 3 milestones will require and promote advances in technology, in understanding, and in predictive capability. Innovative solutions to these Level 3 technical challenges

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[3] Responding to the Call: Aviation Plan for American Leadership, *National Institute of Aerospace*, May 2005 (http://www.nianet.org/nianews/AviationPlan.php)

[4] Porter, L.: Reshaping NASA's Aeronautics Program. AIAA, Reno, 2006. (http://www.aeronautics.nasa.gov)

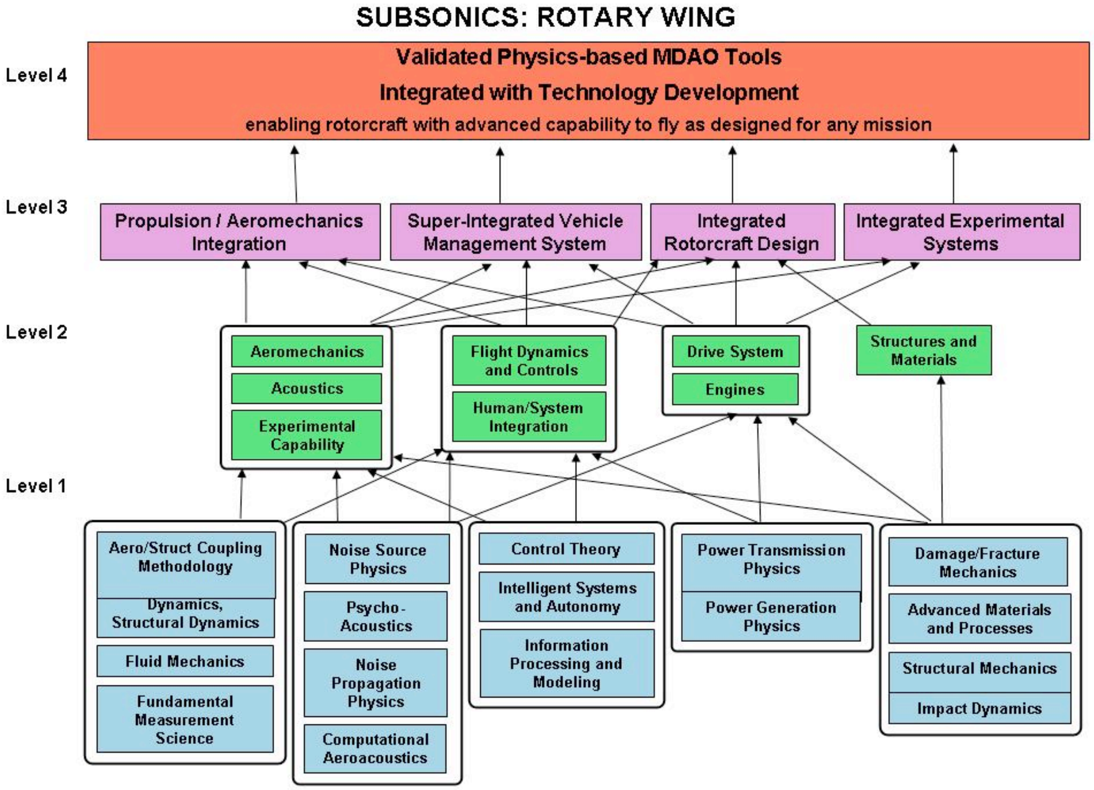

Figure 1. SRW Level Diagram.

coupled with the increased ability to predict with certainty the solutions will drive breakthrough technology for the rotorcraft industry. By making progress in the ability to predict a complete set of integrated technologies, SRW will deliver the Level 4 product: developing state-of-the-art prediction technology and providing validation databases and technology demonstrations that will be used immediately and for years to come by the rotorcraft industry. These Level 3 research areas are highlighted in more detail in the milestone and technical approach section, but the areas and their potential are described briefly here.

The first Level 3 technical challenge is propulsion-airframe integration research that seeks to combine the engine and drive train effects of a slowed rotor concept with the aeroperformance and acoustics of the main rotor for a range of rotor speeds. The development of slowed rotor technologies enables high-speed and/or low-noise possibilities for all weight classes of rotorcraft, integrates several disciplines and also challenges the prediction capability within each discipline. In addition, the concept is of interest for both civil and military applications and is an area where breakthrough technology innovations could significantly revolutionize the industry.

The second Level 3 technical challenge is the development and integration of a new approach to flight vehicle control systems that integrates control of propulsion and airframe loads, vibration and noise, and pilot workload. This technical effort requires the development of a completely new type of flight control system architecture — one that is flexible, multi-tasking and considers the real-time flight dynamics and control during different flight conditions. The development of this prediction and control technology will enable the safe, effective, and publicly acceptable operation of advanced configuration rotary wing vehicles in many different environments. This technology is critical for advancing the civil competitiveness of rotorcraft.

The third Level 3 technical challenge addresses issues of passenger comfort and airframe fatigue and maintenance. The technical challenge is the reduction of cabin noise to levels that are commensurate to those of a fixed wing cabin. This will be accomplished through combinations of drive train vibration reduction, new structural materials and construction, and improvements in acoustic interior noise modeling. When successfully completed, the demonstration of low-noise cabin technology will provide the comfort levels in a rotary wing vehicle that will enable increased civil use of rotary wing transportation.

The fourth Level 3 technical challenge is interactional aeroacoustics, which has been a persistent and intractable problem for rotary wing system development. In this document, the intent is to concentrate on the understanding and prediction capability for the aerodynamics and acoustics of configurations as they operate in environments where the rotor wake impinges on other parts of the vehicle. This is a particularly difficult flight regime for predicting the aircraft performance, and the inability to predict accurately the wake effects has led to many unfortunate developmental issues and operational failures. The goal of this effort is to promote physics-based understanding and prediction of the rotor wake and its effects on conventional and unconventional configurations. The interactions will include the empennage, anti-torque devices, acoustic reflection, and also the engine inlets and distortion. Significant improvements in prediction capability for interactional aeroacoustics will advance the design and development cycle for all types of rotorcraft configurations.

The fifth Level 3 technical challenge is for the development of experimental techniques required to provide essential validation data in an efficient and integrated environment. This validation data is critical to the understanding of technology improvements both in configurations and in prediction capability. In order to make progress in the first four Level 3 technical challenges, this fifth area must be pursued vigorously and simultaneously. In particular, the acquisition of high-quality experimental data for the rotor wake and its vortex structure and the rotor blade position and its deformation for the entire range of rotor azimuth and wake history is essential to understanding the fundamental issues associated with improving rotorcraft technology. This work will provide a capability not only to NASA, but also to the nation through the unique facility capabilities that will be developed.

These five Level 3 efforts represent some of the most important technical problems facing the rotorcraft industry and some of the most difficult areas to predict with today's methodology and understanding. The milestones intentionally are not specific to one type or class of vehicle, but rather allow the thrust to assess the progress in predicting the characteristics of a range of vehicle types and the variety of fundamental issues that arise among vehicles of different classes. Different rotorcraft configurations will provide new challenges for analysis and technology solutions; at the same time, understanding the fundamental aspects of technology will spur the development of new configurations.

The Subsonic Rotary Wing team proposes a project containing research goals that are relevant, technically challenging, multi-disciplinary, multi-Center, measurable, and executable. The following pages describe in detail the proposed research effort.

1.2 Milestones and Metrics

The SRW team concentrated the majority of the planning effort in defining a 5-year plan that sets the stage for a long-term, visionary research effort. The numbering system for discussing the milestones is shown in Table 1. A 10-year (FY07-FY16) milestone roadmap that shows the 5-year connection to the long-range plan is presented in Figure 2. Detailed milestone and metric descriptions with deliverables and resources are included in the Technical Approach section

1.2 Milestones and Metrics

Figure 2a. 10-year Milestone Roadmaps

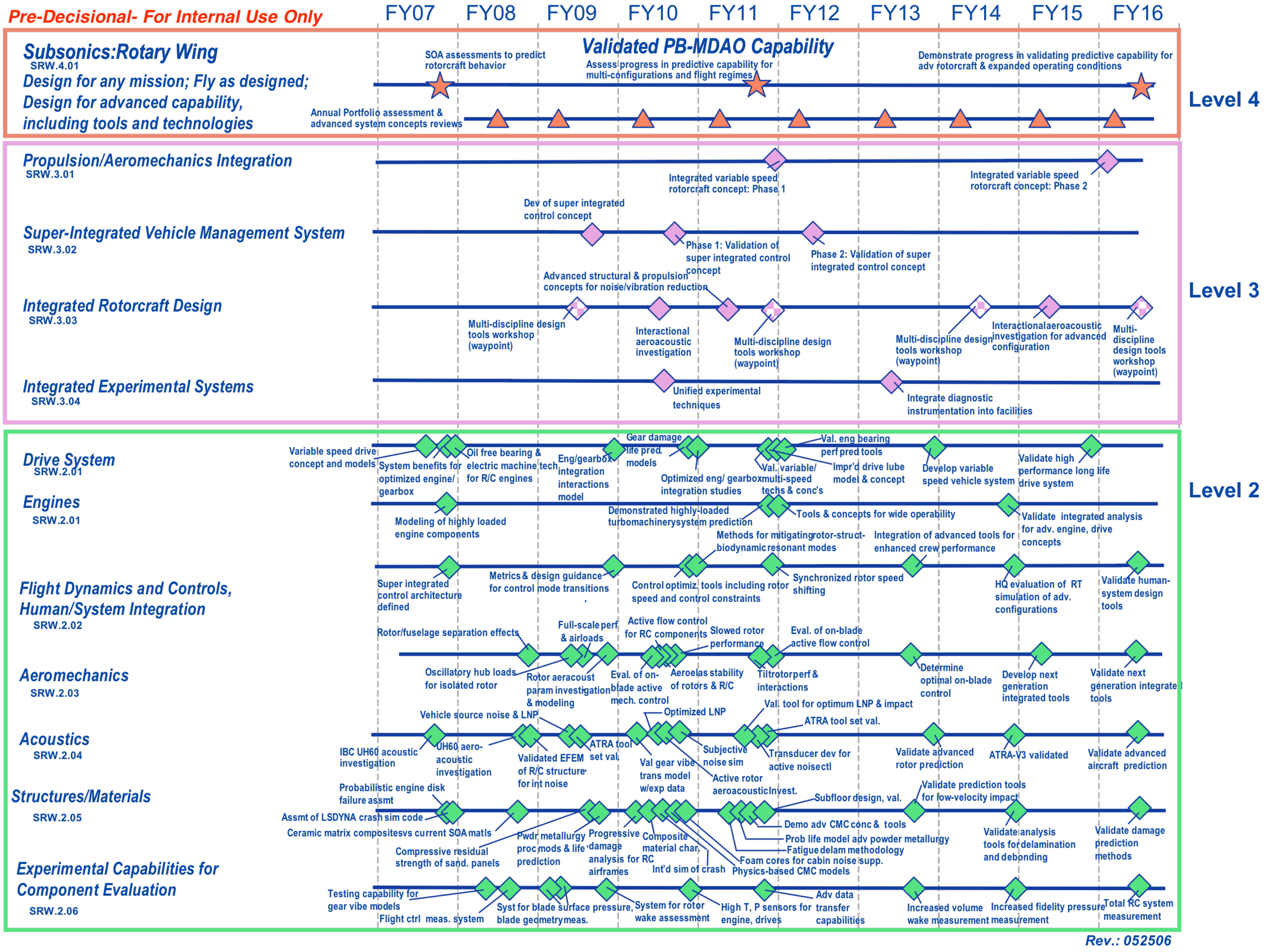

Figure 2b. 10-Year Milestone Roadmaps (concluded).

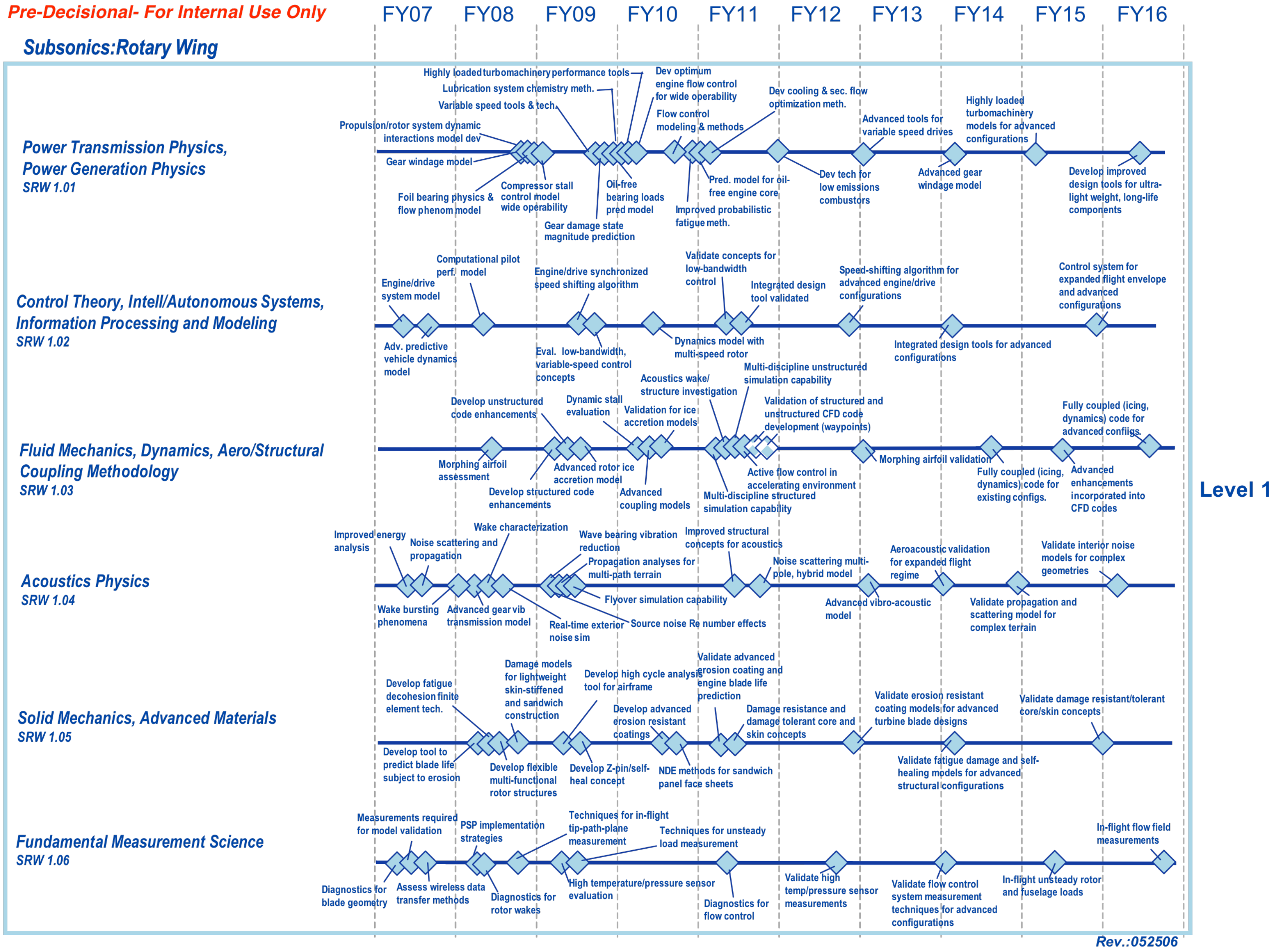

Table 1. SRW Milestone Numbering Scheme.

Project	Level	Area	Description
SRW	.1	.01	Power Transmission Physics, Power Generation Physics
		.02	Control Theory, Intelligent/Autonomous Systems, Information Processing & Modeling
		.03	Fluid Mechanics, Dynamics, Aero/Structural Coupling Methodology
		.04	Acoustic Physics
		.05	Solid Mechanics, Advanced Materials
		.06	Fundamental Measurement Science
	.2	.01	Drive Systems, Engines
		.02	Flight Dynamics and Control, Human/System Integration
		.03	Aeromechanics
		.04	Acoustics
		.05	Structures/Materials
		.06	Experimental Capability
	.3	.01	Propulsion/Aeromechanics Integration
		.02	Super-Integrated Vehicle Management System
		.03	Integrated Rotorcraft Design
		.04	Integrated Experimental Systems
	.4	.01	Validated PB-MDAO Capability

1.3 Technical Approach

The approach and feasibility of major research tasks in each Level and Discipline area are described in the following sections. Techniques, methods, technologies, resources, and leveraging opportunities are cohesively integrated to produce innovative solutions addressing fundamental technical challenges in rotorcraft.

Integration between discipline areas is a key requirement in establishing the research tasks. The Level 1 and 2 tasks are grouped by discipline and then by Level. The numbering scheme provided in Table 1 is used to identify the topic areas. Milestones, key deliverables, and resources are provided for each major task.

SRW Level 4

SRW.4.01 Validated Physics-Based Multidisciplinary Design-Analysis-Optimization Capability

SRW will develop validated physics-based multidisciplinary design-analysis-optimization tools for rotorcraft, integrated with technology development, enabling rotorcraft with advanced capabilities to "fly as designed" for any mission. Accomplishing this objective requires an emphasis on integrated, multidisciplinary, first-principle computational tools that address the unique problems of rotary wing aircraft.

An assessment of the state-of-the-art in predictive capability will be conducted for integrated rotorcraft behavior as well as for the specific disciplines. SRW needs to document the baseline SOA in FY07 for all areas of the project. This enables technical progress to be measured at the 5, 10 and 15-year marks relative to the FY07 established SOA baseline. SOA assessments will include work performed at NASA, other government agencies, industry, universities, and non-U.S. organizations. The assessments also will serve to engage and train those who have not worked rotorcraft technology and can lead to new partnerships when new work in an area is uncovered. For some disciplines (Aeromechanics, for example), the SOA for prediction capability is well established. In other areas, primarily empirical and experimental methods are used, so SOA for prediction capability needs to be defined. The deliverable for the Level 4 SOA assessments will be a white paper for each discipline, collected and published as a NASA technical report. This report will describe what can be predicted, the accuracy of the prediction, and specific areas requiring more work in order to achieve the desired level of accuracy. This report will be very important to the SRW project, since it will provide a quantitative basis for defining expected progress and improvements and measuring the success of validation activities in subsequent milestones. In addition, refinements of the milestone metrics will be made based on the results of the assessments.

Several recent correlation studies highlight the need for progress in the prediction of rotorcraft characteristics. Table 2 shows nominal goals for predictive capability in some areas and some recent assessments of current capabilities using an engineering tool analysis and a physics-based model for arbitrary rotorcraft designs and operating conditions. Note that in most cases the goal is an order of magnitude improvement over current capabilities of either tool. The percentages given are SOA accuracy of calculations compared to measured values (based on full amplitude of the measured data). Figure 3 illustrates an example of the data supporting Table 2. In Figure 3, the ability to calculate pitching moment (without mean) is shown to be only 20% accurate using a first-principles-based computational tool (coupled CFD/CSD codes; for 1 rotor, 9 radial stations, 3 operating conditions). Clearly there is a requirement for significant improvement in the prediction capability for this and many other areas.

Table 2. Estimate of Predictive Capability for SOA Rotorcraft

	Goal	**Engineering tool**	**Physics-Based Model**
Forward flight performance	1%	4%	20%
Hover performance	0.5%	2%	2% (but flowfield not correct)
Airloads (c_n/c_m), without mean	1%	10% / 35%	6% / 20%
Airloads (c_n/c_m), with mean	1%	10% / 35%	15% / 40%
Blade loads (Flap/Chord/Torsion)	3%	20% / 35% / 25%	20% / 35% / 25%
Vibration	10%	100%	Not available
Stability (fraction critical damping)	0.002	0.02	Not available
Noise	3 dB	10 dB	15 dB
Handling qualities rating (HQR)	0.5 HQR	2 HQR (for well-defined criteria)	Not available

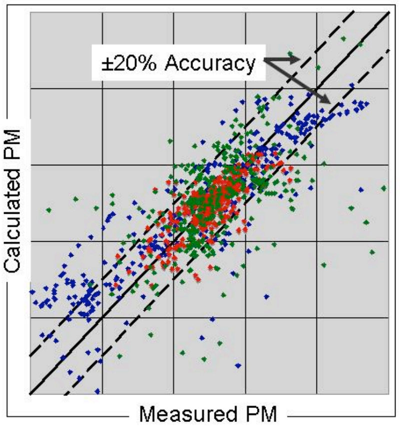

Figure 3. Calculated vs measured pitching moment.

The general metric for progress at Level 4 is a factor of 10 improvement in design-analysis-optimization capability at the end of a 15-year program. This metric can also be characterized as a factor of 2 improvement in prediction accuracy every 4.5 years. Separate metrics for individual milestones have been defined, with specific rates and levels of improvement appropriate for each task and each discipline. The Level 4 metric for SRW.4.01.02 is intended to provide a measure of progress for the overall program. Achieving an order-of-magnitude improvement in prediction accuracy will not be easy, but would be a tremendous accomplishment.

Reviews will be conducted at the midpoint and the fifth year of the project to determine the progress achieved in improving predictive capability for integrated rotorcraft behavior as well as for the following disciplines: aeromechanics, computational fluid dynamics, propulsion, acoustics, structures and materials, flight dynamics and control, and experimental techniques. Predictive capability for helicopter and tiltrotor configurations and for various flight regimes will be addressed. A major part of the review will come from the results of the Level 3 FY10-11 milestones and the multi-discipline tools workshops. A report documenting progress and state-of-the-art will include recommended areas for future research. The milestones and deliverables for the Level 4 effort are provided below.

Number	Title	FY	Metric	Dependencies
SRW.4.01.01	Assessment of SOA capability to predict rotorcraft behavior	07	Delivery of SOA prediction capability NASA report for L2 Disciplines. Assess SOA capability to predict each discipline and quantify in terms of percentage difference from available validation data.	
SRW.4.01.02	Assess progress in predictive capability for several config and flight regimes	11	Factor of 10 improvement in overall prediction accuracy within 15 years.	SRW.3.03.01 SRW.3.03.04

Key Deliverables for SRW.4.01 Validated Physics-Based MDAO Capability	FY	Related Milestones
Report documenting state of the art design and analysis capability.	07	SRW.4.01.01
Report documenting state of the art of rotorcraft design and analysis capability, methodologies contributing to improvement in capability, and recommendations for directions of future research.	11	SRW.4.01.02

SRW Level 3

Level 3 milestones are defined with two principal objectives. First, the milestones bring together several disciplines. Second, the Level 3 milestones provide technology pull and focus for the Level 2 and Level 1 tasks. The metric for Level 3 milestones is in general a factor of two improvement in prediction accuracy every four years. Each milestone will have specific metrics for each discipline, reflecting Level 2 and Level 1 metrics.

SRW.3.01 Propulsion/Aeromechanics Integration

In this task, the disciplines of propulsion, aeromechanics and acoustics are emphasized. This effort represents research in the integration of transmission and engine technologies for slowed rotor concepts together with the ability to predict aeromechanics and acoustics parameters for such a configuration. This milestone requires close collaboration between analytical work and experimental methods before, during, and after the wind tunnel experiment. The experiment will be designed to acquire data that is required for validation of the prediction of rotor forces, power, rotor blade loads, rotor blade pressures, blade motion, drive system loads and speed change dynamics, engine inlet flow, rotor wake-induced flow and far-field external acoustics. The milestone and deliverable for this task are:

Number	Title	FY	Metric	Dependencies
SRW.3.01.01	Integrated variable speed rotorcraft concept	11/ 12	Validate overall factor of 2 improvement relative to 2007 SOA. This should result in prediction accuracy relative to wind tunnel test data for: airloads (7% cn, 20% cm) blade loads (10% flap, 20% chord), wake position (3%R), drive loads (20%) for high, medium, and low forward speeds, level flight and descending conditions, and rotor speed variations between 50-110% nominal design rpm.	SRW.2.01.02 SRW.2.03.07 SRW.1.04.07 SRW.2.04.12

Key Deliverables for SRW.3.01 Propulsion/Aeromechanics Integration	FY	Related Milestones
Test data to be used for future design and analysis tool development and validation.	12	SRW.3.01.01

SRW.3.02 Super-Integrated Vehicle Management System

Super-integrated Vehicle Management System refers to an integrated, broadband rotorcraft control system incorporating a flight control system, engine control, airframe/drive train/rotor load control, active rotor control of vibration and noise, vehicle health management, and guidance for low noise operation. This task integrates the Level 2 disciplines of flight dynamics and control, acoustics and propulsion.

A new type of control design methodology and architecture will be supported both in-house and through the NRA research opportunities. First-principles analyses (CFD/CSD) will be used to provide a plant model for design, considering both linear and non-linear modeling. Control design methodology will be validated by comparing predicted control system performance with results from a Phase 1 flight test. A subset of the super-integrated control design will be incorporated into a flight control system for flight evaluation, validating the modeling capability and control design methodology. The milestones and deliverable for this task are:

Number	Title	FY	Metric	Dependencies
SRW.3.02.01	Development of super-integrated control concept	09	Design of control system architecture and vehicle system simulation demonstration of flying low noise profile with Level 1 handling qualities complete	SRW.4.01.01 SRW.2.02.01
SRW.3.02.02	Phase 1: Validation of super-integrated control concept	10	Flight test demonstration of maintaining Level 1 handling qualities during a low noise flight profile	SRW.3.02.01 SRW.2.04.04-05

Key Deliverables for SRW.3.02 Super-Integrated Vehicle Management System	FY	Related Milestones
Technical report describing control system architecture for integrated broadband rotorcraft control and results of simulation testing	09	SRW.3.02.01
Technical report documenting flight test data, and comparison with simulation results.	10	SRW.3.02.02

SRW.3.03 Integrated Rotorcraft Design

The Integrated Rotorcraft Design task enables and encourages integration of multiple sets of disciplines, with particular emphasis on those technologies that affect rotorcraft configuration design, such as interactional aero/aeroacoustic effects and transmission/cabin noise interactions. In this task, a validation of noise and vibration analysis capability for the internal cabin draws together the drive train vibration reduction technologies, the structural fatigue and advanced construction or materials for acoustic attenuation, and the acoustic modeling and treatment for internal acoustic predictions. This task also emphasizes the importance of interactional aerodynamics, acoustics, and propulsion technologies with a research effort directed at improving the prediction of rotorcraft wakes, separation effects, inlet distortion characteristics, and external acoustics. In addition, in this task, SRW recognizes that some prediction tools may be extremely useful to the community for individual discipline design analysis. To promote dissemination of the discipline prediction tool capability and improvements, SRW will be supporting multi-discipline design tool workshops every 2.5 years for industry, OGA, and university participation. This approach facilitates a wide and timely technology transfer from the SRW to the rotorcraft community. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.3.03.01	Multi-discipline design tools workshop	09	Waypoint: No metric needed	SRW.4.01.01 SRW.2.03.04-06 SRW.2.03.08 SRW.2.04.10
SRW.3.03.02	Interactional aeroacoustic investigation	10	Validate overall improvement relative to 2007 SOA. Prediction accuracy goals relative to wind tunnel test data are: rotor performance and forces (15%), blade airloads (10% cn, 30% cm), rotor wake position (5%R), noise (3dB of peak levels) for high and low forward speeds, level flight and descending conditions	SRW.2.03.04 SRW.2.03.07 SRW.1.04.06-07 SRW.1.04.10
SRW.3.03.03	Acoustic prediction of internal cabin noise in the presence of advanced structural and propulsion concepts designed for interior noise and vibration	11	Predict broadband sound field within 5 dB (peak levels) of experimental data for simulated transmission noise input to medium weight rotorcraft cabin treated with advanced acoustic structural material. Advanced structural material is designed to reduce interior noise	SRW.2.04.11 SRW.2.04.03

	reduction		by 3 dB with no increase in structural weight relative to medium weight rotorcraft in base cabin configuration. Transmission noise reduced by 2 dB through advanced gear and mounting design over conventional systems.	
SRW.3.03.04	Multi-discipline design tools workshop	11	Waypoint: No metric needed	SRW.3.01.01 SRW.3.03.01 SRW.2.03.01-03 SRW.2.03.08 SRW.2.03.10 SRW.2.04.11-12

Key Deliverables SRW.3.03 Integrated Rotorcraft Design	FY	Related Milestones
Report on status of multi-disciplinary design tools	09	SRW.3.03.01
Test data to be used for future design and analysis tool development and validation.	10	SRW.3.03.02
Structural and propulsion concepts resulting in low interior noise and vibration	11	SRW.3.03.03
Report on status of multi-disciplinary design tools	11	SRW.3.03.04

SRW.3.04 Integrated Experimental Systems

This task will assess and develop capability and accuracy for integrated experimental techniques that enable efficient, multi-parameter, simultaneous measurements for characterizing rotorcraft behavior. The required measurements for validation data include unsteady full-azimuth upper and lower surface blade pressures, blade deformation from hub to tip, large field-of-view measurement techniques to characterize the rotor wake and wake trajectory, and wake vortex strength. The venues for demonstration of integrated techniques will be wind tunnel tests of other Level 3 milestones; instrument-development testing will be planned in conjunction with other technical goals. The instrumentation will be targeted to be viable in the three major NASA rotorcraft testing facilities: 14- by 22-Foot Subsonic Tunnel, Transonic Dynamics Tunnel, and National Full-Scale Aerodynamics Complex (NFAC). The milestone and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.3.04.01	Unified experimental techniques	10	Measure blade flapping to within 0.5 mm and blade pressures to within 2% of reference pressure transducers.	SRW.2.06.01-03

Key Deliverables SRW.3.04 Integrated Experimental Systems	FY	Related Milestones
Measurement system for simultaneous blade geometry / surface pressure measurements over full rotor azimuth	10	SRW.3.04.01
Measurement system for simultaneous blade geometry / rotor wake measurements	10	SRW.3.04.01

SRW Level 2 and Level 1

This section discusses the Level 2 discipline goals and the Level 1 research that is required to accomplish this research. The Level 2 disciplines develop technology specific to the discipline area, relying on the Level 1 contributions to the fundamental understanding of the technology. In addition, the Level 2 disciplines target technology developments that will enable the achievement of the integration milestones at the Level 3. In most cases, technologies that support disciplines and were considered foundational efforts within a discipline were classified as Level 1.

SRW.2.01: Drive System, Engines

SRW.1.01: Power Transmission Physics, Power Generation Physics

Rotorcraft propulsion is a critical element of the overall aircraft. Unlike fixed wing aircraft, the rotor/propulsion system is used for aircraft lift, forward flight, and maneuvering. As a result, the rotorcraft engine/gearbox system must be highly reliable and efficient. Future rotorcraft trends call for more versatile, efficient, and powerful aircraft, which will, in turn, further challenge state of the art propulsion system technologies. It is thus imperative that advanced tools and methodologies be developed to allow the US aircraft industry to more accurately and effectively develop and design new engine and drive system technologies to meet the future challenges. Six tasks have been formulated for the engine/drive system area to cover the main research efforts proposed herein.

Task 1: Variable/Multi-Speed Drive System Technologies

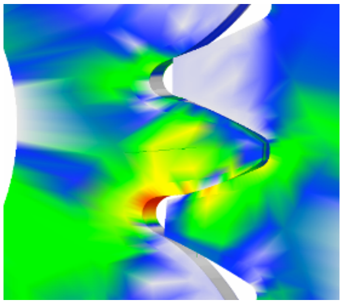
Figure 4. 3D analysis of spur/helical gears

Variable speed rotors can have a large impact on many critical rotorcraft issues for vehicles of any weight class. Currently, rotor speed can vary over a small range, when necessary, purely by adjusting the speed of the engine. Current engine efficiency and stall margin limitations result in only a 15% maximum speed change allowable. The recent NASA Heavy Lift Study (NASA TP-2005-213467) has shown that variable speed propulsion was necessary for all aircraft concepts studied. Variable speed propulsion, without loss of efficiency and torque, is necessary to permit high-speed operation with reduced noise. Speed variations in excess of 50% will have a dramatic effect on reducing external noise while increasing rotorcraft performance. To achieve this large speed variation capability, advanced variable/multi-speed drive system modeling tools (Fig. 4) and concepts need to be developed. This task outlines the tools and technologies that will be developed to enable the variable speed requirement.

An assessment will be performed in FY07 to determine tools and technologies currently available to enable the variable/multi-speed gearbox concept. Based on the assessment, specific tools and technologies will be developed, such as a propulsion/rotor system dynamics interaction model. This model is needed to predict inertial loads and vibrations resulting from speed changes. Results of the Level 1 research efforts will culminate with a laboratory test of a reduced scale variable/multi-speed drive system to validate system level tools and concepts. The scaled unit and resulting data will be used to integrate with the joint aeromechanics/propulsion integration Level 3 test in FY11. Milestones and deliverables for this task are provided below.

Number	Title	FY	Metric	Dependencies
SRW.2.01.01	Variable speed drive concept and models	07	Develop approach and identify concepts for variable ratio mechanical power transmission that enables 50% or greater speed change with less than 10% weight penalty	SRW.2.01.05
SRW.1.01.01	Propulsion/Rotor System Dynamic Interactions Model Development	08	Validate technologies to predict propulsion system dynamics within 25% of measured data.	SRW.2.01.01
SRW.1.01.02	Variable Speed Tools and Technologies	09	Validate operational parameters of variable speed concepts within 10% of predictions	SRW.2.01.01 SRW.1.01.01
SRW.2.01.02	Validate Variable/Multi-Speed Technologies and Concepts	11	Validate by ground test, concepts and technologies that enable 50% or greater speed change with less than 10% weight penalty	SRW.2.01.01 SRW.2.01.07 SRW.1.01.01–02

Key Deliverables for Task 1: Variable/Multi-Speed Drive System Technologies	**FY**	**Related Milestones**
Technical report reviewing variable speed concepts identified for rotorcraft application	07	SRW.4.01.01
Lumped mass dynamic model developed to evaluate effects of speed / inertia changes on variable speed propulsion system	09	SRW.1.01.02
Variable speed concept validated	11	SRW.2.01.02

Task 2: Improved Drive System Analytical Tools

The development of advanced analytical tools is essential for many aspects of mechanical component technology analysis that has been traditionally determined using empirical methods. Improvements in current algorithms and extension to other areas where no physics-based models exist are critical to future rotorcraft design. In a recent study, it was shown that the propulsion system accounts for up to 25% of empty vehicle weight. The drive system accounts for up to 72% of the total propulsion system weight. As such, the technology to enable the design of lightweight, reliable drive system with high torque capacity was identified as a high-risk technology item in this study. Developing advanced tools that enable the development of these high efficiency drive systems is of critical importance for all types of future rotorcraft. In order to develop these tools, basic Level 1 research is needed to understand the fundamental physics inherent in drive systems. Relationships between elastohydrodynamic film thickness, contact and bending fatigue (Fig. 5), and gear surface finish (Fig. 6) are needed to develop accurate tools to design highly efficient drive systems with a high level of confidence. Another example of an advanced tool that is needed is an accurate gear windage prediction model. This prediction capability will be necessary as future transmissions will be run at higher operating temperatures with minimal lubrication (NASA TM-2003-212371). Power loss due to windage can be high, and the resulting heat load to the system requires additional cooling capacity which significantly adds weight. In addition, advanced gear and bearing diagnostics and prognostics technologies will be developed to address technology shortfalls in the current state-of-the-art. Current drive system diagnostics technology has a fault detection rate of only 70%, and a false alarm rate of one every 100 hours of flight. This work will involve developing basic methods and technologies to identify the state of damage while a drive system is in operation. Physics-based tools need to be developed to identify changes in the non-linear gear-mesh generated vibration signal and oil debris generation that can correlate with the magnitude of damage and remaining life prediction models.

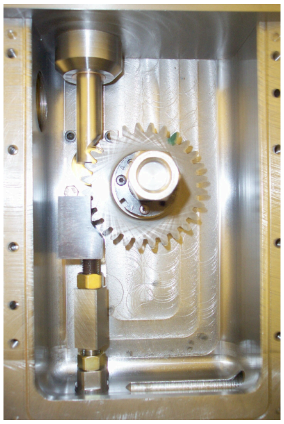
Figure 5. 1KHz Gear Bending Fatigue Rig.

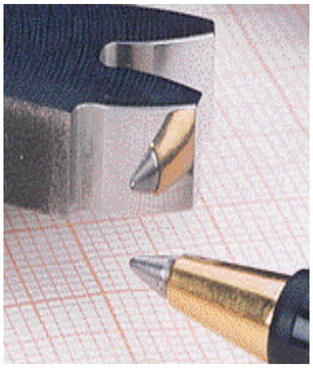
Figure 6. Advanced Gear Surface Technology.

An assessment will be performed in FY07 to determine tools and technologies currently available to predict fatigue, life, durability, etc., of drive systems and related components. Based on the assessment, specific tools and technologies will be developed in the areas of gear bending and surface fatigue modeling, on-line gear damage magnitude assessment, gear windage power loss prediction model, gear life models, and surface lubrication technology development. These fundamental model and technology development efforts will be validated using experimental data from gear surface and bending fatigue component test facilities (Fig. 5). The improved drive lubrication model will be validated in the high-speed gear test facility at Glenn Research Center (GRC). Tests in the high-speed gear facility will also be used to validate improved lubrication concepts capable of at least 2X life extension at loss of lubrication conditions. Validated models and technologies developed will be available at the Multi-Discipline Design Tools Workshop in FY09 and FY11.

Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.01.03	Gear Windage Model	08	Validate gear windage prediction model with 80% accuracy of prediction compared to measurement	
SRW.1.01.04	Gear Damage State Magnitude Prediction	09	Validate in-situ gear damage state magnitude prediction tool accuracy within 20% of prediction to measurement	SRW.1.01.03
SRW.1.01.05	Lubrication Surface Chemistry Methodology	09	Validate predicted performance of advanced lubricants to within 20% of measurement	
SRW.2.01.03	Gear Damage Life Prediction Models	10	Validate prediction with 90% accuracy to the measured level of remaining component life	SRW.1.01.03 06
SRW.1.01.06	Improved Probabilistic Fatigue Methodology	10	Validated 75% improvement in gear surface and bending gear fatigue failure distribution prediction utilizing laboratory bench test methods	SRW.1.01.04
SRW.2.01.04	Improved Drive Lubrication Model and Concepts	11	Validate drive system loss of lubrication life prediction model prediction within 10% of measurement	SRW.1.01.03 SRW.1.01.05

Key Deliverables for Task 2: Improved Drive System Analytical Tools	FY	Related Milestones
Technical report assessing predictive capability versus existing validated data	07	SRW.4.01.01
Validated gear windage model	09	SRW.1.01.03
Improved probabilistic methodology validated for gear bending and surface fatigue life	10	SRW.1.01.06

Task 3: Optimized Gearbox/Engine System

This task addresses the overall propulsion systems integration and optimization issues. It also addresses alternate technologies that could result in a more optimized engine/drive system package. For instance, combining an Oil-Free engine with an optimized gearbox utilizing a gearbox specific lube system could result in significant improvements in performance and efficiency. State-of-the-Art gearboxes share their lubrication system with the engine. This results in a compromised lubrication system for both engine and drives but has low weight. Advances in engines may allow the deployment of oil-free turbines enabling a gearbox to be deployed with an optimized lubrication system. Laboratory tests (NASA TM-106663) have shown greater than 8X improvement in gear surface fatigue life using transmission-optimized lubrication as compared to standard turbine oil.

An assessment will be performed in FY07 to determine tools and technologies currently available to model engine/gearbox integration interactions. Based on the assessment, tools and models will be enhanced and developed to predict engine/gearbox interactions and optimum speed and torque match parameters for near-zero torque spikes at speed changes. In addition, tools will be developed to evaluate engine/gearbox integration technologies that result in optimum operating conditions for each unit. Validated models and technologies developed will be available at the Multi-Discipline Design Tools Workshop in FY09 and FY11. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.01.05	System level benefits estimate for Optimized Engine/Gearbox	07	Estimate performance and weight improvements for optimized system within 15% using current models	SRW.2.01.01 SRW.2.01.08
SRW.2.01.06	Engine/Gearbox Integration Interactions Model	09	Complete system model capable of predicting effects on optimized lubricant on life and performance within 25%	SRW.2.01.01 SRW.2.01.05 SRW.2.01.08 SRW.1.01.07-08
SRW.2.01.07	Optimized Engine/Gearbox Integration Studies	10	Technologies and concepts identified for 1.5 X increase in system life over 2007 SOA as determined by validated and improved models	SRW.2.05-06 SRW.1.01.07-09

Key Deliverables for Task 3: Optimized Gearbox/Engine System	FY	Related Milestones
Technical report assessing predictive model capability compared to identified concepts and existing validated data for optimizing engine/gearbox system	07	SRW.4.01.01
Validated optimized engine /gearbox concept demonstrated in laboratory environment	11	SRW.2.01.07

Task 4: Oil Free Engine Technology

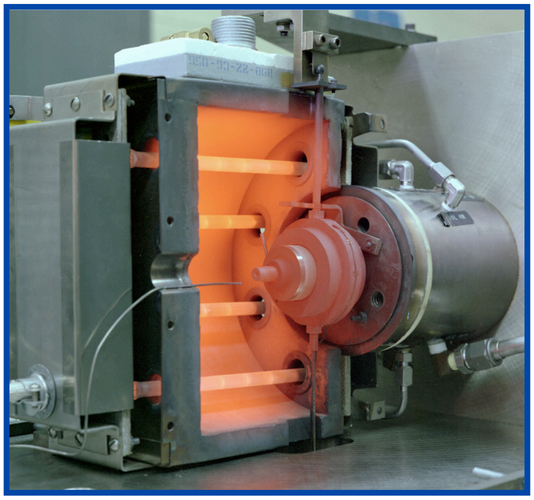

Figure 7. High Temperature Foil Bearing Test Facility

Foil gas bearings have begun to replace traditional oil-lubricated rolling element bearings in small gas turbines used for terrestrial power generation (Fig. 7). In addition, field trials of foil gas bearing-supported APU's are underway which demonstrate that the foil bearing technology is ready for consideration for small propulsion gas turbines for rotorcraft. Significant improvements in thrust/weight ratio and lowered maintenance are primary benefits of enabling oil-free rotorcraft engines. Improved fundamental understanding of compliant surface foil gas bearing technology is required to ready oil-free rotorcraft turbine engines. Basic Level 1 research is needed to develop accurate hydrodynamic fluid film modeling of a non-isothermal case with a fluid, pressure-dependant, moveable boundary. This is a highly nonlinear problem that needs to be addressed in order to obtain the prediction accuracy needed. Due to the proximity of hot section components and bearings, small turbine engines suffer thermal management problems more so than large turbines. Because rotorcraft require a gearbox for speed reduction, the unique opportunity exists for thrust load sharing between an oil-free engine and an optimized gearbox. Further, to take full advantage of this approach, high power density electrical machines are needed for core shaft power generation and starting. This technology will be worked as well. This novel arrangement could allow higher power density engines and drive systems.

An assessment will be performed in FY07 to determine tools and technologies currently available to predict foil bearing performance and life. The technical approach will begin by candidate rotorcraft system studies to guide proper modeling and laboratory validation tests. Bearing characteristics and reasons for this behavior will result from concurrent analytical and experimental activities. Advanced modeling technologies will be developed to predict bearing power loss, stiffness and damping coefficients and tolerance to misalignment and shaft imbalance. Models developed will be validated in the rotor dynamic and high temperature bearing test facilities at GRC. The needs for electrical power generation will be determined and coupled with the bearing and rotor activities. Validated models and technologies developed will be available at the Multi-Discipline Design Tools Workshop in FY09 and FY11. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.01.08	Oil Free Bearing and Electric Machines Technologies for Rotorcraft Engines	07	Define approaches and quantify weight/performance benefits within 95% certainty for Oil-Free Core shaft with Integral Electric Machine	SRW.2.01.05
SRW.1.01.07	Foil Bearing Physics and Flow Phenomenon Model	08	Model of percentage of cross and circulated flow in radial and journal bearings within 25 % of experiment	SRW.2.01.08
SRW.1.01.08	Oil Free Engine Bearing Loads Predictive Model	09	Validate high temperature rotor/bearing dynamic system response prediction within 20% accuracy compared to experimental data	SRW.2.01.08
SRW.1.01.09	Predictive Model for Oil-Free Engine Core	10	Validate bearing performance prediction within 20% of experimental data	SRW.2.01.08 SRW.1.01.01

				SRW.1.01.07 - 08
SRW.2.01.09	Validate Engine Bearing Performance Prediction Tools	11	Validate prediction of thrust and radial bearing performance within 10% of measurement	SRW.2.01.08 SRW.1.01.07 – 09

Key Deliverables for Task 4: Oil Free Engine Technology	FY	Related Milestones
Technical report assessing predictive capability versus existing validation data	07	SRW.4.01.01
Data base for validation of predictive physics-based bearing model	08	SRW.1.01.07
Data base for validation of predictive physics-based propulsion system	11	SRW.2.01.09

Task 5: Wide Operability Engine Technology

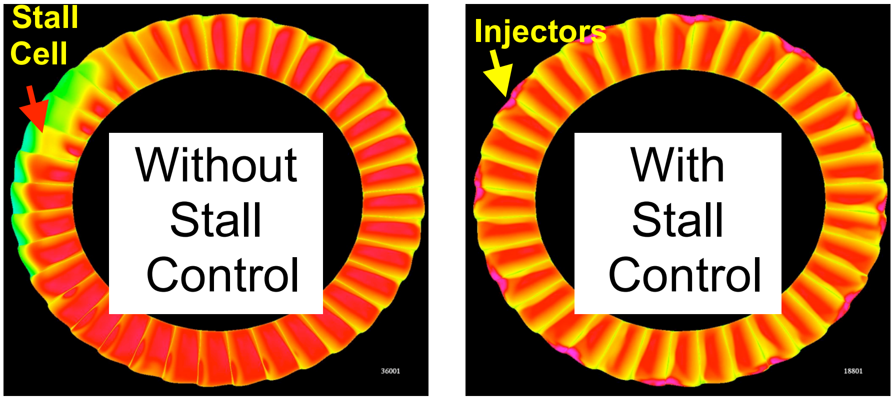

Figure 8. Unsteady full-annulus simulation of stall inception.

The ability to vary the speed of the rotor by over 50%, while maintaining adequate power and efficiencies will require an integrated gearbox/engine systems approach. Advanced modeling tools and concepts are needed to allow an engine to achieve a larger speed range without sacrificing power and efficiency. Concepts which are prime candidates include engine flow controls for enhanced stall margins (Fig. 8), combustor technologies and modeling capabilities specific to small geometry propulsion systems, advanced cooling methods to enable durable, high power output, and modeling to understand the effects of atmospheric water and particle ingestion that can inhibit wide operability.

An assessment will be performed in FY07 to determine tools and technologies currently available for enhanced wide operability engine operation. Advanced modeling and concepts to be developed include stall control technology to mitigate detrimental impact of inlet distortions and blade erosion on engine performance, alternate flow concepts to allow an engine to run efficiently at different speeds, and high temperature technologies to allow an engine to produce high power at low speeds. In particular, basic Level 1 research is needed in the area of stall control physics. The phenomenon of stall on-set and control is still not well understood. Fundamental questions of how and why compressible flows separate and what can be used to address this phenomenon need to be answered using compressible fluid dynamics physics. In addition, fundamental combustion physics will be studied and modeled to address efficiency limits of small engine combustors. Validation of models and concepts developed will be conducted using engine component and combustion test facilities at GRC. Component testing and validation data experiments will be conducted in test cell CE18. System level tests will be conducted in the ECRL (Engine Combustion Research Laboratory) to study system effects of various wide operability enabling technologies. Resulting data from models and concepts developed will be used to integrate with the joint aeromechanics/propulsion integration Level 3 test in FY12. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies

SRW.1.01.10	Compressor Stall Control Modeling For Wide Operability	08	Validate CFD tools for accurately modeling one stall control concept to predict stall range extension within 10 % of experimental extent	
SRW.1.01.11	Develop Optimum Engine Flow Control for Wide Operability	09	Identify flow insertion locations that improve operability by 5% over 2007 approaches to flow control.	SRW.1.01.10
SRW.1.01.12	Develop Cooling and Secondary Flow Optimization Methodology	10	Identify methods to increase turbine operating temperature by 50 deg F with no life penalty over existing production engines	SRW.1.01.10-11
SRW.1.01.13	Develop technology for Efficient Low Emissions Combustors	11	Validate combustor model to improve performance prediction to 20% accuracy of prediction to measurement	
SRW.2.01.10	Tools and Concepts for Wide Operability Engine	11	Validate predictive tools resulting in at least 10% operability improvement over 2007 standards for a T700 production engine	SRW.1.01.10–11

Key Deliverables for Task 5: Wide Operability Engine Technology	**FY**	**Related Milestones**
Technical report assessing predictive capability versus existing validation data for wide operability engine systems	07	SRW.4.01.01
Validated tool for modeling at least one stall control concept	08	SRW.1.01.10
Design guidelines for at least one flow control concept	11	SRW.2.01.10

Task 6: Efficient High Power Density Engine Technologies

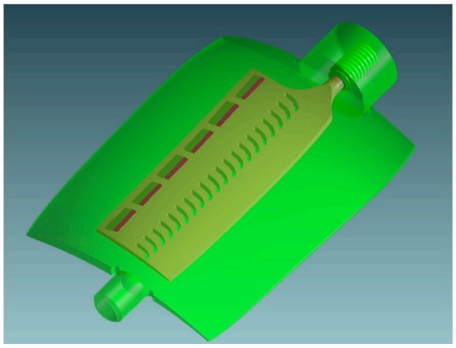

Figure 9. Engine blade flow control for large engine.

Rotorcraft systems typically operate in harsh environments, and are expected to have large cargo carrying capacity with low fuel burn. Technologies for enabling efficient, high power density engine systems have the potential for enabling greater payload capacity with low fuel burn. The challenges of one-engine-inoperative may also be mitigated by high power density engine technology. Engine technologies originally developed for large engines can adapt to rotorcraft propulsion but require research in addition to new models (Fig. 9). These highly efficient, highly loaded turbine systems will benefit from: validated stage loading design and analysis tools which enable higher power density, enhanced secondary airflow and turbine cooling concepts and analysis tools, rotorcraft-sized combustor approaches, and high temperature materials and structures components optimized for small engines.

Figure 10. Highly-loaded compressor test facility

An assessment will be performed in FY07 to determine tools and technologies currently available for high power density engine technologies. The technical approach to be followed will lead to demonstrating concepts to enable high turbomachinery loading capability with adequate efficiency retention, and validation of analytical tools required for development of engines with higher power density. Reducing design margins will be accomplished by developing models to account for particle physics, erosion, and multiphase flows. Models and concepts developed will be validated using engine component test facilities at GRC (Fig. 10). Validated models and technologies developed will be available at the Multi-Discipline Design Tools Workshop in FY09 and FY11. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.01.11	Modeling of Highly Loaded Engine Components	07	Use existing engine/lab data to demonstrate current predictive method accuracy to within 15% of measured data.	SW.2.01.05
SRW.1.01.14	Highly Loaded Turbomachinery Performance Tools	09	Validate performance prediction of highly loaded compressors within 10% accuracy to experimental data	SRW.2.01.11
SRW.1.01.15	Flow Control Modeling and Methods	10	Validate flow control model predictions and technologies achieving 5% higher pressure rise at same efficiency	SRW.1.01.10 - 11
SRW.2.01.12	Demonstrate Highly Loaded Turbomachinery Systems Predictions	11	Validate technologies to predict polytrophic efficiencies within 5% of measurement	SRW.2.01.11 SRW.1.01.14-15

Key Deliverables for Task 6: Efficient High Power Density Engine Technologies	FY	Related Milestones
Technical report assessing predictive capability versus existing validation data for highly loaded components	07	SRW.4.01.01
Validated capability for design of highly loaded compressors	09	SRW.1.01.14
Design guidelines for at least one flow control concept for increased stage static pressure rise capability	11	SRW.1.01.15

SRW.2.02: Flight Dynamics and Control, Human / System Integration

Flight dynamics and control for rotorcraft pose unique challenges due to the inherent instabilities of the flight vehicle, the aerodynamic and mechanical complexity of the system, and the operational environment, which is often obstacle-rich with poor visibility at low altitude. As new designs emerge, such as individual blade control (IBC), on-blade control (OBC), and variable rotor speeds, it is essential that control of flight and the capabilities of the pilot be integrated in the design process. Fundamental research will be conducted to address the implications of higher-bandwidth control arising from IBC and OBC concepts, mitigation of dynamic effects resulting from rotor speed changes, as well as the reduced control response inherent to larger rotorcraft. This research will improve the predictive models for rotorcraft dynamics and will develop the tools needed to ensure desirable handling qualities.

The tasks for this discipline support in particular the Level 3 task SRW.3.02: Super-Integrated Vehicle Management System. “Super-integrated vehicle management system” refers to an integrated, broadband rotorcraft control system incorporating a flight control system, engine control, airframe/drive-train/rotor-load control, active rotor control of vibration and noise, vehicle health management, and guidance for low noise operation. The Level 3 task integrates the Level 2 disciplines of flight dynamics and control, acoustics and propulsion. For flight dynamics and control, the tasks focus on developing new types of control design approaches that will be required to achieve such broadband control, and integrating acoustic, aeromechanic, and propulsion predictive models with handling qualities analysis and design tools. The corresponding Level 1 tasks involve basic building blocks that are needed for the integrated tools at Level 2.

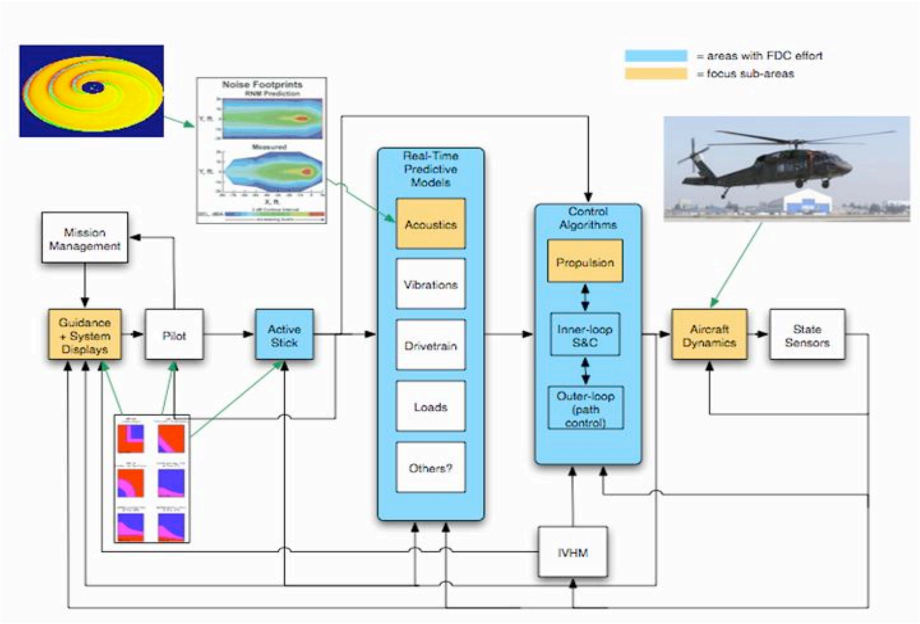

Figure 11. An integrated control system with predictive modeling from multiple disciplines

Consideration of available resources makes it imperative to narrow the scope of the flight dynamics and control work. Hence the emphasis will be on aspects of the program that integrate solution of handling qualities and dynamics problems. Changing the rotor speed over a wide range, depending on the flight state and rotor capabilities, is required to significantly expand rotorcraft capabilities, yet has serious unexplored implications for dynamics and handling qualities that directly affect operational utility. Control methods will be developed to enable the benefits of new rotor dynamics while maintaining desirable handling qualities and aircraft responses. Fundamental research will be conducted to develop real-time predictive acoustic models that account for dynamic flight conditions and control inputs. Precision guidance, navigation and control capabilities will be developed to enable data collection and evaluation for rotorcraft flight experiments, including studies of acoustic properties, vehicle dynamics modeling, noise reduction and terminal-area operations.

Task 1: Advanced Control Methods

This task will develop the control methodologies and tools needed to implement future advances in rotorcraft systems while maintaining desired levels of handling qualities. New technologies requiring flight control and cockpit integration include variable-speed rotor (via variable-speed propulsion system), individual- and on-blade-control, and flight-path and flight-envelope optimization to meet constraints arising from the predictive models developed in Task 2.

An initial architecture will be defined, one which will accommodate multiple predictive models and use the resulting information to improve flight characteristics, including noise reduction, handling qualities, and envelope protection. Initial concepts of predictive acoustic models will be integrated into the control architecture for evaluation and simulation. To enable broadband control, methods for suppressing or eliminating system excitation caused by rotor-structural-biodynamic modes will be demonstrated. An engine control system to enable continuous power transfer during a rotor speed change will be developed. In general, individual tools and methodologies will be developed and validated using existing flight data or flight simulation models. Developed tools will be incorporated in the super integrated control design Level 3 activity. Milestones and deliverables for this task are provided below.

Number	Title	FY	Metric	Dependencies
SRW.2.02.01	Super-integrated control architecture defined	07	New control architecture developed with at least 2 predictive models and 2 control modules	SRW.1.02.01 SRW.1.02.03
SRW.2.02.02	Methods for mitigating rotor-structural-biodynamic resonant modes	10	Concepts demonstrated to achieve Level 1 Handling Qualities in Simulation	SRW.1.02.05
SRW.2.02.03	Synchronized rotor speed	11	Demonstrate that speed-shifting control system can	SRW.1.02.02

	shifting		effect a 50% change in rotor speed	

Key Deliverables for Task 1: Advanced Control Methods	FY	Related Milestones
Technical report documenting control architecture concept, example predictive model implementation, example control module implementation, and test results.	08	SRW.2.02.01
Technical report documenting mode suppression methods and simulation test results.	10	SRW.2.02.02
Technical report documenting speed-shifting control methodology, implementation, and test results.	11	SRW.2.02.03

Task 2: Integrated Predictive Design Tools

Existing predictive tools are not multi-disciplinary, nor are they integrated. Advanced predictive models developed in the Level 1 tasks will be utilized to develop guidance and control systems that achieve acceptable handling qualities while calculating the effects of rotor speed and dynamics, loads and vibration on the pilot-vehicle system. Initial priority will be given to the integration of solutions for handling qualities and new rotor control systems.

Models to predict dynamic response and loads arising from rotor speed variation and new rotor control systems as a function of flight conditions will be developed using a combination of in-house and NRA funded activities. These models will be coupled with pilot controls to develop a systems-level approach to simultaneously optimizing handling qualities and performance, and reducing dynamic loading effects on the aircraft and the pilot. Figure 11 illustrates an integrated control system utilizing predictive modeling from various disciplines. Milestones and deliverables for this task are provided below:

Number	Title	FY	Metric	Dependencies
SRW.2.02.04	Metrics and design guidance for control mode transitions	09	Demonstrate that the application of design guidance results in handling qualities improvement from Level 2 to Level 1 in piloted simulation	SRW.1.02.03
SRW.2.02.05	Control optimization tools that include rotor speed and control constraints	10	Demonstrate tool that can meet Level 1 handling qualities and performance requirements while accommodating a 25% change in rotor speed or 25% IBC/OBC control authority	SRW.1.02.07

Key Deliverables for Task 2: Integrated Predictive Design Tools	FY	Related Milestones
Technical report documenting design guidance and metrics and experimental results.	09	SRW.2.02.04
Control optimization tool that includes rotor speed and control constraints, and associated documentation.	10	SRW.2.02.05

SRW.1.02: Control Theory, Intelligent / Autonomous Systems, Information Processing and Modeling

The tasks under this section directly support the Level 2 tasks in the section: SRW.2.02: Flight Dynamics and Control. These tasks develop and validate basic methodology and algorithms for control of complex systems.

Task 1: Develop Multi-Speed Rotor Control Methodology

This task addresses the challenges of a multiple-speed propulsion system control. To achieve the 50% rotor speed variation envisioned, the engine and transmission will most likely need to provide multiple/variable speed capabilities as a total system. A speed shifting transmission will require advanced controls technologies to ensure proper rotor torque transition with sustained engine power.

An integrated engine/drive system dynamics model will be created to develop a control algorithm for optimum drive system/engine torque matching during shifting operation. This work will be closely coupled with the optimized gearbox / engine system task under the drive systems/engine section of this document. Simulation models will be used to validate the control methodology developed, and the variable speed transmission concept test in FY11 will be used to establish a subsystem validation with actual test data. Milestones and deliverables for this task are provided below.

Number	Title	FY	Metric	Dependencies
SRW.1.02.01	Engine/drive system model developed	07	Demonstrate integrated model with engine and drive system dynamics within 30% of experimental values within range-of-interest for control system	
SRW.1.02.02	Engine/drive synchronized speed shifting control algorithms developed	09	Demonstrate control algorithms for 50% change in rotor speed working in simulation	SRW.1.02.01

Key Deliverables for Task 1: Develop Multi-Speed Rotor Control Methodology	FY	Related Milestones
Technical report documenting integrated engine and drive system model, and comparing performance with experimental values.	07	SRW.1.02.01
Technical report documenting speed-shifting control algorithms and simulation test results.	09	SRW.1.02.02

Task 2: Development of Predictive Models for Guidance and Control

Existing rotorcraft models for control design do not include the next-generation dynamics that will determine the control requirements for future rotorcraft. Similarly, noise models do not account for aircraft dynamics, and pilot models do not account for the effects of acoustics and vibration. Extension of vehicle, acoustics and pilot performance predictive models will enable flight control and pilot interaction for flying rotorcraft on demanding tasks, such as precise 4-D trajectories that minimize perceived noise. The emphasis will be on development of predictive models for control system design of rotorcraft that include new dynamic systems such as variable-speed rotors and individual blade controls.

Additional work will be conducted using existing acoustics and vibration predictive capabilities to extend pilot performance models. Existing acoustics models will be analyzed to identify key features desired for real-time development. Initial low-fidelity models will be refined and flight test data will be collected jointly with acoustics research to validate the tools. The fidelity of real-time predictive acoustics models will be extended for steady-state conditions, and eventually accelerated flight, while reducing execution time as required for coupling with flight dynamics and control design.

Advanced dynamic models are required for use in simulation and flight control system design. These models must include the dynamics of the rotors, fuselage, engine, drive train, servo actuators and control systems, and must accurately represent the vehicle and pilot. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.02.03	Advanced predictive vehicle dynamics models for control design	07	Control-design model responses match comprehensive code responses within 10%.	
SRW.1.02.04	Computational pilot performance models that include effects of vibration and acoustics	08	Predict pilot performance and workload within 20% of experimental values from simulation or flight test	
SRW.1.02.05	Dynamics model including multi-speed rotor and drivetrain dynamics	10	Validate model accuracy by matching frequency- and time-responses of loads at two rotor speed test conditions within 10%, of test rig data from 0.1 rad/sec to 20 rad/sec	SRW.1.02.03
SRW.1.02.06	Real-time predictive acoustics model	11	Predict acoustics to within 3 dB (peak levels) of flight test data for steady-state flight and within 3 dB (peak levels) for at least one accelerated flight condition,	SRW.2.04.04-06

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Key Deliverables for Task 2: Development of Predictive Models for Guidance and Control	FY	Related Milestones
Technical report documenting design and experimental results of pilot performance models.	FY08	SRW.1.02.04
Technical report documenting development and performance of multi-speed rotor and drivetrain dynamics model, including results of validation testing.	FY10	SRW.1.02.05
Technical report documenting real-time predictive acoustics model and comparing prediction results with flight test data.	FY11	SRW.1.02.06

Task 3: Development and Validation of Tools for Integrated Control Design

As variable-speed rotor systems are developed, there will be significant overlap and interaction of the component natural frequencies. Methods and tools for dealing with these effects need to be developed. Additionally, large rotorcraft designs will have unique control system requirements due to their slower rotor response. Using knowledge of existing rotorcraft characteristics and anticipated future design directions, this task will develop and test in simulation concepts for mitigating the effect of dynamic modes on the aircraft and pilot and develop control concepts for large rotorcraft.

Initial concepts and methods for control will be explored (using the predictive models developed under Task 2) and tested in simulation in FY09. These methods will then be validated using flight test data in FY11. The resulting capability to produce control designs will be used in the control architecture developed under SRW.2.02, to create the Super-Integrated Vehicle Management System at L3. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.02.07	Evaluate low-bandwidth and variable-speed rotor control concepts	09	Demonstrate concepts to achieve L1 Handling Qualities for relevant mission task elements in good usable cue environment	SRW.1.02.01 SRW.1.02.03
SRW.1.02.08	Validate concepts for low-bandwidth control	11	Flight test results match simulation predictions of Handling Qualities within 1 Cooper-Harper rating and performance against relevant ADS-33 tasks within 10%	SRW.1.02.05

Key Deliverables for Task 3: Development and Validation of Tools for Integrated Control Design	FY	Related Milestones
Technical report documenting low-bandwidth and variable-speed rotor control concepts and simulation test results.	FY09	SRW.1.02.07
Technical report documenting low-bandwidth control concept validation and flight test results showing accuracy of prediction.	FY11	SRW.1.02.08

SRW.2.03 Aeromechanics

Research in rotorcraft aeromechanics includes the study of isolated and multidisciplinary aerodynamic and dynamic phenomena, including aerodynamic performance, airloads and wakes, interactional aerodynamics, rotor loads, vibration, and aeroelastic stability. Many of these phenomena are poorly understood and remain unsolved. For example, a lack of fundamental knowledge of fluid flow phenomena limits the ability to accurately model and calculate unsteady, compressible, three-dimensional aerodynamics needed for performance and loads predictions. Particularly difficult are highly nonlinear convective wake and separated flow phenomena. There are also important deficiencies in rotorcraft structural dynamics phenomena and multidisciplinary interactions between aerodynamics, structures, engine-drive-trains, and control systems.

In addition, there are new concepts under development in the Government and industry to improve rotorcraft aerodynamic and dynamic characteristics. These include concepts such as active flow control on fuselages (and other fixed surfaces) for drag reduction and active on-blade control (including flow control as well as mechanical controls) for performance improvement and noise, vibration, and load alleviation. Current analysis methods are inadequate to capture the complexity of active-rotor response, and must be further validated and improved before adequate design decisions may be made.

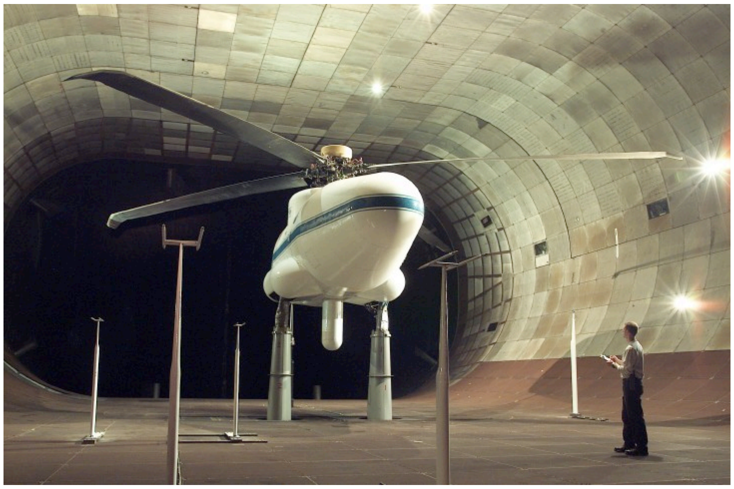

Figure 12. Active Blade Control testing in the NFAC.

Based on current expertise and support from Government and industry partners, NASA will focus its aeromechanics research in the areas of aerodynamics, dynamics, and active controls. The primary goal of this program will be to increase the fundamental understanding of the phenomena and to develop and validate appropriate first-principle-based analysis tools. Experimental test data will be essential to help develop and validate the accuracy of the analysis methods. Existing data will be used where appropriate and new experiments will be undertaken to acquire additional test data where needed. It is anticipated that a broad range of experiments will be needed, including small- and large-scale testing. It will be necessary to obtain high quality, accurate data, of sufficient resolution to discriminate important local aerodynamic phenomena.

Task 1. Active Control for Loads, Vibration and Noise Alleviation

Loads, vibration, and noise reductions are essential for increased acceptance and utilization of rotorcraft. Small-scale efforts indicate high potential for load and vibration control for several active control methods, yet the physics of these are not fully understood. Data for integrated systems and/or large-scale systems are limited. Figure 12 shows one of the recent full-scale experimental efforts. Predictive capability is poor, especially for active flow control effects. The objectives of this task are to validate prediction for control and alleviation of loads, vibration, noise, and to demonstrate effectiveness of control concepts and provide critical validation data through experiment. Milestones involve validation of predictive capability through comparison with wind tunnel test data. The milestones and deliverables for this area are:

Number	Title	FY	Metric	Dependencies
SRW.2.03.01	Active flow control for rotorcraft components	10	Validate component lift and drag predictions with 15% prediction accuracy relative to level flight experimental data	SRW.1.03.01 SRW.1.03.04
SRW.2.03.02	Evaluation of on-blade active mechanical control	10	Validate prediction accuracy relative to level flight / maneuver test data. Accuracy goals are rotor performance (15% / 20%), first-principles vibration and hub loads (100%), and noise (5 dB of peak levels)	SRW.1.03.01 SRW.1.03.04 SRW.2.04.10
SRW.2.03.03	Evaluation of on-blade active flow control	11	Validate prediction accuracy relative to level flight / maneuver test data. Accuracy goals are rotor performance (15% / 20%), first-principles vibration and hub loads (100%), and noise (5 dB of peak levels)	SRW.1.03.02 SRW.1.03.05 SRW.1.03.11 SRW.2.04.12

Key Deliverables for Task 1. Active Control for Loads, Vibration and Noise Alleviation	FY	Related Milestones
Technical report describing SOA to predict effects of active control on performance, loads, vibration and noise	07	SRW.4.01.01
Experimental databases suitable for validation of tools to predict effects of active mechanical control on rotor performance, loads, vibration and noise	10	SRW.2.03.02
Experimental database suitable for validation of tools to predict effects of active flow control on rotor performance, loads, vibration and noise	11	SRW.2.03.03

Task 2. Rotor Aerodynamics and Interactions

Accurate prediction of performance is key to design of all future rotorcraft. Interactional aerodynamics problems are encountered in flight tests of all new rotorcraft. Detailed aerodynamic information required for validation of advanced computational methods are not available, particularly for complex phenomena. Current performance predictions are based on comprehensive analyses with empirical models, not CFD. SOA is 20% accuracy from first principles-based analyses. This task will utilize existing and new experimental data to assess and validate first principle predictions. The document milestones involve validation of predictive capability through comparison with wind tunnel test data. The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.03.04	Rotor/fuselage separation effects	08	Validate rotor and fuselage performance predictions with 20% accuracy relative to level flight experimental data.	
SRW.2.03.05	Full-scale airloads and performance	09	Validate prediction accuracy relative to level flight experimental data. Accuracy goals are rotor performance (15%) and airloads (10% cn, 30% cm)	SRW.1.03.01 SRW.1.03.04
SRW 2.03.06	Rotor aeroacoustic parameter investigation and modeling	09	Validate noise predictions within 3 dB of peak levels and prediction of flow properties (wake position or vortex strength) within 20% of measurements	SRW.1.03.01 SRW.1.03.04 SRW.1.04.06 - 07
SRW.2.03.07	Slowed-rotor performance	10	Validate rotor performance predictions within 20% accuracy relative to level flight experimental data	SRW.1.03.01 SRW.1.03.04
SRW.2.03.08	Tiltrotor performance and interactions	11	Validate rotor performance and download predictions within 15% of test data for level flight conditions	SRW.1.03.02 SRW.1.03.05

Key Deliverables for Task 2. Rotor Aerodynamics and Interactions	FY	Related Milestones
Technical report describing SOA to predict rotorcraft aerodynamic phenomena	07	SRW.4.01.01
Full-scale experimental database of pressure-instrumented UH-60 rotor for validation of performance and airloads predictions	09	SRW.2.03.05
Benchmark rotor noise parameter aeroacoustic database for code validation and noise control physics	10	SRW.2.03.06
Small and full-scale experimental database of slowed-rotor for validation of performance predictions	10	SRW.2.03.07
Experimental databases suitable for validation of tools to predict interactional effects for edgewise rotor and tiltrotor systems	11	SRW.2.03.08

Task 3. Rotor Dynamics and Control

The objective of this task is to validate the capability to confidently calculate aeroelastic stability and rotor-induced oscillatory hub loads and vibration by comparison with existing and new aeroelastic stability test data. Currently rotor stability is calculated based on simplified, empirical, approximate aerodynamic models, approximate beam (1D) models of rotor blades and ad hoc CFD/CSD coupling methodology. The accuracy of calculation of airframe modes is typically 10% for low frequencies. The document milestones involve validation of predictive capability through comparison with wind tunnel test data. The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.03.09	Oscillatory hub loads for isolated rotor	09	Validate oscillatory first-principles vibration and oscillatory hub load predictions within 100% of wind tunnel test data	SRW.1.03.01 SRW.1.03.04
SRW.2.03.10	Aeroelastic stability of rotors and rotorcraft.	10	Validate stability boundary prediction within 10% of flight speed	SRW.1.03.01 SRW.1.03.04

Key Deliverables for Task 3. Rotor Dynamics and Control	FY	Related Milestones
Technical report describing SOA to predict rotorcraft dynamic phenomena	07	SRW.4.01.01
Full-scale experimental database suitable for validation of tools to predict oscillatory hub loads	09	SRW.2.03.09
Experimental databases suitable for validation of tools to predict aeroelastic stability of rotors and rotorcraft	10	SRW.2.03.10

SRW.1.03 Fluid Mechanics, Dynamics, Aero/Structural Coupling Methodology

After reviewing the Rotorcraft CFD (Computational Fluid Dynamics) and MDS (Multi-Discipline Simulation) literature and other programs (including the US Army Aeroflightdyamics Directorate (AFDD) Rotorcraft CFD plan and preliminary results from the DARPA Helicopter Quieting Program), a number of unsolved issues in the area of external flow CFD and MDS analysis for rotorcraft applications were identified. These issues include the following: 1) The rotorcraft wake system is not resolvable with current first principle methods; 2) Simulation throughput, paced by surface and volume grid generation and complications associated with the post processing of large, unsteady databases, is currently too costly for timely turnaround of rotorcraft vehicle analysis; 3) Coupling methodology between CFD and CSD (Computational Structural Dynamics) is not adequately developed for MDS applications involving rotorcraft vehicle; 4) Turbulence modeling for rotorcraft flows, e.g., dynamic stall and transonic shock-induced separation, is currently inadequate for predicting accurate flow simulations; and, 5) Prediction of performance penalties caused by ice buildup suffers from a lack of accuracy near stall, in regions of locally-massive flow separation and in areas of large, highly irregular surface roughness.

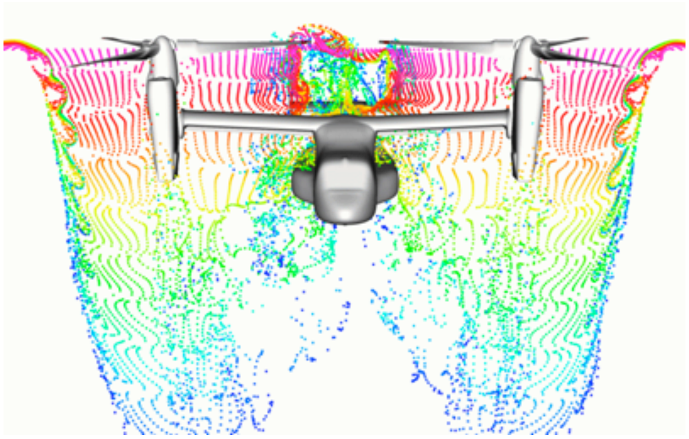
Figure 13. Computed flow field about a tiltrotor

Research and development of new methodology focused within these problem areas will be conducted for two Navier-Stokes solvers — OVERFLOW2, which utilizes a structured grid approach, and FUN3D, which utilizes an unstructured grid approach. The two different types of solvers possess widely different attributes in efficiency, accuracy and throughput characteristics, and thus, will be used in a complementary fashion as the two approaches are compared and contrasted during the course of rotorcraft problem application. Validation is an extremely important part of the present approach, which will be achieved by both code-to-code and experimental comparisons. Many of the validation milestones will involve both codes, and the capabilities of both will be compared in the Level 4 milestone (SRW.4.01.02). In particular, tasks associated with higher-order numerical methods and methods that automatically adapt to solution gradients will be studied to enhance wake capture. Simulation throughput will be improved by automating input, by enhancing parallelization and by automating output file interrogation. Advanced coupling strategies will be developed for structures, acoustics and icing models, thus allowing the development of truly integrated simulation tools. Finally, turbulence models will be implemented and evaluated for a variety of rotorcraft-related test problems. Each task will be coordinated with currently evolving work (for example, the work being performed within the AFDD) to eliminate duplication and amplify productivity.

Task 1: Structured CFD Code Development and Application

This task will advance the SOA in rotorcraft flow field prediction methodology for the structured CFD code OVERFLOW2. Reasonably complete flow solutions have been obtained about moderately complete rotorcraft geometries (Fig. 13) but without accurate treatment of wake or high fidelity inclusion of other disciplines. Throughput for complex geometry cases is not automated. This task will advance the SOA in the areas of accuracy, execution efficiency and throughput efficiency for structured CFD codes. The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.03.01	Develop Structured Code Enhancements	09	Validate prediction accuracy relative to wind tunnel test data. Accuracy goals are: rotor performance (15%) and airloads (10% cn, 30% cm), with factor of 2 improvement in analysis efficiency relative to FY07 SOA	SRW.4.01.01 SRW.2.03.04-05
SRW.1.03.02	Develop Multi-Discipline Structured Simulation Capability	11	Validate prediction accuracy relative to level flight / maneuver test data. Accuracy goals are: rotor performance (10% / 15%) and airloads (7% cn, 20% cm), with factor of 4 improvement in analysis efficiency relative to FY07 SOA	SRW.4.01.01 SRW.1.03.01
SRW.1.03.03	Validation / Support of Rotorcraft CFD Code Development	11	Waypoint: No metric needed	SRW.1.03.09-13 SRW.2.03.01-03 SRW.2.03.04-07

Key Deliverables for Task 1: Structured CFD Code Development and Application	FY	Related Milestones
Technical report documenting SOA in rotorcraft CFD predictive capability using structured grid methods	07	SRW.4.01.01
Improved version of OVERFLOW2 released in production version	09 & 11	SRW.1.03.01-02
Annual report documenting code improvements and validation efforts	07, 08, 09, 10, 11	SRW.1.03.03

Task 2: Unstructured CFD Code Development and Application

This task will advance the SOA in rotorcraft flow field prediction methodology for the unstructured CFD code FUN3D. Reasonably complete flow solutions have been obtained about moderately complete rotorcraft geometries but without accurate treatment of wake or inclusion of other disciplines. Throughput for complex geometry cases is not automated. This task will advance the SOA in the areas of accuracy, execution efficiency and throughput efficiency for unstructured CFD codes. The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.03.04	Develop Unstructured Code Enhancements	09	Validate prediction accuracy relative to wind tunnel test data. Accuracy goals are: rotor performance (15%) and airloads (10% cn, 30% cm), with factor of 2 improvement in analysis efficiency relative to FY07 SOA	SRW.4.01.01 SRW.2.03.04-05
SRW.1.03.05	Develop Multi-Discipline Unstructured Simulation Capability	11	Validate prediction accuracy relative to level flight / maneuver test data. Accuracy goals are: rotor performance (10% / 15%) and airloads (7% cn, 20% cm), with factor of 4 improvement in analysis efficiency relative to FY07 SOA	SRW.4.01.01 SRW.1.03.04
SRW.1.03.06	Validation / Support of Rotorcraft CFD Code	11	Waypoint: No metric needed	SRW.1.03.09-13 SRW.2.03.01-03

	Development			SRW.2.03.04-07

Key Deliverables for Task 2: Unstructured CFD Code Development and Application	FY	Related Milestones
Technical report documenting SOA in rotorcraft CFD predictive capability using unstructured grid methods	07	SRW.4.01.01
Improved version of FUN3D	09 & 11	SRW.1.03.04-05
Annual report documenting code improvements and validation efforts	07, 08, 09, 10, 11	SRW.1.03.06

Task 3: Coupling Technique Development

This task will improve rotorcraft simulation capabilities by advancing coupling methodology between fluid mechanics and other physical models. Reasonably complete flow solutions have been obtained about complete rotorcraft geometries but without accurate treatment of wake or inclusion of other disciplines. Throughput for complex geometry cases is not automated. This task will advance the SOA in rotorcraft simulation methodology in the areas of coupling methodology for multi-discipline applications. The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.03.07	Advanced Rotor Ice Accretion Model	09	Ice mass prediction within 10% of experimental value	
SRW.1.03.08	Advanced coupling models	10	Demonstrate and document coupling procedures for CFD codes including efficiency of coupling method, flexibility of methods, and user interactions. Demonstrate 20% clock-time improvement with comparable accuracy over un-coupled solutions. Demonstrate stability/flutter boundary calculation for an isolated rotor with tight CFD/CSD coupling (24-hour turnaround.	SRW.1.03.03, SRW.1.03.06

Key Deliverables for Task 3: Coupling Technique Development	FY	Related Milestones
Technical report documenting SOA in coupling models used in rotorcraft CFD simulations	07	SRW.4.01.01
Improved coupling techniques + software for ice accretion, rotor dynamics, acoustics models	10	SRW.1.03.07-08

Task 4. Fluid Mechanics for Rotorcraft Applications

Understanding basic fluid physics is critical in the validation of first principle predictions. This task identifies certain areas that need special evaluation. It begins with fundamental small-scale wind tunnel tests for morphing airfoils, dynamic stall, active flow control and airfoils with ice accretion and ends with the validation of the corresponding prediction capabilities by comparing the numerical predictions with test data. The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.1.03.09	Morphing airfoil assessment	08	Validate stall angle predictions for morphing configuration within 20% of wind tunnel test data	
SRW.1.03.10	Dynamic stall evaluation	10	Validate stall angle predictions within 20% of wind tunnel test data	
SRW.1.03.11	Active flow control in accelerating environment	11	Validate separation angle predictions from flow control within 30% of wind tunnel data	
SRW.1.03.12	Acoustic/wake structure investigation	11	Validate prediction accuracy relative to measured data. Accuracy goals are: airloads (7% cn, 20% cm), blade motion (3%R), blade surface pressure (10%), and noise (3 dB of peak levels)	
SRW.1.03.13	Validation Experiments for Ice Accretion Model	10	Reduce the error in prediction of maximum lift coefficient to 30% of wind tunnel test data, for the same number of grid points.	SRW.1.03.07

Key Deliverables for Task 4. Fluid Mechanics for Rotorcraft Applications	FY	Related Milestones
Experimental database for CFD/ice accretion model	10	SRW.1.03.13
Experimental databases suitable for validation of tools to predict fundamental fluid physics (effects of morphing airfoils, active control, dynamic pitch changes)	11	SRW.1.03.09-11
Validated lifting surface turbulence interaction blade response model for acoustics	11	SRW.1.03.12
Benchmark fundamental aeroacoustic and flow physics database	11	SRW.1.03.12

SRW.2.04 Acoustics

The acoustics research consists of four task areas at Level 2 that significantly contribute to the multidisciplinary Level 3 goals and are focused on the development of validated prediction capabilities for the rotorcraft system noise and vehicle components, i.e. rotor, engine, interior noise, propagation and acoustic scattering. The system capabilities combine the components such that rotorcraft source noise and its propagation can be investigated for noise impact due to rotor design and/or rotorcraft operations and procedures. The tools will cover a range of fidelity, in that they will include first principle CFD and CSD capabilities and validated analysis tools that are also appropriate for integration into the multi-disciplinary predictive capabilities defined at Level 2 and more extensively at Level 3.

Much of the noise physics associated with individual vehicle components, the installation of these components for different vehicle configurations and the resulting noise propagation are poorly understood from a first-principles basis. The prediction capabilities, particularly for broadband noise sources, rely on empirical methodologies determined using measured data for specific configurations and operating conditions. In the last year the DARPA Helicopter Quieting Program has made significant progress in developing first-principles based computational methods that provide critical tools and the foundation required to explore and understand fundamental noise source generation associated with the rotor system. Many of these computational tools, particularly the turbulence models and LES methods will be extended and applied to advance prediction capabilities for engine noise and propagation as well as rotorcraft component and system noise capabilities.

Based on current expertise and support from Government and industry partners, NASA will focus its Level 2 acoustic research on developing and validating component and rotorcraft system noise prediction capabilities. Level 1 research will focus on advancing the fundamental understanding of the source noise generation (internal and external) and propagation phenomena to develop and validate physics-based and first-principles-based analysis tools as appropriate. As with the Aeromechanics efforts, experimental test data (model and flight) will be critical in developing, validating and improving the accuracy of physics-based and ultimately first-principles analysis methods. In Table 2 nominal goals for predictive capability as well as estimates for current accuracy of general acoustic engineering analyses and general physics-based models of arbitrary rotorcraft are given. The noise metrics and noise goals provided in the following Level 2 and Level 1 milestones are based on specific vehicles, rotors, operating conditions that data is (or will be) available for validation. Hence noise levels specified are significantly lower than those in Table 2, which are for arbitrary rotorcraft configurations and operating conditions.

Task 1. Cabin Noise Modeling and Reduction

Spatially accurate predictions of the rotorcraft interior sound field are currently limited to low frequencies. Energy finite element methods (EFEM) will be used to extend this frequency range to a few thousand Hz without undue computational burden. Dominant acoustic paths can be evaluated and concepts for passive and active noise control developed using an EFEM model of the sound field. This task integrates efforts in the drive train tasks that provide the forcing function to the fuselage interior and the structures and materials tasks that provide innovative structural concepts with optimized noise transmission and actuators for active vibration control. The milestones and deliverable for this effort are:

Number	Title	FY	Metric	Dependencies
SRW.2.04.01	Validate energy finite element model of representative rotorcraft structure for interior noise	08	Model spatial dependence to within +/-5 dB of measurements in middle frequency range	SRW.1.04.01-02
SRW.2.04.02	Validate gear vibration transmission model with experimental data	10	Validate prediction of gear vibrations transmitted to structure within 90% accuracy of measured data.	SRW.2.04.01 SRW.1.04.02-03
SRW.2.04.03	Transducer development for active noise control	11	Validate interior noise reduction using active materials within 5dB of experimental data	SRW.2.04.01-02 SRW.1.04.04

Key Deliverables for Task 1. Cabin Noise Modeling and Reduction	FY	Related Milestones
Methodology to model rotorcraft structural-acoustic components for interior noise prediction.	08	SRW.2.04.01

Task 2. Vehicle Aeroacoustics and Propagation

The effects of rotorcraft operations and procedures on the radiated noise are to be investigated. Development of low noise procedures requires careful integration of rotorcraft design, flight operations, vehicle handling qualities and flight controls. Through a means of controlling or guiding an aircraft, noise reduction will be achieved using advanced, constrained, and stochastic real-time optimization methods and surface response. Acoustic flight testing in FY08 will be conducted to obtain critical data for validation of rotorcraft system noise prediction and propagation capabilities and to develop and validate processes for determining low-noise procedures with acceptable handling qualities and performance. Optimized low-noise operations are to be validated with acoustic flight test data obtained in FY10. Figure 14 shows the noise footprint predicted for a trajectory. The milestones and deliverables for this task are:

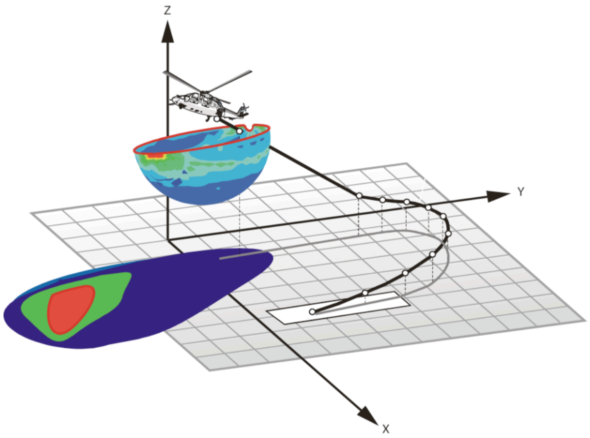

Figure 14: Predicted source noise hemispheres and resulting noise impact on the ground.

Number	Title	FY	Metric	Dependencies
SRW.2.04.04	Prediction capability for flight vehicle source noise and candidate low noise procedures	09	Validate noise prediction for non-steady flight conditions using RNM/QS and ATRA within 5 dB of measured peak noise levels from Bell 206 and XV15 flight test data. Demonstrate capability to determine and predict low noise procedure within 5 dB of max contour area level.	SRW.1.02.04 SRW.1.04.08-11

SRW.2.04.05	Methodology and predictive capability for optimized low noise procedures	10	Predict peak noise levels generated during low noise procedures within 3 EPNdB of flight test data (UH60)	SRW.2.04.04 SRW.1.02.04 SRW.1.04.08-11
SRW.2.04.06	Validated tool for optimum low noise procedures and impact	11	Validate prediction of noise impact within 1 EPNdB for measured low noise procedures using RNM and measured vehicle source noise database	SRW.2.04.04-05 SRW.1.02.06 SRW.1.04.08-11

Key Deliverables for Task 2. Vehicle Aeroacoustics and Propagation	FY	Related Milestones
Comprehensive flight acoustic database for steady and non-steady operations	09	SRW.2.04.04
Low noise flight operations predictive capability and rotorcraft source noise database	10	SRW.2.04.05

Task 3. Rotor Acoustics Characterization and Mitigation

The rotor is a main source of noise from rotorcraft vehicles. Complete understanding of the noise generation and capability to accurately predict the acoustic field from rotors for the full range of flight conditions from low to high speed, descent to climb and for different rotor designs is not fully realized. The problem is complicated because the noise source mechanisms (level and directivity) are functions of operating condition and rotor blade design. Development of accurate noise prediction capabilities requires comprehensive data, that includes not only performance, but also high-resolution unsteady rotor airloads, rotor wake and blade motion. Currently the HART II model rotor data and the UH60 flight database are of the most comprehensive database available, but both have limitations. This task includes a number of new tests and some that build upon these existing databases to include rotors of different designs, active control and operating conditions. The focus is to understand noise physics, as well as develop and validate acoustic prediction capabilities for all rotor noise sources (including blade-vortex-interaction (BVI), broadband, and high speed impulsive noise). The following milestones involve validation of noise prediction capability using wind tunnel test data. Key deliverables are also shown.

Number	Title	FY	Metric	Dependencies
SRW 2.04.07	IBC UH60 Acoustic Investigation	07	Predict, using ATRA, peak noise trends for IBC and non-IBC conditions within 3dB of wind tunnel test data	SRW.4.01.01
SRW 2.04.08	UH60 Aeroacoustic investigation	08	Predict, using ATRA, acoustic directivity trends and maximum noise levels within 3dB of wind tunnel test data	SRW.2.04.07
SRW 2.04.09	Active Aeroacoustic Rotor investigation	10	Predict, using ATRA, peak noise trends within 3dB for active and non-active control conditions (HART, IBC)	SRW.2.03.02 SRW.2.04.07

Key Deliverables for Task 3. Rotor Acoustics Characterization and Mitigation	FY	Related Milestones
Aeroacoustic database of active/passive noise controlled rotor systems	10	SRW.2.04.09
Validated active noise control prediction capability	11	SRW.2.04.07-09

Task 4. Component and Rotorcraft System Noise

Accurate prediction of rotorcraft noise is key to enabling existing and new designs of future rotorcraft. Prediction of rotorcraft vehicle and component noise requires accurate and high-resolution aeromechanics and performance prediction capabilities for the rotor wake geometry and vortex details, rotor blade airloads and blade motion. Specific CFD analyses tools using structured (OVERFLOW2) and unstructured grids (FUN3D) are to be integrated as part of the rotorcraft component and system noise toolset, ATRA (Aeroacoustic Toolset for Rotorcraft Analysis). The CFD codes will be assessed for their improvements in acoustic prediction compared to more traditional comprehensive analyses. The computational and accuracy costs will be documented and allow the user to determine the correct analyses tools for specific applications. The validation of these tools for acoustic applications rely on both flight and model data obtained at the other Level 2 and 1 tasks in Acoustics and Aeromechanics. The milestones and deliverables are:

Number	Title	FY	Metric	Dependencies
SRW.2.04.10	ATRA tool set validation	09	Validate ATRA component prediction capabilities for engine, rotor and interior noise within 5dB of peak noise levels of measured wind tunnel (HART) and flight measurements (UH60, Bell 206).	SRW.2.04.07-08
SRW.2.04.11	Subjective noise simulation capability	10	Demonstrate subjective assessments of simulated using RNM (and measured vehicle source noise database) and ATRA and recorded flyovers within 3dB of peak noise levels.	SRW.2.04.10
SRW.2.04.12	ATRA tool set validation.	11	Validate component, system, and interior noise predictions within 3 dB of peak noise levels for level flight and within 5 dB of peak noise level for maneuvers, relative wind tunnel and flight test data (Uh60, HART, Bell 206)	SRW.2.04.10-11

Key Deliverables for Task 4. Component and Rotorcraft System Noise	FY	Related Milestones
Technical report assessing component and system noise tools	07	SRW.4.01.01
Rotorcraft component noise (broadband, engine) and propagation models for system noise analyses	09	SRW.2.04.10
Rotorcraft subjective noise simulator and database	10	SRW.2.04.11
Validated Aeroacoustic Toolset for Rotorcraft Analysis	11	SRW.2.04.12

SRW.1.04 Acoustic Physics

Level 1 Acoustics research consists of three task areas that concentrate on the fundamental understanding of exterior and interior source noise physics and noise propagation that are most unique to rotorcraft with the goal of developing and validating prediction capabilities based on first principles. For the accurate prediction of exterior noise sources, accurate predictions of the wake geometry and vortex properties including turbulence levels are critical. For rotors as tip speeds decrease the broadband self-noise physics can become dominant. The vortex properties and associated turbulence levels also are significantly altered and change the BVI noise generation physics. For interior noise developing a fundamental understanding of gear vibration transmission through the shaft/bearing/housing system is crucial to developing effective vibration attenuation technologies. The determination of noise impact and low noise procedures requires methods to account for acoustic scattering and propagation need to be developed and validated. The efforts and milestones for each of the three tasks are critical and directly feed into one or more of the Level 2 acoustic elements.

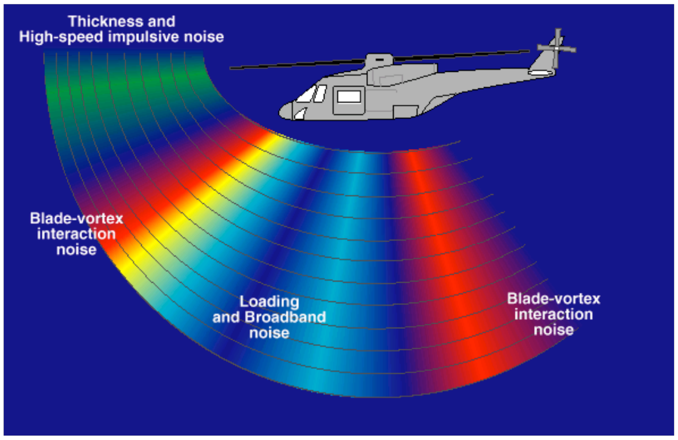

Figure 15. External noise source mechanisms and their directivity.

<u>Task 1. Fundamental vibro-acoustic modeling and validation</u>

Interior noise is dominated by the meshing frequencies of the drive train. Vibrations from the drive train are structurally transmitted to the cabin resulting in high noise levels. Novel gear vibration reduction and isolation technologies such as active control of rotating components and vibration isolation wave bearings are needed to mitigate structure-borne gear noise. Models to predict the gear noise generation and vibration transmission through the shaft/bearing/housing system, including bearing isolation effects, and active control theory are to be developed and validated. Models for predicting interior noise are limited to a small number of low frequencies. Emerging energy finite element methods are to be applied to the rotorcraft interior noise problem, hence this work extends the state-of-the-art for interior noise prediction tools. EFEM avoids low frequency limitations and provides continuous energy spatial information. Integrating the drive train, interior noise and structural materials prediction capabilities will produce a tool than can be used to derive acoustic requirements for active damping treatments, transmission mounts, and novel structural concepts. The milestones and deliverables are:

Number	Title	FY	Metric	Dependencies
SRW.1.04.01	Develop improved energy analysis method for mid/high frequency for simple metallic/composite structure	07	Model mid-frequency sound field in simple enclosed space within 5 dB of experimental data	
SRW.1.04.02	Advanced gear vibration transmission model developed	08	Complete model development to predict gear vibration within 20% of measured data	
SRW.1.04.03	Wave bearing vibration reduction concept developed	09	Demonstrate 50% reduction in transmitted vibration using advanced wave bearing	SRW.1.04.01, SRW.1.04.02
SRW.1.04.04	Structural concepts with improved acoustical properties	11	Demonstrate 5dB interior noise reduction at targeted frequencies using novel structural concepts	SRW.1.04.01-03

Key Deliverables for Task 1. Fundamental vibro-acoustic modeling and validation	FY	Related Milestones
Energy finite element model of simple structural-acoustic components relevant to rotorcraft.	07	SRW.1.04.01
Material systems with optimized noise transmission loss properties	11	SRW.1.04.04

Task 2. Source Noise Physics

Key rotor source noise generation (Fig. 15) is due to the rotor blade interacting with its own wake or the wake of another blade (BVI, BWI), blade self noise (turbulent boundary layer trailing edge (TBL-TE) noise, bluntness noise and laminar boundary layer TE noise) and high speed impulsive noise (shock formation on or near rotor blade surface). The BVI, BWI and self-noise sources are the most common for civil rotorcraft designs. Broadband sources can dominate for lower speed rotors. Accurate rotor wake prediction is critical for BVI and BWI noise prediction. Current wake prediction capabilities based on CFD lack the fidelity to define the vortex details for any extent of the wake geometry without significant smearing, even though much progress has been made. Assessment of the CFD methods compared to advanced wake models and alternate models based on vortex transport equations for acoustic tool development is needed. This will identify available wake predictions capabilities for acoustics and identify the acoustic requirements for CFD wake prediction capabilities. Wake bursting phenomena is not well understood and measured data are needed to advance the understanding in order to develop and validate prediction methodologies. Broadband rotor noise prediction capability exists for wind tunnel conditions based on a specific rotor design and boundary layer characteristics. A more general broadband capability that is validated for wind tunnel and flight conditions as well as arbitrary blade wake interaction and boundary layer characteristics will be developed using existing data from HART II and CFD predictions. The method is to be further validated using data from future tests. The milestones and deliverables are:

Number	Title	FY	Metric	Dependencies
SRW.1.04.05	Acoustic concept evaluation and wake bursting phenomena investigation	08	Validate noise prediction tools within 3 dB relative to peak noise level measurements from benchmark wind tunnel test, for multiple wake interaction and BVI conditions	

SRW.1.04.06	Wake characterization and modeling sensitivities critical for acoustics	08	Validate wake geometry and vortex definition for first 4 wake revolutions with 20% predictive accuracy relative to measured HART II wake data.	SRW.1.04.05
SRW.1.04.07	Source noise Reynolds number effects	09	Validate acoustic predictions within 3 dB of peak noise levels from wind tunnel measurements (HART, UH60, aeroacoustic parameter test results), for rotors operating at low tip speeds	SRW.1.04.05-06

Key Deliverables for Task 2. Source Noise Physics	**FY**	**Related Milestones**
Technical report assessing source noise prediction capability for broadband noise and HSI	07	SRW.4.01.01
Validated rotor broadband and BVI noise prediction capability for flight and model rotors	09	SRW.1.04.05-07

Task 3. Noise propagation and scattering

Current noise propagation methods are based on single ray tracing, do not account for shadow zones and caustics, and are limited to mid to high frequencies (greater than 100Hz). Multi-path ray tracing methods are to be developed and validated in order to account for terrain and three-dimensional atmospheric affects. The ray tracing methods are unable to account for shadow zones and caustics. Methods based on parabolic equations using Green's functions can account for shadow zones and caustics and are more accurate for lower frequencies (less than 100Hz). The approach is to develop a hybrid method that merges the two methodologies and applies the appropriate approach based on frequency, height, atmospheric and terrain conditions. Noise scattering from fuselages can be accounted for using equivalent source methods with multi-pole techniques to extend to higher frequencies. The synthesis of component noise sources and propagation through a relevant atmosphere and terrain is to be developed. This will require subjective assessment of predicted noise and enhancements to that obtained using measured noise. Propagation and scattering research highly leverages SFW supported work. The milestones and deliverables are:

Number	**Title**	**FY**	**Metric**	**Dependencies**
SRW.1.04.08	Noise scattering and propagation capability	07	Validate accuracy of curved ray propagation methodology to predict MD600 flight acoustic data within 5dB at 150ft altitude for temperature inversion weather condition.	
SRW.1.04.09	Real time exterior noise simulation capability	08	Demonstrate simulated 3-D exterior acoustic environment with localization accuracy better than 30-deg.	SRW.1.04.08
SRW.1.04.10	Propagation analyses for multi-path, terrain, atmospheric effects	09	Validate low frequency noise propagation predictions within 5 dB of peak noise level measurements obtained in representative non-uniform 2-D atmosphere (MD600)	SRW.1.04.09 SRW.2.04.04
SRW.1.04.11	Rotorcraft flyover simulation capability	09	Demonstrate ability to simulate rotorcraft noise sources with RNM (and measure vehicle source noise database) within 3 EPNdB of target sound level	SRW.1.04.10
SRW.1.04.12	Noise scattering/multipole, hybrid propagation model	11	Demonstrate capability to predict the peak levels of the scattered noise field within 3dB of target sound level (HART, JVX).	SRW.1.04.11

Key Deliverables for Task 3. Noise propagation and scattering	**FY**	**Related Milestones**
Hybrid acoustic propagation prediction capability for low to high frequencies	09	SRW.1.04.10
Validated prediction capability for rotorcraft acoustic scattering and propagation in 3-D environment	11	SRW.1.04.12

SRW.2.05: Structures and Materials

More than any other vehicle class, rotorcraft are extremely weight-sensitive due to the hover requirement. Hence, rotorcraft are often designed with minimum-gage shear-loaded skins that are allowed to buckle in service. Damage tolerance requirements for thin-face sheet sandwich and skin-stringer constructions typically drive these designs. The harsh cyclic load environment in which rotorcraft operate and the need to ensure survivability in low-speed crashes impose severe durability and structural integrity requirements. Furthermore, rotorcraft have unique engine and transmission configurations that drive material development for reduced cabin noise, increased engine durability, and lower weight. For these reasons, NASA has chosen to focus on three Structures and Materials topic areas for the subsonic rotary wing program. These are:

1) Development of methodologies for predicting fatigue life of rotorcraft components
2) Development of methodologies for advanced damage tolerance and predicting crashworthiness of rotorcraft structural configurations
3) Development of advanced materials concepts

Task 1: Development of methodologies for predicting fatigue life of rotorcraft components

Durable, lightweight rotorcraft designs require accurate fatigue life prediction technologies. This is becoming increasingly important, as future rotorcraft designs will require higher and higher power-to-weight ratios. Currently, fracture mechanics is not used at all in the design and certification of composite rotor and airframe components. Industry and FAA acceptance of a delamination fatigue methodology based on Interlaminar Fracture Mechanics (ILFM) requires the successful demonstration at the structural level. Several areas need to be validated by testing on small subcomponents, and full-scale articles such as a stringer stiffened panels. Implementation of a damage tolerance methodology may require modeling an assumed initial flaw, either from manufacturing or handling during assembly. In addition, delamination growth prediction is particularly challenging due to progressive damage and multiple delamination paths observed in real components. Finally, limitations in life prediction criteria need to be identified and addressed through developing new methodologies and approaches.

Life prediction is also an area of research for the rotorcraft engine disk. The many high-speed excursions and loads that the rotary engine experiences during missions can result in lower efficiencies and power/weight ratios because of the engine disk's susceptibility to fatigue damage. Superalloys produced using powder metallurgy processes are of interest because of their superior durability at higher temperatures and stress levels, but disk designer acceptance relies upon tightly controlled processing and the ability to successfully predict the reliability of these components. In order to move this technology forward, a validated, probabilistic life prediction methodology will be developed.

An assessment will be performed in FY07 to determine tools and technologies currently available to enable life prediction of various rotorcraft components and systems. Specific tools and concepts will be developed in the areas of powdered metal disk alloys and delamination technologies to advance the state of the art in these technologies along with the ability to accurately predict life. Tools developed will be validated using various component test facilities at Glenn Research Center, and the fatigue and fracture laboratory at Langley Research Center. The developed tools and concepts will be part of the Level 3 Design Tools Workshop in FY09 and FY11.

Milestones and deliverables for this task:

Number	Title	FY	Metric	Dependencies
SRW.2.05.01	Probabilistic engine disk failure assessment	07	High probability failure regions identified within 95% confidence level	
SRW.2.05.02	Identify the effect of	09	Quantify impact of inclusion levels in complex-shaped	SRW.2.05.01

	inclusions on the fatigue life of disk materials by experimental seeded inclusion studies and modeling.		PM superalloy disk material life to standard deviation of ±3%.	
SRW.2.05.03	Validate probabilistic life model of PM superalloy disk material.	11	Demonstrate 50% improvement in predicted superalloy disk life with a probability of failure at < 10^{-5} with the probabilistic inclusion life model.based on 2007 SOA.	SRW.2.05.01 -02
SRW.2.05.04	Fatigue delamination methodology for rotorcraft components	11	Predict composite fatigue life within 10% of measured component life.	SRW.1.05.04 - 07

Key Deliverables for Task 1: Development of methodologies for predicting fatigue life of rotorcraft components	**FY**	**Related Milestones**
Incorporation of fatigue life prediction methodology for rotorcraft design into Mil-Hbk-17	11	SRW.2.05.04
Verified methodologies to predict the reliability of critical superalloy engine components	11	SRW.2.05.03

Task 2: Development of methodologies for advanced damage tolerance and predicting crashworthiness of rotorcraft structural configurations

New computational methods are needed to predict the structural response, durability, and damage tolerance of multifunctional thin-face sheet sandwich and skin-stringer constructions for rotorcraft airframes. Achieving substantiation of structural performance by testing alone—as is the current industry practice—is prohibitively expensive because of the number of specimens and components required to characterize all loading conditions. The use of advanced analytical or numerical models for the prediction of the mechanical response and damage of composite structures can replace some of the mechanical tests and can significantly mitigate the technological risks of designing with composites while providing to the engineers the information necessary to achieve optimized designs (Fig. 16). New robust physics-based structural analysis methods must be developed that allow the evaluation of the structural performance of new materials and structural concepts. These tools will provide a better understanding of the impact resistance and damage tolerance in composite structures.

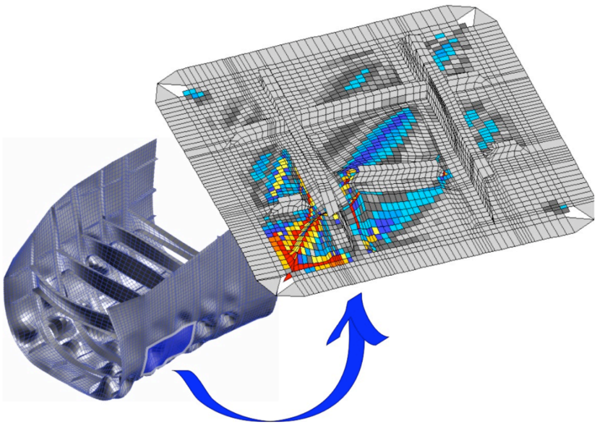

Figure 16. Advanced modeling for predicting the strength and damage tolerance of new airframes and rotors.

In a separate research area requiring tool development, the verification of analytical/computational tools for accurate crash simulation is imperative to fully utilize the recent advances in computational speed and thus greatly enhance crashworthy design and evaluation. Recently, crash simulations have been performed using nonlinear, explicit transient dynamic finite element codes. While some progress has been made in validation of these codes, a general lack of confidence in the accuracy of analytical crash predictions remains, especially for airframes constructed of advanced composite materials. An assessment will be performed in FY07 to determine tools and technologies currently available to simulate helicopter crashworthiness and predict resulting structural damage. A variety of tools and concepts will be developed to more accurately predict the performance of materials and structures subject to crash impact, thus leading to the increase of the crashworthiness technologies of rotorcraft structures. A comprehensive validation strategy will require conducting tests ranging from material characterization specimens for impact loads all the way to a full-scale helicopter crash test at the Langley Landing and Impact Dynamics Facility. The helicopter will be retrofitted with novel energy absorbing concepts. Data collected would include accelerometers, load cells, strain gages, etc. at a sampling rate of 10,000 samples per second. Volumetric change in the cabin would be determined by photogrammetric methods. State-of-the-art simulation codes would be used to develop a finite element model of the test article and occupants. Validated models and technologies developed will be available at the Multi-Discipline Design Tools Workshop in FY09 and FY11. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.05.05	Assessment of LSDYNA crash simulation code	07	Evaluate three material characterization models and identify best model	
SRW.2.05.06	Predict compressive residual strength of thin-skin rotorcraft sandwich panels	09	Predict compression after impact strength w/in 10% of measured values	SRW.1.05.08 - 09
SRW.2.05.07	Develop progressive damage analyses for rotorcraft airframes	10	Predict damage initiation and damage propagation rates in representative thin-skin airframe components with an error smaller than 15% compared to test values.	SRW.1.05.08 SRW.1.05.10
SRW.2.05.08	Develop approaches for composite material characterization under impact loading	10	Quantify the effect of impact loading on the engineering properties of 2 common composite materials.	SRW.2.05.05
SRW.2.05.09	Integrated simulation of helicopter crash	10	Predict cabin volumetric reduction w/in 20% of measured data	SRW.2.05.05 SRW.2.05.08
SRW.2.05.10	Develop and validate sub floor conceptual design models	11	Demonstrate occupant survivability to 5 m/s	SRW.2.05.08 - 09 SRW.2.05.05

Key Deliverables for Task 2: Development of methodologies for advanced damage tolerance and predicting crashworthiness of rotorcraft structural configurations	**FY**	**Related Milestones**
Design methodologies for improved residual strength after low-velocity impact of sandwich structures	09	SRW.2.05.06
Strength analysis methodologies for predicting the strength and durability of composite airframes	10	SRW.2.05.07
Predictive capabilities for full-scale helicopter crash simulations	10	SRW.2.05.09

Task 3: Development of advanced material concepts

Weight, durability and performance are critical concerns for any rotorcraft. Newly emerging advanced engine material systems will be developed that combine load bearing and acoustics/vibration damping capabilities for engine noise reduction at high temperatures. In this task, two materials will be evaluated for effectiveness in improving small engines suitable for rotorcraft applications. Monolithic silicon nitride is an ideal material for hot sections due to its high strength, erosion resistance, and other properties. The key technical challenge is the environmental durability of the coating. Studies of the impact resistance against foreign object damage of modified environmental barrier coatings will be evaluated in order to improve performance of silicon nitride. Silicon carbide fiber-reinforced silicon carbide (SiC/SiC) is the second material that will be investigated for its ability to offer the benefits of Ceramic Matrix Composites (CMCs) such as significant weight reductions, high temperature capability, and noise reduction for application as engine components, exhaust heat shields and acoustic materials. Other advanced materials will also be investigated for rotorcraft-specific applications, such as multi-functional polyimide foam cores for active/passive cabin noise suppression will be evaluated at the polymeric laboratory at the Langley Research Center (LaRC).

An assessment will be performed in FY08 to determine tools and technologies for CMC engine components, along with identifying quantitative benefits over current SOA. Advanced models and concepts will be validated using high temperature engine component test facilities at GRC. Validated models and technologies developed will be available at the Multi-Discipline Design Tools Workshop in FY09 and FY11. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.05.11	Investigate benefits of CMC and silicon nitride materials compared to current SOA materials	08	Identify and demonstrate bond coat for SiN that extends life 2X over uncoated SiN	
SRW.2.05.12	Develop physics based modeling tools for ceramic systems	10	Model predictions within 10% of test data	SRW.2.05.11
SRW.2.05.13	Develop and validate polyimide foam core concepts for cabin noise suppression	11	20 dB cabin noise reduction with active core, 10 dB with passive core compared to conventional cabin liners	SRW.1.04.04 SRW.1.05.08
SRW.2.05.14	Demonstrate advanced CMC concepts and modeling tools	11	Extend life of selected CMC component structure beyond today's metallic-based construction by 3X	SRW.2.05.11 - 12

Key Deliverables for Task 3: Development of advanced material concepts	FY	Related Milestones
Damage models for predicting the nonlinear material response of CMC engine components	10	SRW.2.05.12
Structural concept with integrated active/passive noise attenuation	11	SRW.2.05.13

SRW.1.05: Solid Mechanics, Advanced Materials

The tasks below outline specific research in fundamental solid mechanics modeling and development of advanced concepts to provide the necessary support for various Level 2 disciplines.

Task 1: Development of physics-based tool for predicting the impact of erosion and reducing its severity on coated turbine blade life

Ingestion of soil, small pebbles and debris into the rotorcraft engine leading to turbine and compressor blade/vane degradation, is common. Advancements in providing protection require an understanding and an ability to model the effects of erosion under the realistic blade/vane thermal gradient conditions experienced in a rotorcraft engine. Models and concepts will be developed to extend turbine blade life and provide more accurate life prediction tools. An experimental plan to acquire critical property/performance data will be developed with support from industry, and the new test data will be used to address model deficiencies. Milestones and deliverables for this task:

Number	Title	FY	Metric	Dependencies
SRW.1.05.01	Develop physics based tool for predicting blade life subject to erosion	08	Predict blade life subject to erosion within 30% of measured values	
SRW.1.05.02	Develop advanced erosion resistant coatings	10	Extend erosion resistance (coating life) by 3X with the use of erosion resistant coating beyond the current state-of-the-art thermal barrier coating (7-weight percent yttria-stabilized zirconia)	
SRW.1.05.03	Validate advanced erosion coating and engine blade life prediction model	11	Demonstrate agreement between predictive model and experiment within 10%	SRW.1.05.01 – 02

Key Deliverables for Task 1: Development of physics-based tool for predicting erosion resistant coatings impact on turbine blade life	**FY**	**Related Milestones**
Advanced erosion resistant coatings for engine blades	10	SRW.1.05.02
Predictive methods for the erosion rates of advanced coatings for engine blades	11	SRW.1.05.03

Task 2: Develop methodologies for the prediction of fatigue damage and self-healing

This task focuses on developing physics-based tools to assess fatigue damage in materials and structures. Composite rotorcraft fuselage structures typically consists of very thin skins in either a sandwich or skin/stiffener configuration. For the skin/stiffener configuration, low-weight designs require that the thin skins be designed for post-buckled operations. The stiffeners are also usually bonded to skins, and they debond due to large out-of-plane displacements when buckling occurs. Delamination in skins made with polymer matrix composites further complicates the failure. A unique solution to improve damage tolerance is to reinforce the skin/stiffener bond line with small diameter carbon pins (z-pins). Investigation into this and other self-healing concepts of critical components will be evaluated and modeled. Models and concepts will be validated using the fatigue and fracture laboratories at LaRC. Milestones and deliverables for this task are:

Number	**Title**	**FY**	**Metric**	**Dependencies**
SRW.1.05.04	Develop fatigue decohesion finite element technology	08	Predict delamination growth w/in 20% of measured value	
SRW.1.05.05	Develop methodologies for flexible multi-functional composite rotor structures	08	Life loss due to embedded sensor less than 5% original component	
SRW.1.05.06	Develop high cycle analysis tool for airframe structure	09	Acoustic load life prediction w/in 50% of measured value	
SRW.1.05.07	Develop Z-pin / self heal concept	09	Demonstrate that self-healing matrix with z-pin reinforcement recovers 90% of fatigue life of skin-stiffened composite	

Key Deliverables for Task 2: Develop methodologies for the prediction of fatigue damage and self healing	**FY**	**Related Milestones**
Finite element analysis tool for predicting high-cycle fatigue crack propagation	08	SRW.1.05.04
Fatigue-resistant self-healing joint reinforcement concept	09	SRW.1.05.07

Task 3: Develop methodologies for the prediction of damage tolerance and strength of thin-skin composite airframes

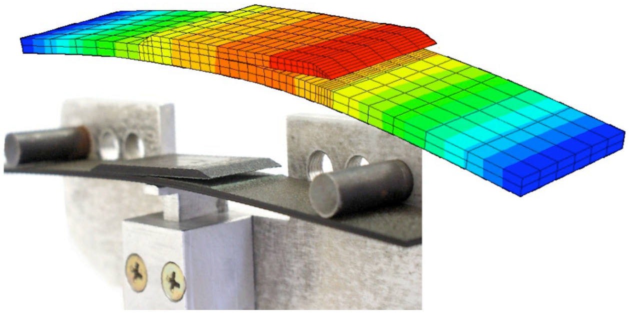

Figure 17: Interlaminar fracture mechanics modeling.

The lowest weight solution for rotorcraft airframes is the skin-stiffener composite construction. However, this construction often results in minimum-gage shear-loaded skins that must operate deep into post buckling, presenting rotorcraft configurations with unique structural issues. This Level 1 task will develop efficient global/local analysis procedures to calculate the load distributions, strength, and damage tolerance of thin-skin rotorcraft airframes (Fig. 17). NDE inspection techniques will be developed to detect damage and monitor damage propagation. Results of tests conducted at the Langley structures and materials laboratories, the materials research laboratory, industry partner laboratories, and other available data will be used for the validation of the analysis methods. Industrial partners are expected to provide specimens for testing as part of collaborative agreements established within this project.. We anticipate participating with the AAD Project on areas of overlap. Milestones and deliverables for this task:

Number	Title	FY	Metric	Dependencies
SRW.1.05.08	Develop damage models for lightweight skin-stiffened and sandwich constructions	08	Predict ultimate failure load of notched panels w/in 10% of experimental values	
SRW.1.05.09	Develop accurate NDE method for sandwich panel face sheets	10	Detect facesheet disbonds greater than 1 in.	
SRW.1.05.10	Develop damage resistance and damage tolerant core and skin concepts	11	Demonstrate compression after impact strength increase of 15% for same-weight sandwich panels tested FY05-07	SRW.1.05.08 – 09 SRW.2.05.06

Key Deliverables for Task 3: Develop methodologies for the prediction of damage tolerance and strength of thin-skin composite airframes	FY	Related Milestones
Verified Progressive Damage Analysis tools for predicting the initiation and propagation of damage in thin-skin composite constructions	09	SRW.1.05.08
Predictive tool for residual strength after impact for thin-skin structural concepts	11	SRW.1.05.10

SRW.2.06 Experimental Capability
SRW.1.06 Fundamental Measurement Science

With validated, physics-based design tools as an over-arching goal for SRW, experimental techniques must keep pace with advances in computational modeling. If the analyses can model a phenomenon, there must be a way to measure the phenomenon in order to validate the analytical model. Current state-of-the-art CFD analyses are able to model the entire rotor disk and surrounding flow field, but the equivalent information has yet to be measured. The highly integrated nature of rotorcraft problems pose very difficult challenges to the experimentalist in terms of developing and applying techniques that result in quantitative measurements that satisfy the needs of the technical disciplines described earlier. These challenges include measuring the rotor wake, the blade airloads, the blade deformation, and the in-flight rotor state (position of tip-path-plane). In the last 10 years, advances in imaging technology have enabled detailed measurements of the rotor wake including the core size of the blade tip vortex. However, these measurements are typically restricted to a small range in rotor azimuth. Similarly, blade surface pressure measurements using paints have only been acquired for limited regions of the rotor disk in terms of azimuth and blade span and only on the blade upper surface. Improving efficiency in acquiring measurements in the rotating frame is also a major challenge. Set-up time for optics and imaging equipment is substantial so re-positioning equipment to acquire data covering different sections of the rotor disk is severely restricted in a time-constrained wind tunnel test. Innovative techniques for the rapid acquisition of flow measurement data are crucial for meeting the validation milestones established by the other technical disciplines.

The proposed research at Level 2 concentrates on the development and implementation of functionally independent instrumentation systems for rotorcraft applications. These systems will be used throughout the SRW project for the acquisition of experimental data in laboratory, wind tunnel, or flight tests for validation of rotorcraft predictive codes. The development of independent instrumentation systems at Level 2 is also a precursor to achieving the Level 3 Milestone SRW.3.04.01, wherein multiple instrumentation systems will be integrated and applied simultaneously to investigate interactional aeromechanics and acoustics phenomena.

Fundamental research and technology assessments of measurement techniques for rotorcraft testing represent the key activities at Level 1. Future instrumentation systems arising from the Level 1 fundamental research must be robust enough to operate in the primary SRW testing facilities: the 14- by 22-Foot Subsonic Tunnel, the Transonic Dynamics Tunnel (TDT), and the National Full-Scale Aerodynamics Complex (NFAC). These facilities have completely different characteristics, and fundamental research is required to determine which techniques can be optimally deployed in each facility. Many of the milestones are directed toward investigating and quantifying the expected performance characteristics of candidate measurement techniques for different facilities, such that the best choice for implementation can be made in Level 2 and 3.

Research in the Experimental Capability discipline is grouped into three primary tasks.

<u>Task 1. Advanced Instrumentation for Aeromechanics</u>

Optical instrumentation systems for wind tunnel experiments will be developed to satisfy three primary measurement requirements for validation of rotorcraft aeromechanics predictive codes. These are 1) measurement of blade geometry (e.g. shape, attitude, deformation) over the full rotor azimuth; 2) measurement of blade surface pressure distribution over the full rotor azimuth; and, 3) large-field assessment of the rotor wake flow. Figure 18 shows a demonstration optical system in the 14- by 22-Foot Subsonic Tunnel (14x22-FST). Figure 19 shows the application of pressure sensitive paint to the tip region of a model rotor. Fundamental research will be conducted in optical measurement techniques for acquiring experimental data for validation of aeromechanics predictive codes. This research includes exploring implementation issues, quantifying the expected performance characteristics of candidate techniques if used in the primary SRW testing facilities, and documenting the uncertainty in each type of measurement. Each measurement system milestone is comprised of a set of demonstrations documenting the instrumentation performance of the system.

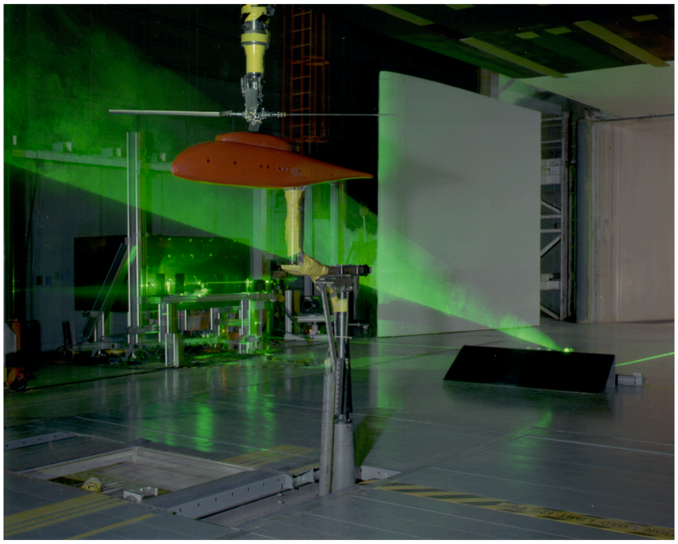

Figure 18: Optical wake measurement demonstration in the 14-x 22-FST

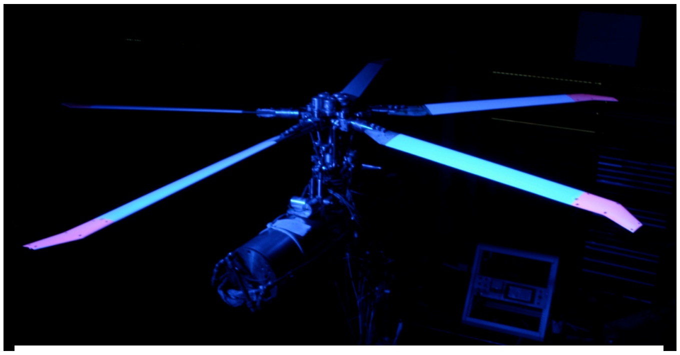

Figure 19. Dynamic Pressure Sensitive Paint (PSP) on the blades of a spinning rotor. PSP is pink area near blade tips.

The milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.06.01	System for blade geometry measurement	09	Measure rotating blade flap deflection with 0.5mm accuracy	SRW.4.01.01 SRW.1.06.01 SRW.2.03.02 SRW.2.03.04 SRW.1.06.02
SRW.1.06.01	Diagnostics for blade geometry	07	Develop full-azimuth blade geometry measurement concepts for primary SRW testing facilities with accuracy no less than 2003 partial-azimuth data	SRW.4.01.01
SRW.2.06.02	System for blade surface pressure measurement	09	Verify pressure measurement accuracy based on Pressure Sensitive Paint (PSP) technology within 2% of reference pressure transducers	SRW.4.01.01 SRW.1.06.02
SRW.1.06.02	PSP Implementation strategies	08	Pressure sensitivity, accuracy, dynamic range, and time response within 30% compared to conventional surface pressure transducers.	SRW.4.01.01
SRW.2.06.03	System for rotor wake assessment	09	Demonstrate ability to measure 2 components of flow velocity within 1.5 m/s	SRW.4.01.01 SRW.1.06.03 SRW.2.03.06 SRW.2.03.07
SRW.1.06.03	Diagnostics for rotor wake	08	Performance characteristics of non-intrusive measurement techniques quantified to 80% certainty level when applied in the primary SRW testing facilities	SRW.4.01.01
SRW.1.06.04	Diagnostics for flow control	11	Demonstrate measurement uncertainty of methods to within 95% confidence level for unsteady flow pressure measurements.	SRW.4.01.01

Key Deliverables for Task 1. Advanced Instrumentation for Aeromechanics	**FY**	**Related Milestones**
Instrumentation system for blade geometry measurements over full rotor azimuth	09	SRW.2.06.01
Instrumentation system for blade surface pressure measurements	09	SRW.2.06.02
Instrumentation system for large field-of-view rotor wake assessment	09	SRW.2.06.03

Task 2. Sensor systems for Engines and Drive Trains

The transfer of unsteady loads from the rotor through the hub, shaft, and drive train can result in excessive vibration and acoustic emission in the fixed system. Careful design of drive train components can minimize the detrimental effects of unsteady loads. High temperature, high pressure sensor systems will be developed to measure the data required to validate gear, drive train, and engine loads, vibration, and acoustics models for improved design capabilities. This task area also encompasses fundamental research on silicon carbide manufacturing techniques for high temperature sensors. Milestones and the deliverable for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.06.04	Testing Capabilities for Validation of Gear Vibration Models	08	Demonstrate 20% transmission system vibration and noise measurement improvements beyond current limits of +- 5% for high frequency measurements >20kHz	SRW.4.01.01 SRW.1.06.05
SRW.1.06.05	Determine measurements required for model validation	07	Required measurement uncertainty limits estimated at 95% confidence level to achieve meaningful validation.	SRW.4.01.01
SRW.2.06.05	High temperature/pressure sensors for engine and drive train	10	Develop enhanced measurement systems for lightweight, on-component sensing, with high dynamic range compared to current remote sensing using traditional measurement methods with fidelity improvement of 15% over current technology.	SRW.1.06.05 SRW.1.06.06
SRW.1.06.06	Evaluate high	09	Demonstrate improved sensor technology for a 500	SRW.4.01.01

	temperature/pressure sensor technologies		deg C operational environment without water cooling requirements (SOA is complex water-cooled sensors) to measure pressure and/or vibration with a resolution of +/- 3 psi or +/- 1kG.	

Key Deliverables for Task 2. Sensor systems for Engines and Drive Trains	FY	Related Milestones
Lab / Facility test bed and sensor suite for validation of gear, engine, and drive train predictive codes	10	SRW.2.06.04-05

Task 3. Improved Rotorcraft Testing Capabilities

Systems for improving rotorcraft testing efficiency or to provide entirely new experimental measurement capabilities will be developed. These systems will address specific critical technology gaps impeding the acquisition of experimental data during wind tunnel and flight tests for validation of rotorcraft predictive codes. Fundamental research will be conducted to examine the feasibility of creating instrumentation systems that could provide significant breakthroughs in rotorcraft testing capabilities. These include wireless data transfer methods for transferring signals/data from the rotating system, methods to measure blade position in flight, and validated techniques for measuring unsteady hub loads during wind tunnel tests. Milestones and deliverables for this task are:

Number	Title	FY	Metric	Dependencies
SRW.2.06.06	Flight control measurement system	08	Develop system to measure flight control positions within 1 mm	SRW.2.02.02
SRW.2.06.07	Advanced data transfer capability	11	Demonstrate hardware to transfer data from the rotating system at 104 Mb/second	SRW.1.06.07
SRW.1.06.07	Assess wireless data transfer methods	07	Demonstrate feasibility for wireless data transfer from rotating sys at 3.25 Mb/second	SRW.4.01.01
SRW.1.06.08	Evaluate techniques for in-flight measurement of blade tip path plane	08	Demonstrate feasibility to measure blade position within 0.25 inch	SRW.4.01.01
SRW.1.06.09	Techniques for measurement of unsteady loads	09	Validate wind tunnel balance dynamic calibration procedures result in measurement of dynamic loads to within 10% accuracy	SRW.4.01.01

Key Deliverables for Task 3. Improved Rotorcraft Testing Capabilities	FY	Related Milestones
Flight control measurement system	08	SRW.2.06.06
System to measure blade tip path plane in flight	09	SRW.1.06.08