

Structural Mechanics and Dynamics Branch 2002 Annual Report

George Stefko
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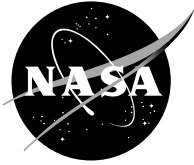
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Summary

The 2002 annual report of the Structural Mechanics and Dynamics Branch reflects the majority of the work performed by the branch staff during the 2002 calendar year. Its purpose is to give a brief review of the branch's technical accomplishments. The Structural Mechanics and Dynamics Branch develops innovative computational tools, benchmark experimental data, and solutions to long-term barrier problems in the areas of propulsion aeroelasticity, active and passive damping, engine vibration control, rotor dynamics, magnetic suspension, structural mechanics, probabilistics, smart structures, engine system dynamics, and engine containment. Furthermore, the branch is developing a compact, nonpolluting, bearingless electric machine with electric power supplied by fuel cells for future "more electric" aircraft. An ultra-high-power-density machine that can generate projected power densities of 50 hp/lb or more, in comparison to conventional electric machines, which generate usually 0.2 hp/lb, is under development for application to electric drives for propulsive fans or propellers. In the future, propulsion and power systems will need to be lighter, to operate at higher temperatures, and to be more reliable in order to achieve higher performance and economic viability. The Structural Mechanics and Dynamics Branch is working to achieve these complex, challenging goals.

Introduction



The 2002 annual report of the Structural Mechanics and Dynamics Branch reflects the majority of the work performed by the branch staff during the 2002 calendar year. Its purpose is to give a brief review of the branch's technical accomplishments. As in the reports for previous years, the report is organized topically. The descriptions of the research reflect some of the work that was reported in NASA Glenn's Research & Technology 2002 report (<http://www.grc.nasa.gov/WWW/RT/>).

The Structural Mechanics and Dynamics Branch comprises a staff of approximately 30 engineers and scientists. In partnership with U.S. industries, universities, and other Government institutions, we are responsible for developing innovative computational tools, benchmark experimental data, and solutions to long-term barrier problems in the areas of propulsion aeroelasticity, active and passive damping, engine vibration control, rotor dynamics, magnetic suspension, structural mechanics, probabilistics, smart structures, engine system dynamics, and engine containment.

Furthermore, under the auspices of the Revolutionary Aeropropulsion Concept (RAC) program, the structural Mechanics and Dynamics Branch is developing a compact, nonpolluting, bearingless electric machine with electric power supplied by fuel cells for future "more electric" aircraft. An ultra-high-power-density machine that can generate projected power densities of 50 hp/lb or more, in comparison to conventional electric machines, which generate usually 0.2 hp/lb, is under development for application to electric drives for propulsive fans or propellers.

Knowledge, technology transfer, and highly trained graduate engineers for industry are some of the end results of our activities. This annual report—along with NASA Glenn's Research & Technology 2002 report and presentations at conferences, companies, and meetings—helps make our results fully available to potential users in the aircraft engine, space, energy, aerospace, and other industries. In the future, propulsion and power systems will need to be lighter, to operate at higher temperatures, and to be more reliable in order to achieve higher performance and economic viability. Achieving these goals is complex and challenging. If you need additional information, please do not hesitate to contact me or the appropriate branch staff contact provided in this publication.

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Aeroelasticity

Fast-Running Aeroelastic Code Based on Unsteady Linearized Aerodynamic Solver Developed

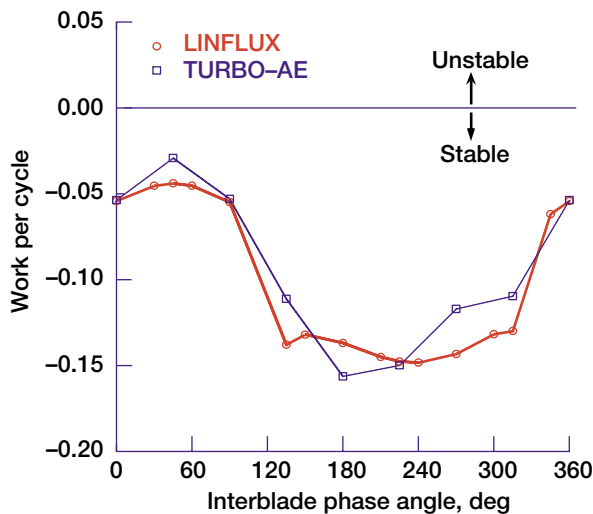
The NASA Glenn Research Center has been developing aeroelastic analyses for turbomachines for use by NASA and industry. An aeroelastic analysis consists of a structural dynamic model, an unsteady aerodynamic model, and a procedure to couple the two models. The structural models are well developed. Hence, most of the development for the aeroelastic analysis of turbomachines has involved adapting and using unsteady aerodynamic models.

Two methods are used in developing unsteady aerodynamic analysis procedures for the flutter and forced response of turbomachines: (1) the time domain method and (2) the frequency domain method. Codes based on time domain methods require considerable computational time and, hence, cannot be used during the design process. Frequency domain methods eliminate the time dependence by assuming harmonic motion and, hence, require less computational time. Early frequency domain analyses methods neglected the important physics of steady loading on the analyses for simplicity. A fast-running unsteady aerodynamic code, LINFLUX, which includes steady loading and is based on the frequency domain method, has been modified for flutter and response calculations.

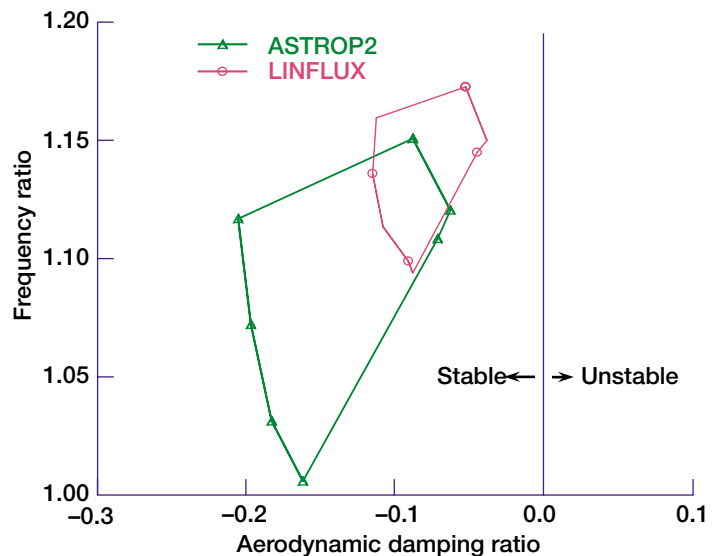
LINFLUX solves unsteady linearized Euler equations for calculating the unsteady aerodynamic forces on the blades, starting from a steady nonlinear aerodynamic solution. First, we obtained a steady aerodynamic solution for a given flow condition using the nonlinear unsteady aerodynamic code TURBO. A blade vibration analysis was done to determine the frequencies and mode

shapes of the vibrating blades, and an interface code was used to convert the steady aerodynamic solution to a form required by LINFLUX. A preprocessor was used to interpolate the mode shapes from the structural dynamic mesh onto the computational dynamics mesh. Then, we used LINFLUX to calculate the unsteady aerodynamic forces for a given mode, frequency, and phase angle. A postprocessor read these unsteady pressures and calculated the generalized aerodynamic forces, eigenvalues, and response amplitudes. The eigenvalues determine the flutter frequency and damping.

As a test case, the flutter of a helical fan was calculated with LINFLUX and compared with calculations from TURBO-AE, a nonlinear time domain code, and from ASTROP2, a code based on linear unsteady aerodynamics.



Work per cycle versus interblade phase angle for the pitching motion of a helical fan.



Root locus plot showing frequency versus aerodynamic damping for the second mode of a helical fan.

On the preceding page, the graph on the left shows the work done per cycle for the pitching mode calculated by LINFLUX and TURBO-AE. The LINFLUX calculations show a very good comparison with TURBO-AE calculations.

The graph on the right shows the eigenvalues calculated for a helical fan. The calculations were plotted as frequency versus damping for the second mode. As seen in the figure, the predictions made with LINFLUX agree well with those made with ASTROP2.

The LINFLUX code was 6 to 7 times faster than the nonlinear time-domain code and can be used in the initial design phase. The aeroelastic development calculations described here were performed under a NASA grant by University of Toledo researchers in collaboration with Glenn researchers.

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Forward-Swept Fan Flutter Calculated Using the TURBO Code

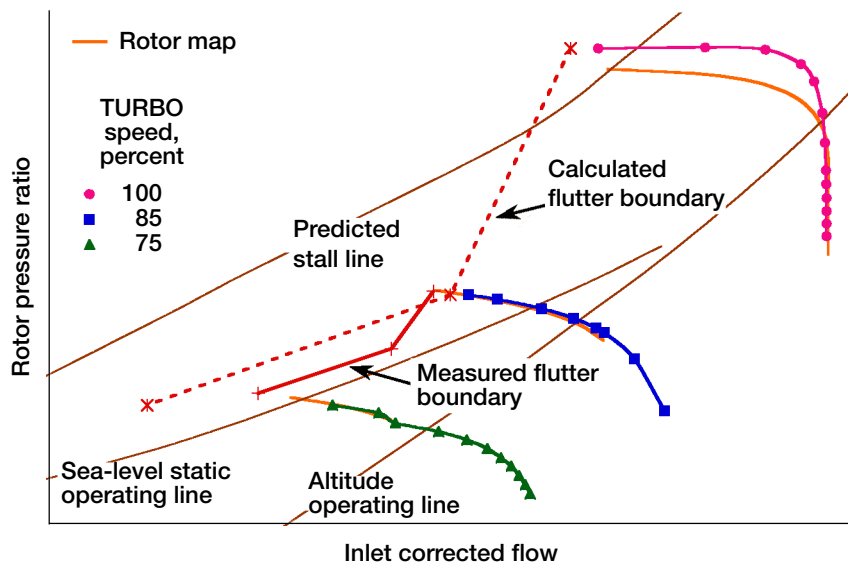
Flutter, a self-excited dynamic instability arising because of fluid structure interaction, can be a significant design problem for rotor blades in gas turbines. Blade shapes influenced by noise-reduction requirements increase the likelihood of flutter in modern blade designs. Validated numerical methods provide designers an invaluable tool to calculate and avoid the flutter instability during the design phase. Toward this objective, a flutter analysis code, TURBO, was developed and validated by researchers from the NASA Glenn Research Center and other researchers working under grants and contracts with Glenn. The TURBO code, which is based on unsteady three-dimensional Reynolds-

averaged Navier-Stokes equations, was used to calculate the observed flutter of a forward-swept fan. The forward-swept experimental fan, designed to reduce noise, showed flutter at part-speed conditions during wind tunnel tests.

The forward-swept experimental fan shown in the photograph consisted of 22 forward-swept inserted blades. The steady performance of the fan was mapped first at three different speed lines. Then, we calculated flutter by calculating the work done by the fluid on the rotor blades for the three speed lines. The blades were prescribed a harmonic motion at the natural frequency, mode shape, and nodal diameter of interest. The work done on the blade by the fluid over one cycle of vibration was converted to a more meaningful damping value referred to as aerodynamic damping. A negative aerodynamic damping implies a dynamically unstable blade, or blade with flutter. The aerodynamic damping was calculated at a minimum of two operating points on a given speed line. The flutter point was then calculated as the mass flow point where the aerodynamic damping value went to zero.



Forward-swept fan.



Comparison of calculated flutter boundary and performance for the forward-swept fan with experimental data.

The results obtained for three different speed lines are shown in the graph. The steady performance and the calculated and observed flutter points are also shown in this figure. The flutter was observed for a two-nodal-diameter forward traveling wave in the first natural mode. The calculated flutter point also corresponds to the first natural mode and the two-nodal-diameter pattern. Very good correlation was found between the analysis and measurements. The code correctly identified the observed flutter and the characteristics of the flutter. Several parametric studies were also carried out to better understand the flutter behavior. During the study, we found that the effect of variations in inflow and exit boundary conditions, tip gap, and vibration amplitude was limited and did not

strongly affect the calculated flutter point. We also found that for operating conditions where flutter was dictated by the presence of a shock wave, an inviscid analysis gave results qualitatively similar to viscous analysis. Thus, the inviscid analysis could be used successfully in a design environment for screening the designs. A more rigorous viscous analysis could then be calculated at critical points identified by the inviscid analysis. Both the viscous and the inviscid analyses with the TURBO code are currently being used to redesign the forward-swept fan to be flutter free.

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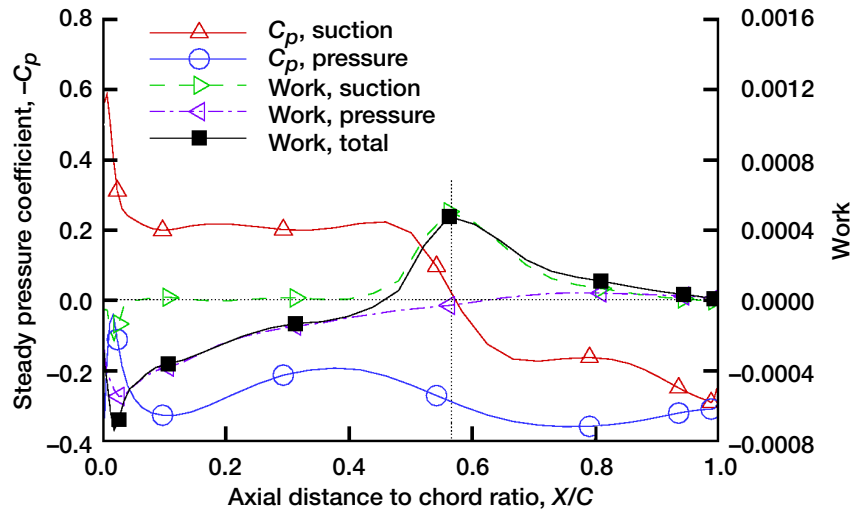
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Influence of Shock Wave on the Flutter Behavior of Fan Blades Investigated

Modern fan designs have blades with forward sweep; a lean, thin cross section; and a wide chord to improve performance and reduce noise. These geometric features coupled with the presence of a shock wave can lead to flutter instability. Flutter is a self-excited dynamic instability arising because of fluid-structure interaction, which causes the energy from the surrounding fluid to be extracted by the vibrating structure. An in-flight occurrence of flutter could be catastrophic and is a significant design issue for rotor blades in gas turbines. Understanding the flutter behavior and the influence of flow features on flutter will lead to a better and safer design. An aeroelastic analysis code, TURBO, has been developed and validated for flutter calculations at the NASA Glenn Research Center. The code has been used to understand the occurrence of flutter in a forward-swept fan design. The forward-swept fan, which consists of 22 inserted blades, encountered flutter during wind tunnel tests at part speed conditions.

The TURBO code solves the Reynolds-averaged three-dimensional Navier-Stokes equations to calculate the work done on a vibrating blade by the surrounding fluid. The work is calculated for a prescribed harmonic motion in the mode and nodal diameter pattern of interest. The work done over one cycle of blade vibration can be converted to a more meaningful damping value referred to as aerodynamic damping. The flutter point can then be calculated by extrapolating the

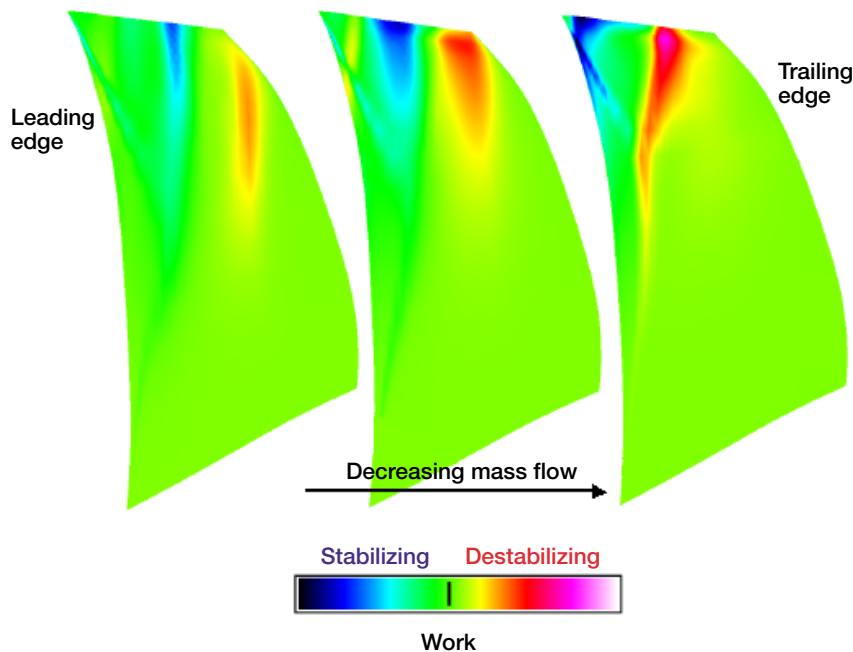
performance characteristics at which the aerodynamic damping goes to zero. The TURBO code calculated the observed flutter of the forward swept fan, correctly identifying the mode and nodal diameter of the observed flutter. The study indicated that the shock wave location and strength have a strong influence on blade stability. The following graph shows the distribution of work on the blade surface at 95 percent of the span. Also shown on this figure is the steady pressure coefficient identifying the shock wave and its location. It is clearly seen that the



Pressure coefficient and work distribution at 95-percent span for the forward-swept fan blade operating near stall.

work done by the fluid is centered around the shock wave. It was found that as the operating conditions changed and the shock wave location moved on the blade surface, the area of work associated with the shock wave also moved. The work calculated was found to be strongly dependent on the shock wave strength as well.

The bottom figure shows the distribution of total work on the blade surface for different mass flow conditions. Both stabilizing and destabilizing areas of work were found to be associated with shock waves present on the blade surfaces. For the fan geometry analyzed, we found the suction surface shock wave to be destabilizing, whereas the pressure surface shock wave had a stabilizing effect. We also found that accurate blade shape, accounting for deformations due to operating aerodynamic and centrifugal loading, is important for the accurate prediction of the flutter boundary.



Work distribution on the blade surface for various mass flows operating at a part speed operating condition.

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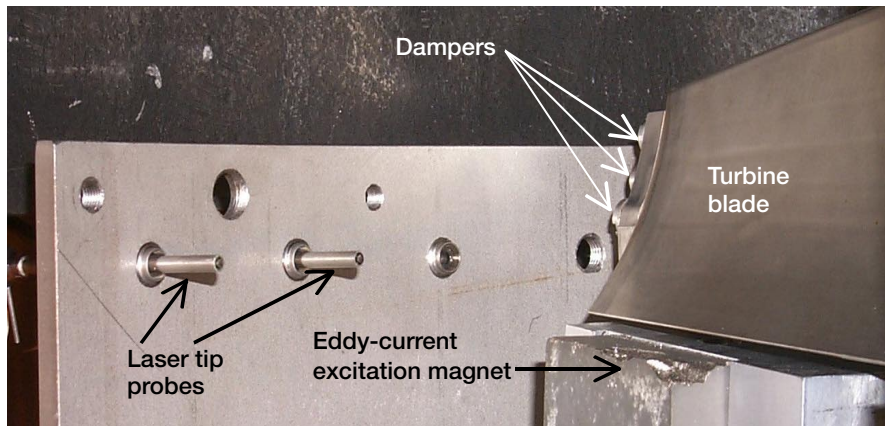
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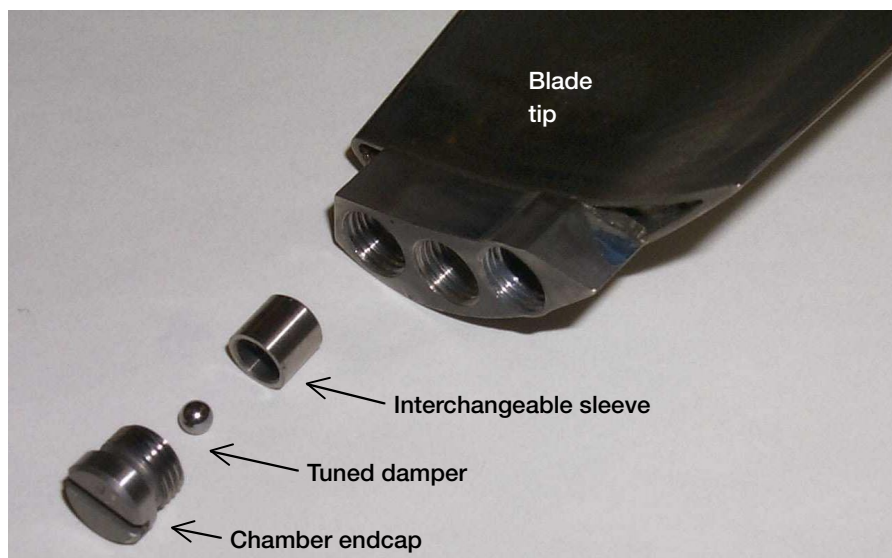
Spin Testing for Durability Began on a Self-Tuning Impact Damper for Turbomachinery Blades



Glenn's Dynamic Spin Facility—Pratt & Whitney turbine blade with self-tuning impact dampers installed at the blade tip.

NASA has a program to develop passive damping technology for turbomachinery blade airfoils to reduce blade vibration. Spin tests in flat plates and turbine blades have shown that a self-tuning impact damper being developed is effective. Spin testing completed this year in NASA Glenn Research Center's Dynamic Spin Rig showed as much as a 50-percent reduction in the resonant response of a damper in a Pratt & Whitney turbine blade. We plan to investigate its durability and effectiveness in upcoming spin tests.

NASA and Pratt & Whitney will collaborate under a Space Act Agreement to perform spin testing of the impact damper to verify damping effectiveness and damper durability. Pratt & Whitney will provide the turbine blade and damper hardware for the tests. NASA will provide the facility and perform the tests.



Turbine blade with exploded view of the self-tuning impact damper.

Effectiveness and durability will be investigated during and after sustained sweeps of rotor speed through resonance. Tests of a platform wedge damper are also planned to compare its effectiveness with that of the impact damper. Results from baseline tests without dampers will be used to measure damping effectiveness.

The self-tuning impact damper combines two damping methods—the tuned mass damper and the impact damper. It consists of a ball located within a cavity in the blade. This ball rolls back and forth on a spherical trough under centrifugal load (tuned mass damper) and can strike the walls of the cavity (impact damper). The ball's rolling natural frequency is proportional to the rotor speed and can be designed to follow an engine-order line (integer multiple of rotor speed). Aerodynamic forcing frequencies typically follow these engine-order lines, and a damper tuned to the engine order will most effectively reduce blade vibrations when the resonant frequency equals the engine-order forcing frequency.

This damper has been tested in flat plates and turbine blades in the Dynamic Spin Facility. During testing, a pair of plates or blades rotates in vacuum. Excitation is provided by one of three methods—eddy-current engine-order excitation (ECE), electromechanical shakers, and magnetic bearing excitation. The eddy-current system consists of magnets located circumferentially around the rotor. As a blade passes a magnet, a force is imparted on the blade. The number of magnets used can be varied to change the desired engine order of the excitation. The magnets are remotely raised or lowered to change the magnitude of the force on the blades. The other

two methods apply force to the rotating shaft itself at frequencies independent of the rotor speed. During testing, blade vibration is monitored with strain gauges and laser displacement probes.

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Unsteady Flowfield in a High-Pressure Turbine Modeled by TURBO

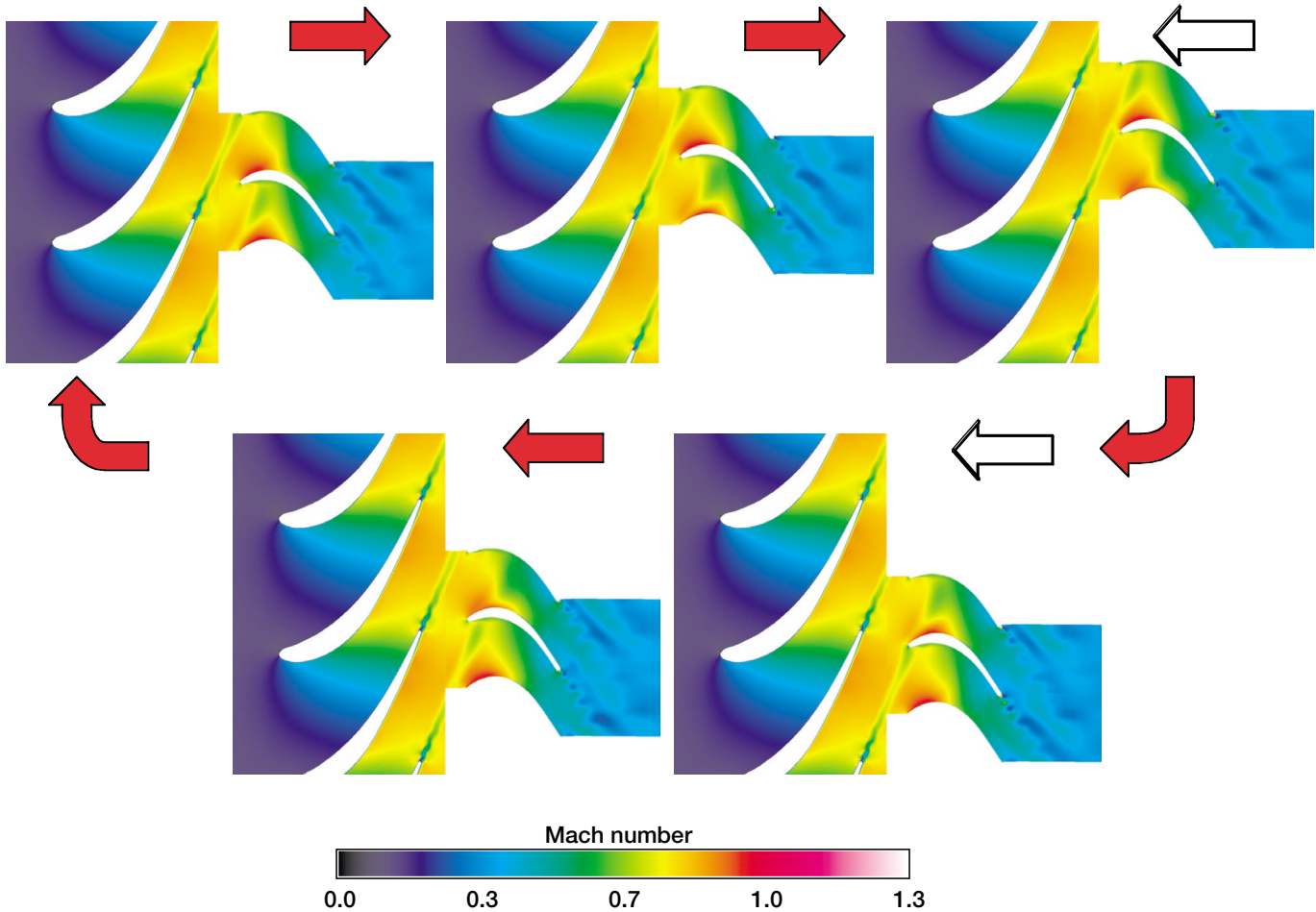
Forced response, or resonant vibrations, in turbomachinery components can cause blades to crack or fail because of the large vibratory blade stresses and subsequent high-cycle fatigue. Forced-response vibrations occur when turbomachinery blades are subjected to periodic excitation at a frequency close to their natural frequency. Rotor blades in a turbine are constantly subjected to periodic excitations when they pass through the spatially nonuniform flowfield created by upstream vanes. Accurate numerical prediction of the unsteady aerodynamics phenomena that cause forced-response vibrations can lead to an improved understanding of the problem and offer potential approaches to reduce or eliminate specific forced-response problems.

The objective of the current work was to validate an unsteady aerodynamics code (named TURBO) for the modeling of the unsteady blade row interactions that can cause forced-response vibrations. The three-dimensional, unsteady, multi-blade-row, Reynolds-averaged Navier-Stokes turbomachinery code named TURBO was used to model a high-pressure turbine stage for which benchmark data were recently acquired under a NASA contract by researchers at the Ohio State University. The test article was an initial design for a high-pressure turbine stage that experienced forced-response vibrations which were eliminated by increasing the axial gap. The data, acquired in a short duration or shock tunnel test facility, included unsteady blade surface pressures and vibratory strains.

The unsteady flowfield was computed using the TURBO code for two axial gaps at resonant crossings of modes 2, 3, and 4. Two grids were used to evaluate the effects of spatial discretization. Numerical studies were performed to ensure that the computational results were nearly independent of the choice of numerical input parameters. Unsteady blade surface pressures were compared with data

at 50- and 85-percent span, which were the locations of the pressure transducers in the experiment. In addition, plots of the flowfield were prepared to understand how the upstream vane wakes interacted with the downstream rotor (see the figure on the following page).

The computational results agreed quite well with the experimental data at both spanwise locations and at the various operating conditions. The mean loading was seen to be higher near the tip than at the midspan location. The trend was reversed for unsteady loading, with the higher unsteady loads occurring at the midspan. A comparison of the surface pressure for small and large gaps showed that the main pressure peak near the leading edge was smaller for the larger axial gap. This work has provided further validation of the TURBO code for unsteady aerodynamic computations of turbomachinery blade rows. The unsteady aerodynamic calculations described



Unsteady flowfield in a high-pressure turbine stage shown as a sequence of five plots of instantaneous Mach number contours.

here were performed under a grant by a University of Toledo researcher in collaboration with NASA Glenn Research Center and Honeywell researchers.

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Propulsion Systems R&T

Noninterference Systems Developed for Measuring and Monitoring Rotor Blade Vibrations

In the noninterference measurement of blade vibrations, a laser light beam is transmitted to the rotor blade tips through a single optical fiber, and the reflected light from the blade tips is collected by a receiving fiber-optic bundle and conducted to a photodetector. Transmitting and receiving fibers are integrated in an optical probe that is enclosed in a metal tube which also houses a miniature lens that focuses light on the blade tips. Vibratory blade amplitudes can be deduced from the measurement of the instantaneous time of arrival of the blades and the knowledge of the rotor speed.

The in-house noninterference blade-vibration measurement system was developed in response to requirements to monitor blade vibrations in several tests where conventional strain gauges could not be installed or where there was a need to back up strain gauges should critical gauges fail during the test. These types of measurements are also performed in the aircraft engine industry using proprietary in-house technology.

Two methods of measurement were developed for vibrations that are synchronous with a rotor shaft. One method requires only one sensor; however, it is necessary to continuously record the data while the rotor is being swept through the resonance. In the other method, typically four sensors are employed and the vibratory amplitude is deduced from the data by performing a least square fit to a harmonic function. This method does not require continuous recording of data through the resonance and, therefore, is better suited for monitoring. The single-probe method was tested in the Carl facility at the Wright-Patterson Air Force Base, and the multiple-probe method

was tested in NASA Glenn Research Center's Spin Rig facility, which uses permanent magnets to excite synchronous vibrations. Representative results from this test are illustrated in the bar chart.

Nonsynchronous vibrations were measured online during testing of the Quiet High Speed Fan in Glenn's 9- by 15-Foot Low-Speed Wind Tunnel. Three sensors were employed, enabling a reconstruction of the vibratory patterns at the leading and trailing edges at the tip span, as well as a determination of vibratory amplitudes for every blade.

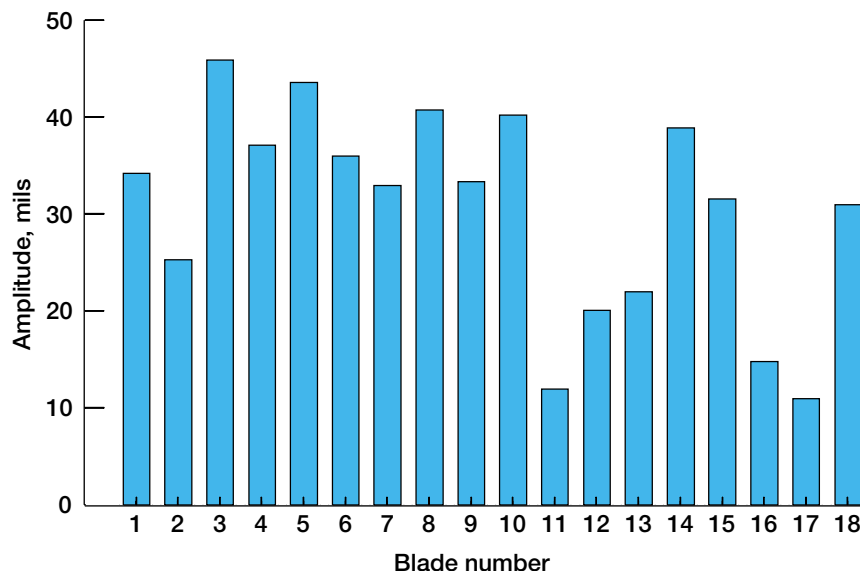
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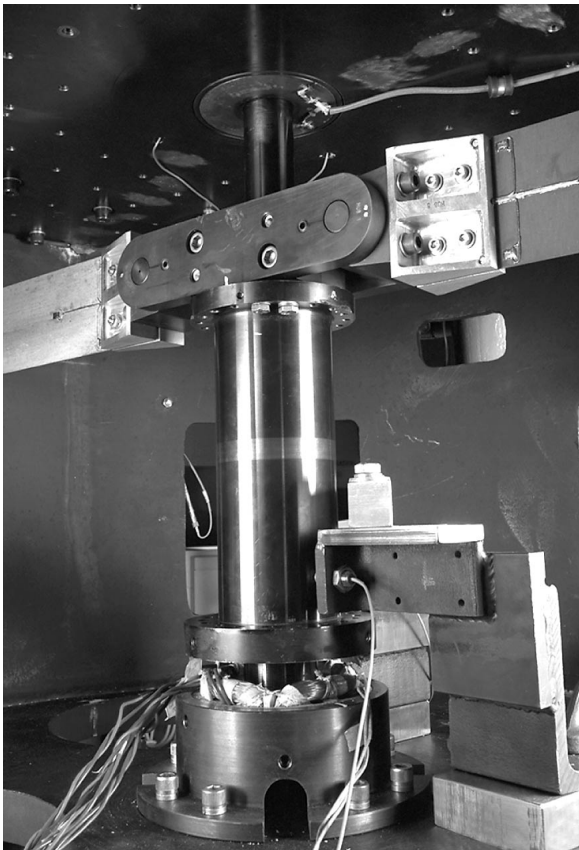
Blade-to-blade resonant amplitude variation for a fan rotor subject to a 5-engine-order excitation.

Magnetic Suspension and Vibration Control

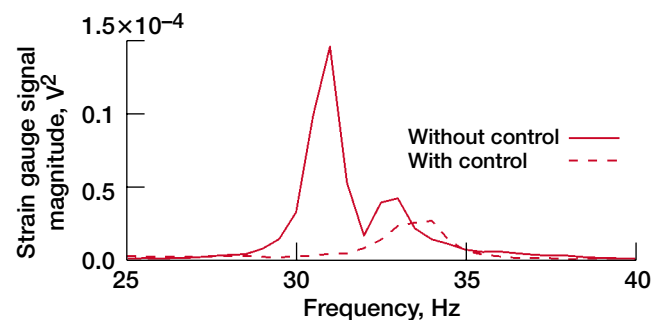
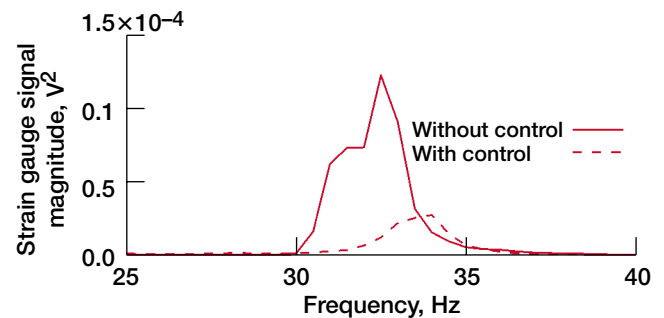
Active Blade Vibration Control Being Developed and Tested

Gas turbine engines are currently being designed to have increased performance, lower weight and manufacturing costs, and higher reliability. Consequently, turbomachinery components, such as turbine and compressor blades, have designs that are susceptible to new vibration problems and eventual in-service failure due to high-cycle fatigue. To address this problem, researchers at the NASA Glenn Research Center are developing and testing innovative active blade vibration control concepts. Preliminary results of using an active blade vibration control system, involving a rotor supported by an active magnetic bearing in Glenn's Dynamic Spin Rig, indicate promising results (see the photograph). Active blade vibration control was achieved using feedback of blade strain gauge signals within the magnetic bearing control loop. The vibration amplitude was reduced substantially (see the graphs). Also, vibration amplification was demonstrated; this could be used to enhance structural mode identification, if desired. These results were for a nonrotating two-bladed disk. Tests for rotating blades are planned.

Current and future active blade vibration control research is planned to use a fully magnetically suspended rotor and smart materials. For the fully magnetically suspended rotor work, three magnetic bearings (two radial and one axial) will be used as actuators instead of one magnetic bearing. This will allow additional degrees of freedom to be used for control. For the smart materials work, control effectors located on and off the blade will be considered. Piezoelectric materials will be considered for on-the-blade actuation, and actuator placement on a stator vane, or other nearby structure, will be investigated for off-the-blade actuation. Initial work will focus on determining the feasibility of these methods by performing basic analysis and simple experiments involving



A two-bladed rotor, oriented vertically, which is supported by a radial active magnetic bearing used for active blade vibration control in the NASA Glenn Dynamic Spin Rig facility.



Power spectral density of strain gauge signals for flat plates using the active blade vibration control system with and without strain gauge feedback to the magnetic bearing, for a nonrotating shaft. Top: Blade B. Bottom: Blade A.

feedback control. Further development will include a detailed design of the system along with an extensive test and evaluation plan.

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Find out more about this research:
<http://structures.grc.nasa.gov/5930/>

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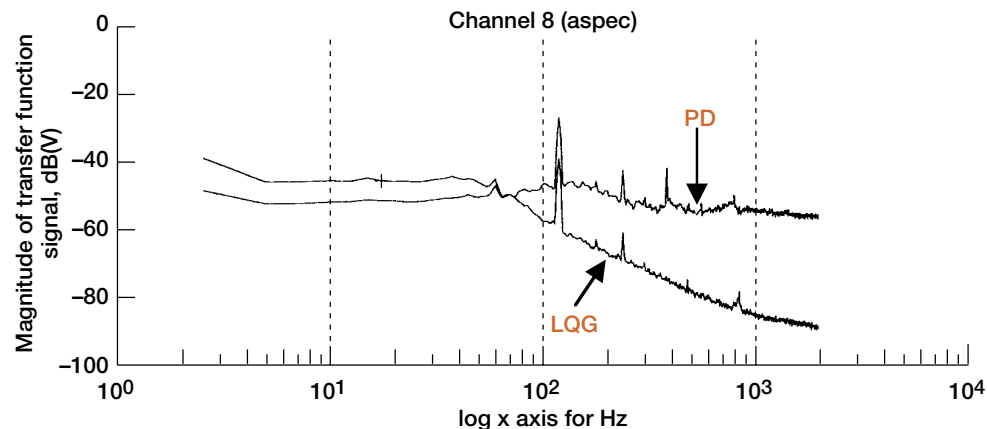
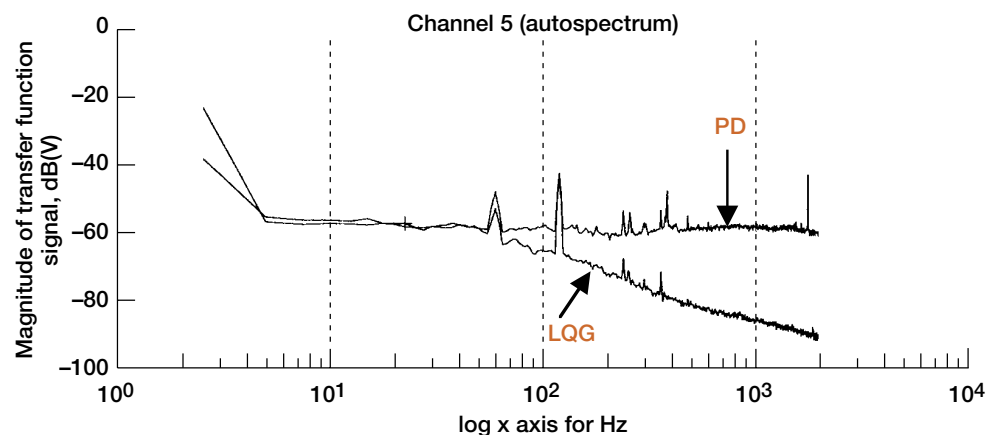
Headquarters program office: OAT

Programs/Projects: SEC

Optimal Controller Tested for a Magnetically Suspended Five-Axis Dynamic Spin Rig

NASA Glenn Research Center's Structural Mechanics and Dynamics Branch has developed a fully suspended magnetic bearing system for their Dynamic Spin Rig, which performs vibration tests of turbomachinery blades and components under spinning conditions in a vacuum. Two heteropolar radial magnetic bearings and a thrust magnetic bearing and the associated control system were integrated into the Dynamic Spin Rig to provide magnetic excitation as well as noncontact magnetic suspension of the 35-lb vertical rotor with blades to induce turbomachinery blade vibration (ref. 1).

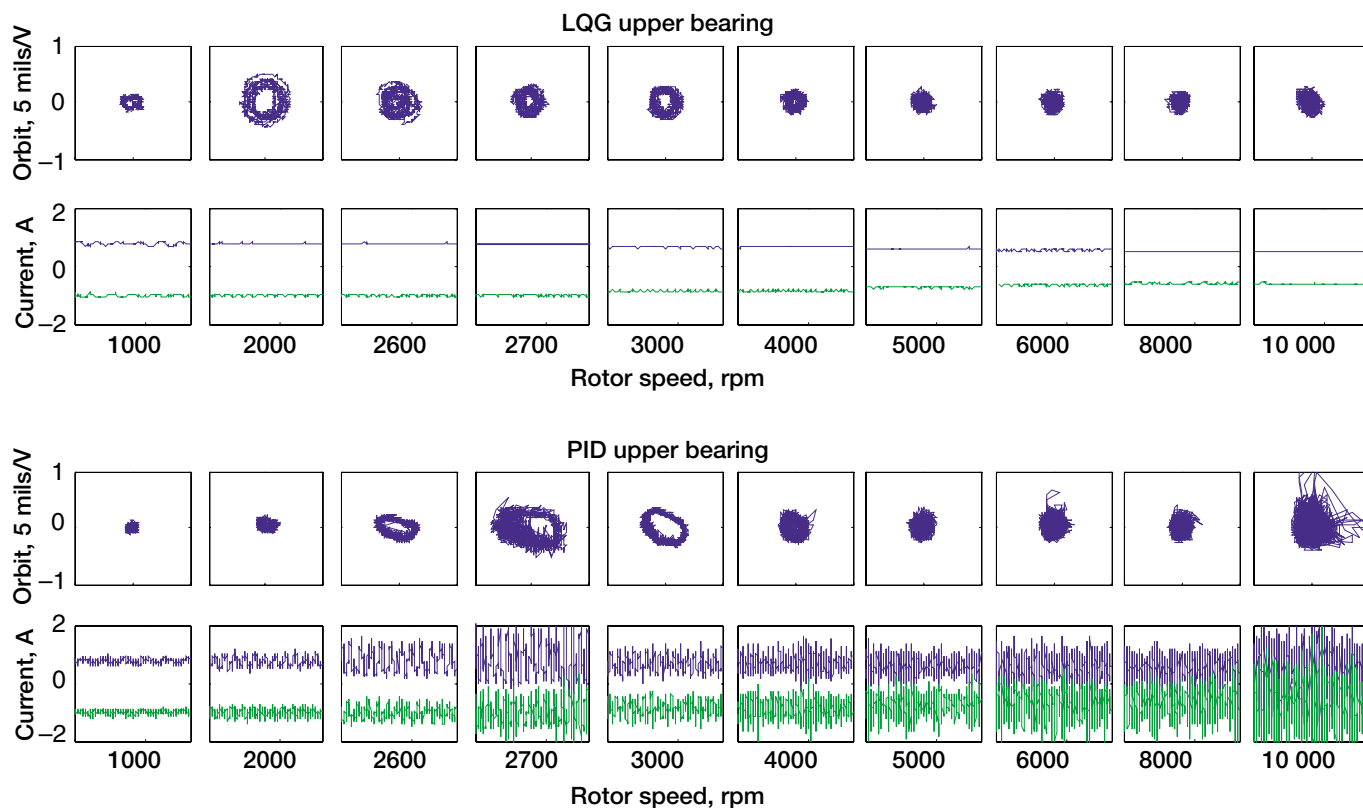
The new system can provide longer run times at higher speeds and larger vibration amplitudes for rotating blades. Also, it was proven that bearing mechanical life was substantially extended and flexibility was increased in the excitation orientation (direction and phasing).



Power spectrum of the upper and lower control currents with the PD controller and LQG regulator, respectively.

The first controller we tested for the rotor magnetic suspension was a decentralized proportional-integral-derivative (PID) controller because it was easy to implement. A simple PID controller was sufficient to suppress the vibration amplitude at critical modes. The PID controller had a relatively large control current with high-frequency noise that frequently caused power amplifier and coil burnouts.

Looking for more vibration amplitude suppression and stable rotor orbits at critical modes, we tested a centralized modal controller, which can inherently control critical modes, including bouncing and tilting modes. The rotor orbit over the operating range was reduced by approximately 20 percent, but control current and noise level remained almost the same as for the proportional-derivative (PD) controller.



The upper rotor orbits and control currents with the PD controller and LQG regulator.

Next, we tested a control force integral feedback, where the control force was integrated over time slowly and added to the feedback force output until the time-averaged control force became zero (ref. 2). The test results showed better rotor orbit and control current, but the high-frequency noise level that is crucial to good experimental damping test results still remained.

All the controllers worked well in terms of the rotor orbit (position control) and control current level throughout the operating range up to 10 000 rpm. However, we needed to reduce the high-frequency magnetic bearing control noise, which may couple into the blade vibration measuring circuits and provide poor experimental damping test results. Consequently, we tested a linear quadratic gaussian (LQG) regulator that was developed on the basis of a simple second-order experimental plant model that approximates the rotor and magnetic bearing system. The test results showed that in comparison to the PID controller, the LQG controller reduced rotor orbit by about 50 percent. In addition, it significantly reduced the high-frequency control noise level throughout the operating range (see the graphs on the preceding page). Finally, clean rotor orbits and lower control current were achieved over the operating range (see the figures on this page). Thus, the LQG controller was the best controller to use for damping tests on the new magnetically suspended five-axis Dynamic Spin Rig.

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SW-18 Room-Temperature Conical Magnetic Bearing Test Rig



Conical magnetic bearing.

A conical magnetic bearing test rig was procured and installed in NASA Glenn Research Center's SW-18 facility during fiscal year 2002. The test rig features two conical magnetic bearings which can be laminated, resulting in increased bandwidth in the axial direction and a unique, modular, tie-rod design to simplify modifications and maintenance. Funded by a Glenn fiscal year 2002 Director's Discretionary Fund, the rig was needed because none of the existing rigs has an axial degree of freedom. Magnetic bearings are being investigated to improve the performance, safety, and reliability of turbomachinery by eliminating the oil-related delays and failures of engine components, and as a new method of active stall control. Active stall control is a current research area at Glenn where work is being done to greatly reduce specific fuel consumption (SFC) by allowing a gas turbine to operate beyond the onset of stall. The test rig was purchased from Revolve Magnetic Bearings, Inc., and was originally built for Honeywell as part of the Air Force's Integrated Power and Attitude Control System demonstration project. Further funding will allow facility completion, component testing, and adaptation of well-proven magnetic bearing control codes and stall cell tracking methods to establish the efficacy of conical magnetic bearings for active stall control in gas turbine engines, as well as provide test data to guide the design of high-temperature magnetic bearings for turbomachinery.



SW-18 conical magnetic bearing test rig.

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Dynamic Spin Rig Upgraded With a Five-Axis-Controlled Three-Magnetic-Bearing Support System With Forward Excitation

The NASA Glenn Research Center Dynamic Spin Rig is used for experimental evaluation of vibration analysis methods and dynamic characteristics for rotating systems (ref. 1). Measurements are made while rotors are spun and vibrated in a vacuum chamber. The rig has been upgraded with a new active magnetic bearing rotor support and excitation system. This design is expected to provide operational improvements over the existing rig. The rig will be able to be operated in either the old or new configuration.

In the old configuration, two ball bearings support the vertical shaft of the rig, with the test article located between the bearings. Because the bearings operate in a vacuum, lubrication is limited to grease. This limits bearing life and speed. In addition, the old configuration employs two voice-coil electromagnetic shakers to apply oscillatory axial forces or transverse moments to the rotor shaft through a thrust bearing. The excitation amplitudes that can be imparted to the test article with this system are not adequate for components that are highly damped. It is expected that the new design will overcome these limitations.

A preliminary upgrade of the Dynamic Spin Rig (ref. 2) incorporated a single heteropolar radial active magnetic bearing, which allows for both magnetic excitation and suspension of the rotor. The magnetic bearing replaced the lower mechanical ball bearing and gave improved operations. Results from that upgrade have been used in building a total magnetically suspended rotor (see the engineering drawing of the rig on the next page). The new design, called the Five-Axis Three Magnetic Bearing Dynamic Spin Rig, has five independent axes of controlled motion. There is an x-axis and a y-axis translation at each upper and lower magnetic radial bearing, as well as a z-axis translation at the magnetic thrust bearing. Both radial bearings are heteropolar. Simultaneously energizing the bearings (refs. 3 and 4) fully levitates the rotor. This rig design allows for higher excitation amplitudes (by virtue of full rotor suspension, which permits larger rotor translation and tilt displacements) than are achievable with the older rig configuration. At the time of this writing, the rig was operated up to 10 000 rpm with an unbladed rotor. For a detailed description of the rig, see reference 5.

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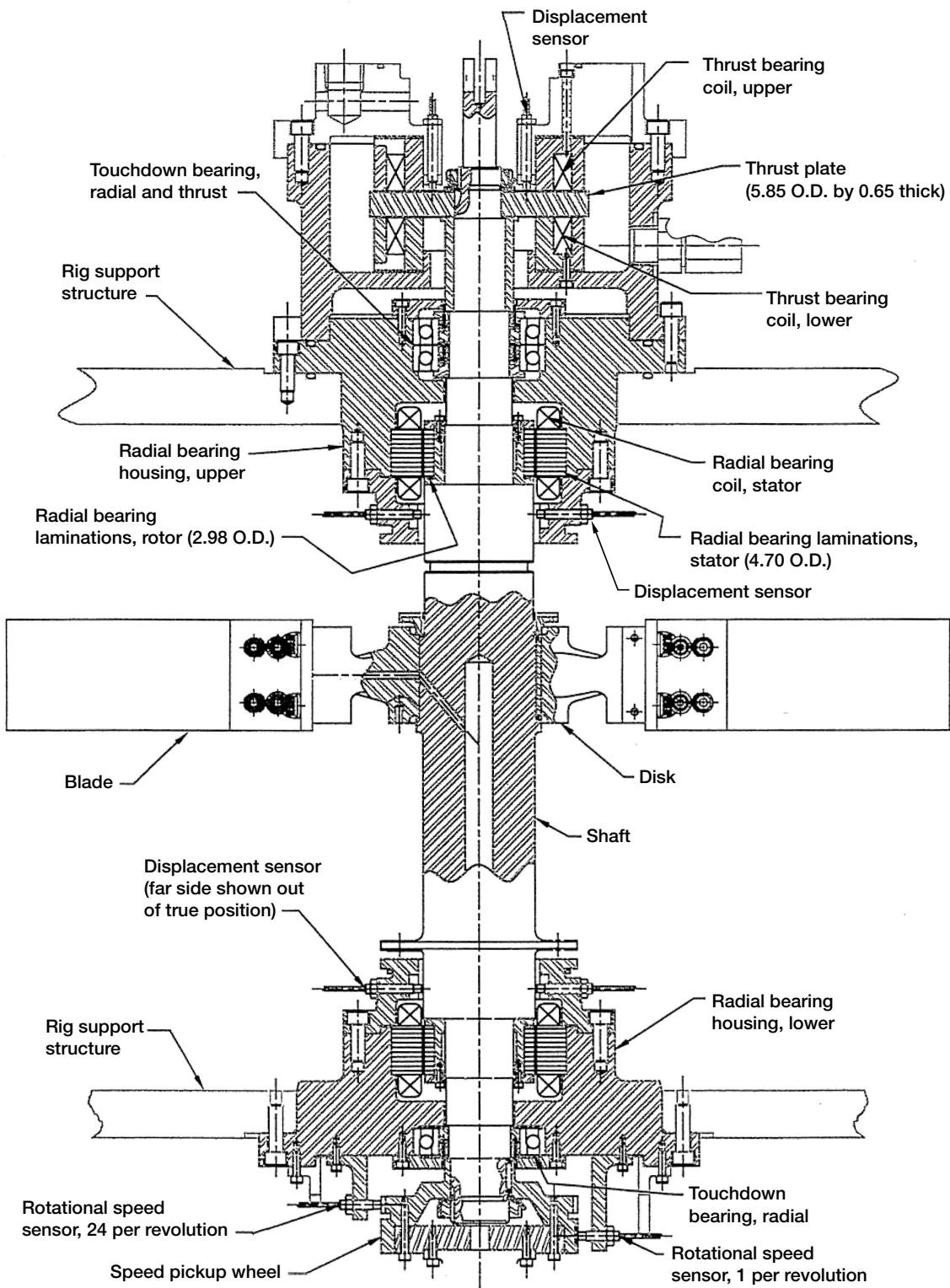
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Glenn's upgraded Five-Axis Three Magnetic Bearing Dynamic Spin Rig. All dimensions are given in inches. O.D., outer diameter.

Flywheels Upgraded for Systems Research

With the advent of high-strength composite materials and microelectronics, flywheels are becoming attractive as a means of storing electrical energy. In addition to the high energy density that flywheels provide, other advantages over conventional electrochemical batteries include long life, high reliability, high efficiency, greater operational flexibility, and higher depths of discharge. High pulse energy is another capability that flywheels can provide. These attributes are favorable for satellites as well as terrestrial energy storage applications. In addition to energy storage for satellites, the several flywheels operating concurrently can provide attitude control, thus combine two functions into one system. This translates into significant weight savings.

The NASA Glenn Research Center is involved in the development of this technology for space and terrestrial applications. Glenn is well suited for this research because of its world-class expertise in power electronics design, rotor dynamics, composite material research, magnetic bearings, and motor design and control. Several Glenn organizations are working together on this program. The Structural Mechanics and Dynamics Branch is providing magnetic

bearing, controls, and mechanical engineering skills. It is working with the Electrical Systems Development Branch, which has expertise in motors and generators, controls, and avionics systems. Facility support is being provided by the Space Electronic Test Engineering Branch, and the program is being managed by the Space Flight Project Branch.

NASA is funding an Aerospace Flywheel Technology Development Program to design, fabricate, and test the Attitude Control/Energy Storage Experiment (ACESE). Two flywheels will be integrated onto a single power bus and run simultaneously to demonstrate a combined energy storage and 1-degree-of-freedom momentum control system. An algorithm that independently regulates direct-current bus voltage and net torque output will be experimentally demonstrated.

The major tasks completed this year were upgrades of the two flywheel modules to be used for the ACESE demonstration and assembly of the High Energy Flywheel Facility where the testing will be conducted. Both flywheel modules received upgraded avionics, position sensors, and control systems. One module was redesigned to incorporate a higher energy, longer life rotor. These upgrades will enable the system-level test program. The two technology demonstrator flywheel modules will be integrated at Glenn's High Energy Flywheel Facility. This facility consists of an airtable where the modules are mounted and surrounded by a water-containment safety system. This photograph of the setup shows thermal, vacuum, and instrumentation support hardware on the upper platform.



Two-flywheel system on airtable.

The current experiment will be a hardware demonstration of a flywheel system that provides both power bus regulation and single-axis torque and attitude control. The long-term objective is to extend this work to a bus regulation and 3-degrees-of-freedom attitude control system representative of a satellite platform.

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Magnetic Suspension Being Developed for Future Lube-Free Turbomachinery Application

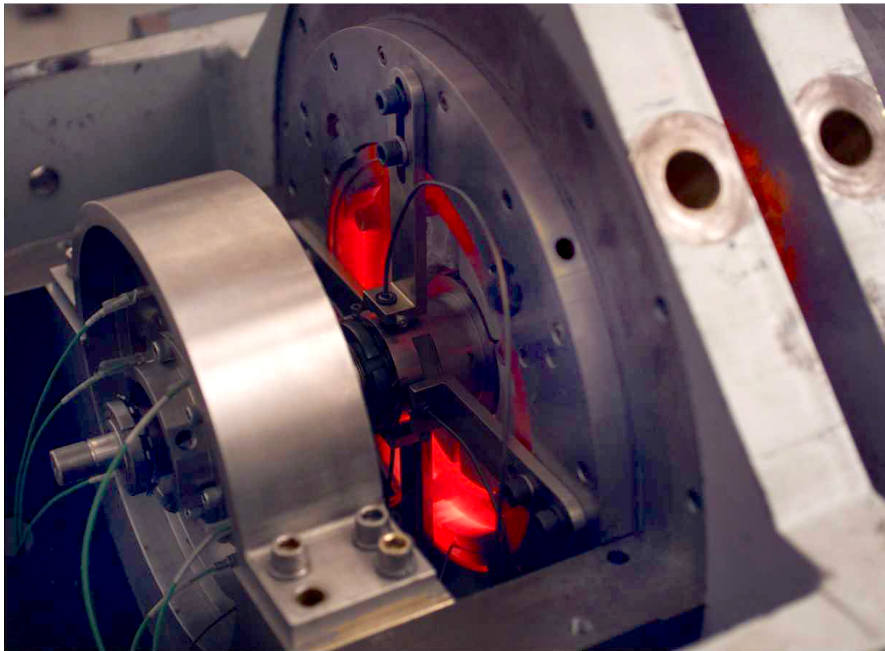
The NASA Glenn Research Center, the U.S. Army, Texas A&M University, and other industrial partners are continuing to work together to develop magnetic suspension technology to withstand the harsh environmental conditions inside current and future turbomachinery. In fiscal year 2002, our third-generation radial magnetic bearing successfully controlled rotor motion while at 1000 °F (540 °C) and 20 000 rpm. The ability to command the rotor's position while spinning at this speed was also demonstrated. Future work is planned to include radial bearing tests to 1100 °F (593 °C) and 30 000 rpm. In fiscal year 2003, we plan to test a high-temperature thrust bearing.

This third-generation radial magnetic bearing was designed specifically to operate at 1000 °F with high force production. The stator design includes six individual C-cores that slide into a common back-iron. The modular nature of the stator allows for improved winding of the poles with specially insulated silver wire.

High-temperature eddy-current probes are used to measure rotor position. Centrifugal and thermal growth are compensated for by summing probes on opposite sides of the rotor on each axis. Currently, only two independent axes are used in the control; however, this bearing can be controlled along three axes to

provide redundancy. A proportional-integral-derivative (PID) controller, rolled off at 400 Hz, was used to provide levitation and control. This controller was written in Simulink and compiled to run on a power-PC-based digital-signal-processing system. The control loop time was 25 μ s. Tri-state pulse width modulators were used to provide alternating-current power to the stator coils.

Open-loop experimental force and power measurements were also recorded at temperatures up to 1000 °F and rotor speeds up to 15 000 rpm. The experimentally measured force produced by a single C-core using 22 A was 600 lb



Glenn's third-generation radial magnetic bearing at 1000 °F.

(2.67 kN) at room temperature and 380 lb (1.69 kN) at 1000 °F. Results of testing under rotating conditions showed that rotor speed has a negligible effect on the bearing's load capacity. A single C-core required approximately 340 W of power to generate 190 lb (8.45 kN) of magnetic force at 1000 °F. However, lower force and higher power at elevated temperatures were due primarily to a larger air gap caused by different component heating rates—they were not due to magnetic material property degradation. Analytical thermal calculations showed that the air gap could have been at least 28-percent larger at 1000 °F.

Ultra-High-Power-Density Motor Being Developed for Future Aircraft

To support the Revolutionary Aeropropulsion Concept Program, NASA Glenn Research Center's Structural Mechanics and Dynamics Branch is developing a compact, nonpolluting, bearingless electric machine with electric power supplied by fuel cells for future more-electric aircraft. The use of such electric drives for propulsive fans or propellers depends on the successful development of ultra-high-power-density machines that can generate power densities of 50 hp/lb or more, whereas conventional electric machines generate usually 0.2 hp/lb.

One possible candidate for such ultra-high-power-density machines, a round-rotor synchronous machine with an engineering current density as high as 20 000 A/cm² was selected to investigate how much torque and power can be produced. A simple synchronous machine model that consists of rotor and stator windings and back-irons was considered first. The model had a sinusoidally distributed winding that produces a sinusoidal distribution of flux P poles. Excitation of the rotor winding produced P poles of rotor flux, which interacted with the P stator poles to produce torque.

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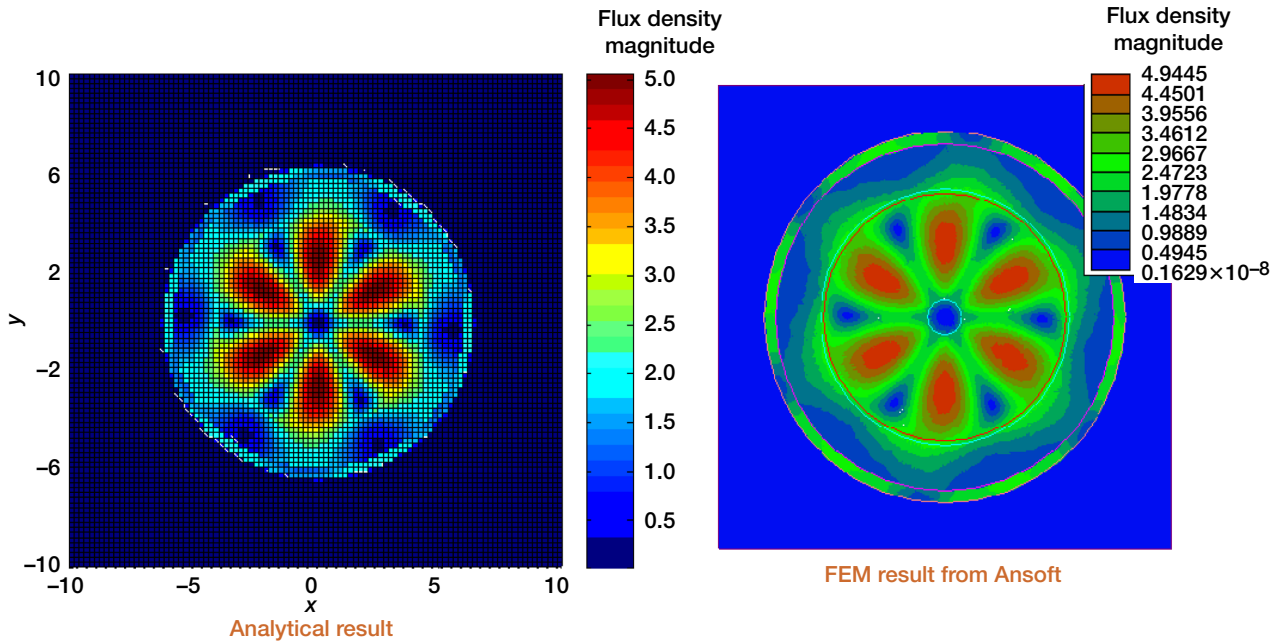
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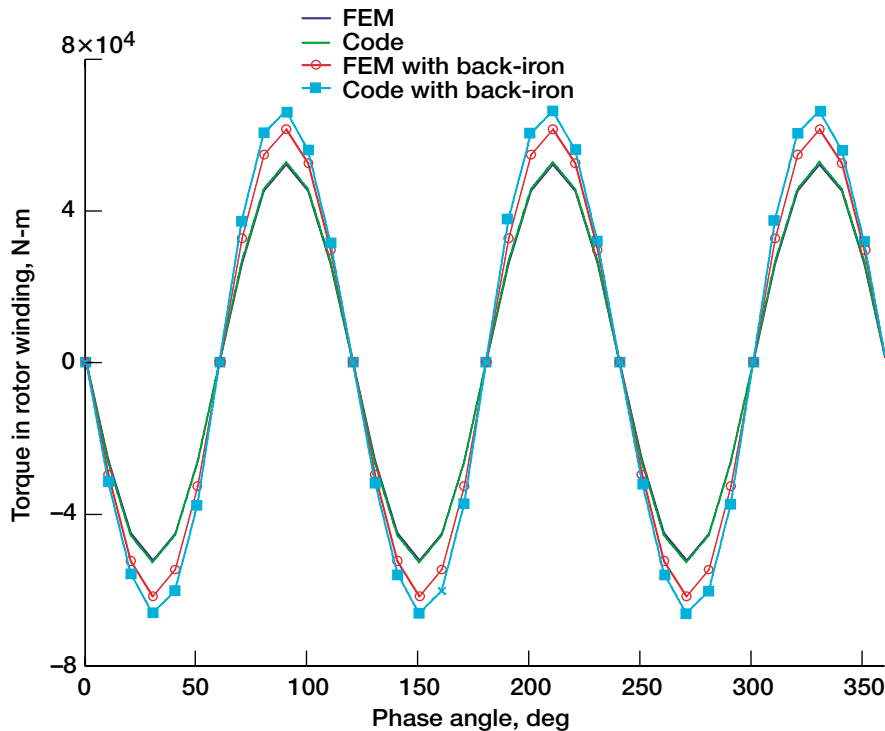
SEC, TBCC, IHPTET, VAATE

This year we made significant contributions to this research:

(1) We conducted a constant-tip-speed scaling study for synchronous round-rotor machines. To obtain the specified design and geometry of this high-power-density motor, we had to optimize the design. We analytically verified that Long's contention, "Specific power is mainly a function of rotor surface speed," is approximately correct. At first, we kept the rotor surface speed constant for the scaled-up motors. Then, we increased the gap diameter by integer multiples of its initial value. It was proven that if



Flux density magnitude of a six-pole analytical model with a 1-cm-thick back-iron¹ (90° phase angle).



Torque in the six-pole synchronous motor with and without 1-cm-thick stator back-iron (10° increment).

surface speed, pole pitch, and electrical frequency are held constant, motors with different sizes develop the same power density.

(2) We developed the Electro-magnetic Analysis of Synchronous Machines code. This analytical tool and finite element model code uses AnSoft to analyze and optimize the performance of high-power-density synchronous machines (see the figures). This software gives us the basic tools to provide detailed quantitative results and the ability to determine optimal designs for synchronous round-rotor machines. This work showed the feasibility of using this technology for a future more-electric engine, making advances on the Ultra-High Power Density Motor project.

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RAC, Ultra-High Power Density Motor

¹Stack of thin iron layers to hold coil winding.

High-Power-Density Electric Motors Being Developed for Nonpolluting Aircraft Propulsion (“Fan-Tip-Drive” Permanent-Magnet Motor Test Rig)

This program has two thrusts: to raise the power density of axial-gap permanent-magnet motors and to explore the feasibility of tip-drive motors. The top figure shows an aircraft propulsion fan surrounded by a blade tip electric motor drive. Motor power is the magnetic force times the velocity, so power density can be improved by putting as large as possible force at the highest speed. Aircraft propulsion fans tend to operate with a blade tip speed of about Mach 1. Thus, the blade tip location has the highest speed. The circumference around the blade tips encloses the largest area and, thus, provides space for a large magnetic force.

The center figure shows a tangential segment of an axial-gap permanent-magnet, blade-tip-drive electric motor with two rotor sections and three stator sections. The end stator sections are the back-iron for the motor. Repeating the rotor-stator configuration can increase the force per unit length for an axial-gap permanent-magnet motor. The back-iron is only needed at the outside of the axial stack.

The test rig shown in the bottom figure is being designed to verify this concept. It consists of a test generator connected both electrically and mechanically to a test motor. The test motor and a conventional motor (which makes up the losses in the system) drive the test generator. The design will optimize the permanent-magnet motor’s structure: stationary or moving back-iron, speed versus stress, lumped versus distributed permanent magnets, number of poles versus electrical frequency, width of poles versus back-iron thickness, and coil winding distribution. Other topics in the design process are the axial bearings, the thrust load, and the optimized forced-convection cooling of the coils.

Find out more about this research:

<http://structures.grc.nasa.gov/5930/>

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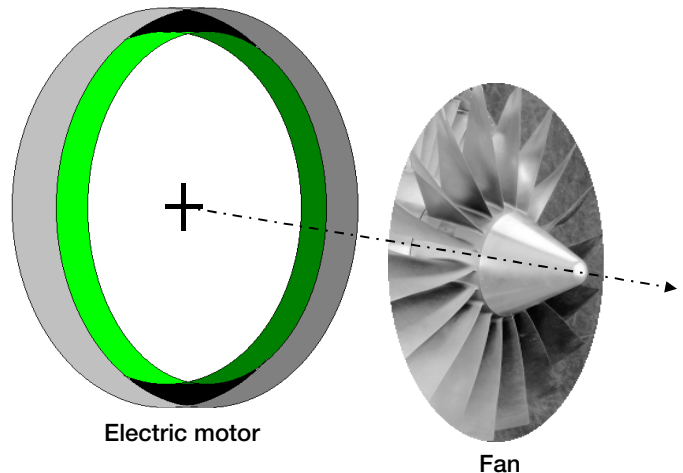
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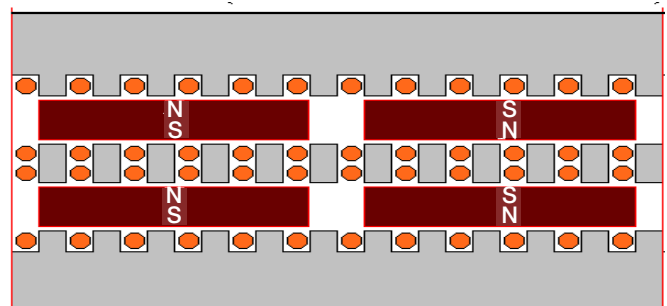
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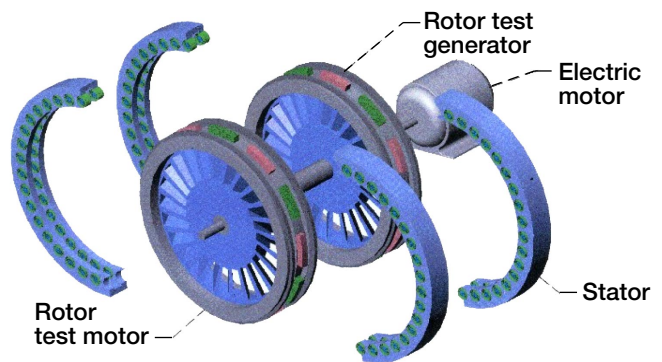
Programs/Projects: RAC



Fan blade tip drive.



Force unit for axial-gap motor with repetition (back-iron less dominant).



Compressor-turbine blade-tip drive rig.

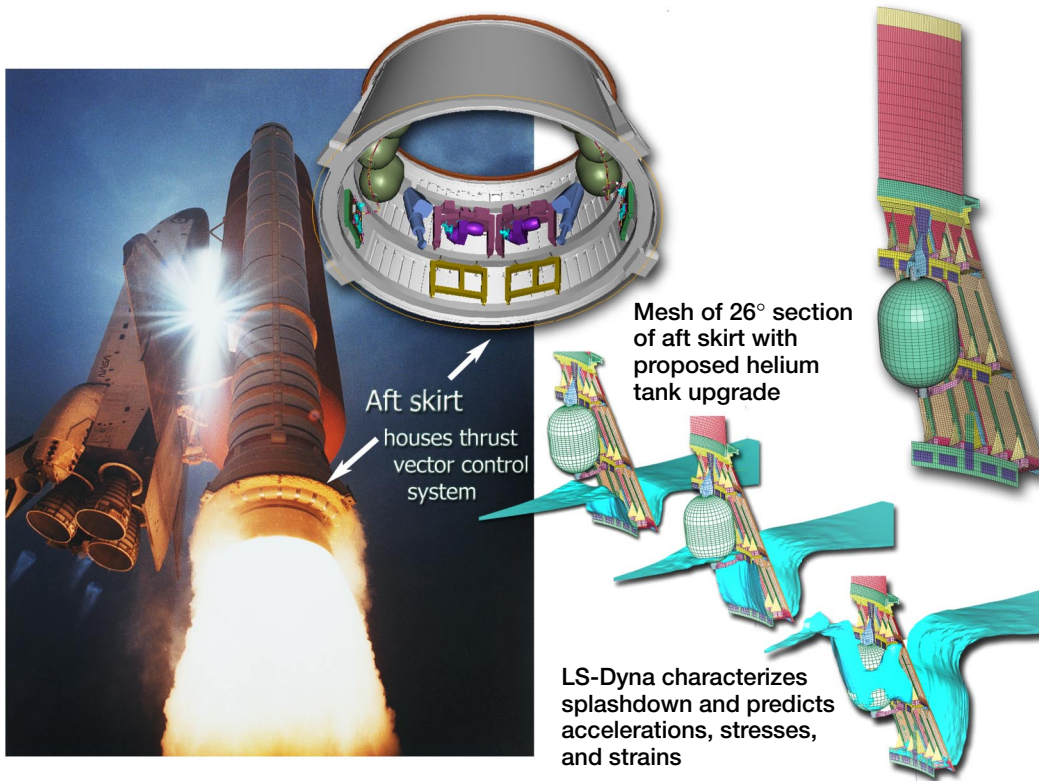
Structural Mechanics, Engine System Dynamics, Fan Containment, and Smart Structures

Explicit Finite Element Techniques Used to Characterize Splashdown of the Space Shuttle Solid Rocket Booster Aft Skirt

NASA Glenn Research Center's Structural Mechanics Branch has years of expertise in using explicit finite element methods to predict the outcome of ballistic impact events. Shuttle engineers from the NASA Marshall Space Flight Center and NASA Kennedy Space Flight Center required assistance in assessing the structural loads that a newly proposed thrust vector control system for the space shuttle solid rocket booster (SRB) aft skirt would expect to see during its recovery splashdown.

The new design was to replace existing hydrazine propellant tanks with helium propellant tanks. The intent of this was to eliminate hydrazine, a toxic and hazardous substance, from the system, making it safer from a propellant stand-

point. The proposed helium tanks, however, required nearly six times the volume of hydrazine tanks, resulting in significantly more tank area exposed to water impact during SRB splashdown. It would be crucial to understand what the new impact loads would be as a result of a design change to the thrust vector control before any such change could be implemented to a flight system.



Thrust vector control system located in the aft skirt of the space shuttle SRB, finite element model of proposed helium tank/aft skirt used to analyze water impact, and three representative images of a predicted splashdown event of this model.

LS-Dyna (Livermore-Software Technology Corp. (LST), Livermore, CA) was employed to perform the analysis, using its multimaterial arbitrary Lagrangian-Eulerian (ALE) methodology to represent water-structure interaction during impact. Impact loads were predicted for the proposed tank upgrades on a 26° section of a full-scale aft skirt, providing insight to the water impact event.

The efforts of this work contribute to the improvement of flight safety for the space shuttles, which is paramount to NASA's strategic mission.

Find out more about this research:

<http://ballistics.grc.nasa.gov>

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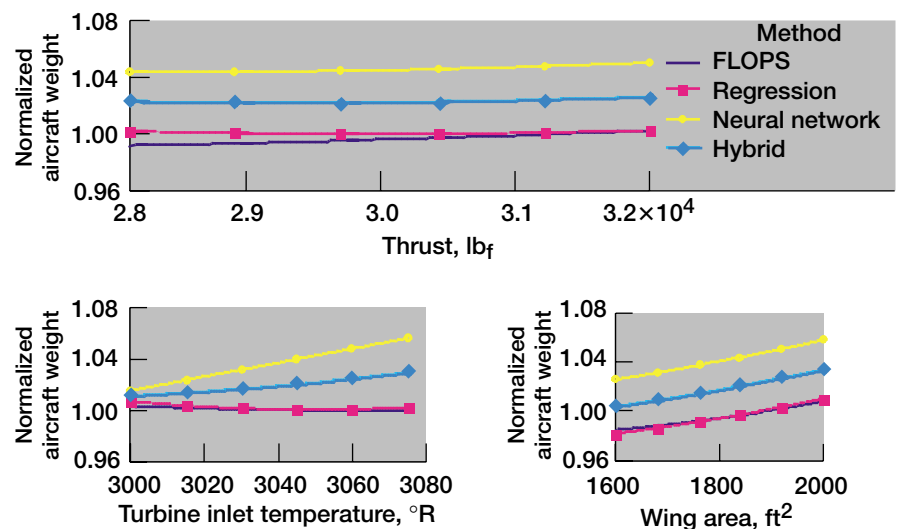
Programs/Projects: RLV, AvSP

Neural Network and Regression Methods Demonstrated in the Design Optimization of a Subsonic Aircraft

The neural network and regression methods of NASA Glenn Research Center's COMETBOARDS design optimization testbed were used to generate approximate analysis and design models for a subsonic aircraft operating at Mach 0.85 cruise speed. The analytical model is defined by nine design variables: wing aspect ratio, engine thrust, wing area, sweep angle, chord-thickness ratio, turbine temperature, pressure ratio, bypass ratio, fan pressure; and eight response parameters: weight, landing velocity, takeoff and landing field lengths, approach thrust, overall efficiency, and compressor pressure and temperature. The variables were adjusted to optimally balance the engines to the airframe. The solution strategy included a sensitivity model and the soft analysis model. Researchers generated the sensitivity model by training the approximators to predict an optimum design. The trained neural network predicted all response variables, within 5-percent error. This was reduced to 1 percent by the regression method.

The soft analysis model was developed to replace aircraft analysis as the reanalyzer in design optimization. Soft models have been generated for a neural network method, a regression method, and a hybrid method obtained by

combining the approximators. The performance of the models is graphed for aircraft weight versus thrust as well as for wing area and turbine temperature. The regression method followed the analytical solution with little error. The neural network exhibited 5-percent maximum error over all parameters. Performance of the hybrid method was intermediate in comparison to the individual approximators. Error in the response variable is smaller than that shown in the figure because of a distortion scale factor. The overall performance of the approximators was considered to be satisfactory because aircraft analysis with NASA Langley Research Center's FLOPS (Flight Optimization System) code is a synthesis of diverse disciplines: weight estimation, aerodynamic analysis, engine cycle analysis, propulsion data interpolation, mission performance, airfield length for landing and takeoff, noise footprint, and others.



Performance of neural network and regression methods for a subsonic aircraft. Top: Normalized aircraft weight versus thrust. Bottom left: Weight versus turbine inlet temperature. Bottom right: Weight versus wing area.

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Propulsion Systems R&T

New Tools Being Developed for Engine-Airframe Blade-Out Structural Simulations

One of the primary concerns of aircraft structure designers is the accurate simulation of the blade-out event. This is required for the aircraft to pass Federal Aviation Administration (FAA) certification and to ensure that the aircraft is safe for operation. Typically, the most severe blade-out occurs when a first-stage fan blade in a high-bypass gas turbine engine is released. Structural loading results from both the impact of the blade onto the containment ring and the subsequent instantaneous unbalance of the rotating components. Reliable simulations of blade-out are required to ensure structural integrity during flight as well as to guarantee successful blade-out certification testing. The loads generated by these analyses are critical to the design teams for several components of the airplane structures including the engine, nacelle, strut, and wing, as well as the aircraft fuselage.

Currently, a collection of simulation tools is used for aircraft structural design. Detailed high-fidelity simulation tools are used to capture the structural loads resulting from blade loss, and then these loads are used as input into an overall system model that includes complete structural models of both the engines and the airframe. The detailed simulation (shown in the figure) includes the time-dependent trajectory of the lost blade and its interactions with the containment structure, and the system simulation includes the lost blade loadings and the interactions between the rotating turbomachinery and the remaining aircraft structural components. General-purpose finite element structural anal-

ysis codes are typically used, and special provisions are made to include transient effects from the blade loss and rotational effects resulting from the engine's turbomachinery. To develop and validate these new tools with test data, the NASA Glenn Research Center has teamed with GE Aircraft Engines, Pratt & Whitney, Boeing Commercial Aircraft, Rolls-Royce, and MSC.Software.

Progress to date on this project includes expanding the general-purpose finite element code, NASTRAN, to perform rotordynamic analysis of complete engine-airframe systems. Capabilities that have been implemented into the code are frequency response (windmilling), complex modes (damped critical and whirl speeds), and static analysis (maneuver loads). Future plans include a nonlinear enhancement for blade-out simulation and construction of a test rig to determine blade-case interaction characteristics.

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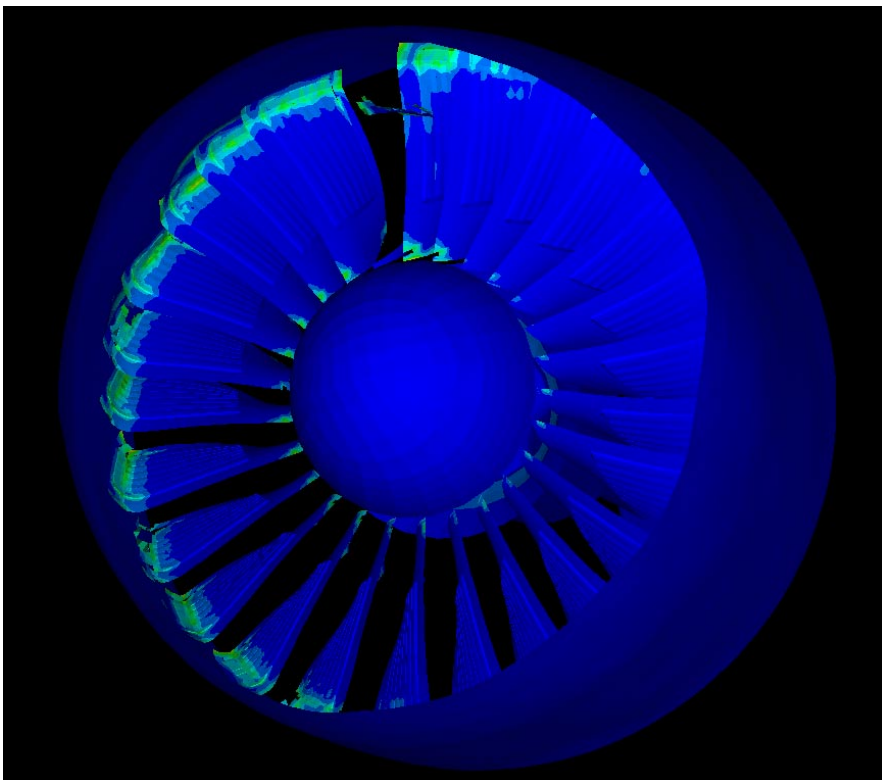
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Propulsion Systems R&T, Ultra Safe



Detailed blade-fan case interaction model.

Analytical Failure Prediction Method Developed for Woven and Braided Composites

Historically, advances in aerospace engine performance and durability have been linked to improvements in materials. Recent developments in ceramic matrix composites (CMCs) have led to increased interest in CMCs to achieve revolutionary gains in engine performance. The use of CMCs promises many advantages for advanced turbomachinery engine development and may be especially beneficial for aerospace engines. The most beneficial aspects of CMC material may be its ability to maintain strength to over 2500 °F, its internal material damping, and its relatively low density. Ceramic matrix composites reinforced with two-dimensional woven and braided fabric preforms are being considered for NASA's next-generation reusable rocket turbomachinery applications (for example, see the top figure on the next page). However, the architecture of a textile composite is complex, and therefore, the parameters controlling its strength properties are numerous. This necessitates the development of engineering approaches that combine analytical methods with limited testing to provide effective, validated design analyses for the textile composite structures development.

A micromechanics textile composite analysis code has been developed at the NASA Glenn Research Center to predict progressive damage for textile composite structures, especially for brittle material composite systems. The repeating unit cell (RUC) of a textile composite is usually used to represent it (ref. 1). The thermal and mechanical properties of the RUC are considered to be the same as those of the composite. In this study, the micromechanics, the shear lag, and the continuum fracture mechanics models were integrated with a statistical model in the RUC to predict the progressive damage failures of textile composite structures. Textile composite failure is defined as the loss of the loading capability of the RUC, which depends on the stiffness reduction due to material slice (matrix slice and yarn slice) failures and nonlinear material properties. To account for these phenomena in a more accurate manner, we developed a new analysis code to demonstrate the proposed methodologies with comparisons to material test data obtained with carbon-fiber-reinforced silicon carbide matrix plain-weave composites as well as various polymer

matrix composites (PMCs) available in the literature for a code validation, and some of the results are presented in reference 2. Good comparisons with a full range of the test data have established the feasibility of the proposed analysis techniques and their ability to model the progressive failure analysis for the textile composite structures, as shown in the graphs on the next page.

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2. Min, J.B.; Shi, Y.; and Card, M.F.: Progressive Failure Analysis Modeling Techniques for Ceramic Matrix Textile Composites. AIAA Paper 2002–1400, 2002.

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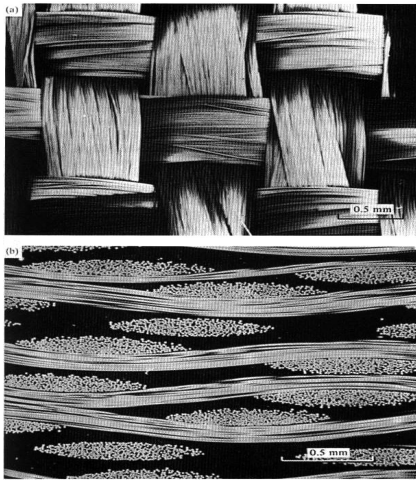
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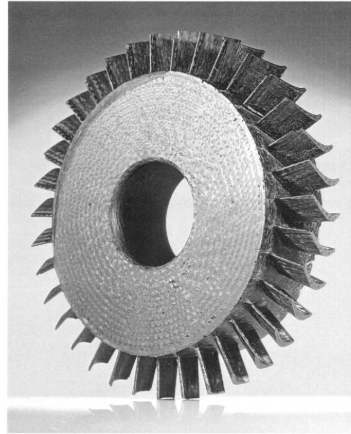
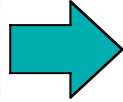
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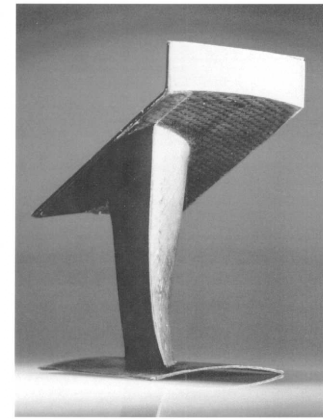
Woven structure



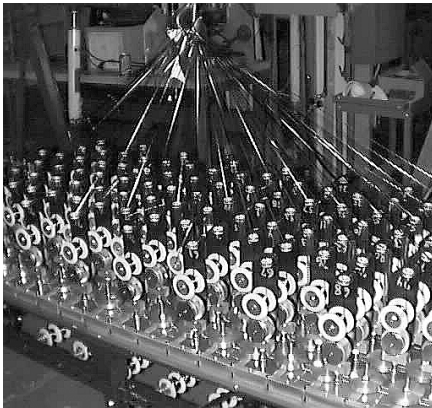
Integrally braided turbine blisk



Rocket exit cone



Integrally braided stator

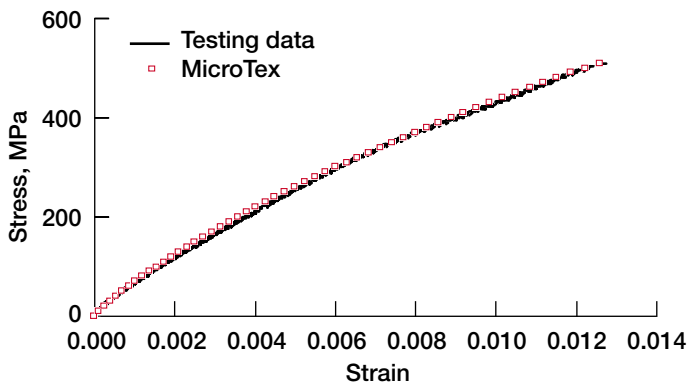


Two- and three-dimensional woven/braiding equipment

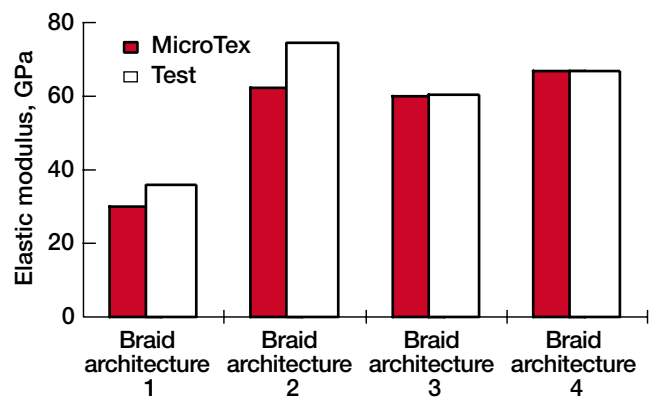


Combustion components

Examples of textile composite components.



Stress-strain for $[0^\circ/90^\circ]$ C/SiC plain-weave composite.



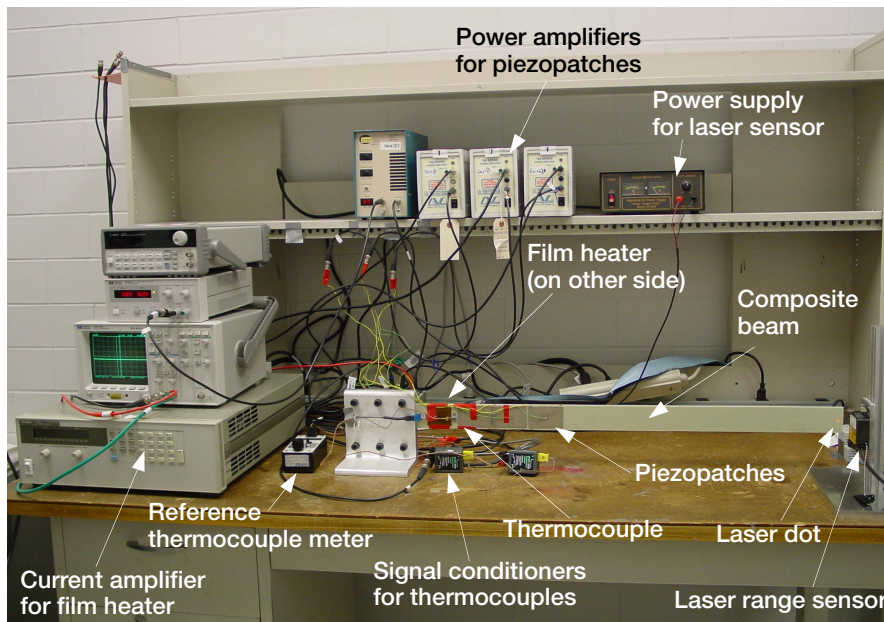
Comparison of elastic modulus for four different braided architectures.

Experimental and Analytical Studies of Smart Morphing Structures Being Conducted

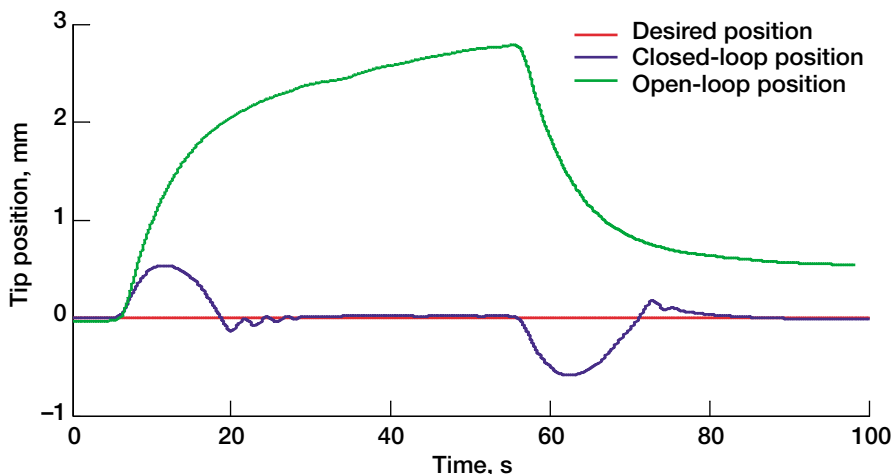
The development of morphing aeropropulsion structural components offers the potential to significantly improve the performance of existing aircraft engines through the introduction of new inherent capabilities for shape control, vibration damping, noise reduction, health monitoring, and flow manipulation. One of the key factors in the successful development of morphing structures is the maturation of smart materials technologies.

In NASA Glenn Research Center's Structural Mechanics and Dynamics Branch, analytical efforts are ongoing to develop comprehensive finite element

models for smart materials to facilitate the experimental characterization of these materials. Finite element studies have been conducted to investigate the impact of stacking and curvature on the force and displacement response of piezoelectric actuators (ref. 1). Experimental studies are also being conducted to characterize a variety of different smart materials in the Smart Materials and Structures Laboratory at the University of Akron under a cooperative agreement. Shape memory alloy actuators have been used to achieve precision position control while reducing energy consumption (ref. 2). Several prototype magnetorheological fluid devices have been developed to investigate the capability to instantaneously damp out motion and to statically hold a position under applied loads. Also, piezoelectric actuators have been successfully used to compensate for thermal distortions generated by film heaters in a composite beam (ref. 3).



Experimental setup for composite beam with attached piezoelectric actuators subjected to thermal loading.



Comparison of the initial thermal deformation at the free end of the beam with the controlled deflection.

The photograph shows the experimental setup for the cantilevered composite beam with attached piezoceramic patches subjected to thermal loadings, along with the instrumentation required to control and acquire data. The graph depicts the corresponding deflection with time near the free end of the beam. The open-loop position indicates the initial thermally induced deformation of the beam, whereas the closed-loop position shows the compensated deformation achieved by activating the piezoceramic actuators. By returning the beam to the original desired position, this research demonstrates the potential use of smart materials for shape control to achieve morphing structures.

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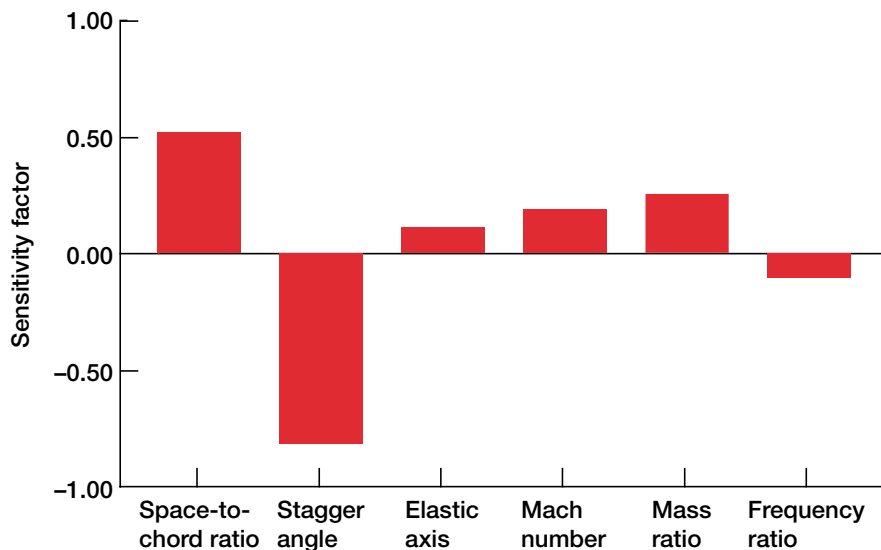
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Headquarters program office: OAT

Programs/Projects: RAC

Probabilistic Analysis and Other Topics

Probabilistic Aeroelastic Analysis Developed for Turbomachinery Components



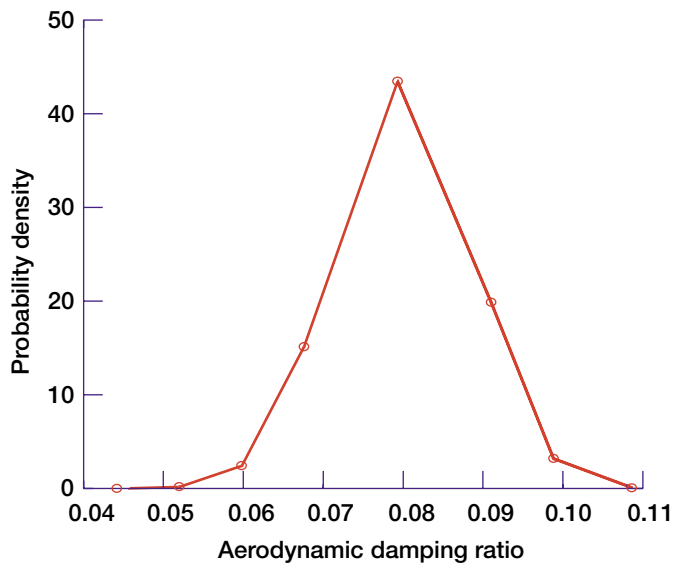
Sensitivity factors of damping (probability level 0.978).

Aeroelastic analyses for advanced turbomachines are being developed for use at the NASA Glenn Research Center and industry. However, these analyses at present are used for turbomachinery design with uncertainties accounted for by using safety factors. This approach may lead to overly conservative designs, thereby reducing the potential of designing higher efficiency engines. An integration of the deterministic aeroelastic analysis methods with probabilistic analysis methods offers the potential to design efficient engines with fewer aeroelastic problems and to make a quantum leap toward designing safe reliable engines.

In this research, probabilistic analysis is integrated with aeroelastic analysis: (1) to determine the parameters that most affect the aeroelastic characteristics (forced response and stability) of a turbomachine component such as a fan, compressor, or turbine and (2) to give the acceptable standard deviation on the design

parameters for an aeroelastically stable system. The approach taken is to combine the aeroelastic analysis of the MISER (MISuned Engine Response) code with the FPI (fast probability integration) code. The role of MISER is to provide the functional relationships that tie the structural and aerodynamic parameters (the primitive variables) to the forced response amplitudes and stability eigenvalues (the response properties). The role of FPI is to perform probabilistic analyses by utilizing the response properties generated by MISER. The results are a probability density function for the response properties. The probabilistic sensitivities of the response variables to uncertainty in primitive variables are obtained as a byproduct of the FPI technique.

The combined analysis of aeroelastic and probabilistic analysis is applied to a 12-bladed cascade vibrating in bending and torsion. Out of the total 11 design parameters, 6 are considered as having probabilistic variation. The six parameters are space-to-chord ratio (SBYC), stagger angle (GAMA), elastic axis (ELAXS), Mach number (MACH), mass ratio (MASSR), and frequency ratio (WHWB). The cascade is considered to be in



Probability density function of damping, torsion mode; mean, 0.0787; standard deviation, 0.0078.

subsonic flow with Mach 0.7. The results of the probabilistic aeroelastic analysis are the probability density function of predicted aerodynamic damping and frequency for flutter and the response amplitudes for forced response.

The bar chart on the preceding page shows the design variables that affect the aerodynamic damping. It can be seen from the figure that the space-to-chord ratio and the stagger angle affect the aerodynamic damping most.

This graph shows the probability density function of aerodynamic damping for the torsion mode. It shows that the aerodynamic damping has a mean

value of about 0.08 and a range of 0.05 to 0.11. The results of the bar chart reveal that reducing the scatter of the space-to-chord ratio and the stagger angle give the highest payoff in reducing the scatter range (standard deviation) of aerodynamic damping. The probabilistic aeroelastic calculations described here were performed under a NASA grant by University of Toledo researchers in collaboration with Glenn researchers.

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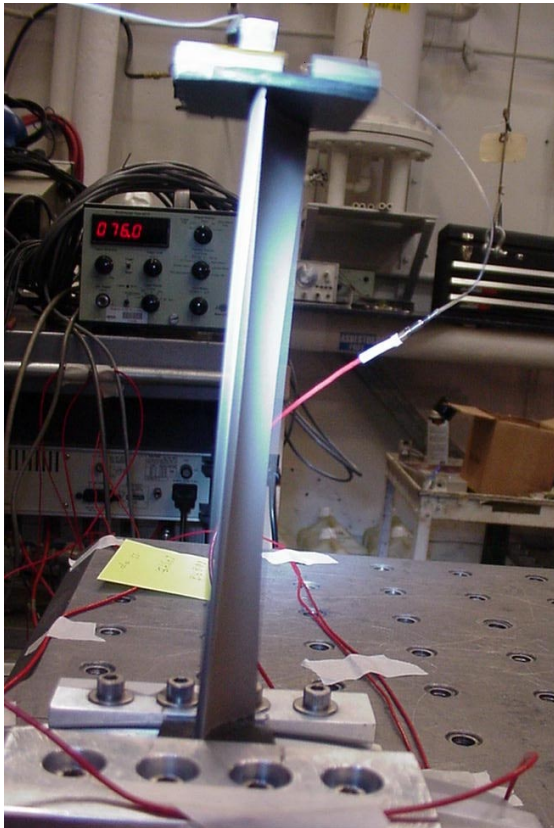
High-Frequency Testing of Composite Fan Vanes With Erosion-Resistant Coating Conducted

The mechanical integrity of hard, erosion-resistant coatings were tested using the Structural Dynamics Laboratory at the NASA Glenn Research Center. Under the guidance of Structural Mechanics and Dynamics Branch personnel, fixturing and test procedures were developed at Glenn to simulate engine vibratory conditions on coated polymer-matrix-composite bypass vanes using a slip table in the Structural Dynamics Laboratory. Results from the high-frequency mechanical bench testing, along with concurrent erosion testing of coupons and vanes, provided sufficient confidence to engine-endurance test similarly coated vane segments. The knowledge gained from this program will be applied to the development of oxidation- and erosion-resistant coatings for polymer matrix composite blades and vanes in future advanced turbine engines.

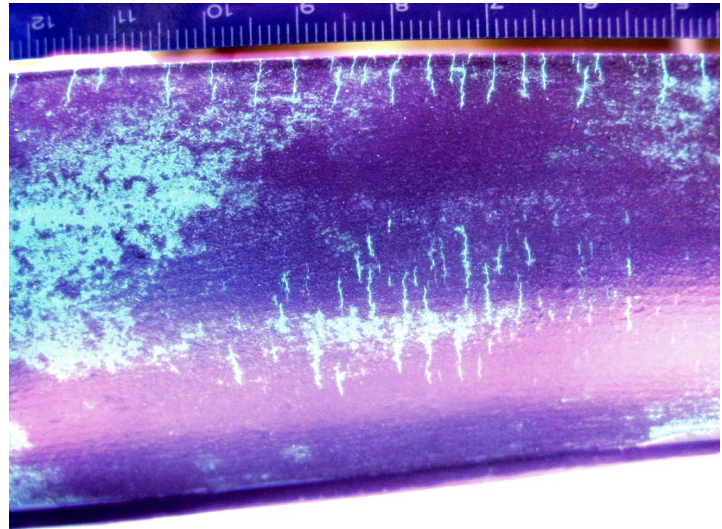
Fan bypass vanes from the AE3007 (Rolls Royce America, Indianapolis, IN) gas turbine engine were coated by Engelhard (Windsor, CT) with compliant bond coatings and hard ceramic coatings. The coatings were developed collabor-

atively by Glenn and Allison Advanced Development Corporation (AADC)/Rolls Royce America through research sponsored by the High-Temperature Engine Materials Technology Project (HITEMP) and the Higher Operating Temperature Propulsion Components (HOTPC) project. High-cycle fatigue was performed through high-frequency vibratory testing on a shaker table.

Vane resonant frequency modes were surveyed from 50 to 3000 Hz at input loads from 1g to 55g on both uncoated production vanes and



Coated vane undergoing vibratory testing with displacement amplitudes visible in photograph shadowing. Total vane height is approximately 15 cm (6 in.).



Trailing edge and convex midsection cracks visible with fluorescent dye after 10 million cycles at a strain amplitude of 1300 to 1400 $\mu\epsilon$. The scale marker is in centimeters. Maximum crack length is about 0.7 cm on the edge and 1.8 cm in the midsection.

vaness with the erosion-resistant coating. Vanes were instrumented with both lightweight accelerometers and strain gauges to establish resonance, mode shape, and strain amplitudes. Two high-frequency dwell conditions were chosen to excite two strain levels: one approaching the vane's maximum allowable design strain and another near the expected maximum strain during engine operation. Six specimens were tested per dwell condition. Pretest and posttest inspections were performed optically at up to $\times 60$ magnification and using a fluorescent-dye penetrant.

Accumulation of 10 million cycles at a strain amplitude of two to three times that expected in the engine (approximately 670 Hz and 20g) led to the development of multiple cracks in the coating that were only detectable using fluorescent-dye penetrant inspection. Cracks were prevalent on the trailing edge and on the convex side of the midsection. No cracking or spalling was evident using standard optical inspection at up to $\times 60$ magnification. Further inspection may reveal whether these fine cracks penetrated the coating or were strictly on the surface.

The dwell condition that simulated actual engine conditions produced no obvious surface flaws even after up to 80 million cycles had been accumulated at strain amplitudes produced at approximately 1500 Hz and 45g.

Find out more about this research:
Structural Mechanics and Dynamics Branch:

<http://structures.grc.nasa.gov/5930/>

Polymers Branch:

<http://www.grc.nasa.gov/WWW/MDWeb/5150/Polymers.html>

Structural Dynamics Laboratory:

<http://www.grc.nasa.gov/WWW/Facilities/int/sdl/>

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Programs/Projects:

Propulsion and Power, HOTPC, HITEMP

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13. ABSTRACT (Maximum 200 words) The 2002 annual report of the Structural Mechanics and Dynamics Branch reflects the majority of the work performed by the branch staff during the 2002 calendar year. Its purpose is to give a brief review of the branch's technical accomplishments. The Structural Mechanics and Dynamics Branch develops innovative computational tools, benchmark experimental data, and solutions to long-term barrier problems in the areas of propulsion aeroelasticity, active and passive damping, engine vibration control, rotor dynamics, magnetic suspension, structural mechanics, probabilistics, smart structures, engine system dynamics, and engine containment. Furthermore, the branch is developing a compact, nonpolluting, bearingless electric machine with electric power supplied by fuel cells for future "more electric" aircraft. An ultra-high-power-density machine that can generate projected power densities of 50 hp/lb or more, in comparison to conventional electric machines, which generate usually 0.2 hp/lb, is under development for application to electric drives for propulsive fans or propellers. In the future, propulsion and power systems will need to be lighter, to operate at higher temperatures, and to be more reliable in order to achieve higher performance and economic viability. The Structural Mechanics and Dynamics Branch is working to achieve these complex, challenging goals.				
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