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DETERMINING STRUCTURAL PERFORMANCE

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and
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ABSTRACT

The objective of this presentation is give an overview of the methods and concepts developed to enhance and predict structural dynamic characteristics of advanced aeropropulsion systems. Aeroelasticity, Vibration Control, Dynamic Systems, and Computational Structural Methods are four disciplines that make up the structural dynamic effort here at Lewis. The Aeroelasticity program develops analytical and experimental methods for minimizing flutter and forced vibration of aerospace propulsion systems. Both frequency domain and time domain methods have been developed for applications on the turbofan, turbopump, and advanced turboprop. In order to improve life and performance, the Vibration Control program conceives, analyzes, develops, and demonstrates new methods to control vibrations in aerospace systems. Active and passive vibration control is accomplished with electromagnetic dampers, magnetic bearings, and piezoelectric crystals to control rotor vibrations. The Dynamic Systems program analyzes and verifies the dynamics of interacting systems, as well as develops concepts and methods for high-temperature dynamic seals. Work in this field involves the analysis and parametric identification of large, nonlinear, damped, stochastic systems. The Computational Structural Methods program exploits modern computer science to fundamentally improve the usage of computers in the solutions of structural problems. Overall, the structural dynamic methods and concepts presented have greatly enhanced the performance and life of advanced aeropropulsion systems.

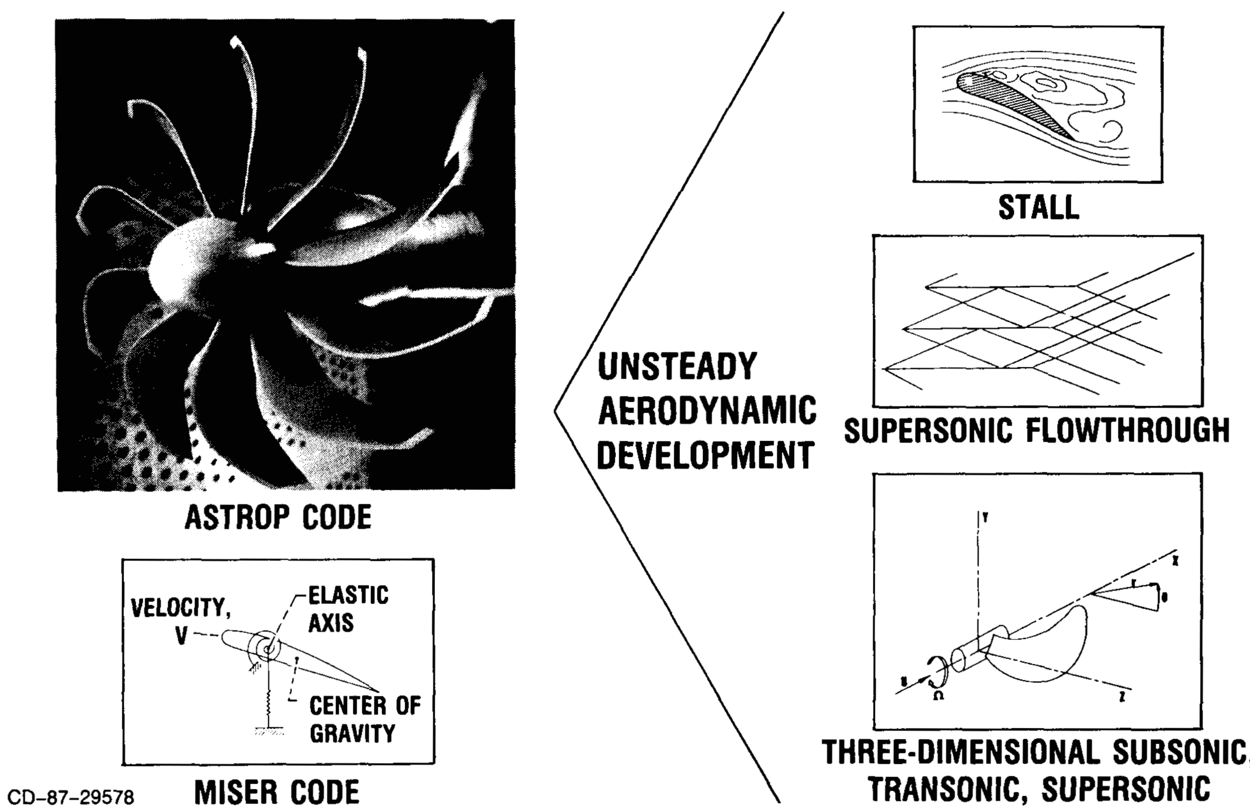
AEROELASTIC METHODS

The computer program MISER (mistuned engine response) is a two-dimensional aeroelastic program that allows the user to explore the effects of mistuning on a series of blade cross sections in cascade. The computer program ASTROP (aeroelastic stability and response of propulsion systems) is a three-dimensional program that allows the user to predict the aeroelastic nature of propfan blades in cascades. Both programs have the capability of analyzing blades in both the subsonic and supersonic (subsonic leading-edge locus) flow regimes.

In order to improve the capability of both MISER and ASTROP, work is in progress to extend the unsteady aerodynamic packages in both programs. For instance, work is currently in progress to extend ASTROP into the stall and transonic flow regimes, and MISER's unsteady aerodynamic package is being extended to handle supersonic axial flowthrough applications.

Over the past five years, both ASTROP and MISER have offered extensive insight into the aeroelastic behavior of propfans, as well as fan stages of turbofan engines.

AEROELASTIC METHODS



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AEROELASTIC STABILITY AND RESPONSE OF PROPULSION SYSTEMS (ASTROP)

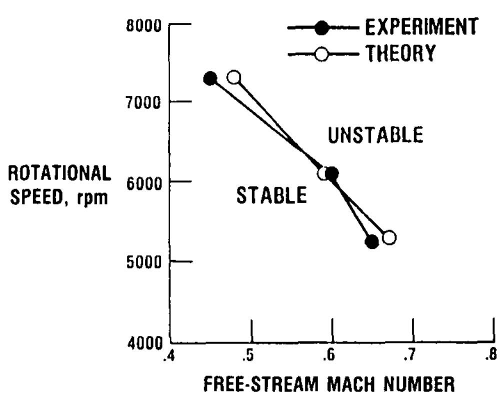
The turbomachinery aeroelastic effort at NASA Lewis Research Center includes unstalled and stalled flutter, forced response, and whirl flutter of propulsion systems. Even though the effort is currently focused on single-rotation and counterrotation propfans, the analytical models and the computer codes are applicable to turbofans with and without blade sweep and compressors. Because of certain unique features of propfans, it is not possible to directly use the existing aeroelastic technology of conventional propellers, turbofans, or helicopters. Therefore, reliable aeroelastic stability and response analysis methods for these propulsion systems must be developed. The development of these methods for propfans requires specific basic technology disciplines, such as two-dimensional and three-dimensional, steady and unsteady (unstalled and stalled), aerodynamic theories in subsonic, transonic, and supersonic flow regimes; modeling of composite blades; geometric nonlinear effects; and passive or active control of flutter and response. These methods for propfans are incorporated in the computer program ASTROP. The program has flexibility such that new and future models in basic disciplines can be easily implemented.

The ASTROP3 code predicted flutter boundary of the SR3C-X2 (eight-bladed composite propfan wind tunnel model) is compared with the measured one. The comparison shows a very good agreement between theory and experiment. More details on the ASTROP code and further code validatory results can be found in NASA TM-88944 and NASA TM-88959.

AEROELASTIC STABILITY AND RESPONSE OF PROPULSION SYSTEMS (ASTROP)

ASTROP2	ASTROP3	ASTROPS	ASTROPW	ASTROPT	ASTROPU
FLUTTER • NORMAL MODES • TWO-DIMENSIONAL SUBSONIC AND SUPERSONIC • MISTUNING	FLUTTER AND RESPONSE • NORMAL MODES • THREE-DIMENSIONAL SUBSONIC AND SUPERSONIC • MISTUNING	STALL FLUTTER • NORMAL MODES • TWO-DIMENSIONAL SUBSONIC STALLED	WHIRL FLUTTER • NORMAL MODES • THREE-DIMENSIONAL SUBSONIC	TRANSONIC FLUTTER • NORMAL MODES • TWO-DIMENSIONAL AND THREE-DIMENSIONAL FULL POTENTIAL	FLUTTER AND RESPONSE • NORMAL MODES • THREE-DIMENSIONAL EULER
COMPLETED	COMPLETED	IN PROGRESS	IN PROGRESS	IN PROGRESS	STARTED

COMPARISON OF EXPERIMENTAL AND THEORETICAL FLUTTER BOUNDARY



PROPFAN WIND TUNNEL MODEL

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BLADE VIBRATION CONTROL

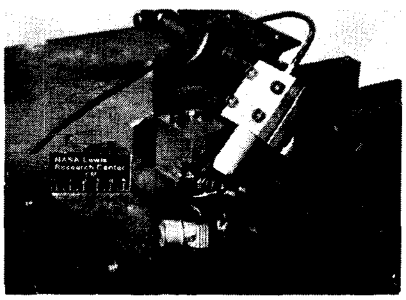
Shown in the figure are examples of projects in passive control of blade vibration. The variable-normal-load friction-damper test fixture was developed to allow detailed study of friction dampers in a rotating environment. The data generated with this test fixture were used to fine tune and verify advanced mathematical models of friction damper behavior. The models were used to show that friction dampers have the potential to stabilize fluttering fan blades.

The first-stage turbine blades of the space shuttle main engine (SSME) high-pressure oxygen pump (HPOTP) have experienced cracking problems due to excessive vibration. A solution is to incorporate a well-designed friction damper to attenuate blade vibration. An integrated experimental-analytical approach was used to evaluate a damper design. An optimized design resulted in a modest microslip damper.

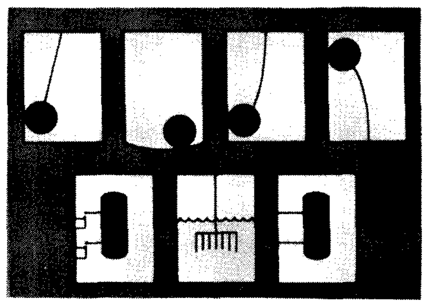
An analytical study of impact dampers has been completed. The model predicts that a relatively light impactor (1 to 4 percent of the blade mass) produces substantial damping. In addition, the phenomenon of frequency tuning is not present for the impact damper. However, it is replaced by what might be called amplitude tuning. Experimental verification is now being planned.

BLADE VIBRATION CONTROL

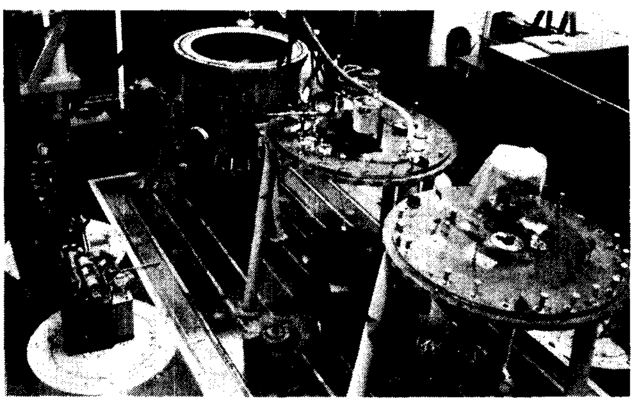
VARIABLE-NORMAL-LOAD FRICTION DAMPER



SSME HIGH-PRESSURE OXYGEN PUMP (HPOTP) FRICTION DAMPER



ADVANCED CONCEPT IMPACT DAMPERS



SPIN RIG VERIFICATION

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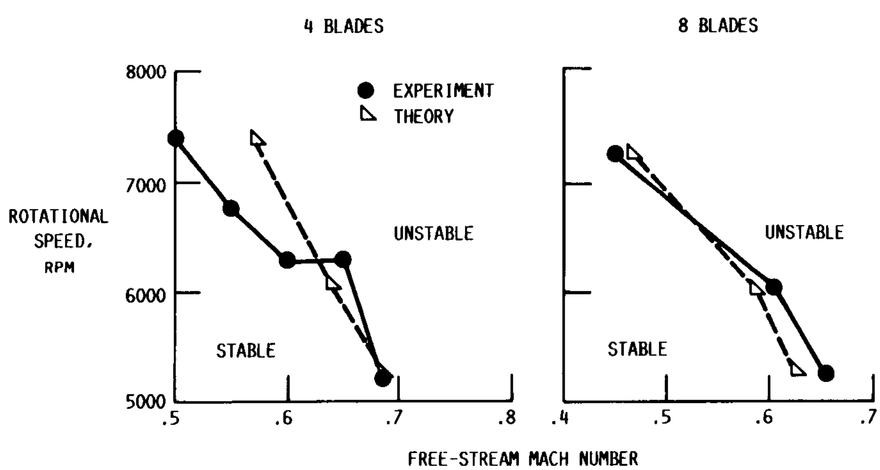
An experimental and analytical research program is being conducted to understand the flutter and forced response characteristics of advanced high-speed propellers or propfans. The aeroelastic analysis for the design of propfans is more complex than for conventional propellers because blade characteristics and aerodynamic operating conditions are different for propfans. Propfans have six or more swept, thin, low-aspect-ratio blades, and the blades operate in subsonic, transonic, and possibly supersonic flows. Flutter and forced response data have been obtained from 2-ft-diameter single-rotation and counterrotation models in NASA and industry wind tunnels. The large-scale demonstrator propfans that have been flight tested during 1986 and 1987 were designed with analyses that were developed and verified with data from this program.

A comparison of measured and calculated flutter boundaries for a propfan model, called SR3C-X2, is shown in the figure. The theoretical results, from the Lewis-developed ASTROP3 analysis, include the effects of centrifugal loads and steady-state, three-dimensional airloads. The analysis does reasonably well in predicting the flutter speeds and slopes of the boundaries. However, the difference between the calculated and measured flutter Mach numbers is greater for four blades than for eight blades. This implies that the theory is overcorrecting for the decrease in the aerodynamic cascade effect with four blades.

COMPARISON OF MEASURED AND CALCULATED FLUTTER BOUNDARIES

SR3C-X2 PROPFAN MODEL



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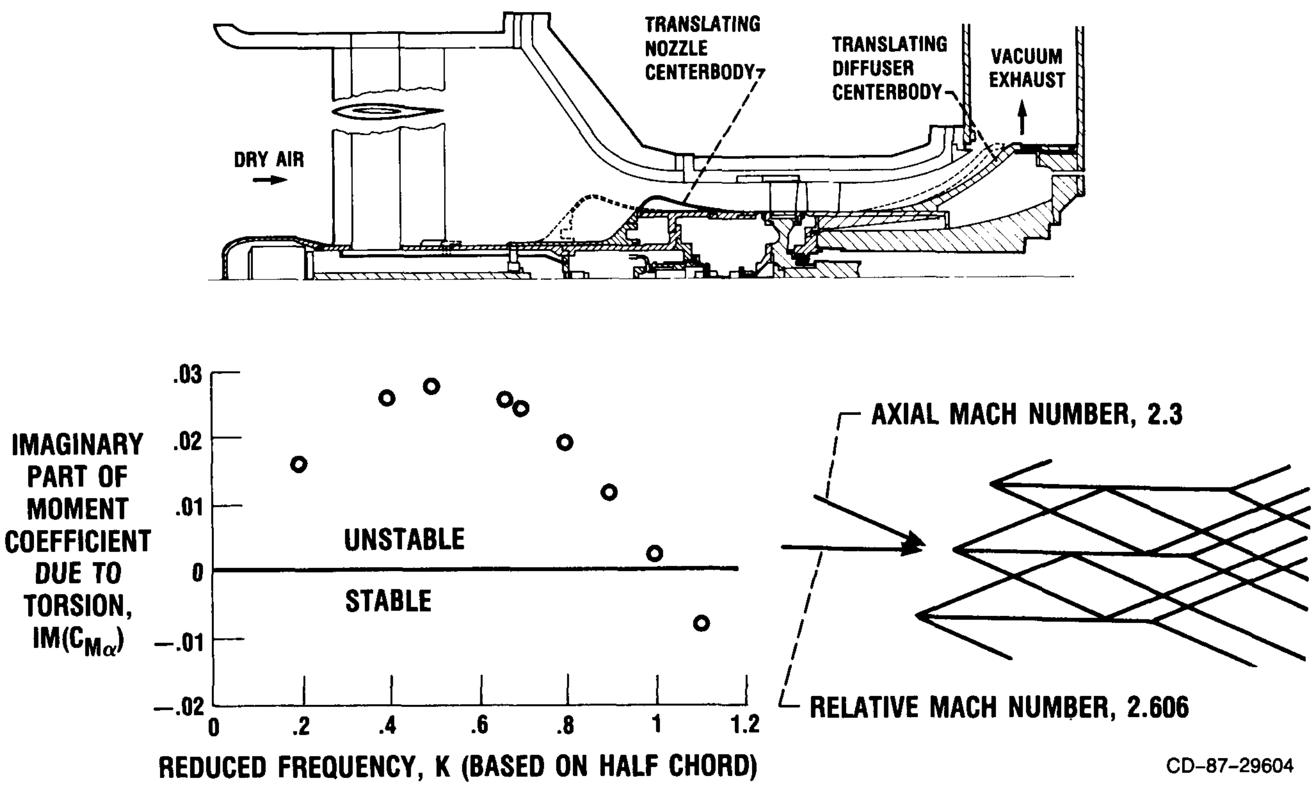
SUPERSONIC AXIAL THROUGHFLOW

Recent interest in supersonic and hypersonic flight has renewed interest in developing propulsion systems which include a supersonic axial-flow fan. As a result, an effort is in progress at NASA Lewis Research Center to build a single-stage, supersonic axial-flow fan.

Conventional fans or compressors normally only encounter supersonic flow relative to the blades, or when subject to supersonic flow normal to the plane of blade rotation, decelerate the flow through shocks which are contained upstream of the locus of blade leading edges. The supersonic axial-flow fan encounters supersonic flow normal to the plane of rotation as well as relative to the blades, and has supersonic flow through the entire blade passage. This fan is characterized by oblique shocks contained downstream of the locus of blade leading edges.

Since the aeroelastic stability of the proposed single-stage fan was a concern, an analytical capability was needed to predict the unsteady aerodynamic loading. Consequently, a computer program was developed by John K. Ramsey, using Lane's equation for the unsteady pressure distribution, for the case of supersonic axial flow. This code (Lane's code) predicts the unsteady pressure distribution for a cascade or isolated airfoil in supersonic axial flow. This code can be connected to any aeroelastic code.

SUPERSONIC AXIAL THROUGHFLOW



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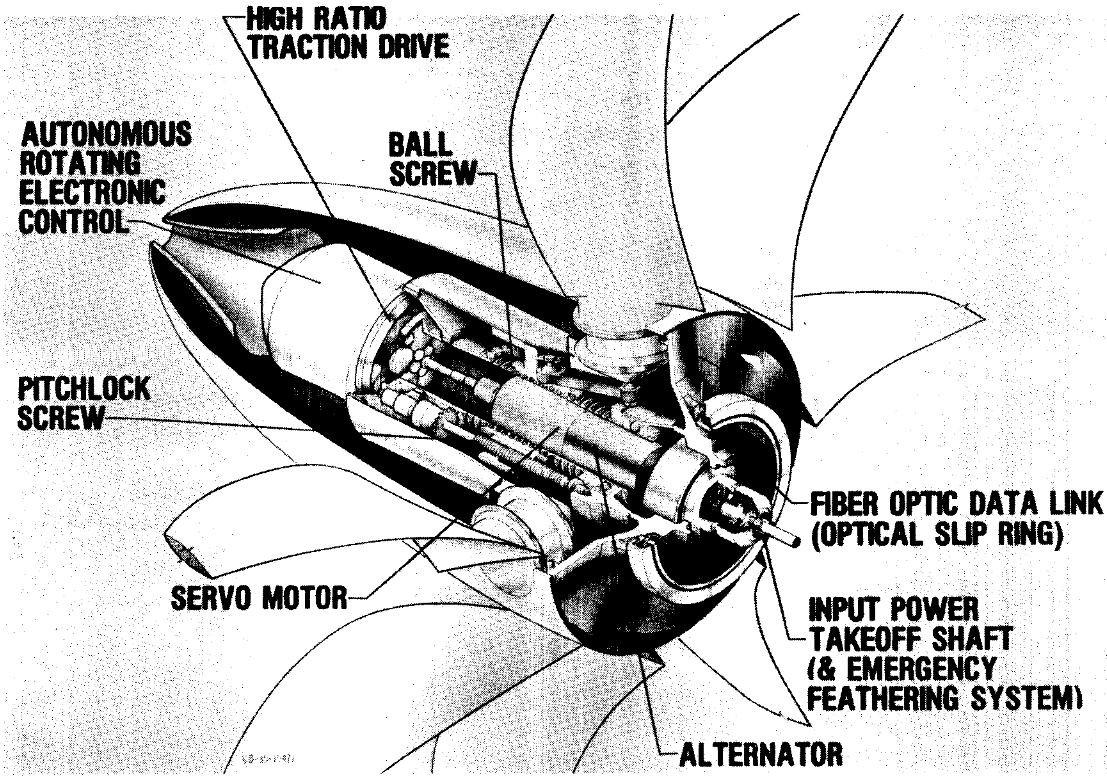
ADVANCED TURBOPROP PITCH-CHANGE MECHANISM

NASA Lewis, in conjunction with General Electric Company, developed a high-precision servomechanism for controlling turboprop aircraft blade angles. The pitch-change mechanism can accurately control the variable pitch of large (13 000 hp) turboprop aircraft propellers over the complete spectrum of flight operating conditions and helps attain advanced turboprop performance goals of improving propulsion system efficiency by 30 percent and reducing operating costs by 10 percent.

Advanced design features include a fiber-optic data link, a high-speed electric motor/alternator combination, a high-mechanical-ratio blade articulating mechanism, and an autonomous propeller that generates its own electrical power and has an independent self-contained control module.

The key to minimizing noise with these large propeller systems is accurate synchrophasing (or precise blade speed and phase synchronization of left and right propellers). The blade angle resolution capabilities of this pitch-control mechanism have been theoretically shown to meet or exceed the requirements for minimizing blade noise experienced by passengers onboard aircraft expected to be flying in the 1990's.

ADVANCED TURBOPROP PITCH-CHANGE MECHANISM



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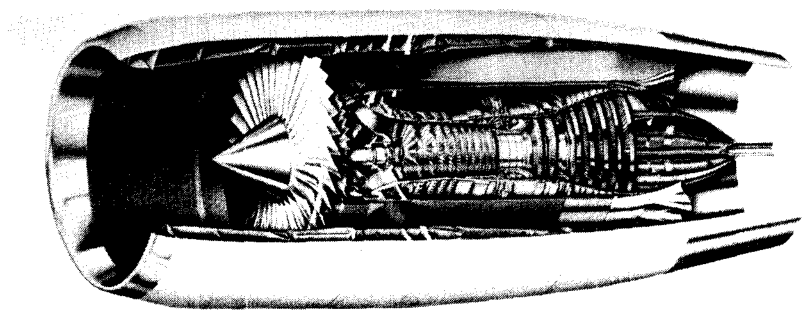
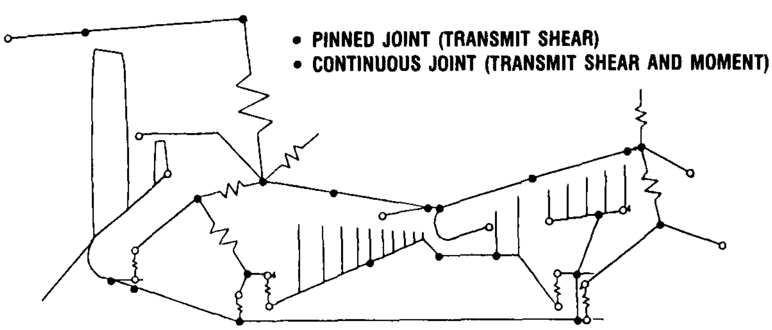
ROTOR SYSTEMS MODELING

Three nonlinear transient computer codes to model complex aerospace structures were developed. The first code, TRAN, integrates the physical system of equations and is used for short-time, high-frequency events. The next two programs, ARDS and TETRA, use component modal synthesis methods using an appropriate set of modes and are, therefore, more applicable for longer transients. The ARDS code has been enhanced to provide shock spectrum analysis and automatic optimum rotor design. The TETRA code can use either modal data generated by NASTRAN or experimental data and has been further enhanced by a steady-state analysis.

ROTOR SYSTEMS MODELING



ENERGY EFFICIENT ENGINE (E^3) SYSTEM (GENERAL ELECTRIC CONFIGURATION)



MODEL OF E^3 ENGINE SYSTEM

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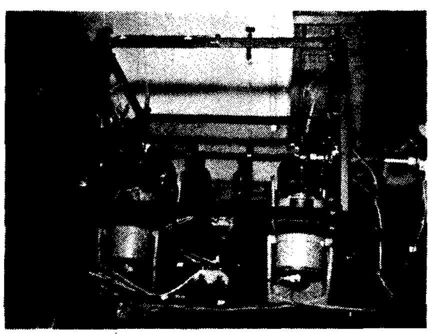
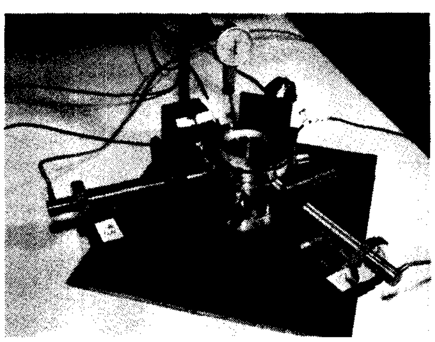
ACTIVE ROTOR CONTROL

Active control of rotor vibrations offers important advantages over passive methods, especially greater damping. The principle is illustrated in the center of the figure. Shaft position sensors send signals to a controller which, guided by a control algorithm, operates actuators located at bearings. The actuators oppose undesired shaft vibrational motion. Three types of actuators are illustrated. In the upper left is a research rig with electromagnetic shakers. In the lower left is a group of three piezoelectric actuators, which change length when a voltage is applied to them. In the upper right is an electromagnetic device which both reduces vibration and replaces the conventional shaft bearings. Magnetic attraction between frame-mounted, fast-acting coils and iron disks mounted on and rotating with the shaft carries the weight of the shaft and exerts the vibration control forces. When sensors detect unwanted shaft movement, currents in the appropriate coils increase to pull the shaft back. This system permits higher shaft speed, automatic balancing, and better shaft positioning. Magnetic bearings need improvements in the speed and size of the electronics and in the actuator to meet flight requirements. Among the exciting possible advances in the actuator is the use of high-temperature superconductors which would make the windings more compact and eliminate the iron cores. The much more compact result is illustrated in the lower right.

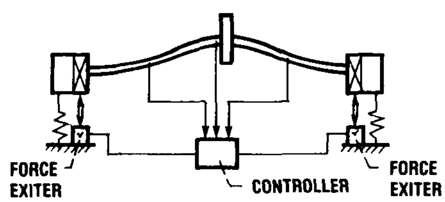
ACTIVE ROTOR CONTROL

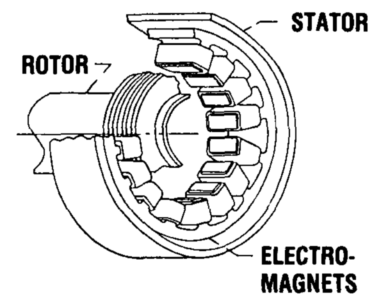


ACTIVE CONTROL TEST RIG

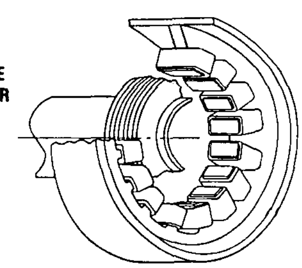


PIEZOELECTRIC ACTUATORS





MAGNETIC BEARING



MAGNETIC BEARING
WITH HIGH-TEMPERATURE
SUPERCONDUCTOR WINDINGS

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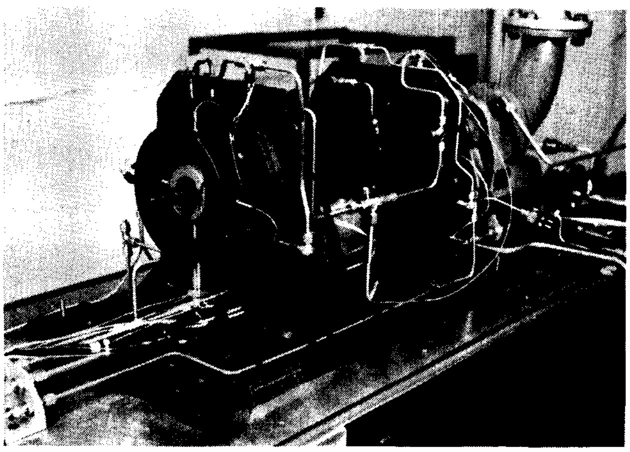
ROTOR DAMPERS

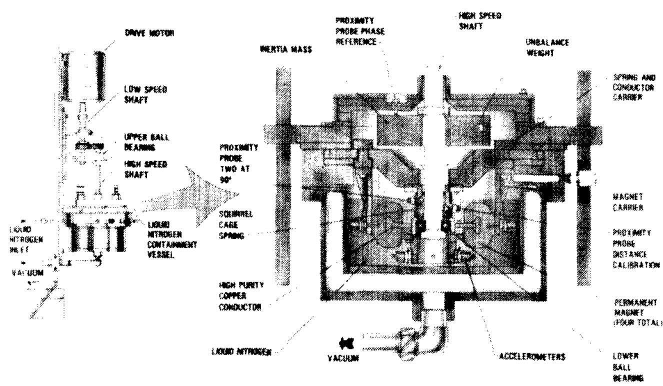
In conventional gas turbine engines, squeeze-film dampers are used to control nominal rotor unbalance. To control a transient blade-loss event, active damping may have to be used. The figure on the left shows a blade-loss test rig with piezoelectric actuators as active dampers. The object of the test was to investigate various algorithms to control the transient. A magnetic damper is being designed for this rig.

In the case of the space-plane, cryogenic fluids could be used as the fuel. At cryogenic temperatures there is no verified damper. There is a need for passive (or active) dampers. Potential passive cryo dampers are elastomeric, curved-beam, hydrostatic, closed-cartridge, non-Newtonian fluid, and eddy current. The figure on the right shows the liquid nitrogen damper test rig. A liquid hydrogen test rig is available.

ROTOR DAMPERS



BLADE-LOSS TEST RIG



LIQUID NITROGEN DAMPER TEST RIG

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HIGH-LOAD, THRUST-BEARING DAMPER RIG

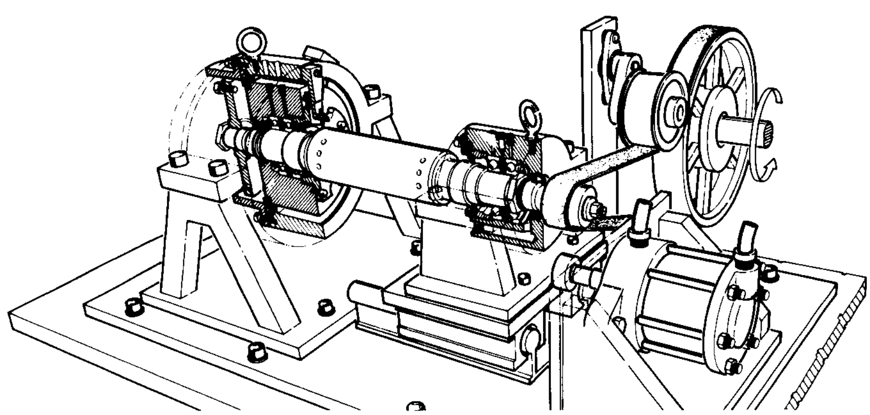
This rig was designed to test engine dampers which carry a larger than normal radial load (e.g., due to blade loss). It can also apply a thrust load to the test damper, for testing of radial dampers used at thrust bearing locations. The damper is loaded by unbalancing the disc at the left end of the shaft. Eddy current probes measure shaft and damper vibration, and quartz load washers measure the force applied to the damper. From these measurements, the stiffness and damping of the test damper can be calculated.

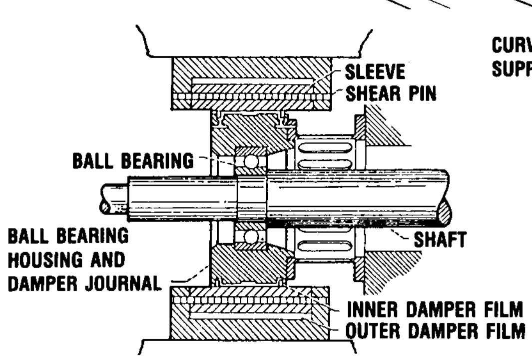
Three dampers are shown which may be tested in the rig. The dual squeeze-film damper has a conventional low-clearance film which provides the required damping at low imbalance levels. When the imbalance increases (as from a blade loss), a second, large-clearance film becomes active. This allows the damper amplitude needed to handle the higher imbalance.

The curve beam damper uses beam elements to provide stiffness. Fluid is forced through orifices to provide damping. This damper is inherently linear; stiffness and damping coefficients do not vary with vibration amplitude.

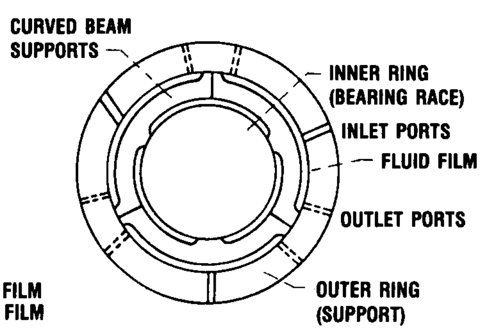
A magnetic damper applies a damping force to the rotor through electromagnets. The damper control system allows active control of rotor vibration, in which effective stiffness and damping are varied with speed and imbalance to optimize rotor performance.

HIGH-LOAD, THRUST-BEARING DAMPER RIG

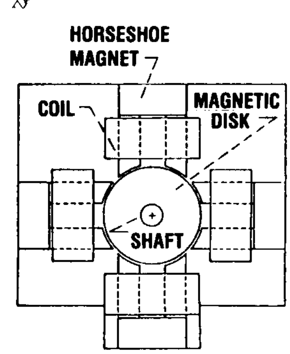




DUAL SQUEEZE-FILM DAMPER



CURVED BEAM DAMPER



MAGNETIC DAMPER

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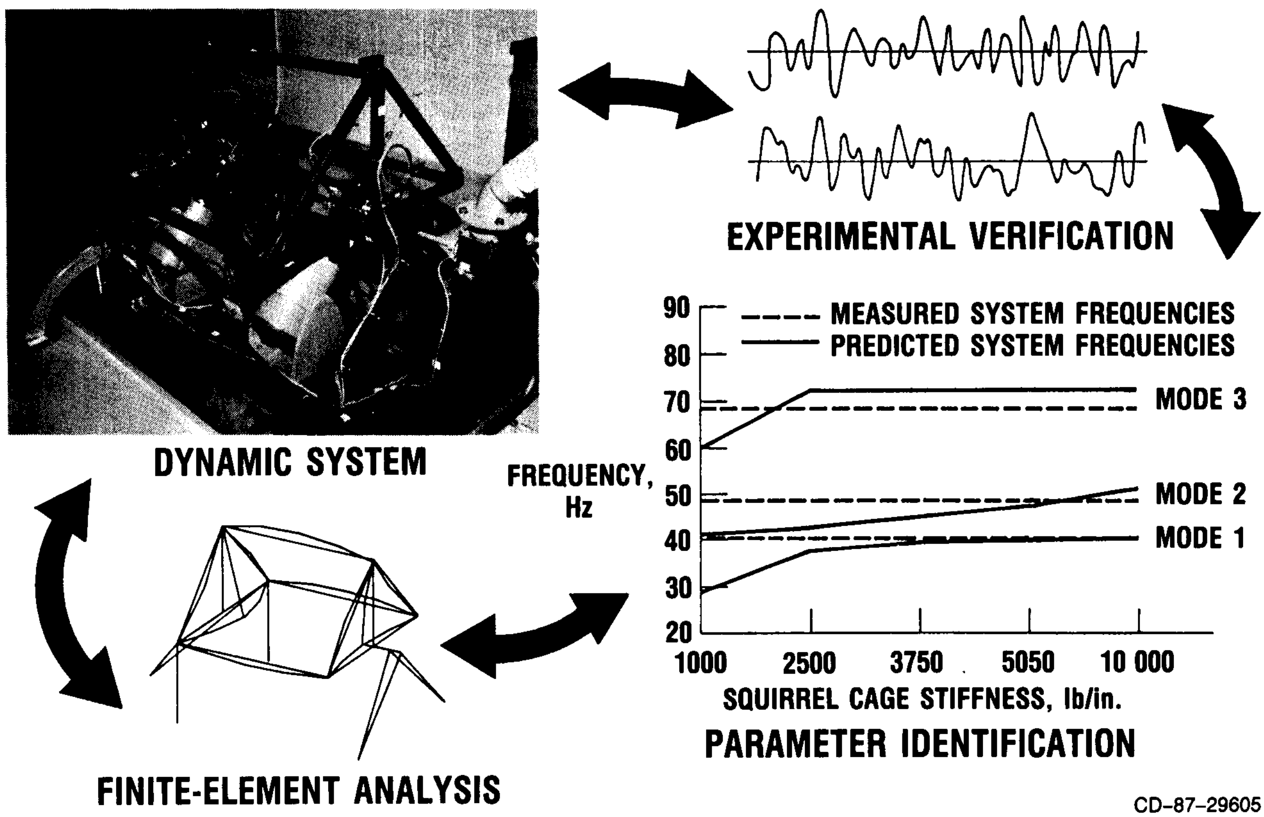
CHARACTERIZATION OF STRUCTURAL CONNECTIONS

An analytical and experimental program was carried out to develop improved methods for characterizing connections between structural components. Of particular interest was the identification of stiffness properties. The procedures developed in this program were evaluated with experimental vibration data obtained from the Rotating System Dynamics Rig.

Deficiencies in existing modeling techniques limit an analyst's ability to adequately model the connections between components. Connections between structural components are often mechanically complex, and hence very difficult to accurately model analytically. The influence that connections exert on overall system behavior can be profound. Thus, to refine the prediction of overall system behavior, improved analytical models for connections are needed.

Modeling accuracy is improved through the use of optimization methods by reducing discrepancies between the measured characteristics of an actual structural system and those predicted by an analytical model of the system. The approach used in this work involves modeling the system components with either finite elements or experimental modal data and then connecting the components at their interface points. Experimentally measured response data for the overall system are then used in conjunction with optimization methods to make improvements in the connections between components. The improvements in connections are computed in terms of physical stiffness parameters so that the physical characteristics of the connections can be better understood.

CHARACTERIZATION OF STRUCTURAL CONNECTIONS



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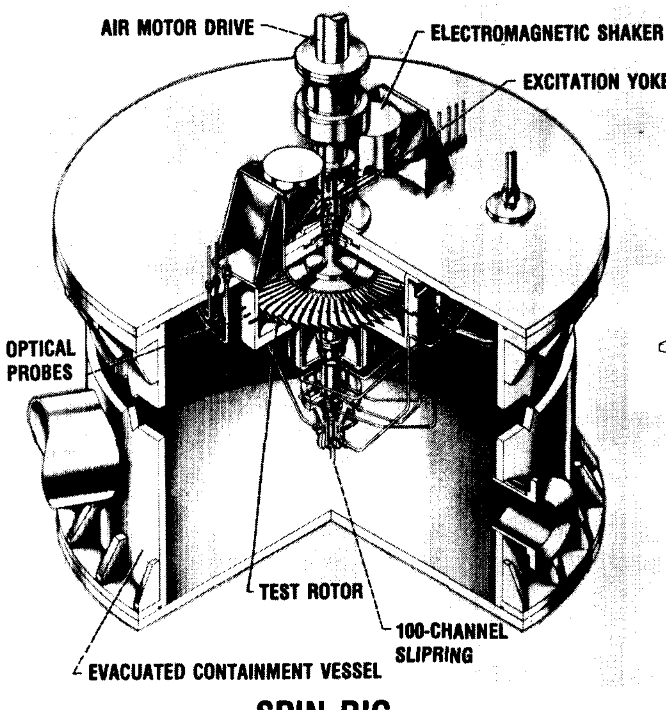
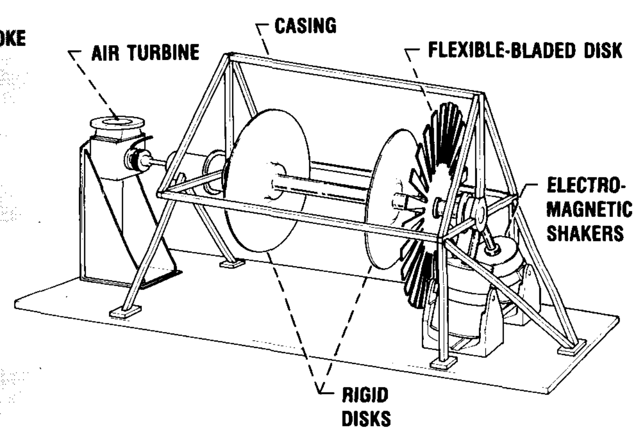
The Spin Rig is a facility which performs rotating dynamic spin tests of rotors in a vacuum to measure their vibratory and steady-state deflections and strains. The rotor wheel is contained in an armored test tank, where it can be spun up to 18 000 rpm. The tank can be evacuated to 0.001 atm, reducing air friction and blade loads to near zero. Up to 50 strain gages can be bonded to the rotor blades at strategic locations. These signals can be recorded on two 14-channel tape recorders. Data from the strain gages can then be analyzed. A laser system is also available to facilitate the measurement of centrifugally produced deflections.

The Rotating System Dynamics (RSD) Rig is a general facility for the purpose of determining the dynamic characteristics of rotating systems. Instrumentation consists of displacement measurement (9 channels); acceleration and velocity measurement (18 channels), and force measurement (4 channels). Fourteen channels of data can be recorded on tape, and all data can be monitored on oscilloscopes during testing. Four electrodynamic shakers, which are driven by a signal generator, provide forcing function input to the system under test. The rotating shafting is driven by an air turbine. Maximum rotating speed is currently 10 000 rpm.

PARAMETER VERIFICATION



SPIN RIG



ROTATING SYSTEMS DYNAMICS RIG

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COMPUTATIONAL METHODS

Our computational methods research is directed to finding new and more efficient ways of performing structural computations. There is a heavy emphasis on emerging parallel processing methods. Our research uses many different mainframe computers as well as our transputer system. A 67-processor transputer system is used for most of our parallel methods research. This system is designed to be electronically reconfigured into a variety of different equivalent architectures so that the interplay between algorithms and architectures can be fully explored. The system is built with high-performance processors, but is not expected to perform as well as a dedicated function computer could. When new methods are fully developed, they will be transferred to larger dedicated computer facilities within the NASA computer network.

In one approach, finite-element analyses are conducted by distributing stiffness matrices throughout the processor array. Multigridding analysis methods, which employ successive refinement of mesh sizes, have the refined meshes assigned to successive processors. Problems involving the management of global variables are being studied in order to distribute graphics primitives to a processor array to support high-speed animation. Eigenvalue solution routines which employ recursive, binary, tree-structured search algorithms are taking advantage of the transputer network ability to reconfigure processor interconnections.

COMPUTATIONAL METHODS