N92-22519

DETERMINING STRUCTURAL PERFORMANCE

Edited by Michael A. Ernst

SUMMARY

The objective of this paper is to 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 for controlling 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 system. The computational structural methods program exploits modern computer science as an aid to the solutions of structural problems.

INTRODUCTION

Overall, this paper will present (1) methods that have been developed to dynamically characterize the components of aeropropulsion systems, (2) advanced concepts that are being applied for the benefit of system and durability, and (3) test rigs and facilities that are used to validate the methodologies developed.

The editor wishes to acknowledge the following authors for their contributions to this paper.

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ANALYTICAL METHODS

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.

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 (fig. 1). 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 cascade (fig. 2). 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. Currently, work is in progress to extend ASTROP into the stall and transonic flow regimes, while MISER's unsteady aerodynamic package is being extended to handle supersonic axial throughflow applications. For example, recent interest in supersonic and hypersonic flight has renewed interest in the development propulsion systems that include a supersonic axial-flow fan (fig. 3). 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 is a concern, an analytical capability is needed to predict the unsteady aerodynamic loading. Consequently, a computer program was developed using Lane's equation for the unsteady pressure distribution in the case of supersonic axial flow. This code predicts the unsteady pressure distribution for an isolated airfoil, or a series of blades in cascade.

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.

Capabilities exist not only to dynamically characterize fan blades, but also to characterize the vibrations of entire rotor systems (fig. 4). Three nonlinear transient computer codes were developed to model complex aerospace structures. The code TRAN integrates the physical system of equations and is used for short-term, high-frequency events. The programs ARDS and TETRA employ 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.

Deficiencies in existing modeling techniques, however, 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 effect that connections have on overall system behavior can be profound. Thus, to refine the prediction of overall system behavior, improved analytical models for connections are needed. An analytical and experimental program was carried out to develop improved methods for characterizing connections between structural components (fig. 5). 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.

The accuracy of modeling is improved through the use of optimization methods that reduce 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.

As new methodologies are being developed and state-of-the-art programs become more cumbersome, there arises a critical need to be able to run these programs in a timely and efficient manner.

Computational methods research is directed toward finding new and more efficient ways of performing structural computations (fig. 6). There is a heavy emphasis on emerging parallel processing methods. Many different mainframe computers are used, as well as a 67-processor transputer system for most of the 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. This system is built with high-performance processors, but is not expected to perform as well as a dedicated computer.

In one approach, finite-element analyses are conducted by distributing stiffness matrices throughout the processor array. Multigridding analysis methods, which employ successive refinements 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 that employ recursive, binary, tree-structured search algorithms are taking advantage of the transputer network's ability to reconfigure processor interconnections. When new methods are fully developed, they will be transferred to larger dedicated computer facilities within the NASA computer network.

APPLICATIONS OF ADVANCED CONCEPTS

Research does not stop with the development of new methodologies. Advanced concepts are being applied to aeropropulsion systems to improve both performance and durability.

NASA Lewis, in conjunction with the General Electric Company, has developed a high-precision servomechanism for controlling turboprop aircraft blade angles (fig. 7.). 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. It also 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 (i.e., 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 that will be experienced by passengers on board aircraft flying in the 1990's.

Shown in figure 8 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.

For example, 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 the 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.

Active control of rotor vibrations offers important advantages over passive control, especially in the matter of greater damping. This principle is illustrated in the center of figure 9. Shaft position sensors send signals to a controller which, guided by a control algorithm, operates actuators located at the 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 that 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 that would make the windings more compact and eliminate the iron cores. The much more compact result is illustrated in the lower right.

TEST RIGS AND FACILITIES

Test rigs and facilities are employed for the experimental verification of the methodologies and advanced concepts that have been developed. For example, an experimental research program is being conducted in the 8- by 6-Foot Supersonic Wind Tunnel to understand the flutter and forced-response characteristics of advanced high-speed propellers or propfans (fig. 10). Flutter and forced-response data have been obtained from 2-ft-diameter single-rotation and counterrotation models. This has allowed researchers to compare measured and calculated flutter boundaries.

The Spin Rig is a facility that performs rotation dynamic spin tests of rotors in a vacuum to measure their vibratory and steady-state deflections and strains (fig. 11). The rotor wheel is contained in a 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 Rotation System Dynamics (RSD) Rig is a general facility that is used for determining the dynamic characteristics of rotating systems (fig. 12). Instrumentation consists of (1) displacement measurement (9 channels), (2) acceleration and velocity measurement (18 channels), and (3) 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 shaft is driven by an air turbine. Maximum rotating is currently 10 000 rpm.

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. Figure 13 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 National Aerospace Plane, cryogenic fluids could be used as the fuel. At cryogenic temperatures, there is no verified damper. There is a need for either passive or active dampers. Potential passive cryogenic dampers are elastomeric, curved-beam, hydrostatic, closed-cartridge, non-Newtonian fluid, and eddy current. Figure 14 shows the liquid nitrogen damper test rig. A liquid hydrogen test rig is available.

The High Load Thrust Rig, shown in figure 15, was designed to test engine dampers that 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 radial dampers used at thrust-bearing locations. The damper is loaded by unbalancing the disk 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.

Figure 15 shows three dampers that may be tested in the rig. The dual squeeze-film damper has a conventional low-clearance film that 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 provides 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.

CONCLUDING REMARKS

Programs such as ASTROP, TETRA, TRAN, and ARDS are state-of-the-art tools for the dynamic analysis of aeropropulsion components. Work involved in computational methods, and in the characterization of structural connections, is expected to add greatly to the efficiency and accuracy of many of the programs already developed. Advanced concepts, such as electrodynamic dampers or piezoelectric actuators, will continue to be explored in order to improve the life and performance of aeropropulsion systems. Test facilities such as the Spin Rig and the 8- by 6-Foot Supersonic Wind Tunnel will continue to be used by both government and industry for the experimental validation of the methodologies developed and of the advanced concepts applied.

Lewis Research Center is committed to aeropropulsion excellence. In turn, the structural dynamic effort continues to be devoted to the development of new methodologies and the application of advanced concepts in order to meet this commitment.

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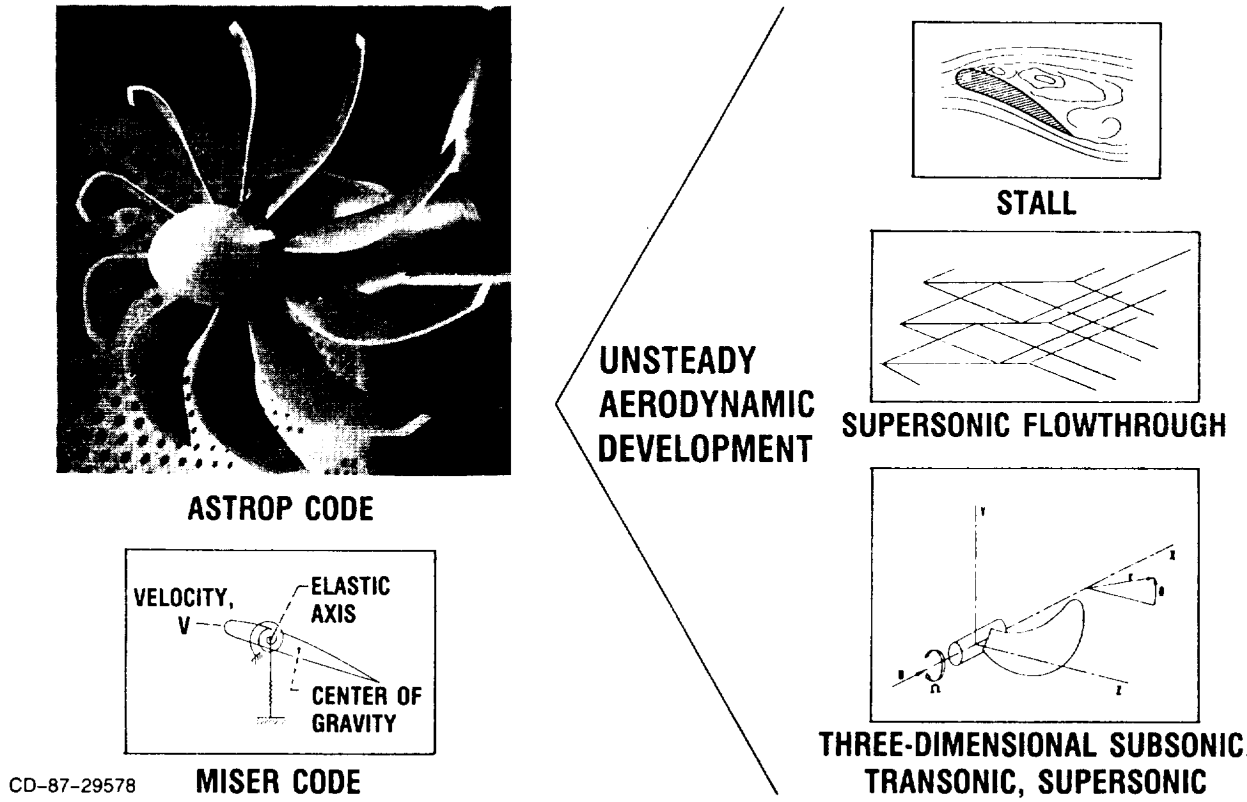

Figure 1. - Aeroelastic methods.

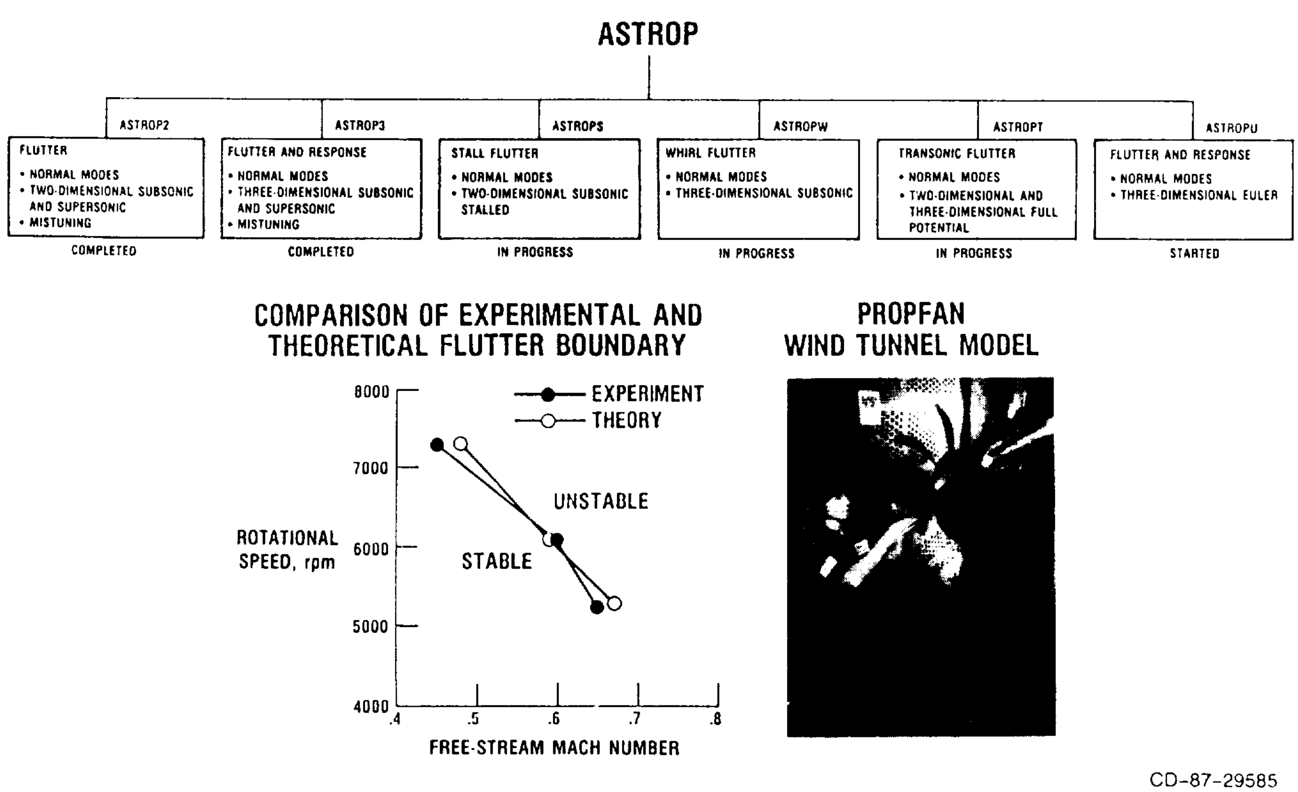

Figure 2. - Aeroelastic stability and response of propulsion systems (ASTROP).

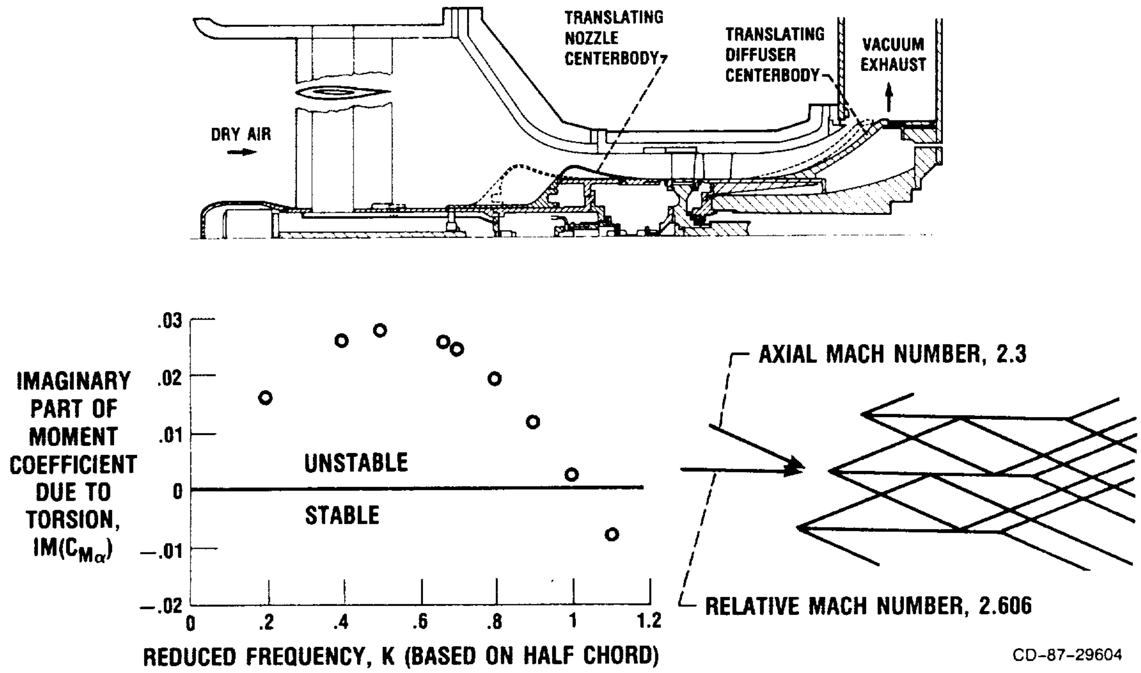

Figure 3. - Supersonic axial throughflow.

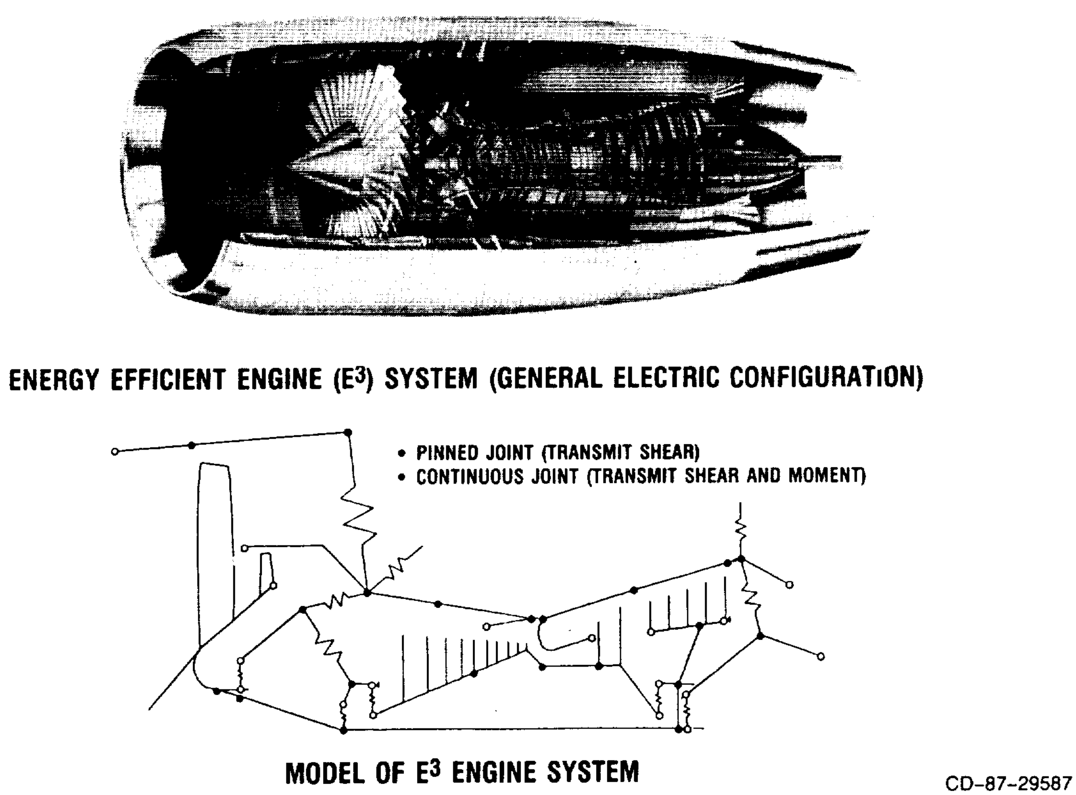

Figure 4. - Rotor systems modeling.

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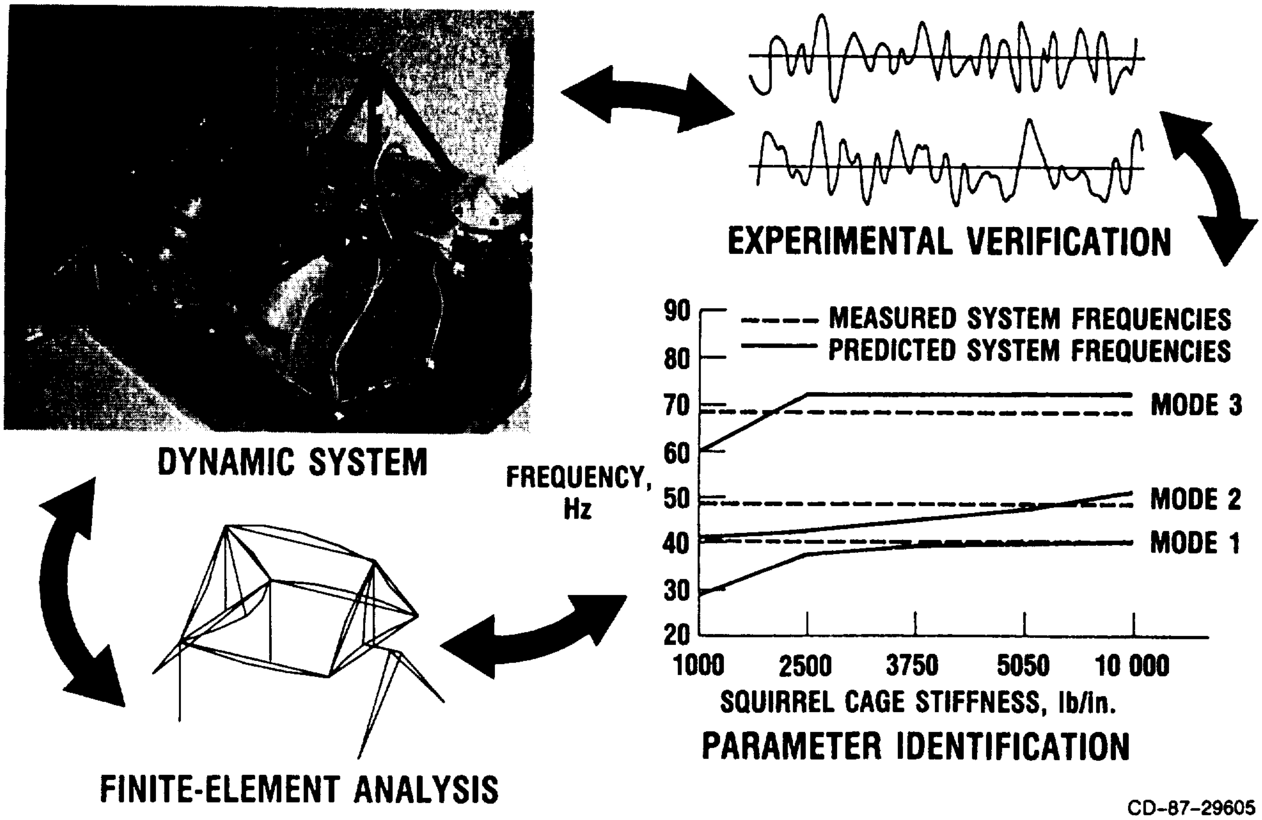

Figure 5. - Characterization of structural connections.

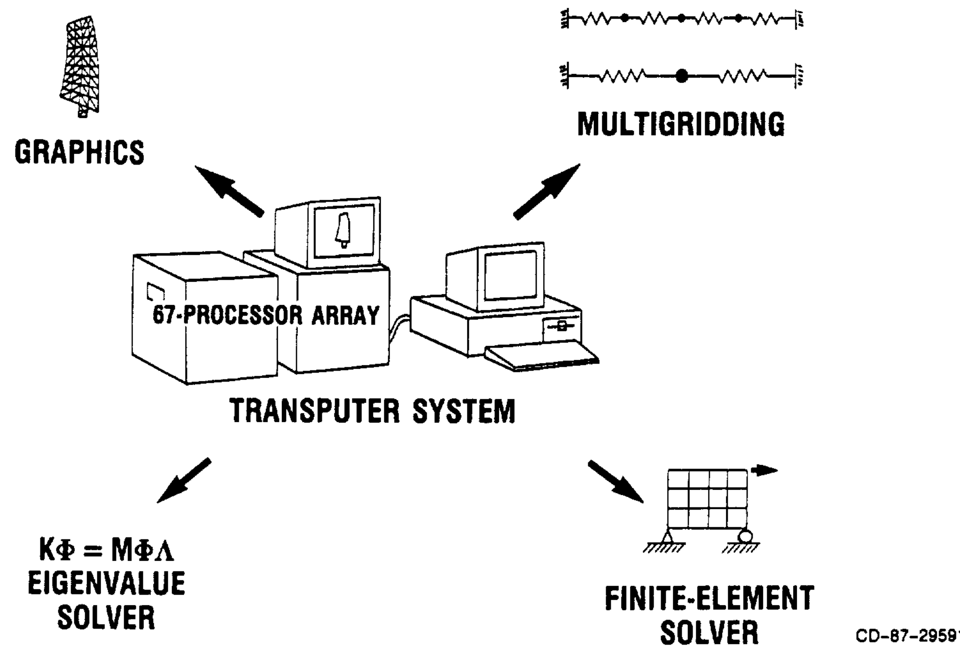

Figure 6. - Computational methods.

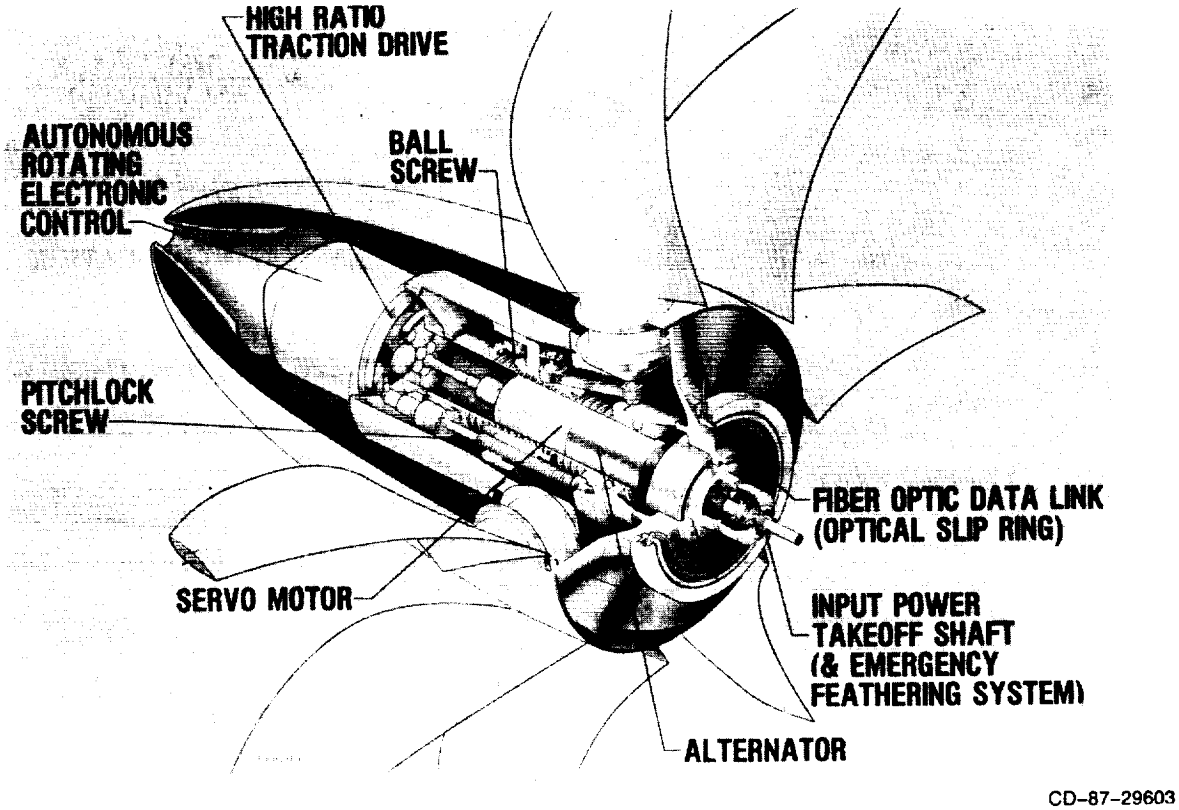

Figure 7. - Advanced turboprop pitch-change mechanism.

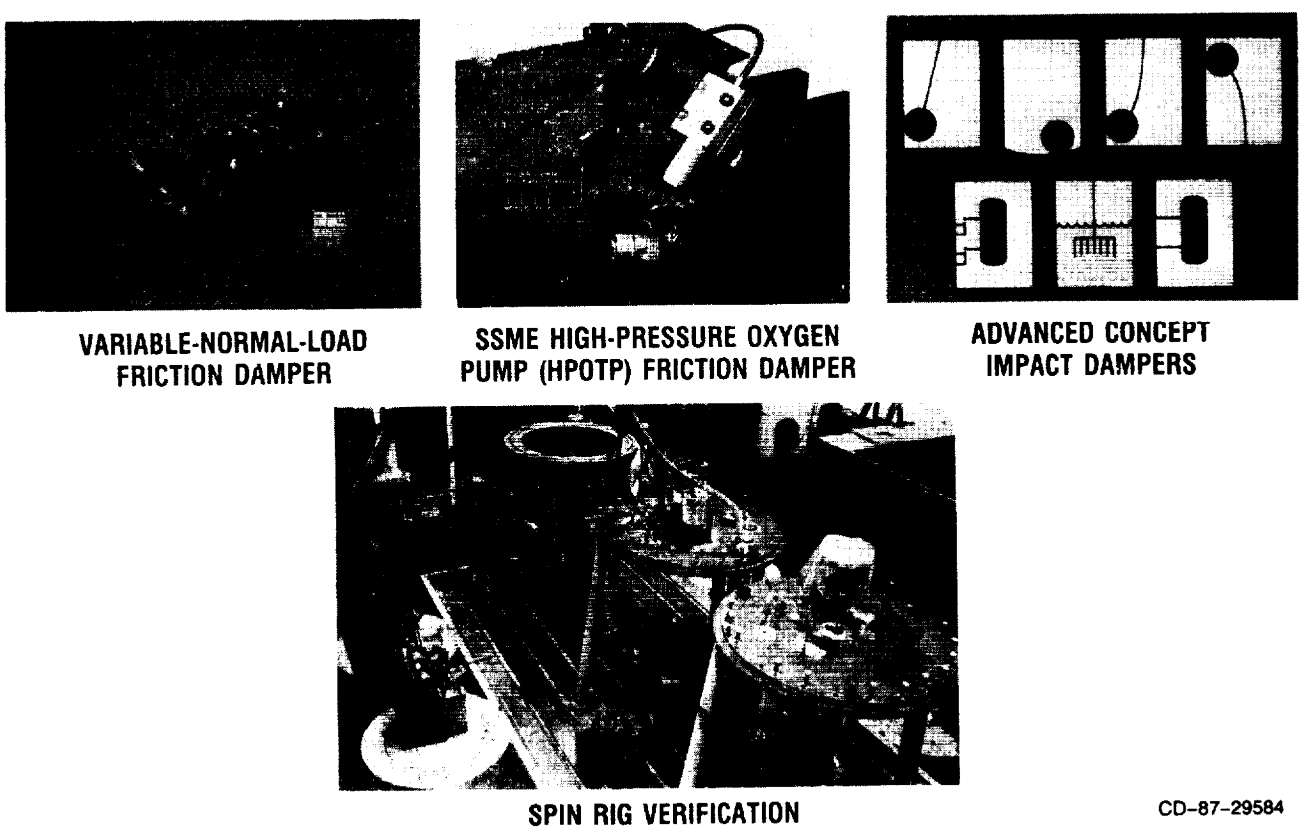

Figure 8. - Blade vibration control.

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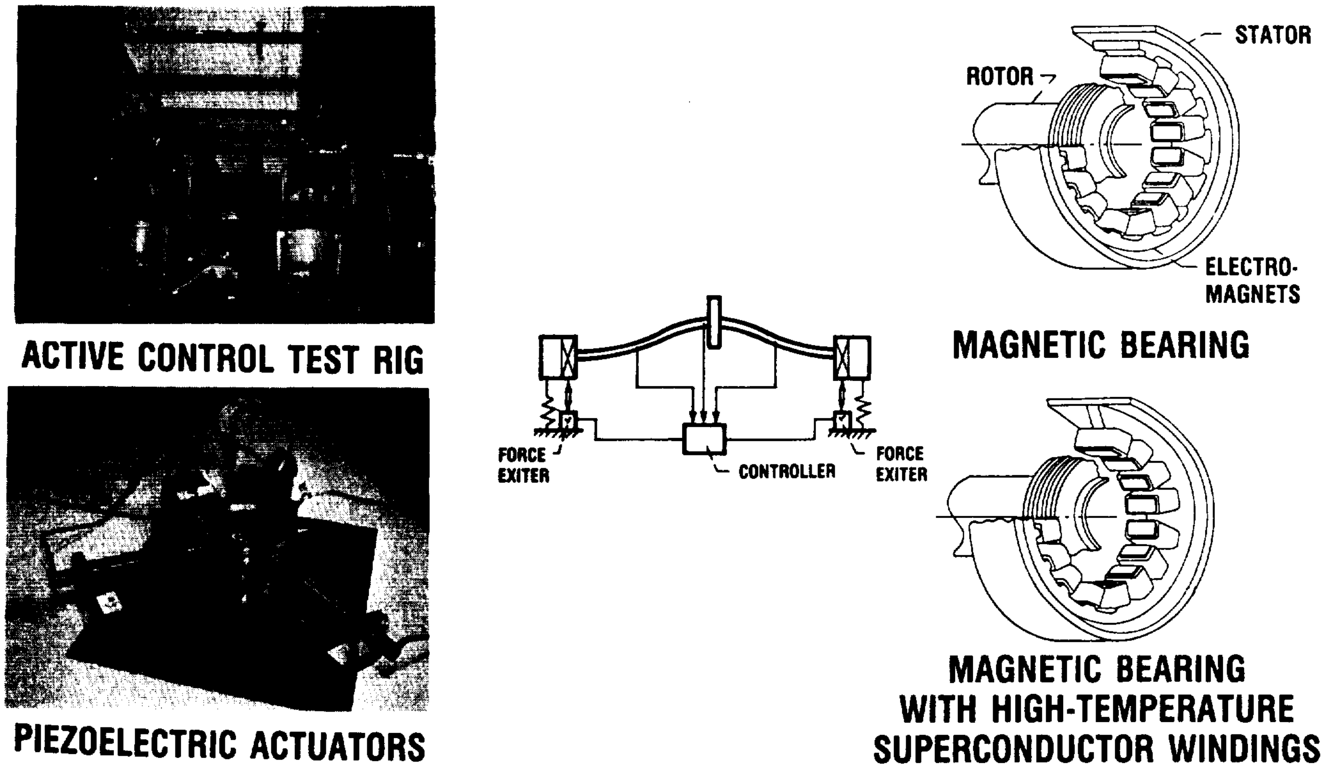

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Figure 9. - Active rotor control.

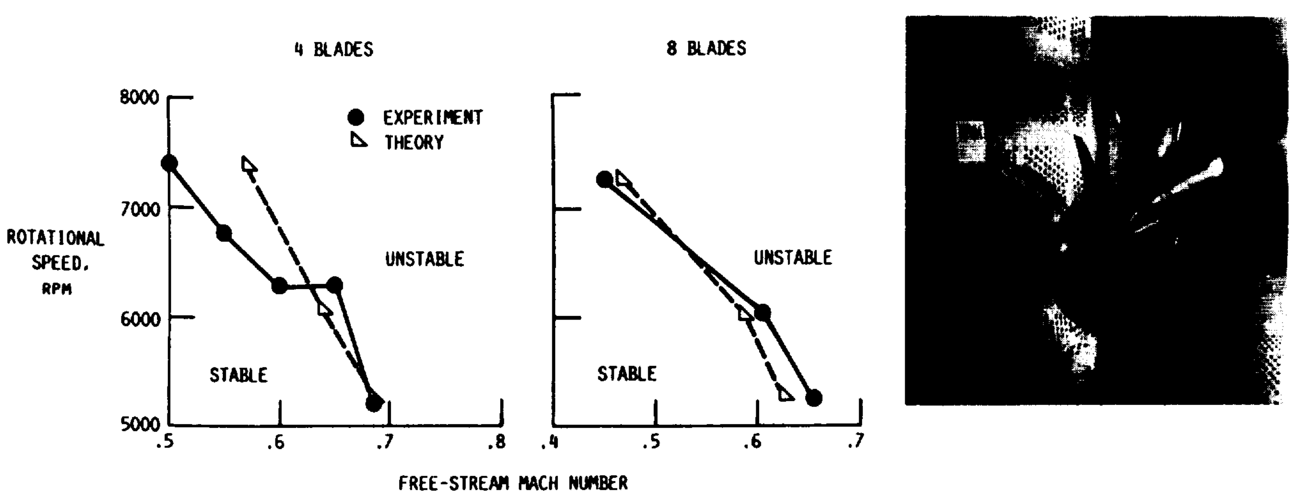

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Figure 10. - Comparison of measured and calculated flutter boundaries (SR3C-X2 propfan model).

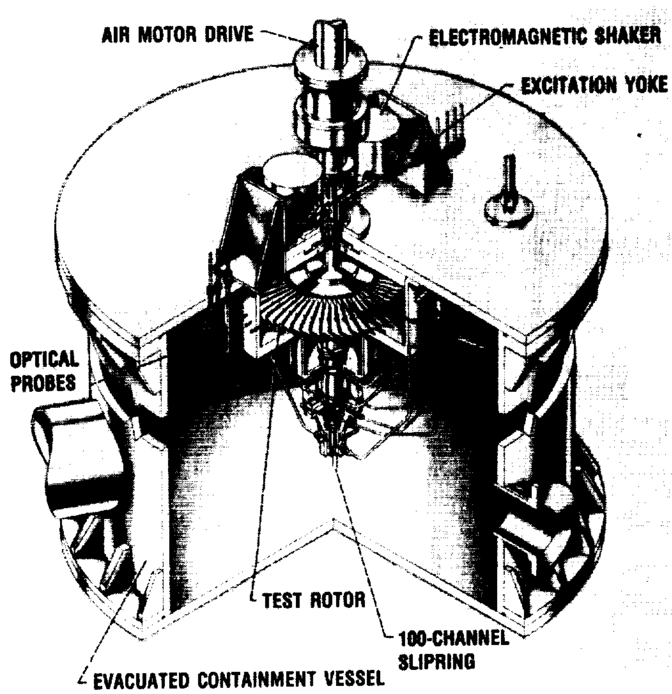

Figure 11. - Spin rig.

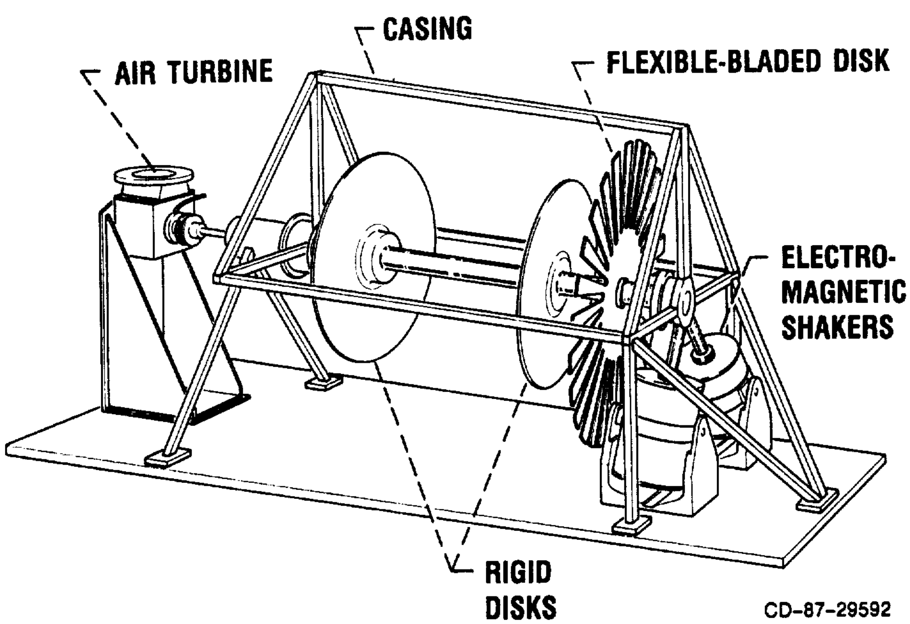

Figure 12. - Rotating systems dynamics rig.

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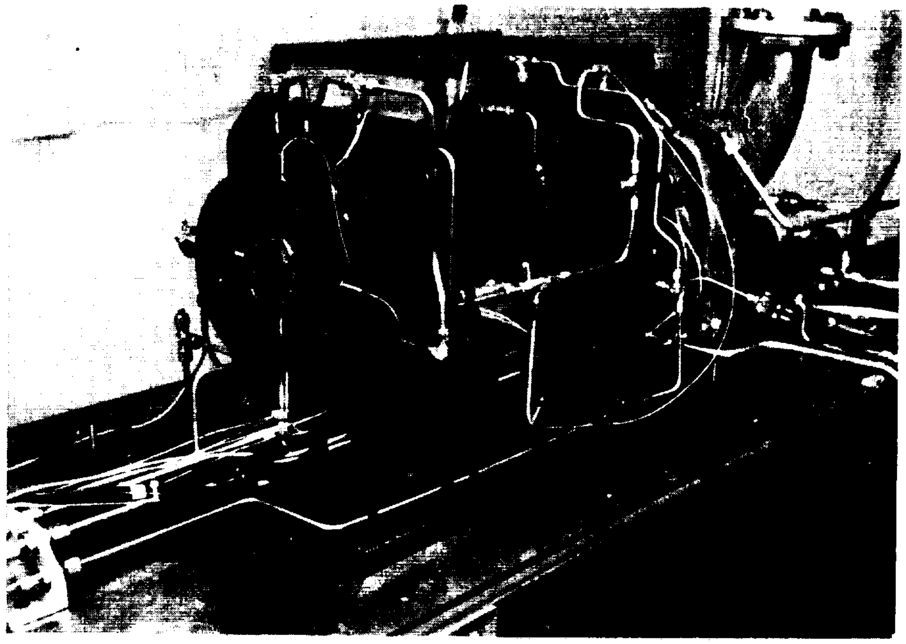

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Figure 13. - Blade-loss test rig.

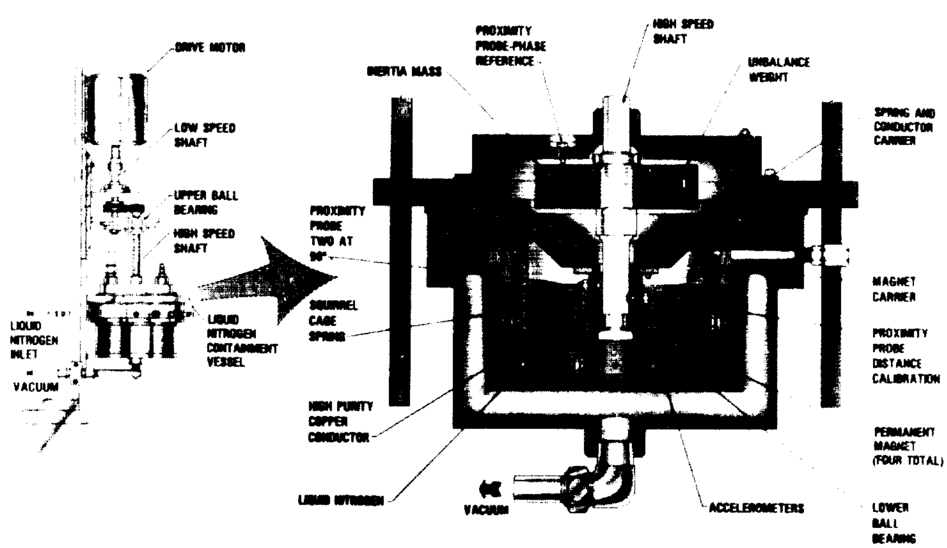

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Figure 14. - Liquid nitrogen damper test rig.

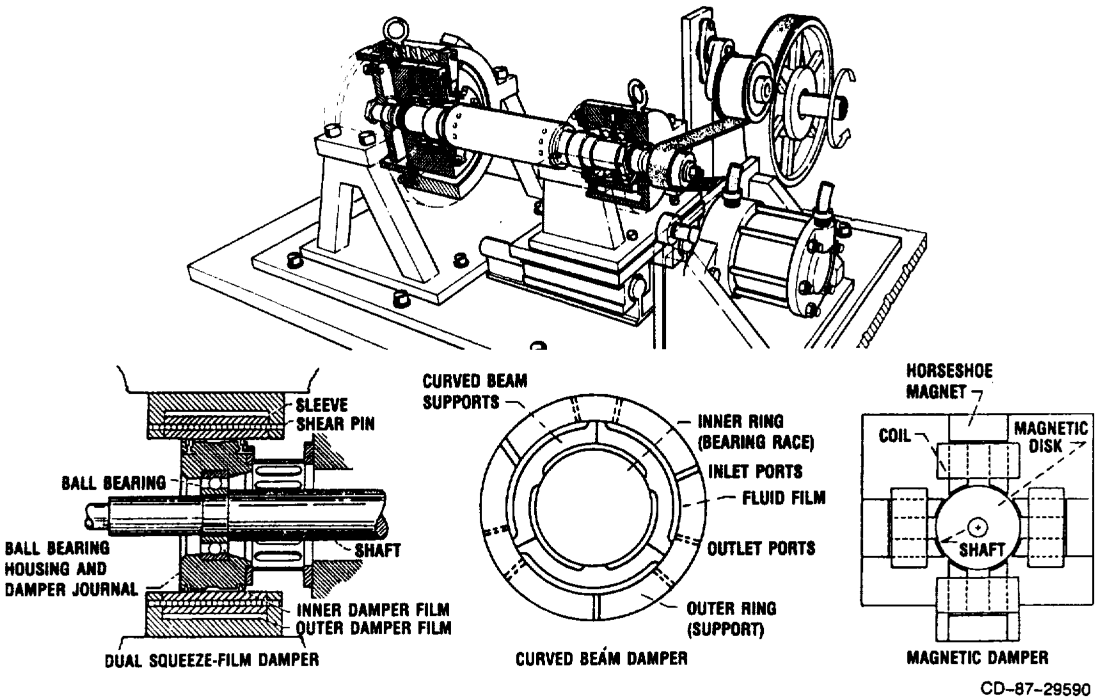

Figure 15. - High-load, thrust-bearing damper rig.