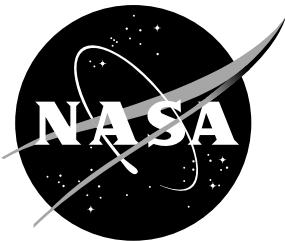


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# Research and Applications in Aeroelasticity and Structural Dynamics at the NASA Langley Research Center

Irving Abel  
*Langley Research Center, Hampton, Virginia*

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National Aeronautics and  
Space Administration  
Langley Research Center  
Hampton, Virginia 23681-0001

# RESEARCH AND APPLICATIONS IN AEROELASTICITY AND STRUCTURAL DYNAMICS AT THE NASA Langley Research Center

Irving Abel  
Structures Division  
NASA Langley Research Center  
MS 121  
Hampton, Virginia 23681 USA  
e-mail address: i.abel@larc.nasa.gov

## ABSTRACT

An overview of recently completed programs in aeroelasticity and structural dynamics research at the NASA Langley Research Center is presented. Methods used to perform flutter clearance studies in the wind-tunnel on a high performance fighter are discussed. Recent advances in the use of smart structures and controls to solve aeroelastic problems, including flutter and gust response are presented. An aeroelastic models program designed to support an advanced high speed civil transport is described. An extension to transonic small disturbance theory that better predicts flows involving separation and reattachment is presented. The results of a research study to determine the effects of flexibility on the taxi and takeoff characteristics of a high speed civil transport are presented. The use of photogrammetric methods aboard Space Shuttle to measure spacecraft dynamic response is discussed. Issues associated with the jitter response of multi-payload spacecraft are discussed. Finally a Space Shuttle flight experiment that studied the control of flexible spacecraft is described.

## INTRODUCTION

The Langley Research Center (LaRC) has been designated by the Agency as the "Center of Excellence" for Structures and Materials research. The Structures Division at LaRC conducts analytical and experimental research (figure 1) in Aeroelasticity, Computational Structures, Structural Mechanics, Structural Dynamics, and Thermal Structures to meet the technology requirements for advanced aerospace vehicles. This paper will address research being done in aeroelasticity and structural dynamics.

The Structures Division supports the development of more efficient structures for airplanes, helicopters, spacecraft, and space transportation vehicles. Research is conducted to integrate advanced structural concepts with active-control concepts and smart materials to enhance structural performance. Research in aeroelasticity ranges from flutter clearance studies of new vehicles using aeroelastic models tested in the wind tunnel, to the development of new concepts to control aeroelastic response, and to the acquisition of unsteady pressures on wind-tunnel models for providing experimental data to validate unsteady theories. Analytical methods are developed and validated to solve the aeroelastic problems of fixed- and rotary-wing vehicles, including the control of instabilities, loads, vibration, and adverse structural response.

This paper presents the results of some selected studies in aeroelasticity and structural dynamics that occurred during the last 2 years. This paper begins with an overview of how flutter clearance studies are performed in the wind tunnel. The paper then addresses research aimed at using smart materials to suppress aeroelastic response, at acquiring an experimental data base to validate computational fluid dynamics codes, at the use of a series of aeroelastic wind tunnel models to support an advanced high speed civil transport program, at advances to the state-of-the-art in small disturbance transonic theory, at the effect of vehicle flexibility on the taxi and takeoff characteristics of an advanced high speed civil transport, at using advanced photogrammetric methods aboard Space Shuttle to measure the dynamic response of spacecraft in orbit, at reducing the jitter of spacecraft through the use of active controls, and at a Shuttle flight experiment on the control of flexible structures.

The aeroelasticity research program at LaRC depends heavily on the support of the Transonic Dynamics Tunnel. A short description of this facility and some current modifications that are in progress will be described.

## TRANSONIC DYNAMICS TUNNEL

The Transonic Dynamics Tunnel (TDT) is a unique "national" facility dedicated to identifying, understanding, and solving aeroelastic problems. The TDT, shown in figure 2, is a closed-circuit, continuous-flow, variable-pressure, wind tunnel with a 16-foot square test section. The tunnel uses either air or a heavy gas as the test medium and can operate at stagnation pressures from near vacuum to atmospheric, has a Mach number range from near zero to 1.2, and is capable of maximum Reynolds numbers of about 3 million per foot in air to 10 million per foot in heavy gas. The TDT is specially configured for flutter testing, with excellent model visibility from the control room and a rapid tunnel shutdown capability for model safety. Model mount systems include two sidewall turntables for semispan models, a variety of stings for full-span models, a cable-mount system for "flying" models, a rotorcraft testbed for rotor blade loads research, and a floor turntable for launch vehicle ground-wind loads studies. The TDT also offers an airstream oscillation system for gust studies and supporting systems for active controls testing. Testing in heavy gas has important advantages over testing in air including improved model to full-scale similitude, higher Reynolds numbers, and reduced tunnel power requirements. The TDT is the only wind tunnel in the world capable of flutter testing large, full-span, aeroelastically-scaled models at transonic speeds.

Facility Modification: As stated above, the TDT relies on the use of a heavy gas as the test medium. Currently the TDT is undergoing a major modification to replace the previous heavy gas (refrigerant R-12) with an environmentally friendly heavy gas (refrigerant R-134a). Facility modifications are expected to be completed in the spring of 1997, followed, first, by an extensive system "shakedown" and, next, by a thorough calibration of the flow characteristics of the wind tunnel. It is anticipated that the TDT will become fully operational with the new heavy gas in the fall of 1997.

Tunnel Calibration: The objectives of the TDT calibration are to determine the operating envelope with the new test medium and to quantify test section flow uniformity and flow quality in air and in R-134a. As shown in figure 3, the operating boundary of the tunnel will be slightly degraded with the new heavy gas. This is due to a reduced density and higher value of the speed of sound for R-134a as compared to R-12. Primary flow parameters will be calibrated using test section centerline and sidewall pressure measurements. Centerline measurements will be obtained with a centerline tube instrumented to measure static pressure in the settling chamber and through the test section. Sidewall pressure measurements will be obtained with instrumentation mounted along the test section walls, ceiling, and floor. Total and static pressure and total temperature will also be measured at discrete locations in the settling chamber and test section. These latter measurements in the settling chamber and test section will be used to calculate the primary flow conditions for the facility.

Measurements using a flow survey rake and boundary layer rakes will also be obtained during the TDT calibration to assess test section flow uniformity and quality. The flow survey rake will be instrumented to measure spatial variations in flow angularity, Mach number, and turbulence as a function of tunnel speed. The boundary layer rakes will measure boundary layer variations along the tunnel walls, ceiling, and floor. Several boundary layer rakes which can be mounted at different streamwise locations within the test section will be used to determine boundary layer characteristics as a function of test section station.

Data Acquisition System: Testing of aeroelastic models in the TDT requires real-time acquisition and display of measured static and dynamic experimental data, and complex, on-line analyses of dynamic data. The TDT open-architecture dynamic data acquisition system (TDT-DAS) is a state-of-the-art system which meets these requirements.

Figure 4 contains a schematic of the TDT-DAS which illustrates how each component of the system is connected to others. The TDT-DAS hardware is comprised of two identical subsystems, each switch-connectable to a subset

of four NEFF "front ends". Each NEFF provides signal conditioning, filtering, and sample-and-hold analog-to-digital conversion for 64 channels for a total capability of 256 channels. Each subsystem is comprised of a Motorola 88K computer which performs the basic data acquisition, archiving to disk, and continuous buffering of data to a fiber-optic data ring. Connected to the fiber-optic ring is an SGI Challenge L computer which provides both on-line frequency analysis, and post-point time- and frequency-domain data analysis.

All computers and terminals are connected, via networks, to workstations at the TDT or to workstations at remote sites, providing a distributed real-time data display capability. One of the first successful demonstrations of this capability was accomplished with a real-time link to the Aeronautical and Maritime Research Laboratory in Melbourne, Australia where they were provided real-time data for a wind tunnel test in progress.

This paper will now present selected results of some recent studies in the area of aeroelasticity.

#### **F/A-18E/F FLUTTER CLEARANCE**

The Transonic Dynamics Tunnel plays a significant role in providing flutter clearance data for new aircraft configurations. Tunnel tests performed on an aeroelastic model tested in a heavy gas can be used to predict the aeroelastic characteristics of the full-scale vehicle flying in the atmosphere. This information can then be used to minimize the flutter risk of new configurations, to provide data so that full-scale calculations can be performed with greater confidence, and to minimize the time required to perform airplane flutter clearance flights. When military fighters are tested in the tunnel many different store configurations can be cleared with relative speed and safety. Such an example is the F-18E/F flutter studies recently completed in the TDT. The flutter clearance study utilized a full-span 18-percent scale model. As shown in figure 5, the model can be sting- or cable-mounted in the test section. Before flutter testing commenced, a rigid model was tested on the cable-mount system to assure flying stability in the tunnel. During tests in the TDT the following accomplishments were achieved; the flexible vehicle components were flutter cleared through M=1.2 on the sting mount,

the flexible wing and fuselage configuration were cleared for flutter on the cable-mount system, numerous store configurations were flutter cleared on the cable-mount system, the stability of all-moveable stabilators with mil-spec freeplay was verified, and the stability of the model with several failure modes was determined. Limited parametric studies were also performed to determine the effect of stabilator free play, wing and fuselage fuel, wing-tip-and wing-pylon-mounted stores/tanks, and control surface restraint springs on flutter.

#### **PIEZOELECTRIC AEROELASTIC RESPONSE TAILORING INVESTIGATION**

The Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI) was the first study in which piezoelectric materials were chosen to control the aeroelastic response of a relatively large, aeroelastic model. Piezoelectric materials possess the ability to develop a mechanical strain when subjected to an electrical charge. Therefore, piezoelectric materials can be used as actuators to control aeroelastic motion. The relationship between an applied electric field and the corresponding behavior of a piezoelectric actuator is well documented in [1, 2, 3]. The conventional configuration for an in-plane displacement piezoelectric actuator consists of a single piezoelectric wafer sandwiched between two electrodes. Increased in-plane actuation can be obtained by grouping multiple wafers into multiple layers.

The model, shown in figure 6a, is a five-foot long, high-aspect-ratio semi-span wing designed to flutter in the TDT. The model is comprised of an exterior fiberglass shell to provide the proper aerodynamic contour and an interior composite plate as the main load carrying structure. A sketch of the major components of the PARTI wing are shown in figure 6b. Piezoelectric actuator patches were attached to the upper and lower surfaces of the composite plate. Fifteen groups of piezoelectric actuator patches covered the inboard 60% of the span. Due to the ply orientation of the material used in the composite plate and the wing sweep, the actuators were able to affect both the bending and torsional response of the model. Ten strain gauges and four accelerometers were used as sensors to provide feedback signals to the piezoelectric actuators. The model is also

equipped with wing-tip flutter-stopper and a trailing-edge control surface. The flutter-stopper was used as a safety device during wind-tunnel testing.

For this program two wind-tunnel test entries were performed. The first entry was used to measure the model's open-loop response including its flutter characteristics and to determine time-history information for each important piezoelectric actuator group. The second entry was used to assess and demonstrate the capability of using piezoelectric actuators to suppress flutter and to reduce aeroelastic response caused by turbulence. Control laws were designed using experimentally determined state-space models and actuator transfer functions measured during the first wind tunnel test. Twenty-eight control laws were designed and tested. Control laws were designed using both single-input/single-output (SISO) and multi-input/multi-output (MIMO) methods that utilized up to five inputs and nine outputs. Each control law varied in design technique, actuator and sensor choices, and complexity of the controller. The most successful control law demonstrated a 12% increase in flutter dynamic pressure and reduced the power spectral density of peak response due to tunnel turbulence at subcritical speeds by 75%. These experimental results are shown in figure 7.

The PARTI program successfully demonstrated the control of aeroelastic response using piezoelectric actuators on a large aeroelastic model tested in the TDT. Results of this investigation are fully documented in [4, 5, 6]. Future plans in this area will be focused on combining the capability of neural network controllers with smart material actuators for aeroelastic applications. The neural network methodology offers the opportunity to adapt to changing flight conditions or dynamics and to reconfigure the sensors and actuators following failures.

### BENCHMARK ACTIVE CONTROLS TECHNOLOGY

NASA Langley's Benchmark Models Program (BMP) was initiated in the late 1980s to study the physics of aeroelastic phenomena and to acquire an experimental aerodynamic data base for code validation. An example of the type of data acquired in this program is presented in [7]. The BMP uses

highly instrumented rigid models that are tested in the TDT on a flexible sidewall mount known as the Pitch and Plunge Apparatus or "PAPA". It provides the two degrees of freedom that are required for classical flutter [8]. Unsteady pressure distributions can then be obtained during sustained model oscillations at flutter onset and can be compared with analytical predictions.

The Benchmark Active Controls Technology (BACT) model is one of a series of five wind-tunnel models developed for the BMP. The objectives of the BACT model tests were to: obtain high quality data to validate computational-fluid-dynamics and computational-aeroelasticity codes; to verify the accuracy of current aeroservoelastic design and analysis tools; and to provide an active controls testbed for evaluating new and innovative control methodologies. Some early results for this BACT model are presented in [9]. The model has a rectangular planform with an NACA 0012 airfoil section and is equipped with a trailing-edge control surface and a pair of independently actuated upper and lower-surface spoilers. All surfaces are moved with independent miniature hydraulic actuators. A photograph of the model on the "PAPA" mount system is shown in figure 8a and a view of the model mounted in the wind tunnel is shown in figure 8b. Instrumentation includes pressure transducers and accelerometers on the model, and strain gages on the mount-system.

During a recent BACT wind-tunnel test entry the primary objective was to investigate a variety of control algorithms, designed using various methods, to suppress flutter and alleviate gust loads. Initially, open-loop tests were conducted to define the model's aerodynamic characteristics, including the flutter boundary across the transonic Mach number range. An extensive database of over 3000 data sets including steady and unsteady control surface effects was obtained [9]. Closed-loop tests were performed next to evaluate various nonadaptive flutter suppression control law concepts. It was found that the spoiler surfaces were effective in preventing flutter and, when used in combination with the trailing edge surface, provided remarkable flutter suppression capability.

Tests were also performed to evaluate a variety of adaptive control algorithms for flutter suppression and gust load alleviation. Figure 9a presents some of the closed-loop results for three different concepts. The solid line is the open-loop flutter

boundary and the circles correspond to the points where the various control concepts were tested. The three concepts evaluated included: a Generalized Predictive Control algorithm that employed an analytical representation of the plant to predict future model responses and to select control surface commands; an Inverse Control method that used a linear neural network and experimental data to define the plant inverse; and a Neural Predictive Control algorithm [10]. All three systems were successful in suppressing flutter. A gust load alleviation system tested was also successfully demonstrated; the system was able to reduce model acceleration response by 80 percent in the presence of flow oscillations created by the TDT flow oscillator system (figure 9b).

### HIGH SPEED RESEARCH AEROELASTICITY PROGRAM

The objective of the aeroelasticity task of the High Speed Research (HSR) program is to provide validated analyses, design tools, and demonstrated technology readiness to accurately predict and solve the aeroelastic problems associated with an advanced high-speed civil aircraft (HSCT). An important element of the aeroelasticity task is a wind-tunnel models' program in which a series of models of increasing complexity are tested in the TDT to study the basic flow physics and flutter mechanisms of an HSCT configuration. Three models are planned to be tested in the program: a rigid semispan model (RSM); a flexible semispan model (FSM); and an actively controlled, flexible, full-span, cable-mount model (FFM). Below, a brief overview of the RSM and FSM tests are provided.

Rigid Semispan Model: The RSM (figure 10) is an extensively instrumented, stiff, semispan wing/fuselage model. The objective of these tests is to provide baseline pressure and loads data independent of significant aeroelastic deformations. The wing is a graphite-epoxy composite structure with removable engine nacelles. A control surface is located near the inboard trailing edge of the wing. The control surface can be statically deflected and/or oscillated. Wing pressure instrumentation consisted of 135 in-situ unsteady pressure transducers distributed along four chords on the upper and lower surface. The wing is mounted to a

force balance which is attached to the TDT sidewall turntable. The fuselage is instrumented at seven fuselage stations with a total of 120 steady pressure orifices and is mounted to the turntable independent of the balance. This allows the RSM wing and fuselage to be pitched to the same angle-of-attack while only the aerodynamic loads on the wing are measured by the balance. A video based deflection measurement system was also used to measure wing-tip deflections during testing. An extensive database consisting of steady wing and fuselage pressure, aerodynamic load, and wing-tip deflection data were obtained over a large range of freestream Mach numbers (0.70 to 1.15), angles-of-attack (-2° to +8°), flap deflection angles (-4° to +4°), and flap oscillations (amplitudes up to 5° at frequencies up to 10 Hz) with and without engine nacelles. In addition, 6200 reflective targets were attached to the upper and lower surfaces of the model and photogrammetric data were obtained to define the exact model shape for CFD modeling and analyses.

Flexible Semispan Model: The FSM is the same geometrical size as the RSM, but has the aeroelastic characteristics of an HSCT design. Like the RSM, the FSM is also highly instrumented. The instrumentation included 135 unsteady pressure transducers on the wing at four chord locations, 80 steady pressure transducers on the fuselage, 14 accelerometers in the wing, and strain gages (to monitor loads at critical areas of the wing). The model was mounted on a five-component balance to measure wing-only loads. A large database consisting of steady and unsteady aerodynamic pressures and loads and forced and unforced dynamic response data (with sine-dwell and sine-sweep excitations to the trailing edge control surfaces) was measured for various angles of attack and control surface deflections at Mach numbers from 0.7-1.15 at dynamic pressures of 100 and 150 psf. Dynamic measurements were also made at conditions near or at flutter and at transonic conditions of high model response. Figure 11 provides a comparison of lift curve slope between the RSM and the FSM.

The flutter, loads, and steady and unsteady pressure measurements made for the RSM and FSM, as well as the model ground test measurements, represents an unprecedented aeroelastic models' data base. The data will

provide the foundation necessary to assess the validity and applicability of various computational fluid dynamics (CFD) and aeroelastic codes that will be used in the HSR program and in the eventual design of an HSCT aircraft.

### **COMPUTATIONAL AEROELASTICITY METHOD FOR PREDICTING TRANSONIC INSTABILITIES**

The Computational Aeroelasticity Program-Transonic Small Disturbance (CAP-TSD) potential equation code was recently extended by Edwards [11] to include a viscous-inviscid interactive coupling method referred to as Interactive Boundary Layer Modeling (IBLM) to better predict unsteady transonic flows involving separation and reattachment. The IBLM is regarded as a simulation of two dynamic systems, the outer inviscid flow (freestream region) and the inner viscous flow (boundary layer region), whose coupling requires active control elements to minimize the coupling error between the two systems. The motivation for this enhancement was to obtain the capability to predict transonic shock-induced flow separation instabilities and response phenomena.

[12] summarizes the results of applying the enhanced code (referred to as CAP-TSDV) in the solution of several difficult aeroelastic problems. Analyses were conducted to predict: the buffet onset boundary of a NACA0012 airfoil; the shock-induced oscillations of an 18% circular arc airfoil; and the transonic wing flutter boundary for both a thin wing and for a typical business jet wing. All the predictions agreed well with experiment. The CAP-TSDV flutter predictions for the relatively thick wing of a business jet are shown in figure 12 in the form of flutter speed index and flutter frequency versus Mach number. As can be seen the CAP-TSDV predictions agreed well with experiment and with higher level Euler and Navier-Stokes CFD code predictions [13].

Present plans are to continue applying the CAP-TSDV code to a variety of transonic aeroelastic phenomena with an emphasis on control surface buzz and limit cycle oscillations. Upon validation, our intent is for the code to be used during the design phase of new flight vehicles and as a means of identifying and assessing "fixes"

following unexpected transonic aeroelastic instabilities that are encountered in flight.

This paper will now present selected results of some recent studies in the area of structural dynamics.

### **HIGH SPEED CIVIL TRANSPORT DYNAMIC SIMULATION**

The unique configuration of a High-Speed Civil Transport (HSCT) and its operational requirements present numerous technical challenges. One such challenge is associated with the nature of the HSCT fuselage geometry. The HSCT has a long, narrow flexible fuselage. That, in conjunction with the relatively long distance from the forward gear to the cockpit, can result in undesirable vibrations in the cockpit and cabin during ground operation. Computer simulations of the HSCT have been conducted to study the vibration levels during takeoff, landing and taxiing; and to define the need for active or semi-active landing gear control systems for vibration control.

Preliminary nonlinear dynamic simulations of a representative HSCT including the landing gear have been conducted. Dynamic response of the aircraft, during taxiing operations at a speed of 30 mph on a simulated runway are used for performance evaluation. Figure 13a shows a sketch of the aircraft with locations along the fuselage labeled 1-27 and wing locations denoted 28-29. Corresponding displacement amplification factors are shown, with the vertical displacement response at various locations computed and normalized with respect to the mean value of runway vertical height. Results in the bar chart in the lower portion of figure 13b, show that the maximum displacement amplification occurs at the cockpit location.

Taxiing simulation results showed potentially unacceptably high vibration levels at the cockpit location. This study suggests a potential problem with the aircraft configuration during ground operations and a need for vibration suppression mechanisms.

These results were incorporated into a study to evaluate the effect of these motions on piloting performance. Cockpit motions and associated outside views and heads-up-display motions were

input into the Langley Visual Motion Simulator (VMS) to allow pilots to experience these motions (figure 14). However, due to limitations of the VMS the predicted motions had to be reduced by one-half. Thus, any performance degradation or discomfort reported for these tests are clear indications that the problem is even more severe than simulated. Pilot performance is evaluated by measuring centerline tracking skills and reaction time to engine failures which necessitate rejected takeoffs. Pilot subjective comments and evaluations are also collected.

Three NASA Langley test pilots were evaluated. The graph in figure 14 shows an example of the ground track of the aircraft and pilot response distance to engine failure both with and without heave motions (with heave - flexible fuselage/rough runway; without heave - rigid fuselage/smooth runway). Reaction distance to engine failure was increased by over 2000 feet due to fuselage flexibility. This general trend is consistently observed and suggests that the motions associated with operating this kind of aircraft without some form of active control will likely be uncomfortable and potentially unsafe. Each pilot has commented that these motions will have to be reduced to make this aircraft comfortable for the pilots and for the passengers as well.

This is the first time that flexible dynamics of an aircraft have been combined with a rough runway in a motion-base-simulator. Results show that motion problems associated with operating long, slender aircraft on the ground are present with the HSCT.

Work on a supersonic transport ground response simulation has prompted a research activity at the Langley Research Center to develop landing gear concepts capable of reducing airframe vibrations. Landing gear systems are designed to withstand impact loads on landing but ground vibrations during taxiing, takeoff, and landing are not usually included in the design criteria. To explore practical options that would lead to improved landing gear systems a variety of control approaches are being studied experimentally. Two competing approaches dominate the literature in this area; one uses semi-active concepts such as variable orifice and the second uses fully active systems. The fundamental difference between the two approaches is the inability of the semi-active system to increase the system energy. Being able

to increase system energy allows for a more capable control system but can lead to system instabilities if not implemented properly.

To experimentally demonstrate benefits and limitations of the various control approaches, a laboratory facility is being completed using an A6-Intruder landing gear system (see figure 15). The landing gear has been modified, as shown in the schematic, with an external hydraulic system that allows implementation of both semi-active and fully active controllers. Shown in the figure, are three independent ways to affect the gear dynamic response; one is by forcing fluid from the lower chamber to the upper chamber of the gear with no added or subtracted fluid through a metered orifice, a second way is by changing the charge pressure of gas occupying the upper chamber, and the third way is by adding or removing fluid from the system. Fluid added or removed is stored in pressurized tanks which are mounted externally. Experimental tests will be performed using a shaker table to provide the proper runway profile input to the gear. Preliminary tests using this hardware will begin in the summer of '97.

## PHOTOGRAMMETRIC APPENDAGE STRUCTURAL DYNAMICS EXPERIMENT

The Photogrammetric Appendage Structural Dynamics Experiment (PASDE) was developed to demonstrate the use of photogrammetric techniques for structural dynamic response measurements of spacecraft solar arrays and similar structures. Development and demonstration of passive, on-orbit structural response measurement methods will increase the amount of spacecraft engineering data available. The availability of low-cost, on-orbit engineering data for the International Space Station is essential for mathematical model and design load verification and subsequent determination of proper operational procedures and constraints.

A photogrammetric structural dynamic response measurement instrument was designed, fabricated, assembled, and tested to meet a flight experiment opportunity on a NASA Shuttle/Mir mission (STS-74) in November 1995. The instrument consisted of six video cameras with 50mm lens and motorized irises, six video tape recorders, video time inserters, and interface electronics. The instrument was packaged in three

standard Shuttle canisters. A mission plan was developed to obtain video image data during STS-74 mission events considered likely to result in structural response motion of the Mir Kvant-II module lower solar array as shown in figure 16.

The PASDE mission was implemented from a Control Center at the Goddard Space Flight Center during the mission. Video data was collected on the PASDE video recorders during the following events: docking of the Shuttle with Mir, three sets of specific Shuttle jet firing sequences designed to excite structural motion of the combined Shuttle/Mir spacecraft, transitions of the combined spacecraft from night-to-day and day-to-night, and sun tracking movements of the solar array. The video data was retrieved from the instrument following the mission, and digitized into standard computer image format. From the digitized data, displacement time histories at points in the video images were computed. The time history data was then triangulated using the known geometry of the instruments in the Shuttle payload bay and the coordinate systems of the Shuttle and Mir to obtain high resolution three-axis motions of multiple points on the solar array. A time history of the normal displacement at the point indicated by the white circle in figure 16 is shown in the graph. A description of the experiment is presented in [14].

The PASDE experiment demonstrated the use of passive photogrammetric techniques to make high resolution structural response measurements of solar arrays and other spacecraft appendages on-orbit. The International Space Station has adopted this technique for on-orbit measurement of solar array response.

### JITTER REDUCTION CONCEPTS FOR SPACECRAFT

Spacecraft instrument pointing jitter is defined as the peak-to-peak variation in the pointing direction within a given time window. A dynamic model of the first Earth Observing System Ante Meridian spacecraft, denoted EOS AM-1, was selected to assess the pointing performance improvements that can be obtained by using jitter reduction technologies on precision pointing, multi-payload spacecraft. Finite element models of the EOS AM-1 spacecraft bus, appendages, and instruments, were assembled and used to compute the on-orbit vibrational modes of the spacecraft at frequencies

up to 250hz. The combined model (figure 17a), which has over 70000 degrees-of-freedom, contains 723 modes in this bandwidth. An efficient simulation code called PLATSIM [15] was developed to compute the closed-loop dynamic response due to 24 disturbance events. The boresight angular displacements of the science instruments were calculated for each disturbance event. Simulations of the dynamic response were made with and without jitter reduction technologies to quantify the improvements.

Instrument jitter, for the baseline spacecraft without the jitter control technologies, showed marginal pointing performance on two key science instruments, the Thermal Infrared (TIR) imager and the Short Wave Infrared (SWIR) imager. Two jitter control enhancements are illustrated in figure 17b - proof mass actuators and isolation concepts. First proof-mass actuators were used to reject periodic disturbances typical of cryocoolers and reaction wheel imbalance (figure 17c). The proof-mass actuator systems provided about 50 percent reduction in the jitter produced by high-frequency ( $>10$  Hz) periodic disturbances. Isolation was next applied to isolate the instruments from spacecraft bus vibrations (figure 17d). The mounts which connect the instruments to the spacecraft bus were actively controlled using strain and strain-rate feedback to piezoelectric actuators. Up to 70 percent of the instrument jitter could be attenuated using active isolation mounts.

Both jitter control enhancements improved pointing performance. For low frequency ( $<0.5$  Hz) disturbances, using the spacecraft's attitude control system in a high bandwidth mode is recommended. For high frequency ( $>5$  Hz) periodic disturbances, compensation using proof-mass actuators appears adequate. Science instrument isolation using active mounts can provide large reductions in jitter and help prevent interactions between instruments on multi-payload spacecraft. Active isolation mounts offer the best promise for managing spacecraft vibrations to improve the pointing performance of scientific instruments.

### MIDDECK ACTIVE CONTROLS EXPERIMENT

The Middeck Active Control Experiment (MACE) was successfully completed during Space Shuttle

flight STS-67 in March 1995. Participants in the program were NASA Langley Research Center, Massachusetts Institute of Technology's Space Engineering Research Center, and Payload Systems, Inc. (PSI). MACE provided on-orbit validation of modern robust control theory and system identification techniques through the testing of a flexible, multi-instrument, science platform in the micro-gravity environment of the Space Shuttle's Middeck. The test article, shown in figure 18, was about 1.7 meters long, weighed approximately 39 kg and was instrumented with multiple actuators and sensors. The bus structure was composed of circular cross-section Lexan struts connected by aluminum nodes. Natural frequencies of the primary structural modes, measured in orbit, ranged from 2.1hz for the first bending mode to 57.4hz for the sixth bending mode. At each end of the bus, a two-axis direct drive gimbal assembly was mounted. The gimbal assemblies acted as the payload at one end of the bus and as a multi-axis disturbance source at the other. A photograph of the hardware being tested by the Shuttle pilot in the middeck is shown in figure 19. The control objective was to isolate a payload sensor from a 50Hz bandwidth disturbance occurring on the test article. Controllers were designed with the use of finite element models and also measurement models constructed from data by applying system identification techniques to open loop data obtained on orbit. Over 50 single-input, single-output (SISO) and multi-input, multi-output (MIMO), single and multi-axis H-infinity control designs were evaluated on-orbit. One example of the performance achieved is shown in figure 20. For this case, up to 19 dB reduction in vibration levels and 25 Hz bandwidth of control were achieved. An overview of results acquired for this test is presented in [16].

## SUMMARY

This paper has presented the results of some recently completed research programs in structures at the NASA Langley Research Center. The results that have been presented indicate the wide range of research being conducted. NASA will continue to conduct research in this area in an effort to fully understand and predict structural response of aerospace vehicles so that future designs can fully exploit these technology advances.

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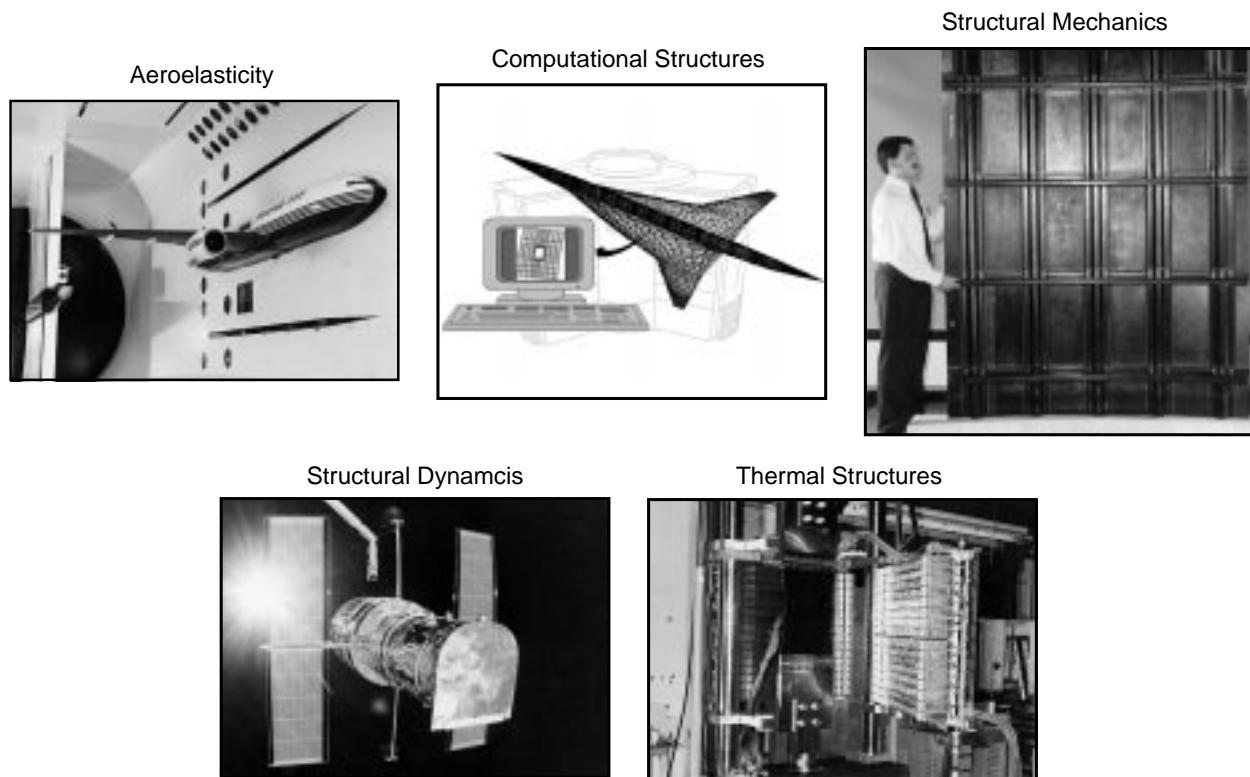


Figure 1. Structures Division research areas.



Figure 2. NASA Langley Transonic Dynamics Tunnel.

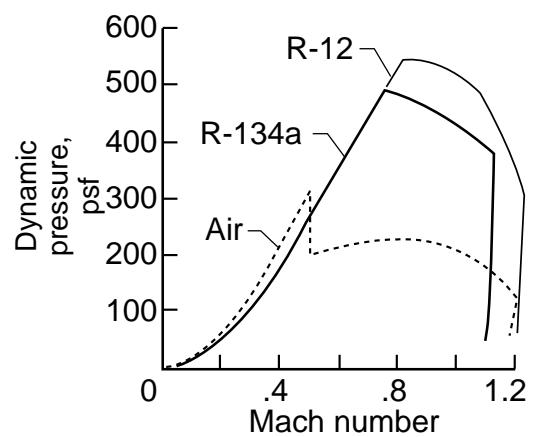


Figure 3. Estimated operating boundary for the TDT.

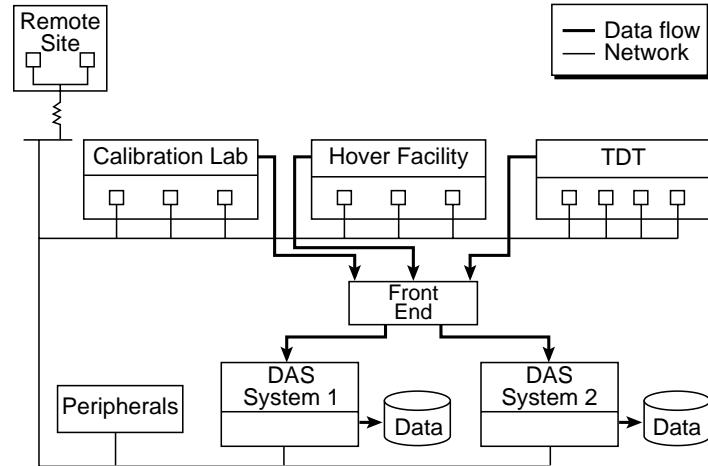


Figure 4. TDT Data Acquisition System.

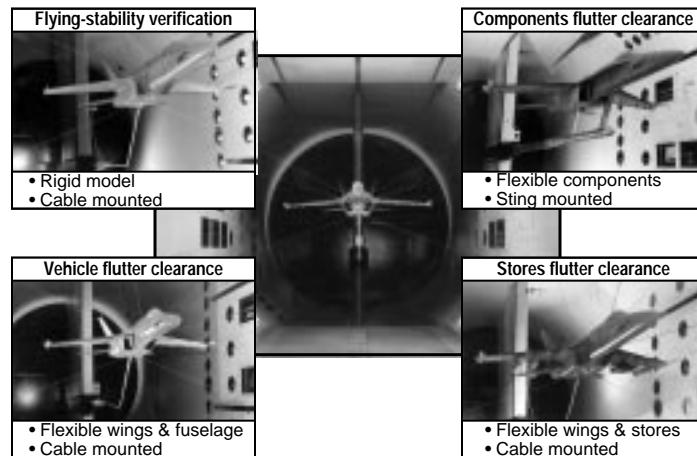
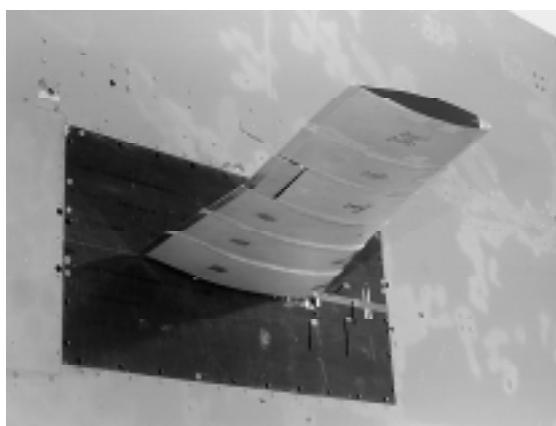
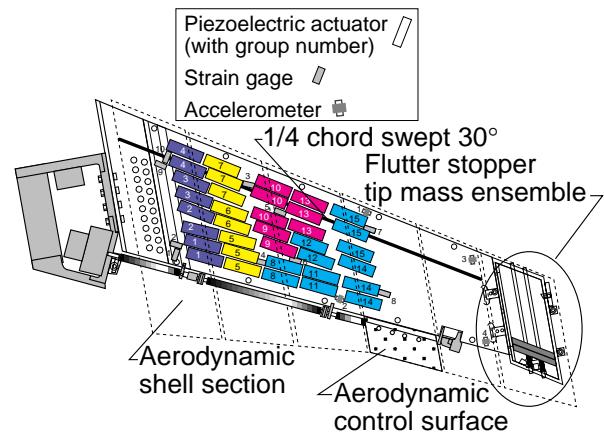


Figure 5. F/A-18 E/F flutter clearance program.

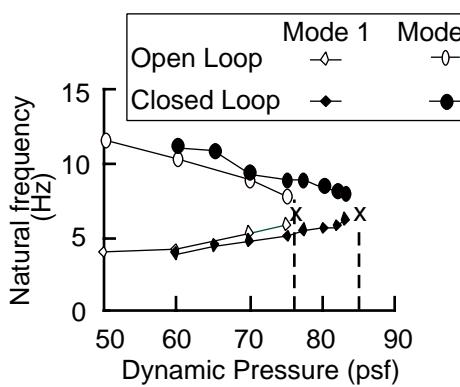


a) Model mounted in the TDT.

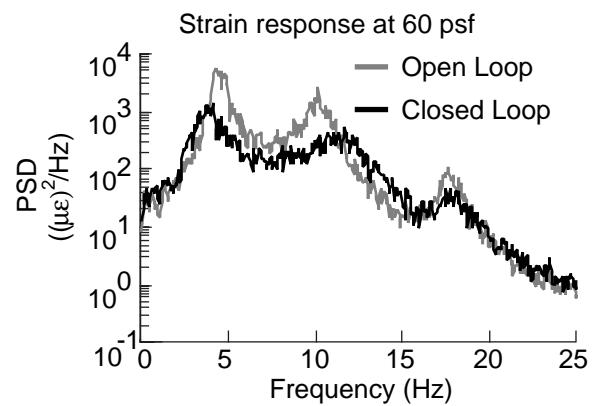


b) Sketch of major components.

Figure 6. Piezoelectric aeroelastic response tailoring investigation.

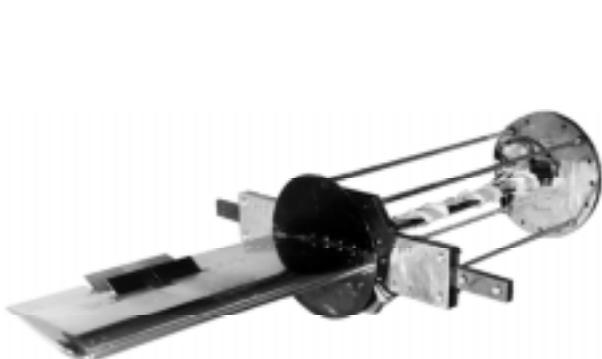


a) Flutter results.

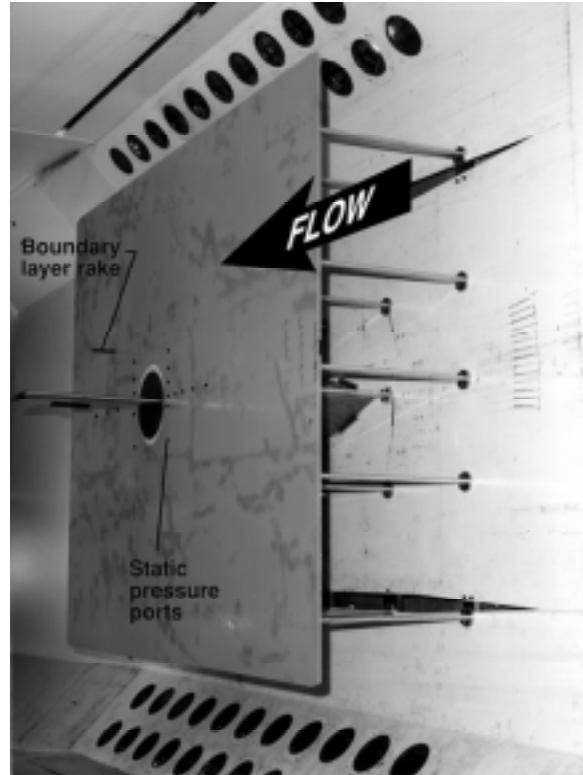


b) Subcritical response results.

Figure 7. Experimental results.



a) Model on flexible mount.



b) Model installed in the TDT.

Figure 8. Benchmark active controls model.

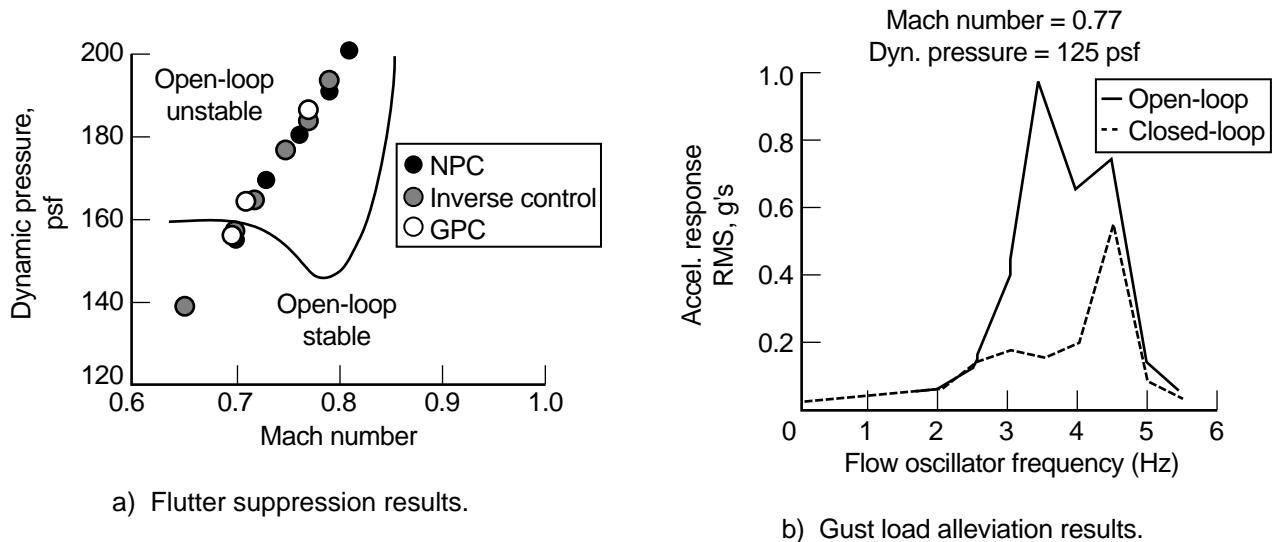


Figure 9. Experimental results.



Figure 10. HSR Rigid Semispan Wing Installed in the TDT.

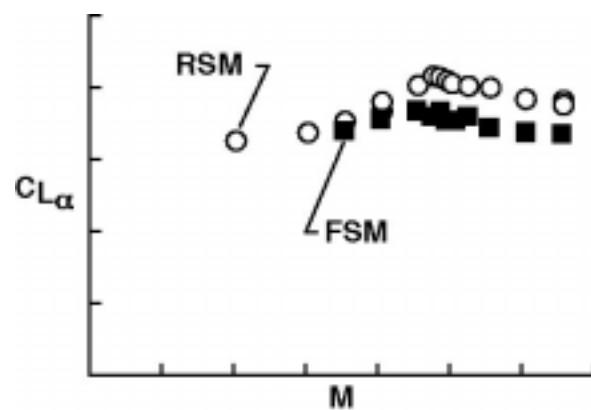


Figure 11. Lift Curve Slope Versus Mach Number Comparisons Between the HSR Rigid and Flexible Semispan Models.

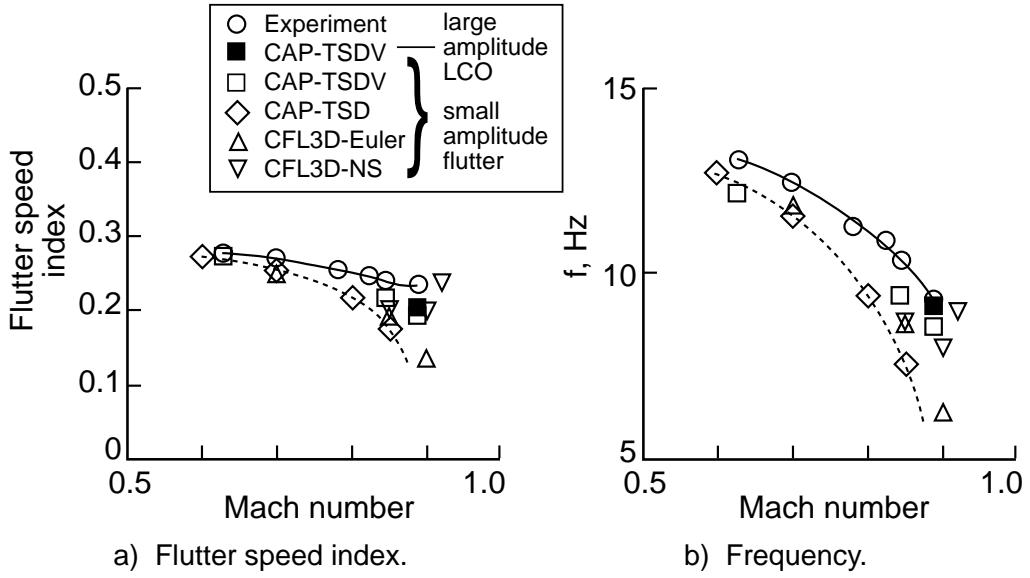
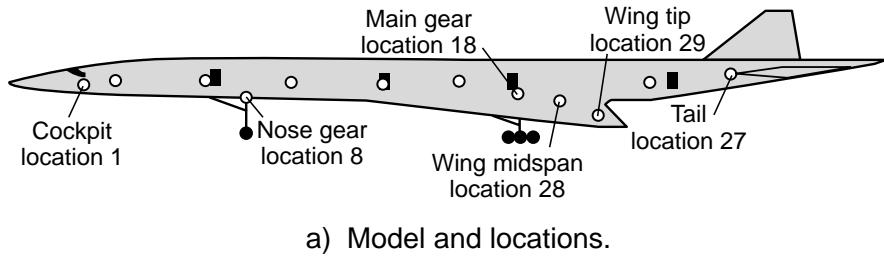
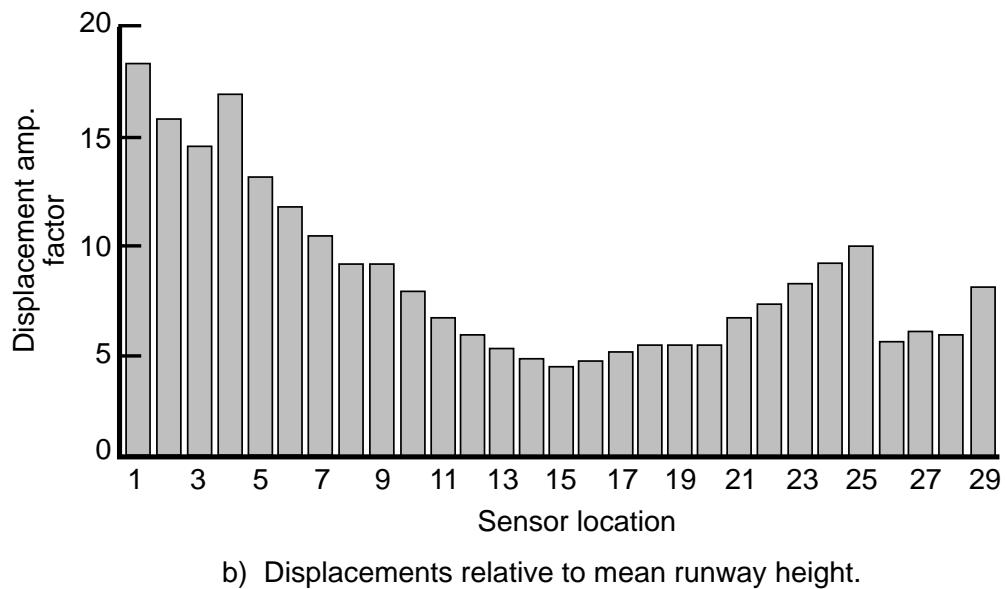


Figure 12. Comparison between experimental and calculated flutter characteristics for a flutter model of a typical business jet.



a) Model and locations.



b) Displacements relative to mean runway height.

Figure 13. High speed civil transport response locations and displacements.

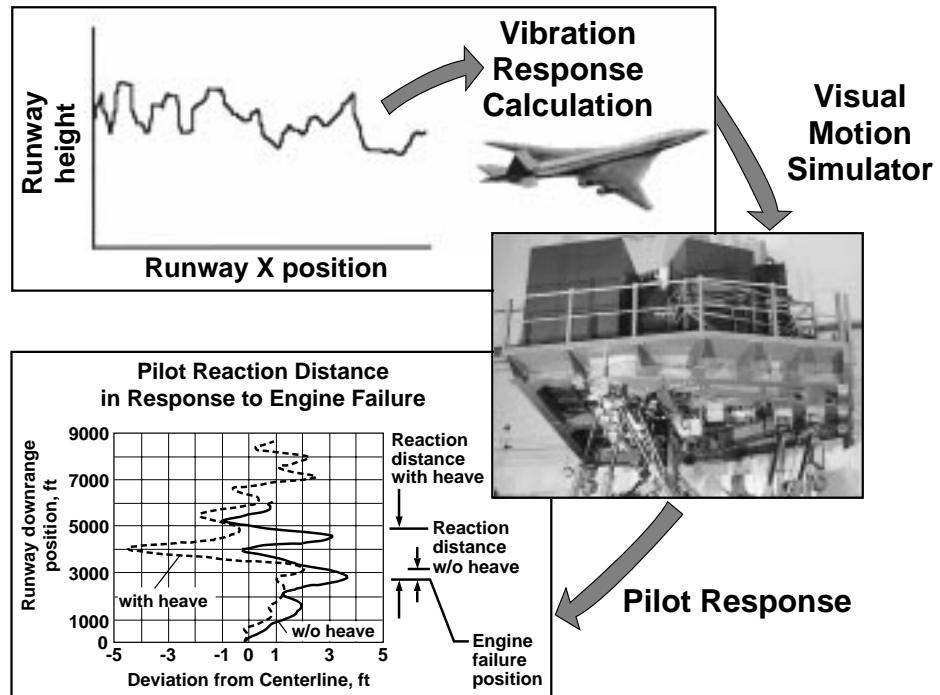


Figure 14. Pilot performance measured in visual motion simulator.

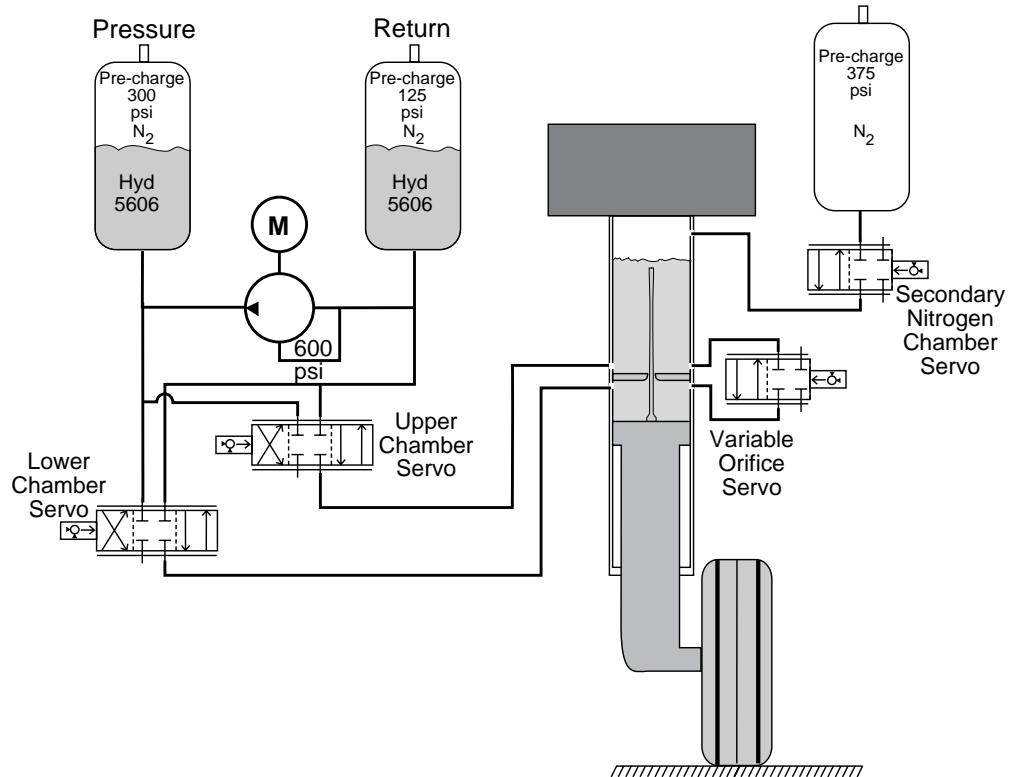
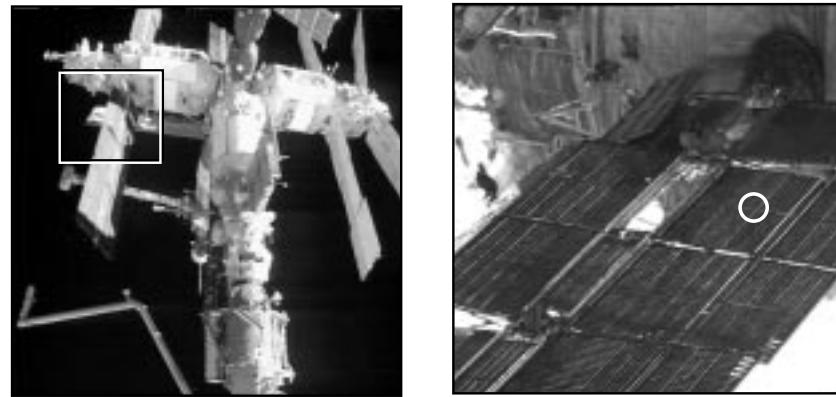
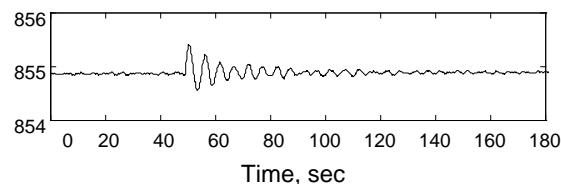


Figure 15. Active controlled landing gear facility.



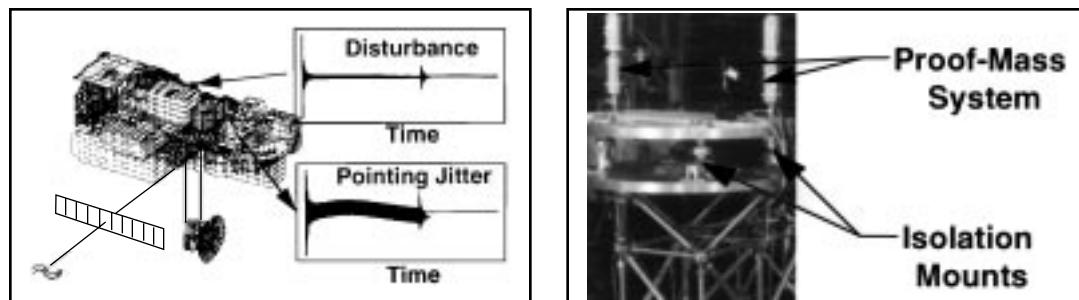
a) Area of Mir imaged.

b) Data image.



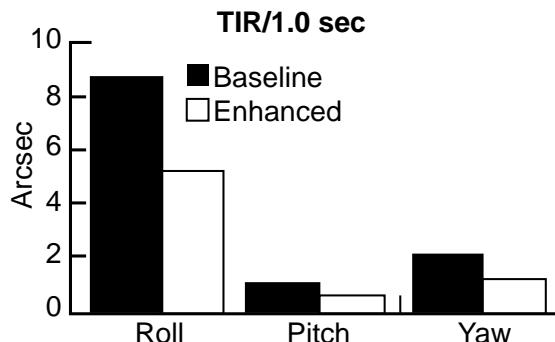
c) Displacement at **o** due  
to Shuttle jet firing, in.

Figure 16. Photogrammetric appendage structural dynamics experiment.

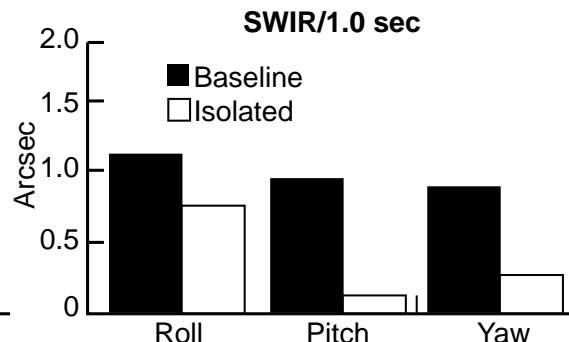


a) Pointing analysis with PLATSIM

b) Jitter reduction concepts



c) Proof-mass actuator system



d) Payload isolation system

Figure 17. Jitter reduction concepts evaluated on EOS spacecraft.

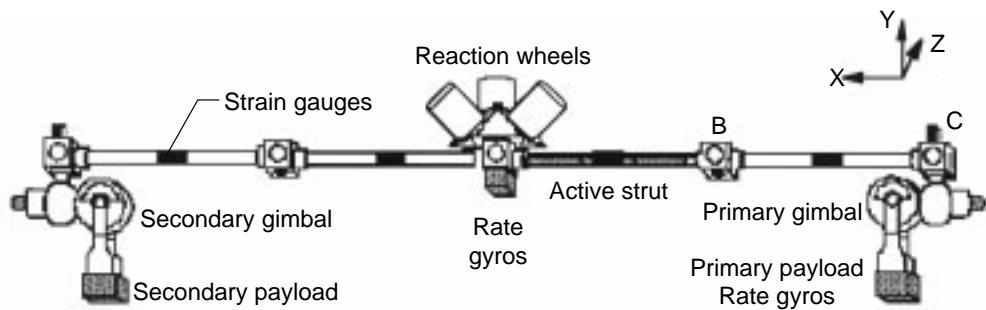


Figure 18. Middeck active controls experiment (MACE) test article.



Figure 19. MACE test article in Shuttle middeck.

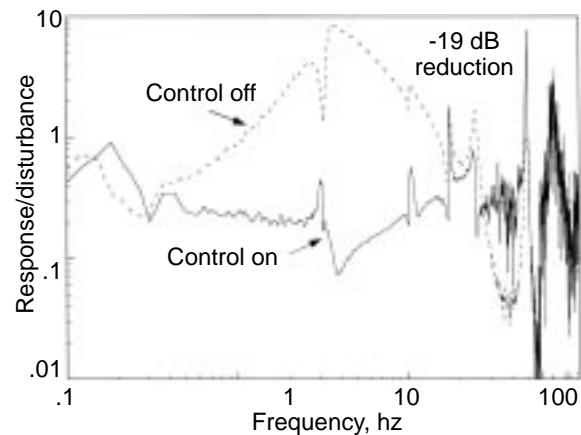


Figure 20. Performance of vibration control for MACE test article.