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# AN OVERVIEW OF THE ACTIVE FLEXIBLE WING PROGRAM

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<u>OUTLINE</u>

This presentation is an overview of the Active Flexible Wing (AFW) project and will serve as an introduction to an entire session of the Computational Control Workshop. Background information concerning the AFW project will first be presented. This will be followed by a description of the AFW wind-tunnel model and results from the initial wind-tunnel test of the AFW model under the current project. Additionally, this presentation will emphasize major project accomplishments and briefly introduce the topics of the following five workshop presentations during the session. Summary remarks and project plans will conclude this presentation.

# OUTLINE

- Project Background
- Model Description
- Test Results
- Session Overview
- Summary

# ACTIVE FLEXIBLE WING PROJECT

The AFW project is a joint NASA/Rockwell International effort to demonstrate aeroelastic control through the application of digital active controls technology. The testbed for this effort is a sophisticated aeroelastically-scaled wind-tunnel model of an advanced fighter concept. The model was built by Rockwell International and had been previously tested under a separate, but closely related, research project. Two primary aspects of aeroelastic control are being examined under the current project. The first is active flutter suppression and the second is active control of maneuver loads during high-speed rolling maneuvers.

The anticipated benefits of this project include the validation of modelling, analysis, and design methods utilized in aeroservoelastic applications and the development of an experimental data base for future research efforts. Other possible benefits from the project may be an enhanced simulation technology for use in aeroservoelastic work and an increased experience base in developing and implementing digital control systems.

# ACTIVE FLEXIBLE WING PROJECT

## A JOINT NASA / ROCKWELL INTERNATIONAL EFFORT

Goal: **Demonstrate** Aeroelastic Control Through the Application of Active Controls Technology

- Flutter Suppression
- Rolling Maneuver Load Alleviation

**Using** a Sophisticated Aeroelastic Wind-Tunnel Model

Anticipated Benefits:

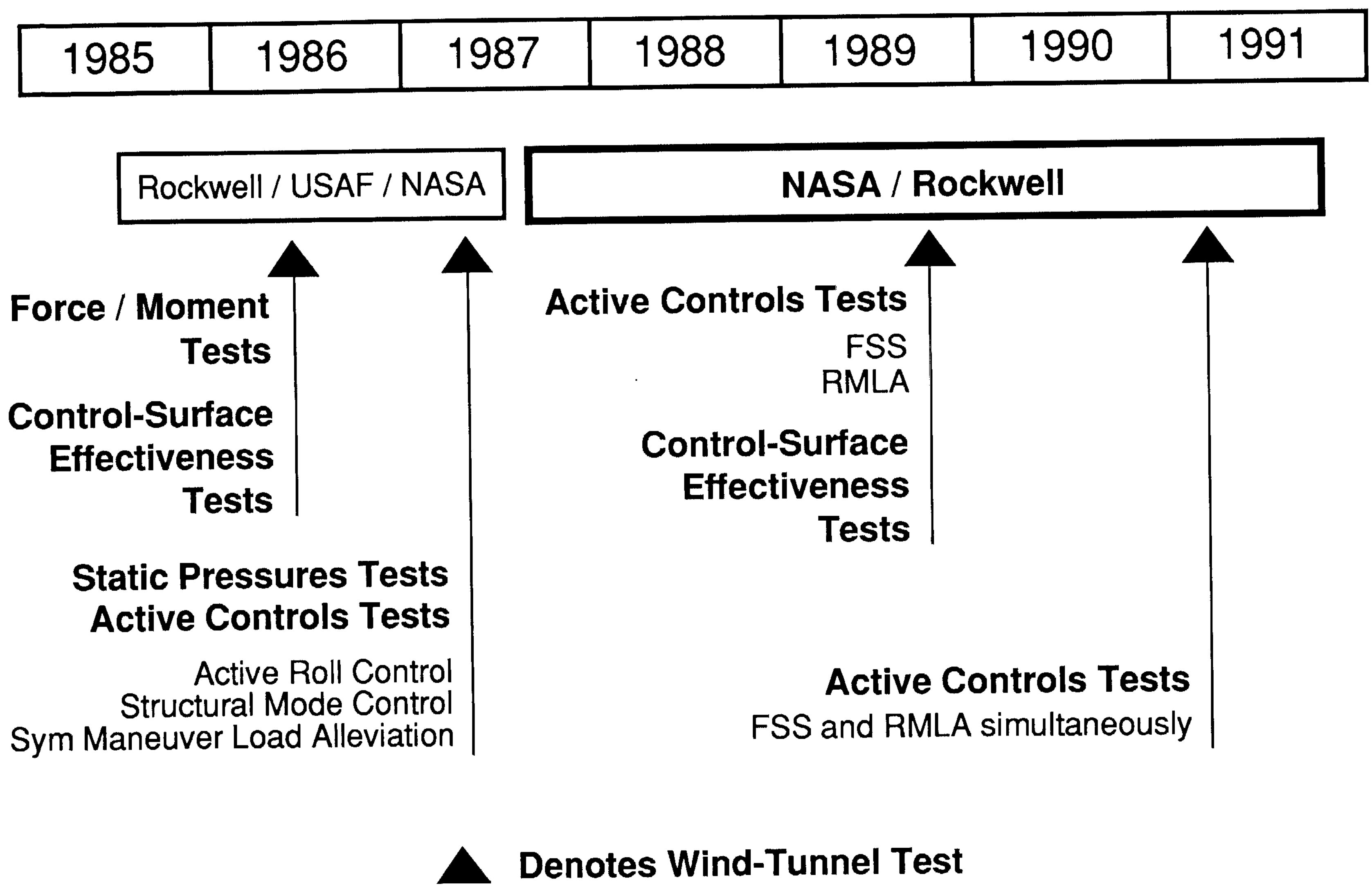
- Validation of Modelling, Analysis, and Design Methods
- Experience with Digital Control Systems
- Enhanced Simulation Technology
- Experimental Data Base

## AFW HISTORY

The AFW wind-tunnel model was originally built by Rockwell International under a joint Rockwell International/United States Air Force/NASA project. Under this initial project effort, the model was tested twice in the NASA Langley Research Center Transonic Dynamics Tunnel. The first test, conducted in 1986, was a static data acquisition effort in which force and moment loads and control-surface effectiveness measurements were made. The second test entry, in 1987, was to obtain wing static pressure measurements and to conduct active controls tests for active roll control, structural mode control, and symmetric maneuver load alleviation.

The current project was officially started in October, 1987 as a new joint initiative involving the NASA Langley Research Center and Rockwell International. The primary goals of this project, as previously described, are to demonstrate active flutter suppression and rolling maneuver load alleviation (RMLA). The first test under the current project was completed during November, 1989. Active flutter suppression was demonstrated during this test. A second test is planned for February, 1991. A major goal of the second entry is to demonstrate active flutter suppression and RMLA simultaneously.

# AFW PROGRAM: PAST, PRESENT, and FUTURE



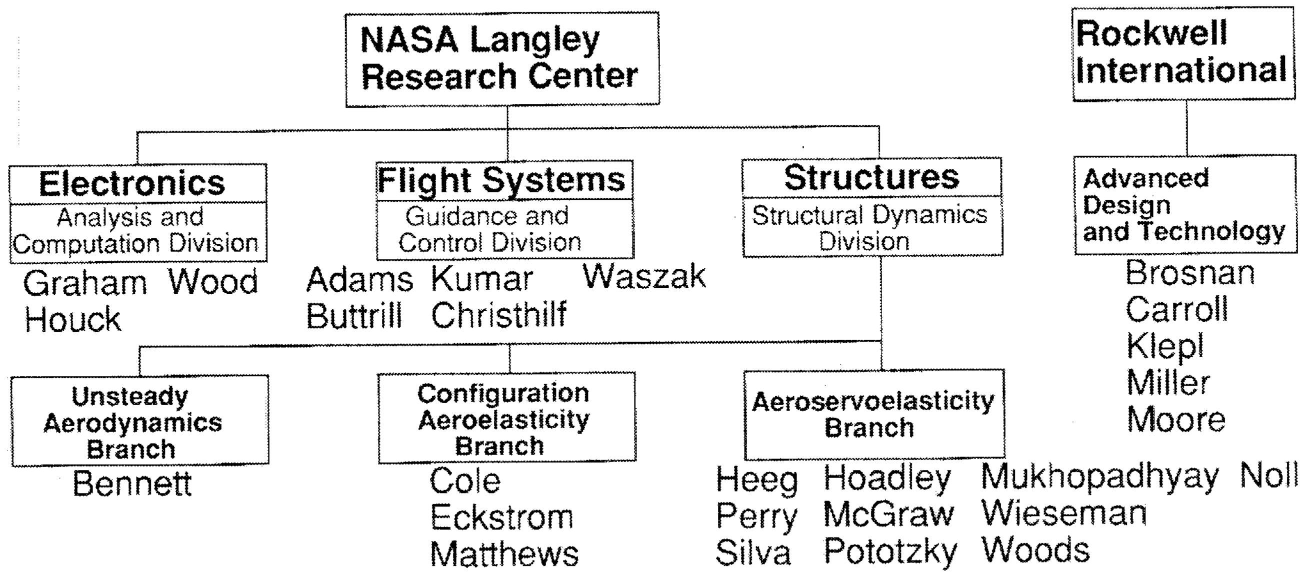
## PROJECT ORGANIZATION

The AFW project has extensive support from various NASA Langley organizations and from Rockwell International. The chart shows the many organizations providing critical support to the project, lists individual members of the AFW team, and shows many of these same personnel in the photograph inset.

Primary work at the NASA Langley Research Center has spanned three of the seven center directorates. The Electronics Directorate has been responsible for coordination of computer allocations for real-time simulation and personnel support to implement and conduct simulation tests with the computer hardware associated with the AFW project. The Flight Systems Directorate has provided several control law designers to develop active flutter suppression system (FSS) control laws and has also conducted the code generation for creating the plant math model on the simulation computers. The Structures Directorate has generated the baseline equations of motion, conducted extensive flutter analyses, designed control laws for both FSS and RMLA, and led the ground and wind-tunnel testing of the AFW model. Additionally, personnel from the Structures Directorate are involved in aeroelastic calculations using advanced nonlinear unsteady aerodynamic codes.

Rockwell International has supported numerous aspects of the project dealing with the physical wind-tunnel model and has provided a finite element model to assist in the development of the AFW equations of motion. Rockwell personnel are also developing a flutter suppression system and rolling maneuver load control laws for testing during the February, 1991 wind-tunnel test.

# PROJECT ORGANIZATION




WIND-TUNNEL MODEL PHOTO

## TEST APPARATUS

### WIND TUNNEL

The AFW model was tested in the NASA Langley Research Center Transonic Dynamics Tunnel (TDT). The TDT is a closed-circuit, continuous-flow wind tunnel capable of testing at stagnation pressures from near zero to atmospheric and over a Mach number range from zero to 1.2. The test section of the TDT is 16.0 ft. square with cropped corners. The TDT has several model support options. The AFW model was sting supported on the tunnel centerline. The TDT is capable of testing with either an air or a heavy gas test medium. The AFW model was tested in air under the present project.

A feature of the TDT which is particularly useful for aeroelastic testing is a group of four bypass valves connecting the test section area (plenum) of the tunnel to the return leg of the wind-tunnel circuit. In the event of a model instability, such as flutter, these quick-actuating valves are opened. This causes a rapid reduction in the test section Mach number and dynamic pressure which may result in stabilizing the model. During the AFW test, instrumentation on the model was monitored using electronic equipment that could automatically command the bypass valves to open if model response exceeded a predetermined criteria of amplitude and frequency.

### WIND-TUNNEL MODEL

The wind-tunnel model is shown mounted in the TDT. The AFW wind-tunnel model is a full-span, aeroelastically-scaled representation of a fighter aircraft concept. It has a low-aspect ratio wing with a span of 8.67 ft. The fuselage of the model is designed to be rigid. It is constructed from aluminum stringers and bulkheads with a fiberglass skin providing the appropriate external shape. The model is supported on the wind-tunnel test section centerline by a sting mount specifically constructed for testing the AFW model. This sting utilizes an internal ballbearing arrangement to allow the model freedom to roll about the sting axis. The fuselage is connected to the sting through a pivot arrangement so that the model can be remotely pitched from approximately -1.5 degrees to +13.5 degrees angle of attack.

#### Wing Structure

The wing of the model is constructed from an aluminum honeycomb core co-cured with tailored plies of a graphite/epoxy composite material. The plies were oriented to permit desired amounts of bending and twist under aerodynamic loads. The surfaces of the graphite/epoxy material were covered by a semi-rigid polyurethane foam to provide the airfoil shape without significantly affecting the wing stiffness.

#### Control Surfaces

The model has two leading-edge and two trailing-edge control surfaces on each wing panel. These control surfaces are constructed of polyurethane foam cores with graphite/epoxy skins. Each control surface has a chord and span of 25 percent of the local wing chord and 28 percent of the wing semispan, respectively. The control surfaces are connected to the wing by hinge-line-mounted, vane-type rotary actuators powered by an onboard hydraulic system. Two actuators are used to drive most of the control surfaces. Only the outboard, trailing-edge control surfaces are driven by a single actuator. This was required due to limited internal space in this region of the wing. The actuators are connected to the wing structure by cylindrical rods which are fitted in titanium inserts in the wing. This arrangement is designed to provide the shear and torsion requirements placed on the wing-to-control surface connections and yet allow for bending freedom of the wing. This also minimizes the contribution of the control surfaces to the wing stiffness. Deflection limits are imposed on the various control surfaces to avoid exceeding hinge-moment and wing-load limitations.

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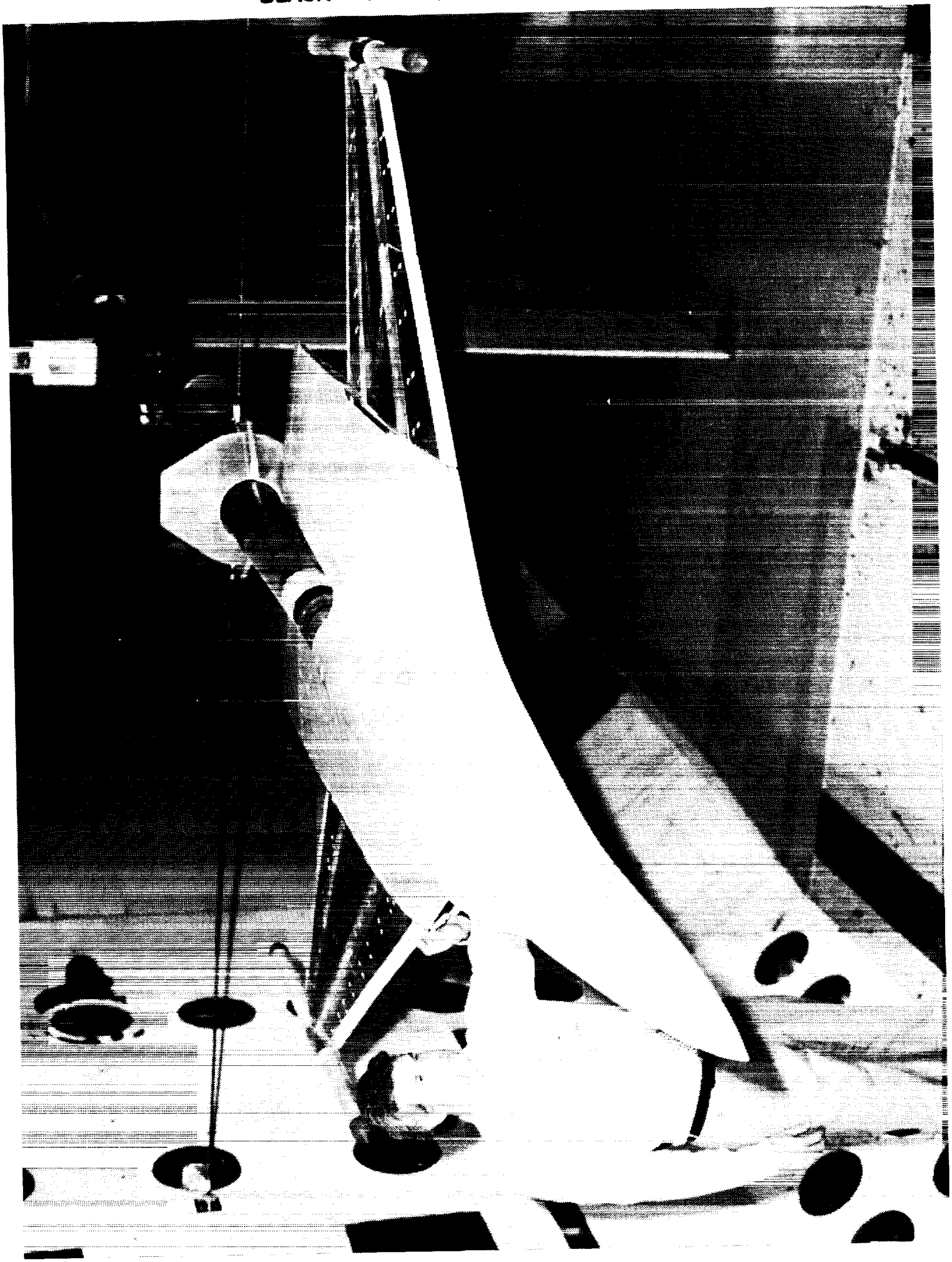
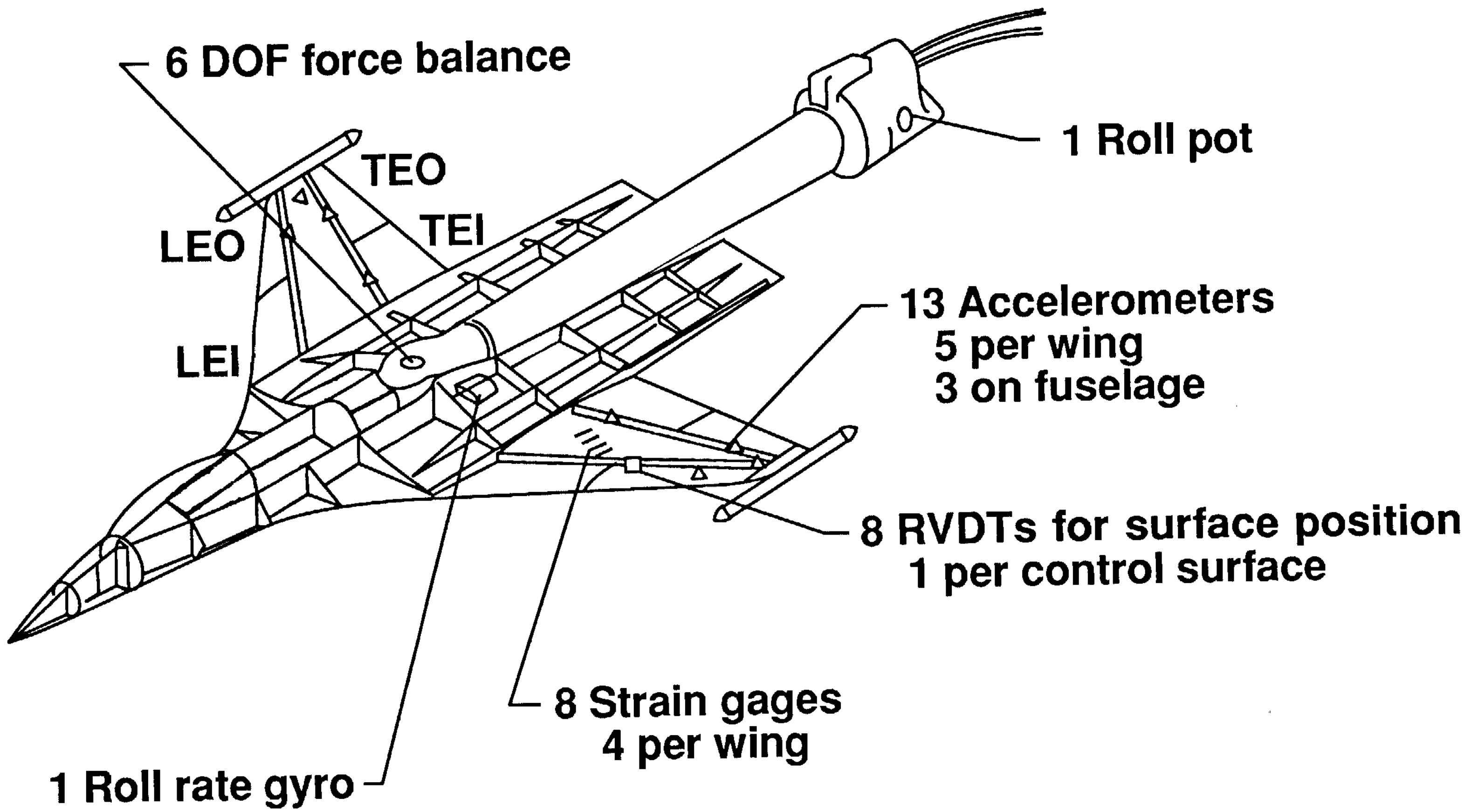


## INSTRUMENTATION

The AFW model was instrumented with a six-component force-and-moment balance, accelerometers, strain-gauge bridges, rotary variable differential transducers (to measure control surface deflection angles), a roll potentiometer, and a roll-rate gyro.

# AFW WIND-TUNNEL MODEL INSTRUMENTATION



# AFW MODEL DETAILS

Some of the special features of the AFW model are shown in the figure. In each of the photographs, the freestream flow direction is indicated to assist in orientation.

The photograph in the upper-left corner of the figure shows a view from upstream and above the model mounted in the TDT. The upper fuselage skin is removed to show the internal complexity of the model. Key features shown are the eight wing control surfaces, the roll brake mechanism located on the sting, and the wing tip ballast mechanism. The roll brake mechanism is designed to hold the model in place for "fixed-vehicle" testing and to stop the roll motion of the model if necessary during rolling maneuver testing. The importance of the wing tip ballast mechanism will be discussed later.

The lower, left photograph is a close-up view of internal fuselage details. Major features shown include the onboard hydraulic pump which supplies pressure to the fourteen control surface actuators and to the model pitch actuator, the pitch actuator itself, and the pitch pivot through which the model is attached to the support sting.

The lower, right photograph is a close-up view from above the trailing-edge-inboard region of the right wing with the right, trailing-edge-inboard control surface removed to show the hydraulic actuators that drive the control surfaces.

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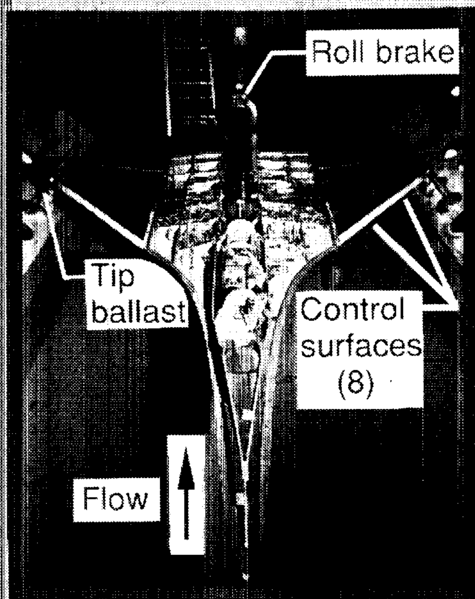
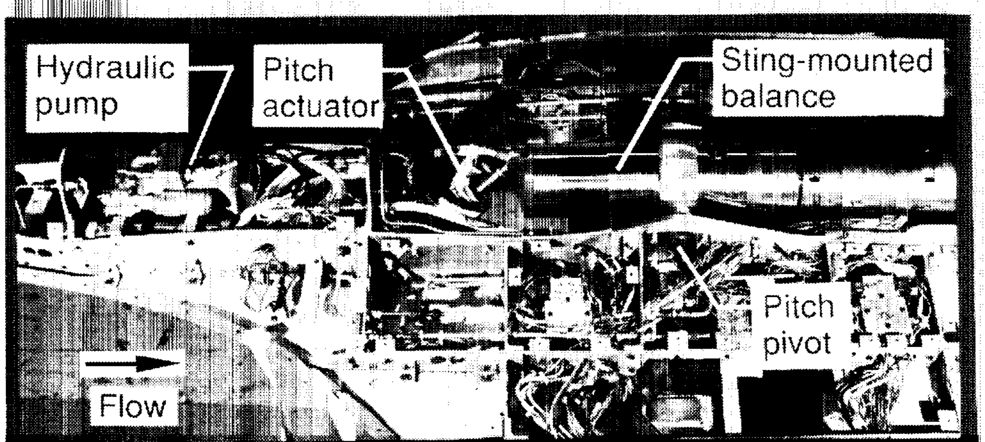
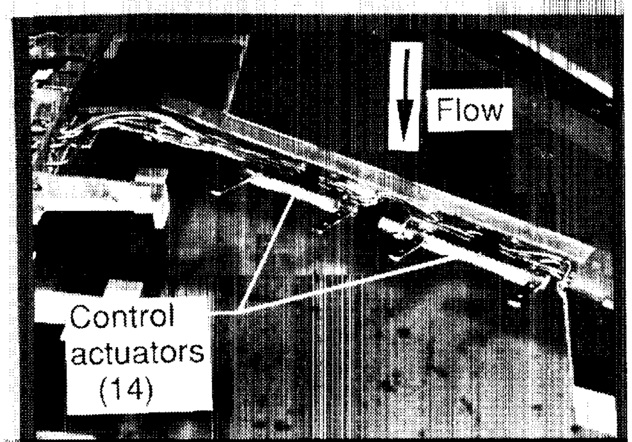
# AFW MODEL DETAILS




## Instrumentation

- 13 accelerometers
- 8 strain gauges
- 8 RVDT
- 1 six-component balance
- 1 roll potentiometer
- 1 roll rate gyro



## ROLL PHOTO

A special capability of the AFW wind-tunnel model is the ball-bearing mechanism built into the support sting which allows the model to have a rigid-body roll degree of freedom. This feature allows for the testing of rolling maneuver load alleviation control laws. The figure is a multiple-exposure photograph showing the model at roll angles of zero (wings level), -30, -60, and -90 degrees. The model is capable of rolling from approximately -135 degrees to +135 degrees.

ORIGINAL PAGE
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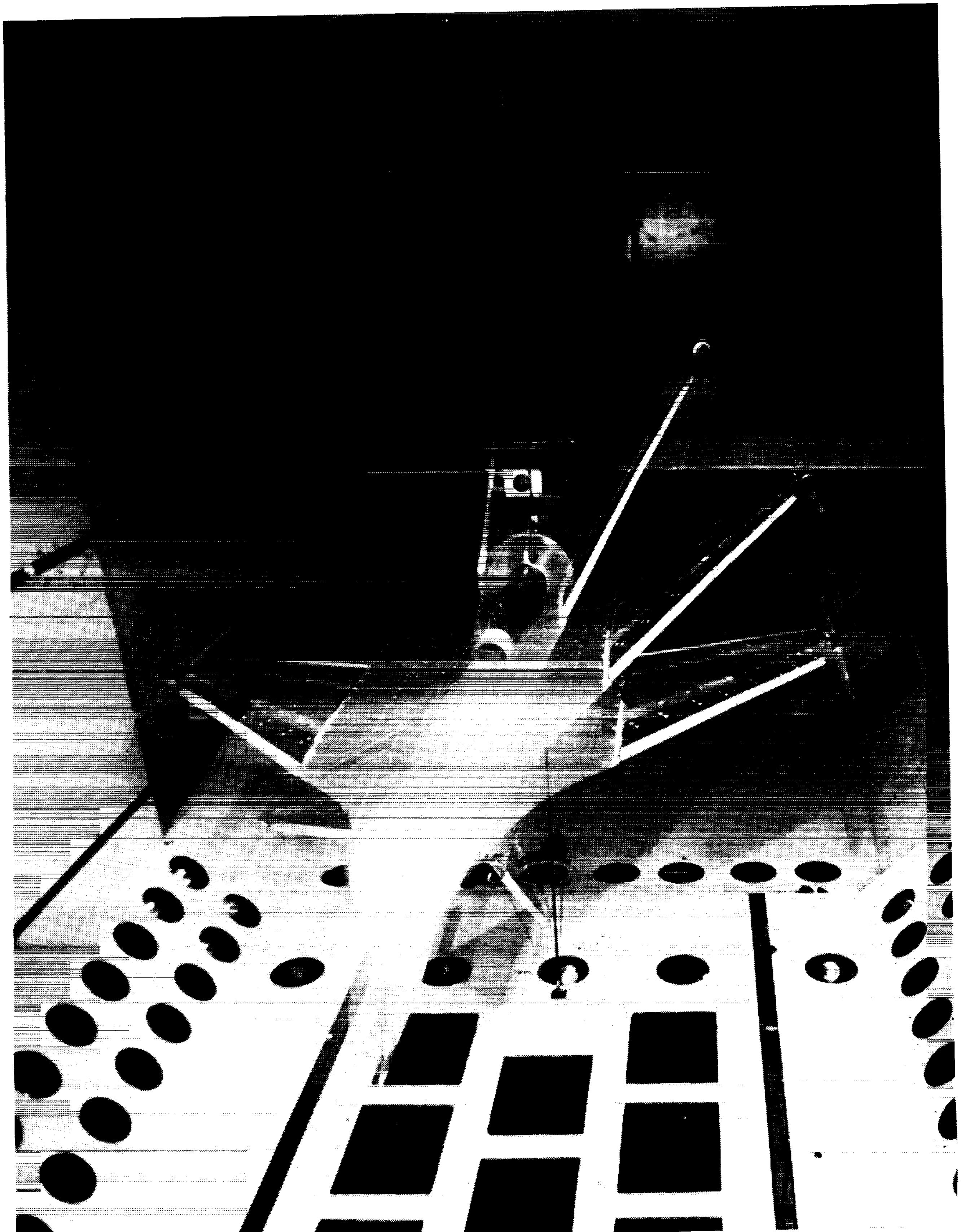


## Flutter

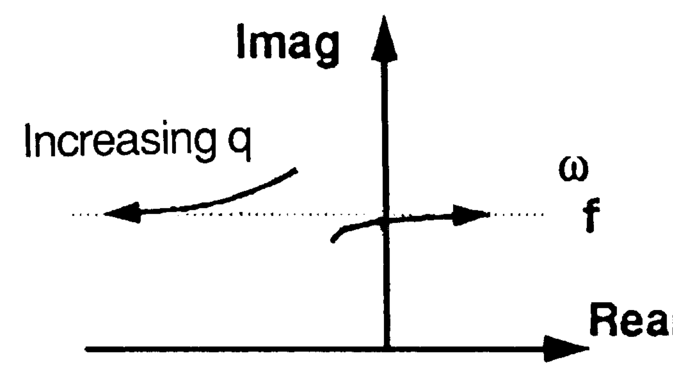
Flutter is a dynamic aeroelastic instability of an elastic body in an airstream. Flutter onset occurs at a flow condition for which the exciting forces acting on a body are equal to the restoring forces. These exciting forces are generally unsteady aerodynamic loads and the restoring forces are usually a combination of structural forces generated through the stiffness of the body and aerodynamic forces. Flutter is characterized as a self-excited, self-sustained oscillation that occurs at a specific dynamic pressure with a specific frequency for a given Mach number condition.

Classical wing flutter occurs through the coupling of, primarily, the first wing bending and first wing torsion vibration modes. This was the type of flutter encountered for the AFW wind-tunnel model. The root locus plot shown in the figure represents a typical mapping of the poles for a bending and a torsion mode of a wing. The arrow heads indicate the direction of increasing dynamic pressure. This plot shows that the frequencies of the two modes migrate toward a common frequency, $\omega_f$, and that the bending mode (lower path on figure) passes into the positive half of the complex plane as the dynamic pressure is increased, indicating that the flutter condition has occurred. The lower-right diagram in the figure shows a typical time history trace of wing acceleration at the flutter condition. This trace characterizes typical flutter in that it indicates a divergent instability (acceleration dynamically increasing with time) at a constant frequency $\omega_f$.

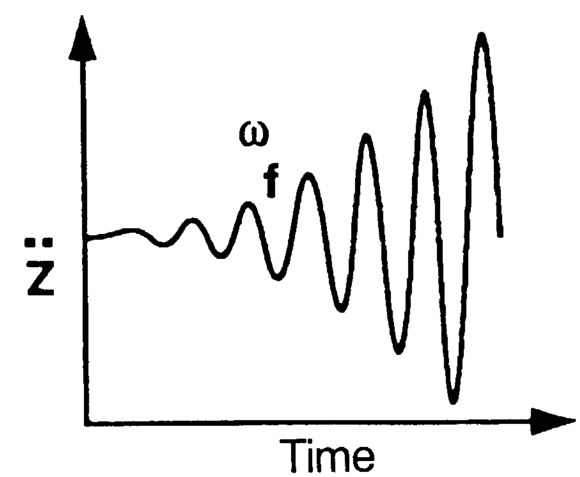
# FLUTTER



- Dynamic instability of an elastic body in an airstream
- Exciting forces equal restoring forces
- Self excited, self sustained oscillation
- Defined by critical dynamic pressure, mode frequency




Open Loop Poles




Unstable Time History

## MODIFICATION OF MODEL FLUTTER BOUNDARY

The AFW model was modified for the current project so that flutter would occur within the operating envelope of the TDT. This modification consisted of adding a tip-ballast store to each wing panel. A drawing of the tip store is shown in the figure. The store is basically a thin, hollow aluminum tube with distributed internal ballast to lower the basic wing flutter boundary to a desired dynamic pressure range. Additionally, the store provides a model safety feature. Instead of a hard attachment, the store is connected to the wing by a pitch-pivot mechanism. The pivot allows freedom for the tip store to pitch relative to the wing surface. When testing for flutter, an internal hydraulic brake held the store to prevent such rotation (coupled configuration). In the event of a flutter instability, this brake was released. In the released configuration (decoupled configuration), the pitch stiffness of the store is provided by a spring element internal to the store as shown in the figure. The reduced pitch stiffness of the spring element (as compared to the hydraulic brake arrangement) significantly increases the frequency of the first torsion mode of the wing. This behavior is related to the concept of the decoupler pylon as discussed in reference 2. The raised torsional frequency leads to a significant increase in the model's flutter dynamic pressure which quickly suppressed the motion of the model on numerous occasions during the test.

# MODIFICATION OF MODEL FLUTTER BOUNDARY

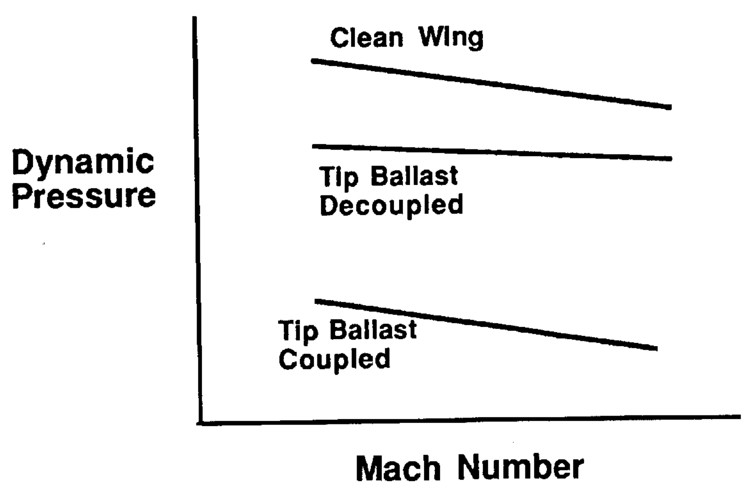
**Goal:** Demonstrate Increase in Flutter Dynamic Pressure

**Problem:** Basic AFW Flutter Boundary Beyond the TDT Operating Limits

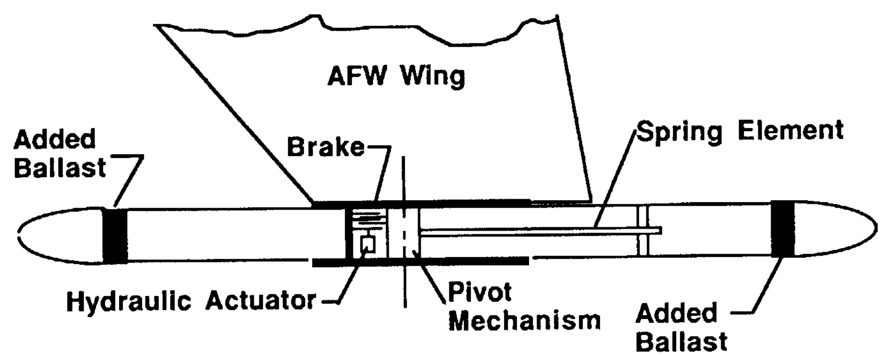
**Solution:** Add Wing Tip Ballast to Lower Flutter Boundary

**Benefit:** Tip Ballast Designed as Flutter Stopper for Safety

FLUTTER BOUNDARIES




WING-TIP BALLAST



## GROUND TESTS

A series of ground tests were conducted on the AFW model including actuator characterization tests, ground vibration tests, and end-to-end tests. The model and sting assembly were cantilever mounted from a backstop for these tests. Hydraulic pressure was supplied to the onboard hydraulic system so that the model would more closely match the wind-tunnel test configuration and so that control surfaces could be actuated. The measurements were made for both the coupled and the decoupled modes of the wing-tip ballast. The decoupled mode refers to the hydraulic brake within the tip ballast store being off and, therefore, the structural pitch stiffness of the tip store being provided through the internal spring mechanism.

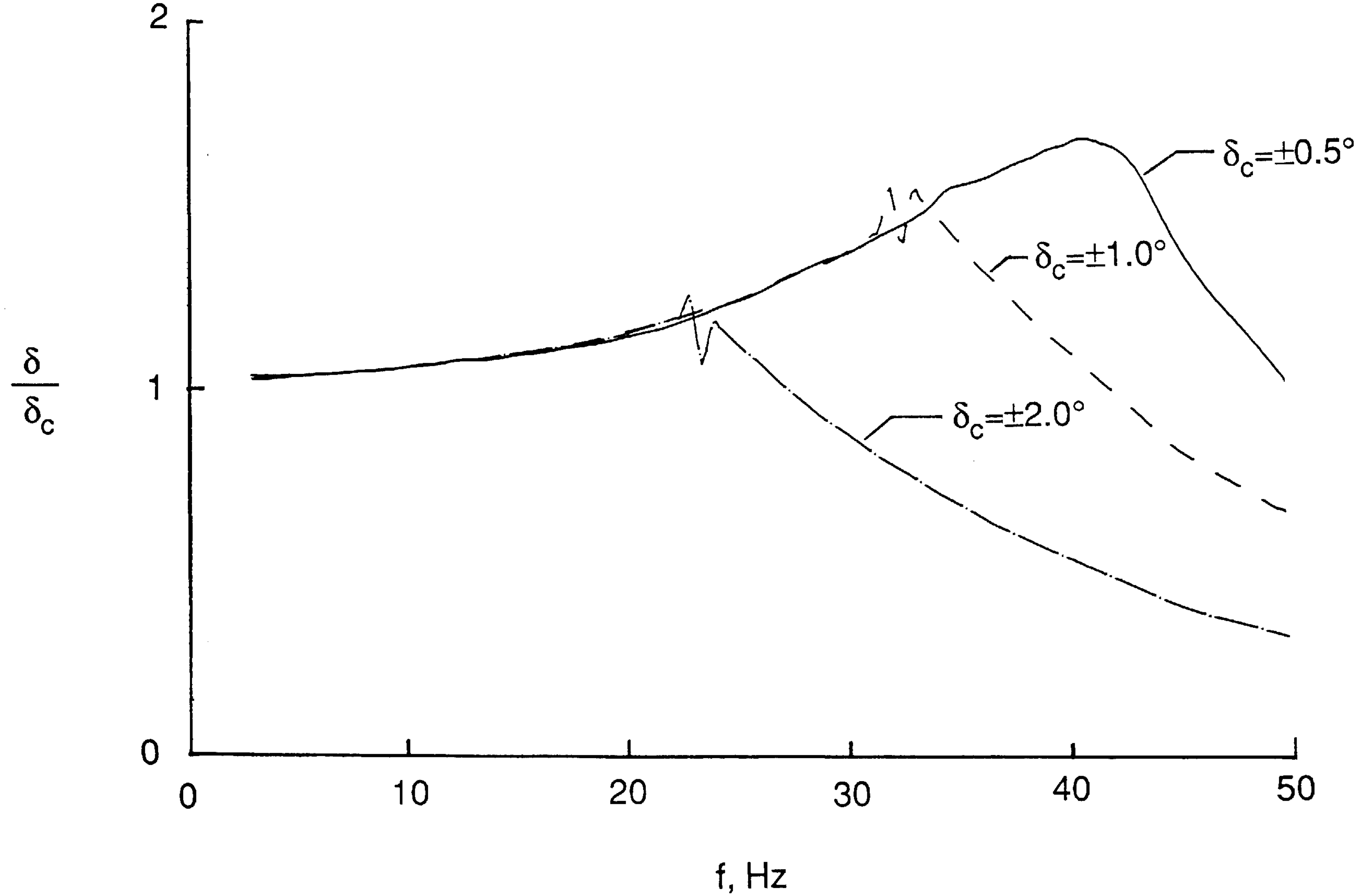
# GROUND TESTS

- Actuator Characterization
- Ground Vibration Tests
- End-to-End Tests

## ACTUATOR CHARACTERIZATION

The control surface actuators were experimentally characterized for correlation with the AFW math model by conducting actuator transfer function measurements. The transfer function measurements were obtained by commanding the actuators with a constant amplitude, sinusoidal signal and sweeping the signal frequency from approximately 4 Hz to 50 Hz. The figure shows typical transfer function measurements (control surface deflection to commanded deflection) for one of the control surfaces at three different command amplitudes. The control surface pairs were oscillated both symmetrically and antisymmetrically for these measurements. The command signal and signals from most of the onboard instrumentation were stored on FM analog tape so that various combinations of transfer functions could be determined at a later time.

# ACTUATOR CHARACTERIZATION



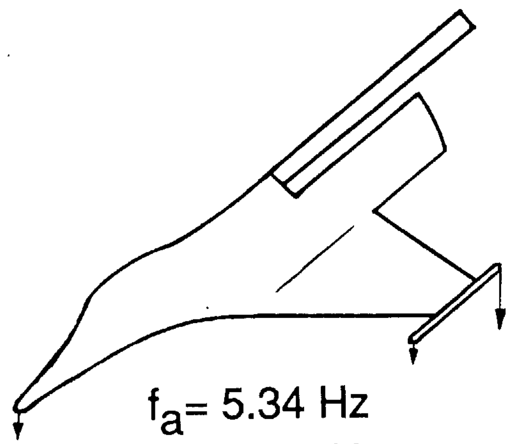
## GROUND VIBRATION TESTS

A ground vibration test (GVT) was conducted on the AFW model to determine its natural frequencies, mode shapes, and damping for a number of primary vibration modes. The GVT measurements were made through the use of externally mounted accelerometers. The model was excited by a pair of electromagnetic shakers mounted under the wing surface. The shakers were driven symmetrically or antisymmetrically to obtain the appropriate results. Initial structural mode frequencies were determined using sine sweep commands to the shakers. Damping values were also assessed from transfer function measurements during the sine sweeps. Following this initial determination, sine-dwell excitation was utilized to determine the final frequencies and mode shapes. The figure shows typical experimental results for the symmetric, coupled tip ballast configuration. Measured natural frequencies and node lines are compared with analytically predicted results.

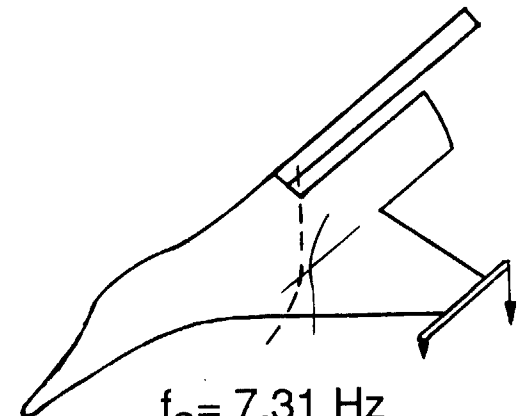
# GVT RESULTS

## Symmetric Coupled

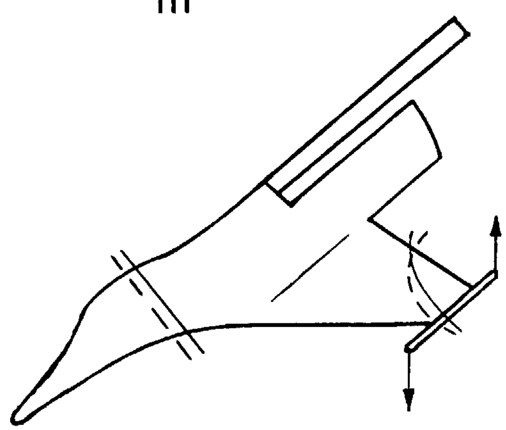
—— Analysis ------ Measured



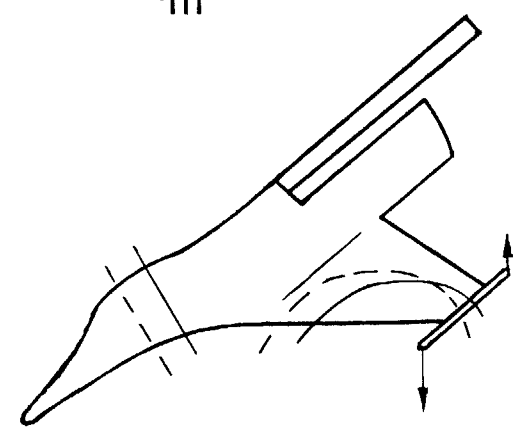
$f_a$= 5.34 Hz
$f_m$= 5.77 Hz



$f_a$= 7.31 Hz
$f_m$= 7.22 Hz



$f_a$= 12.85 Hz
$f_m$= 13.13 Hz



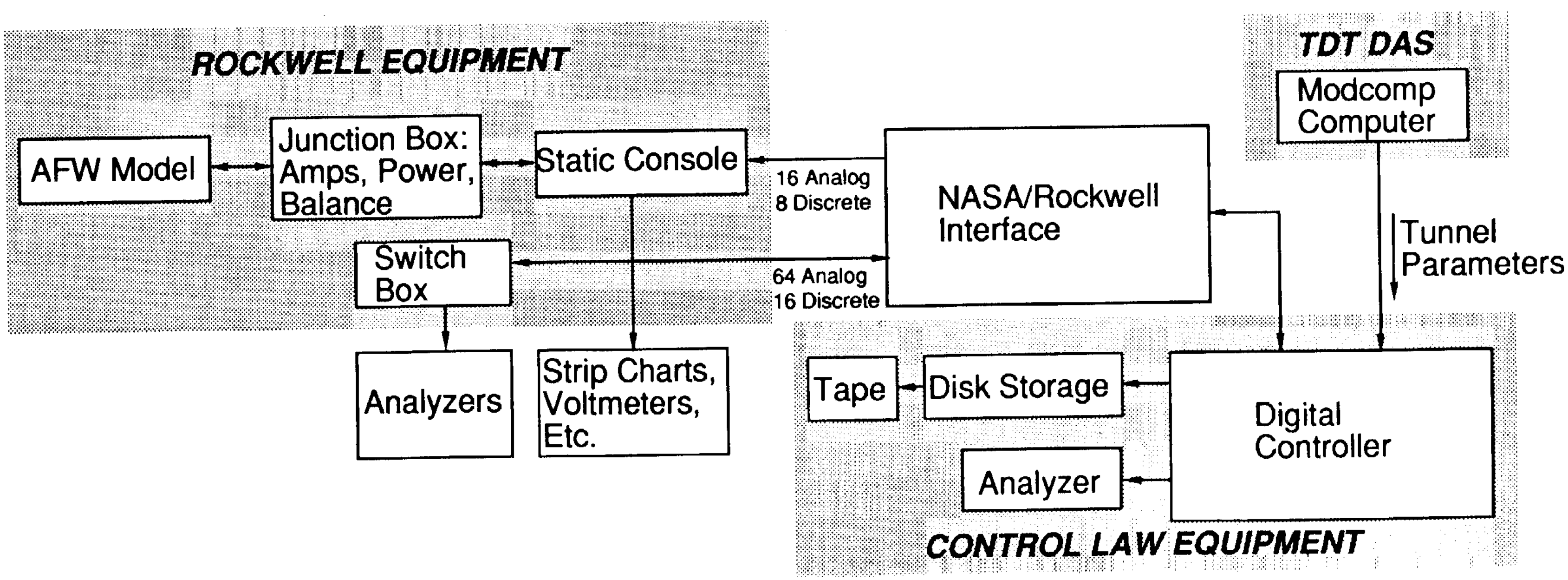
$f_a$= 14.79 Hz
$f_m$= 14.65 Hz

## END-TO-END TESTS

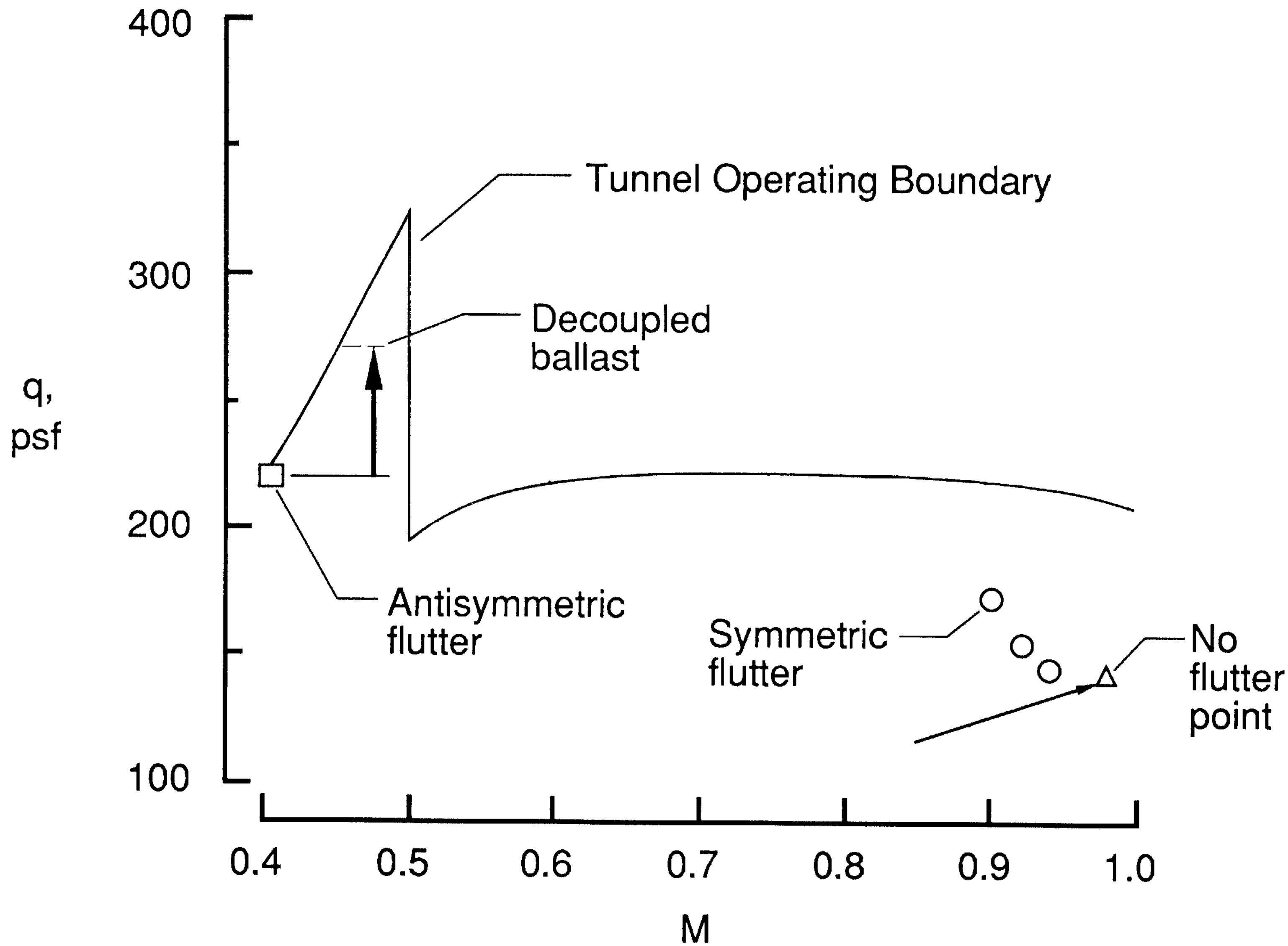
Prior to installation of the AFW model in the wind-tunnel, a series of tests were conducted in which the digital computer hardware was in the loop with the wind-tunnel model. The purposes of these tests were to verify the hardware connectivity, to check numerical sign correlation between model electronics and software setups, to compare wind-off, open-loop control law measurements with analysis, and to verify the capability of sending wind-tunnel flow parameters from the TDT data acquisition system to the AFW digital computer system. The figure gives an indication of the types of equipment which were interconnected for these end-to-end verifications prior to the wind-tunnel test.

# END-TO-END TESTS

- Verify hardware connectivity
- Compare wind-off, open-loop control law measurements with analysis
- Check numerical sign correlation
- Check for software factor errors
- Verify communication with TDT DAS



# TIP BALLAST EFFECTIVENESS



## TIP BOOM EFFECTIVENESS

This figure shows experimental results which demonstrate the effectiveness of the tip ballast mechanism. Coupled-ballast flutter conditions (indicated by symbols in the figure) were found to occur within the operating capabilities of the TDT. Prior to the addition of the tip ballast, flutter could not have been encountered in the tunnel. In the decoupled configuration, the figure shows that the subsonic flutter condition was raised to dynamic pressures well beyond the coupled flutter boundary as indicated by the dashed-line boundary to which the decoupled ballast was tested. No flutter points were determined in the decoupled configuration.

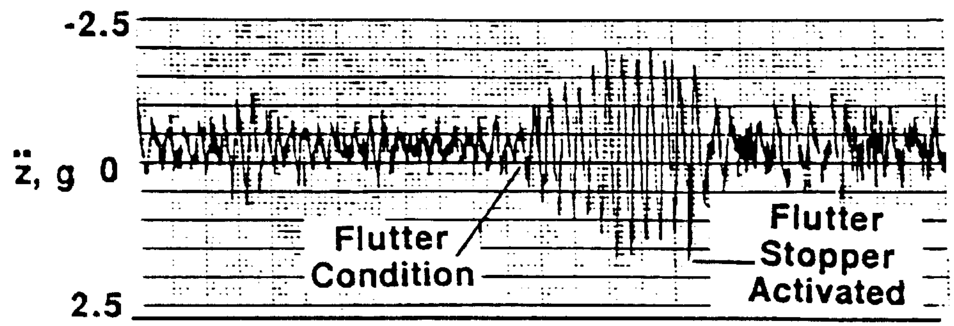
## TEST TIME HISTORIES

This figure shows both an open-loop and a closed-loop time history trace obtained for the AFW model during the wind-tunnel test. The open-loop trace is the antisymmetric flutter condition as measured by a wing accelerometer at tunnel conditions of M=0.40, q=221 psf. The trace shows an increasing amplitude dynamic response indicative of flutter onset. During the wind-tunnel test, this motion caused the automatic safety monitoring system to activate a number of passive flutter suppression systems (including the tip ballast decoupling) to stop the oscillation and save the model. Subtle changes in the character of the wing accelerations can be seen in the time history trace following the flutter-onset condition.

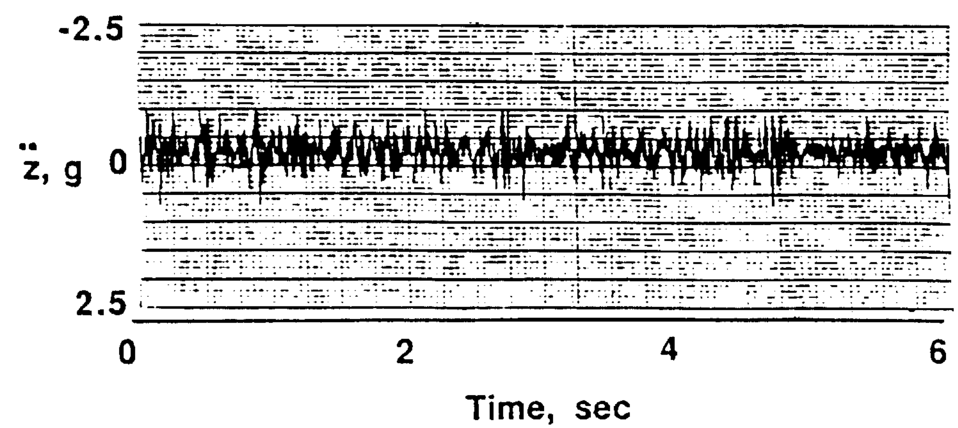
The closed-loop time history included in the figure (from the same wing accelerometer) shows that at a flow condition slightly above the open-loop flutter boundary there are no signs of an organized sinusoidal oscillation that would indicate a flutter condition.

# TEST TIME HISTORIES

Open-Loop, Flutter (M = 0.40, q = 221 psf)




Closed-Loop, No Flutter (M = 0.42, q = 230 psf)



## SESSION OVERVIEW

This presentation has served as an overview of the Active Flexible Wing project and has given background material concerning the wind-tunnel model and the wind-tunnel test. The five remaining presentations in this session of the Fourth Workshop on Computational Control of Flexible Aerospace Systems cover more specific aspects of the project. The figure lists the topic and authors for each of these remaining presentations in this session. The author giving the presentation is underlined.

The first of the remaining presentations covers the work that was accomplished to generate a math model of the AFW for flutter suppression system design and simulation. This presentation will also cover other flutter analyses that were accomplished using an advanced nonlinear unsteady aerodynamics computer code.

The next presentation covers the three flutter suppression systems that were designed and tested on the AFW model. The different design methodologies and performances are discussed in detail.

Following the flutter suppression system presentation, the work accomplished toward demonstrating rolling maneuver load alleviation is discussed. This presentation also touches on some of the flutter suppression system design work being done at Rockwell International in preparation for the next AFW wind-tunnel test.

The fifth presentation in this session covers the development, simulation verification, and testing of the digital controller system which was assembled for carrying out the active control law testing on the AFW model.

The last topic presents a controller performance evaluation capability which was developed specifically for testing on the AFW, but which is applicable to other multiple-input, multiple-output (MIMO) control systems. This capability was very important in predicting closed-loop stability while still in an open-loop condition and in accessing the open-loop instability condition while testing closed-loop.

# SESSION OVERVIEW

- Math Modelling of the AFW (Silva, Heeg, Bennett)
- Active flutter suppression tests (Christhilf, Adams, Waszak, Srinathkumar, Mukhopadhyay)
- Rolling maneuver load alleviaton (Miller, Klepl, Moore)
- Digital controller system (Hoadley, Buttrill, McGraw, Houck)
- Controller performance evaluation (Pototzky, Wieseman, Hoadley, Mukhopadhyay)

## CONCLUDING REMARKS

Some of the key accomplishments of the October, 1989 wind-tunnel test are shown on the attached figure. As presented, an assessment of the open-loop flutter boundary was accomplished near M=0.4 and M=0.9. The tip ballast was shown to provide a safety margin in terms of where the flutter conditions occurred between the coupled and decoupled ballast modes. Additionally, the tip ballast was remotely decoupled several times while experiencing high dynamic response during the wind-tunnel test and no adverse reactions were encountered. It is difficult to directly assess the effectiveness of the tip ballast as a flutter stopper since other passive flutter suppression devices were always activated simultaneously with the decoupling of the tip ballast. A major accomplishment of the 1989 test was the development and testing of the digital controller. The digital controller hardware and software performed very well during the test. Concerning the control law tests, all three flutter suppression systems were tested and one of these control laws took the model to a dynamic pressure 24 percent above the open-loop flutter dynamic pressure.

In terms of future plans, the 1989 test indicated that improvements in the math model of the AFW would be very beneficial for future control law development. Therefore, an extensive task was undertaken to refine the finite element model. This work is now completed. Also, a free-to-roll math model has been developed to allow analyses appropriate for rolling maneuver load alleviation and for free-to-roll flutter suppression testing. Using these new math models, control laws will be developed for both rolling maneuver load alleviation and flutter suppression system testing during the 1991 wind-tunnel test. A major goal of the 1991 wind-tunnel test is to simultaneously demonstrate rolling maneuver load alleviation and flutter suppression.

# CONCLUDING REMARKS

## Oct. '89 Test Accomplishments

- Flutter boundary determined
- Tip-ballast store performed extremely well
- Digital controller hardware and software performed extremely well
- Three digital flutter suppression systems (FSS) tested
- 24% increase in flutter dynamic pressure demonstrated for one control law

## Feb. '91 Test Plans

- Refine finite element model and develop aeroelastic model for free-to-roll
- Demonstrate RMLA control laws
- Demonstrate FSS control laws for free-to-roll
- Combine and demonstrate FSS during rolling maneuvers