EXPERIENCES WITH THE DESIGN AND IMPLEMENTATION OF FLUTTER SUPPRESSION SYSTEMS

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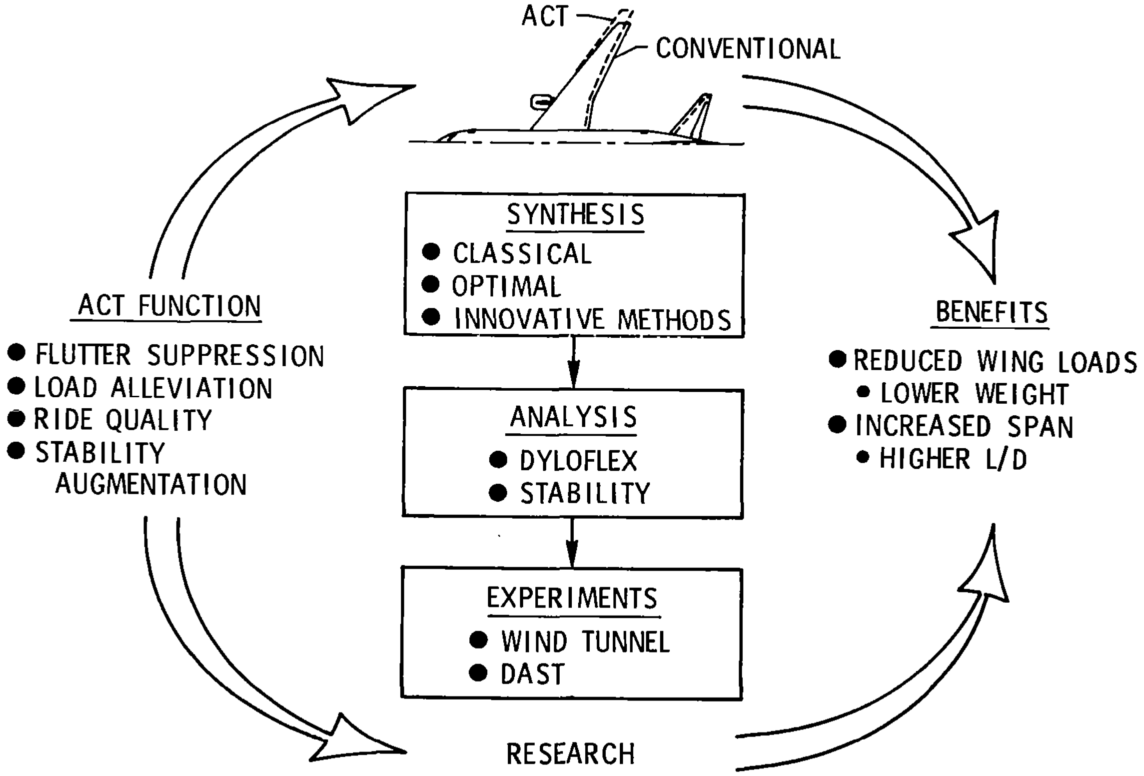
ABSTRACT

A considerable amount of research has been conducted on the application of active controls to increase aircraft performance. Because of its impact on safety of flight, flutter suppression is probably the active controls concept furthest from practical implementation and, therefore, requires significant attention. This attention spans both analytical and experimental studies. Research efforts at NASA have been directed towards the development of analysis and design methodology and the correlation of experimental results with analytical predictions. The purpose of this paper is to discuss some experiences with the design and testing of several flutter suppression systems. Emphasis will be on the experimental activities.

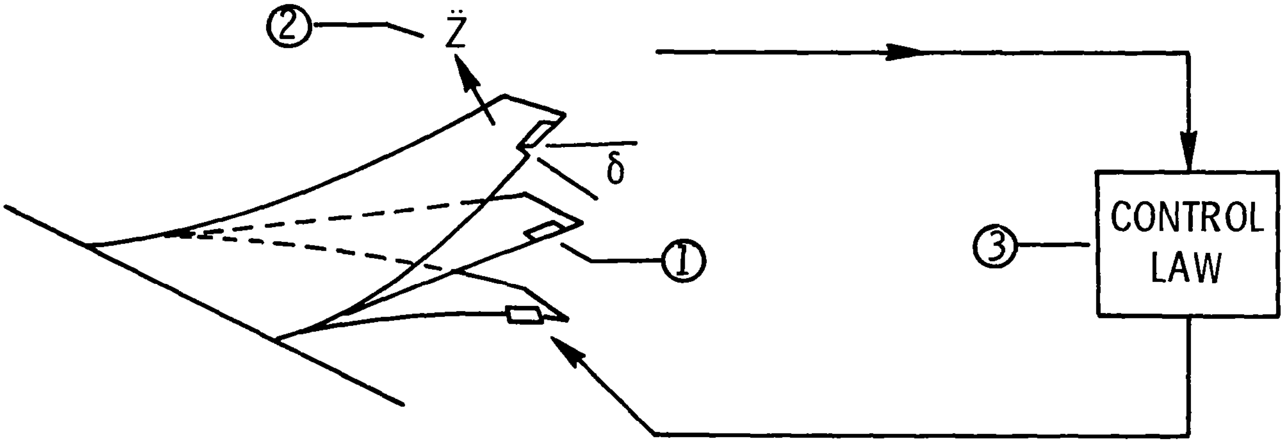
ACTIVE CONTROLS TECHNOLOGY

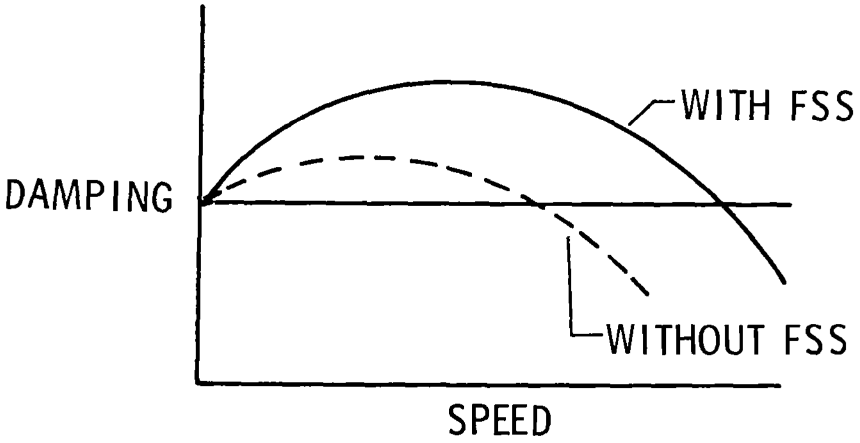
The application of active controls technology (ACT) to reduce aeroelastic response of aircraft structures offers a potential for significant payoff in terms of aerodynamic efficiency and weight savings. To reduce the technical risk associated with this new technology, research was begun in the early 1970's to advance this concept. The technical program encompasses three areas: control law synthesis, aeroservoelastic analysis, and experiments aimed at verifying both the analysis and synthesis methodology. In the area of control law synthesis, classical methods are being applied where applicable. The latest "state-of-the-art" optimal methods are being refined and applied to the aeroservoelastic case. Innovative approaches are being developed to take highly theoretical synthesis methods which result in complex (high-order) control systems and modify these methods in the design of simpler (low-order) control systems. Strategies are being developed to investigate the sensitivity of the resulting control systems to uncertainty and to incorporate this knowledge into the design cycle. Analysis methods include a comprehensive program (DYLOFLEX) (ref. 1) for calculating the loads on an aeroelastic vehicle equipped with active controls. The evaluation of vehicle static and dynamic stability is being accomplished using programs and methods developed in-house at LaRC. The experimental program is aimed at validating the analysis and synthesis methods by comparison with wind tunnel tests and flight results using a remotely piloted drone. The flight test program, called DAST (Drones for Aerodynamic and Structural Testing) (ref. 2), has become the focal point of the experimental validation.



ACTIVE FLUTTER SUPPRESSION

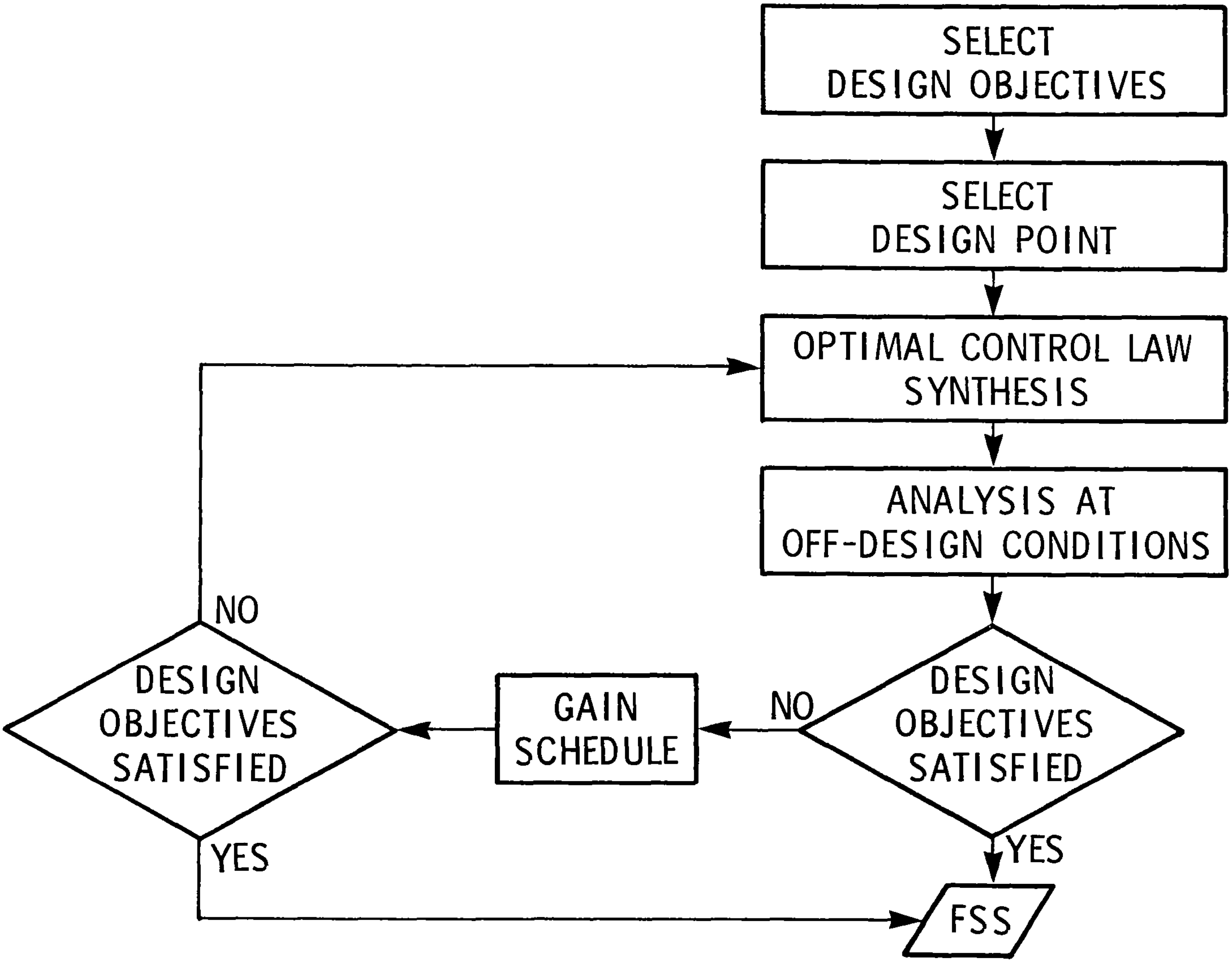
Active flutter suppression is a concept to increase the flutter speed of a vehicle through the use of active feedback control. The active control system consists of (1) control surfaces, (2) sensors, and (3) control laws. Through proper selection of the control surfaces and sensors and design of the control laws, the damping of the aeroelastic system can be augmented and thereby increase the flutter speed. The benefit to be derived from flutter suppression is usually reduced structural weight.





CONTROL LAW DESIGN PROCESS

The development of methodology to design flutter suppression systems has been an integral part of this research program. This development ranges from analytical synthesis techniques to the overall control law design process. A flowchart of the approach to the overall control law design process is shown below. The first element of the process is the selection of design objectives (i.e., gain margin, phase margin, etc.). The second element is the selection of a design point (i.e., Mach number and altitude). Control law synthesis is then performed at the design point. The next element, analysis, provides information on the performance of the control law at off-design flight conditions. If the design objectives at the off-design flight conditions are not met, then a gain scheduler which may be a function of Mach number and/or dynamic pressure is evaluated. If a gain scheduler will not meet the design objectives, then a path back to control law synthesis is selected.



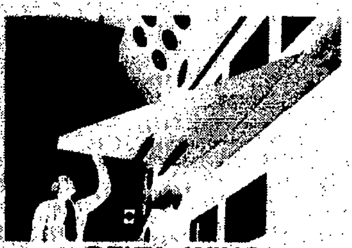
CONTROL LAW SYNTHESIS

The major emphasis in the development of design methodology has been in the area of control law synthesis. To accomplish the objectives of control law synthesis, as stated below, the practical problems in control law implementation must be recognized. The historical development of control law synthesis methodology has proceeded from classical techniques to optimal control theory to optimization techniques (refs. 3-8). Both unconstrained and constrained optimization techniques have been evaluated. Beginning recently, emphasis is being given to the use of constrained optimization techniques since several design objectives can then be satisfied simultaneously.

- OBJECTIVE:
  - DESIGN A LOW-ORDER CONTROL LAW FOR A HIGH-ORDER SYSTEM TO MEET SEVERAL DESIGN OBJECTIVES
  - LOW ORDER → SIMPLE IMPLEMENTATION
HIGH ORDER → CHARACTERISTIC OF AEROELASTIC SYSTEMS
- METHODOLOGY DEVELOPMENT
  - CLASSICAL TECHNIQUES
  - OPTIMAL CONTROL THEORY/ORDER REDUCTION
  - OPTIMIZATION TECHNIQUES
    - UNCONSTRAINED OPTIMIZATION
    - CONSTRAINED OPTIMIZATION

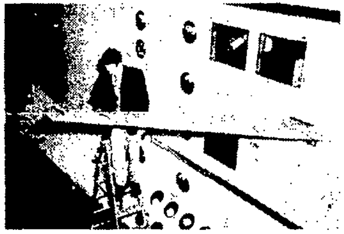
WIND TUNNEL STUDIES

Wind tunnel studies of aeroelastic models have been a cornerstone of the NASA research program. Presented in this chart are a number of models that have been used to demonstrate active control concepts on a variety of configurations. The Delta-wing model was an early experimental demonstration of flutter suppression (ref. 9). The B-52 model was tested in support of a USAF/Boeing flight study on active controls (ref. 10). Wing load alleviation was studied in support of a USAF/Lockheed program using a C-5A model (ref. 11). The DAST ARW-1 model was used for a variety of flutter suppression studies including an evaluation of a control system that would ultimately be tested on a remotely piloted research flight vehicle. Control laws were synthesized and tested on the model using classical, aerodynamic energy, and optimal methods (ref. 12). The F-16 and YF-17 model tests have shown active flutter suppression to be a promising method for preventing wing/external store flutter (refs. 13 and 14). Use of active controls is especially attractive for fighters because of the multitude of possible store configurations. These studies are part of an Air Force Flight Dynamics Laboratory/General Dynamics/Northrop/NASA cooperative effort. A cooperative effort was also conducted with the McDonnell Douglas Corporation on a DC-10 derivative wing. Increases in flutter speeds in excess of 26 percent were demonstrated. This study is reported in reference 15.

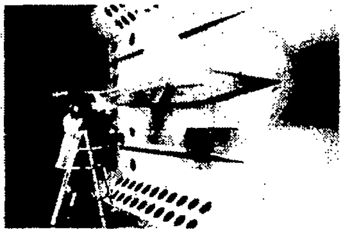

DELTA WING

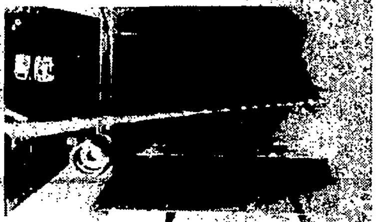

B-52 CCV


C-5A ALDCS


DAST ARW-1

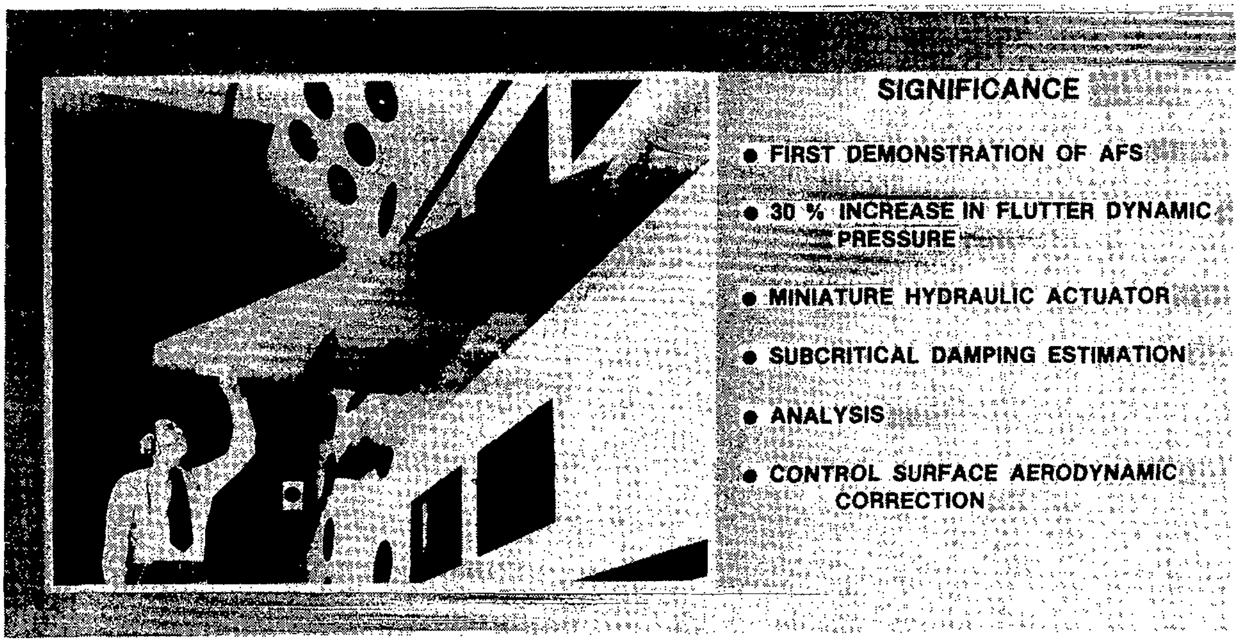

F-16


YF-17


DC-10 DERIVATIVE

DELTA-WING MODEL

Experimental studies have made a major contribution to the active control technology program developed at NASA. The Delta-wing model (whose photograph is in this chart) was the first experimental demonstration of flutter suppression in this country (ref. 9). At a Mach number of 0.9, increases in the flutter dynamic pressure ranging from 12.5 percent to 30 percent were demonstrated with active controls. One of the major contributions of this wind tunnel program was the development of miniature hydraulic actuators. These actuators paved the way for future wind tunnel tests of aeroelastically scaled models. To evaluate the performance of an active flutter suppression (AFS) system, subcritical response techniques must be employed. Three different methods were used to determine subcritical response of the Delta-wing model, and the results are described in reference 9. Analytical methods were used to predict both open-loop and closed-loop stability, and the results agreed reasonably well with the experiment. However, for the closed-loop case, it was necessary to use a control surface aerodynamic correction factor that was derived using measured hinge moment data.

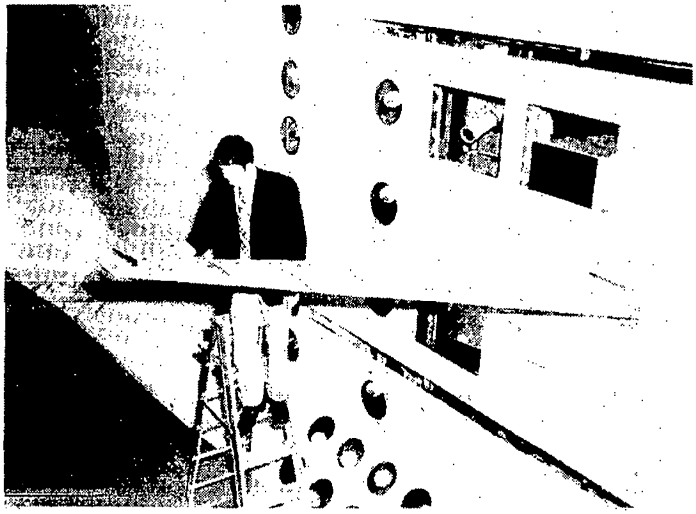


SIGNIFICANCE

- FIRST DEMONSTRATION OF AFS
- 30 % INCREASE IN FLUTTER DYNAMIC PRESSURE
- MINIATURE HYDRAULIC ACTUATOR
- SUBCRITICAL DAMPING ESTIMATION
- ANALYSIS
- CONTROL SURFACE AERODYNAMIC CORRECTION

DAST MODEL

The aeroelastic model used for this study was originally built to support the DAST flight program (ref. 2). The objective of the wind tunnel study was to demonstrate a 44-percent increase in flutter dynamic pressure. Two control laws were designed (ref. 12). One control law was based on the aerodynamic energy method, and the other was based on the results of optimal control theory. At Mach 0.95, a 44-percent increase in flutter dynamic pressure was achieved with both control laws, thereby validating the two synthesis methodologies. Experimental results indicated, however, that the performance of the systems was not as good as that predicted by analysis. The results also indicated that wind tunnel turbulence is an important factor in both control law synthesis and experimental demonstration.

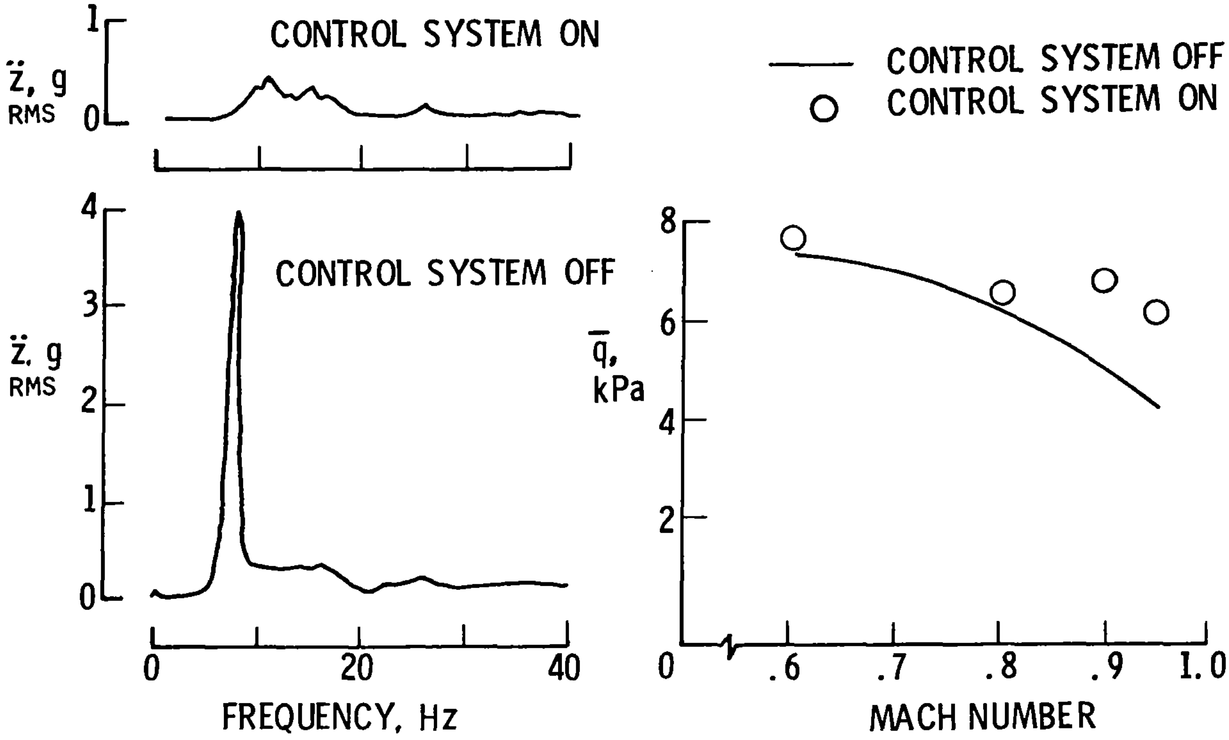


SIGNIFICANCE

- 44 % INCREASE IN FLUTTER DYNAMIC PRESSURE
- VALIDATED SYNTHESIS METHODOLOGY
- WIND-TUNNEL TURBULENCE EFFECTS
- HIGH-FREQUENCY CONTROL/STRUCTURE INSTABILITIES

CONTROL LAW PERFORMANCE

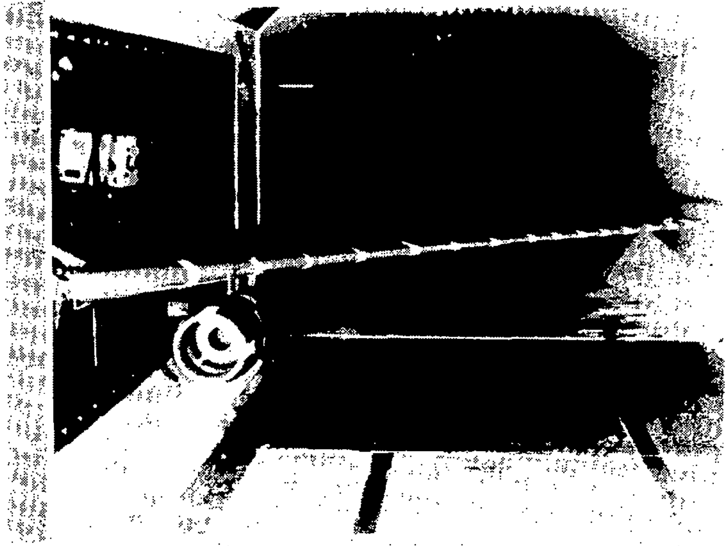
An illustration of flutter suppression performance for the DAST model is shown below. On the left, the spectrum of outboard peak accelerations for the wing with system off is compared to that for the system on. The model was being excited by tunnel turbulence. The data were measured at a dynamic pressure just below the system-off flutter boundary at M = 0.90. The decrease in amplitude and shift in the maximum response frequency resulting from the control law is evident. Also presented is a plot of flutter dynamic pressure as a function of Mach number. Data for both system off and system on are shown. The flutter suppression system is most effective (i.e., provides the largest increase in flutter dynamic pressure) at the higher Mach numbers. The effectiveness is significantly reduced at lower Mach numbers. A discussion of these results is given in reference 12.



DC-10 MODEL

A cooperative study was conducted with the Douglas Aircraft Company to apply control law design methods developed by NASA to a realistic transport configuration and to provide a rapid transfer of research technology to industry. These studies were an extension of previous wind tunnel tests performed by Douglas (ref. 16). The aeroelastic model (shown in the photograph on this chart) is representative of a wing which has a 4.27-m-span increase over the standard DC-10 wing.

Two control laws were designed at NASA Langley using different design methods (ref. 15). Both control laws resulted in a 59-percent increase in flutter dynamic pressure. The performance of the control laws as a function of gain and phase was also evaluated. Calculations performed prior to wind tunnel testing predicted all experimental trends. During the wind tunnel tests, both structural damping and phase characteristics of the actuator were identified as very important factors related to the effectiveness of the control laws. In addition, a correction factor was used to account for control surface effectiveness and did improve the correlation between measured and predicted characteristics.

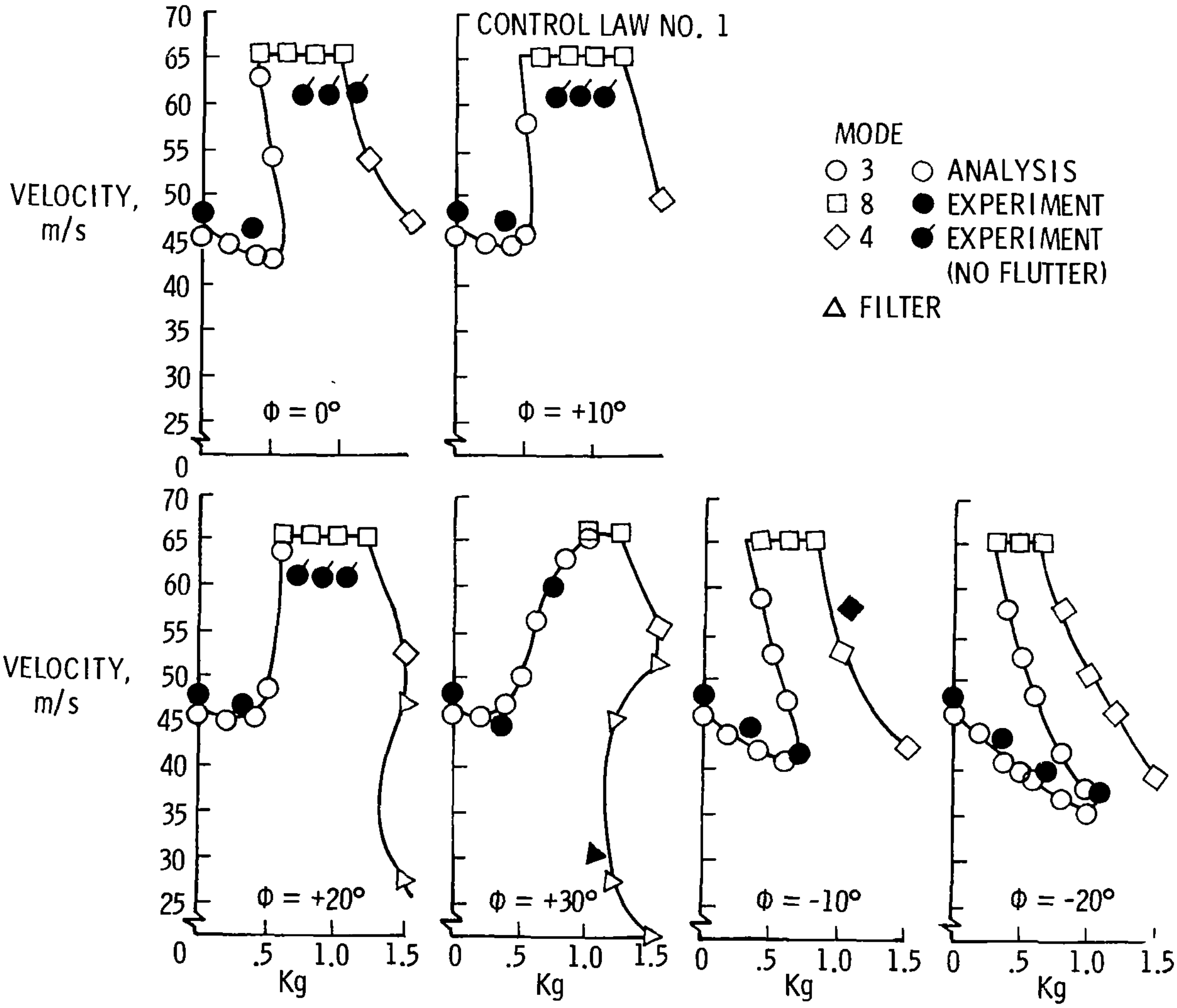


SIGNIFICANCE

- 59 % INCREASE IN FLUTTER DYNAMIC PRESSURE
- PERFORMANCE AS A FUNCTION OF GAIN AND PHASE
- ANALYSIS PREDICTED ALL EXPERIMENTAL TRENDS
- STRUCTURAL DAMPING EFFECTS
- ACTUATOR DYNAMICS
- CONTROL SURFACE AERODYNAMIC CORRECTION

MEASURED AND PREDICTED STABILITY BOUNDARIES AS A FUNCTION OF SYSTEM GAIN AND PHASE FOR DC-10 WIND TUNNEL MODEL

Measured and predicted stability boundaries in terms of flutter velocity versus system gain and phase are presented below. Three or four distinct flutter modes are exhibited, depending on phase angle. For all phase angles analyzed, a decrease in flutter velocity is shown for mode 3 at low values of gain. At negative phase angles, the reduction in flutter velocity is more pronounced. The velocity at which mode 8 goes unstable is nearly independent of system gain and phase. The mode 4 instability is aggravated by negative phase angles and stays relatively fixed for positive phase angles. At phase angles of +20° and above, a new flutter mode resulting from a coupling between the feedback filter mode and the first wing bending mode becomes critical. A detailed discussion of these results can be found in reference 15.



DAST: WHAT IS IT?

The concept of the DAST program (ref. 2) is to provide a focus for evaluation and improvement of synthesis and analysis procedures for aerodynamic loads prediction and design of active control systems on wings with significant aeroelastic effects. Major challenges include applications to wings with supercritical airfoil and tests emphasizing the transonic speed range. The program requires complete solutions to real-world problems since research wings are fabricated and flight tested. Because of the risky nature of the flight testing, especially with regard to flutter, target drone aircraft are modified for use as test bed aircraft.

PRINCIPAL RESEARCH AREAS

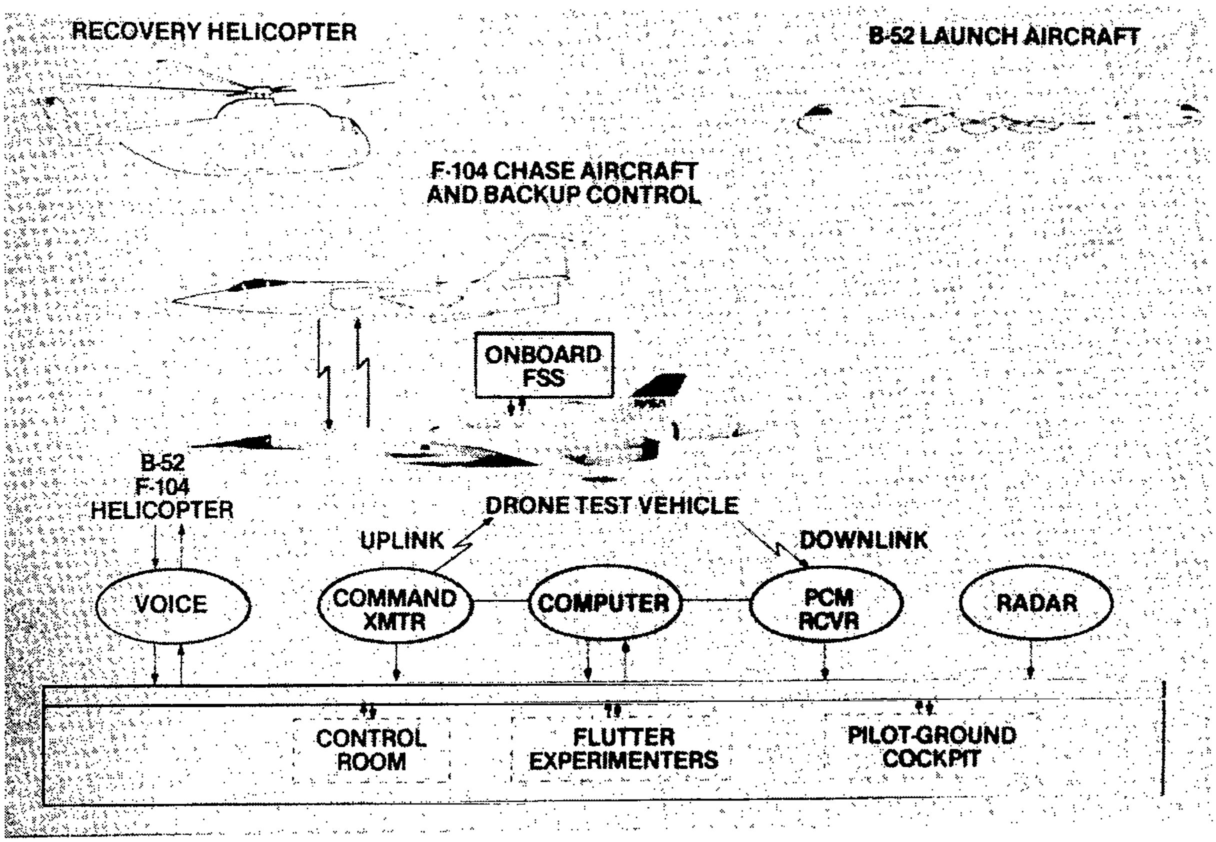
- ACTIVE CONTROL SYSTEMS EVALUATIONS
- AERODYNAMIC LOADS MEASUREMENT
- STRUCTURAL INVESTIGATIONS
- STABILITY AND PERFORMANCE STUDIES

EMPHASIS

- TRANSONIC REGION
- AEROELASTIC EFFECTS

DAST: HOW DO WE DO IT?

DAST uses an Air Force version of the Firebee II target drone as the basic test bed. The standard Firebee wing is removed and replaced with the research wing of interest. The operational sequence, as depicted in this chart, involves an air launch from beneath the wing of a carrier aircraft; a free-flight test phase of between 20 and 40 minutes (depending on Mach number and altitude); followed by a mid-air retrieval by helicopter via a parachute recovery system. During the free-flight phase, a test pilot controls the vehicle from a ground cockpit. An F-104 aircraft is used as chase, and the copilot of this aircraft serves as a backup flight controller for the drone in case of a malfunction with the uplink system. Data from the experiments are provided in real time to the ground by means of a pulse-code-modulated telemetry system. Experimenters provide real-time assessments of the status of the research wing and its associated active control systems. This assessment is based on the response of the wing to control surface sweeps and pulses. Flight tests are performed at the NASA Dryden Flight Research Facility located at Edwards Air Force Base, California.

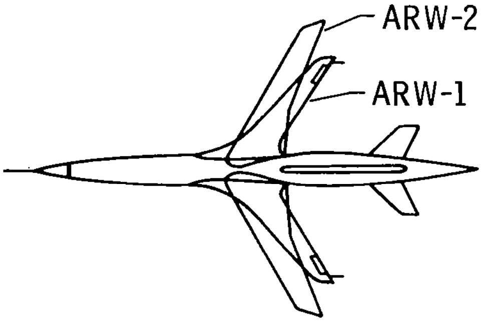


DAST: WHAT ARE WE DOING IT WITH?

Two transport-type research wings have been built for flight testing. The first wing, Aeroelastic Research Wing No. 1 (ARW-1), was designed for M = 0.98 cruise and was purposely designed to flutter within the flight envelope. Tests of the first research wing configuration have been terminated due to loss of the aircraft resulting from vehicle systems problems. However, valuable flutter data and test technique experience were acquired. References 17-20 provide a description of these results.

The wing fabrication and test planning for the second research wing (ARW-2) have been sponsored by the NASA Aircraft Energy Efficiency program. This design involved what is believed to be the first exercise of an iterative procedure integrating aerodynamics, structures, and controls technologies in a design loop resulting in flight hardware. Evaluation of multiple active controls systems operating simultaneously, the operation of which is necessary to preserve structural integrity for various flight conditions, is the primary objective of the flight tests on this fuel-conservative-type research wing.

DAST RESEARCH WINGS



ARW-1

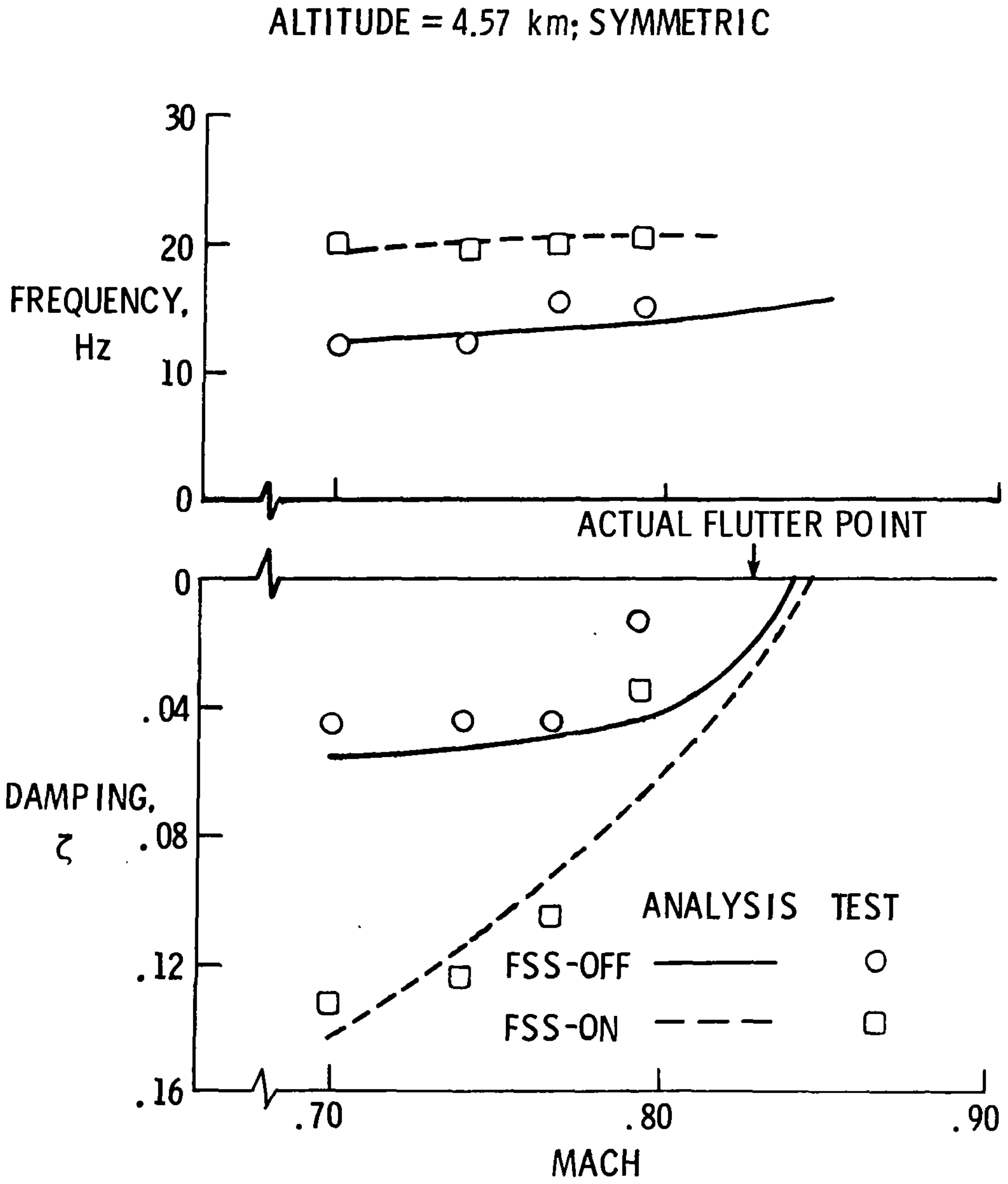
- FLUTTER WITHIN FLIGHT ENVELOPE
- ACTIVE FLUTTER SUPPRESSION SYSTEM
- SUPERCRITICAL AIRFOIL

ARW-2

- FUEL CONSERVATIVE WING DESIGN
  - HIGH ASPECT RATIO (AR = 10.3)
  - LOW SWEEP (Λ = 25°)
  - ADVANCED SUPERCRITICAL AIRFOIL
- MULTIPLE ACTIVE CONTROLS CRITICAL TO FLIGHT OPERATION
  - FSS
  - MLA
  - GLA
  - RSS

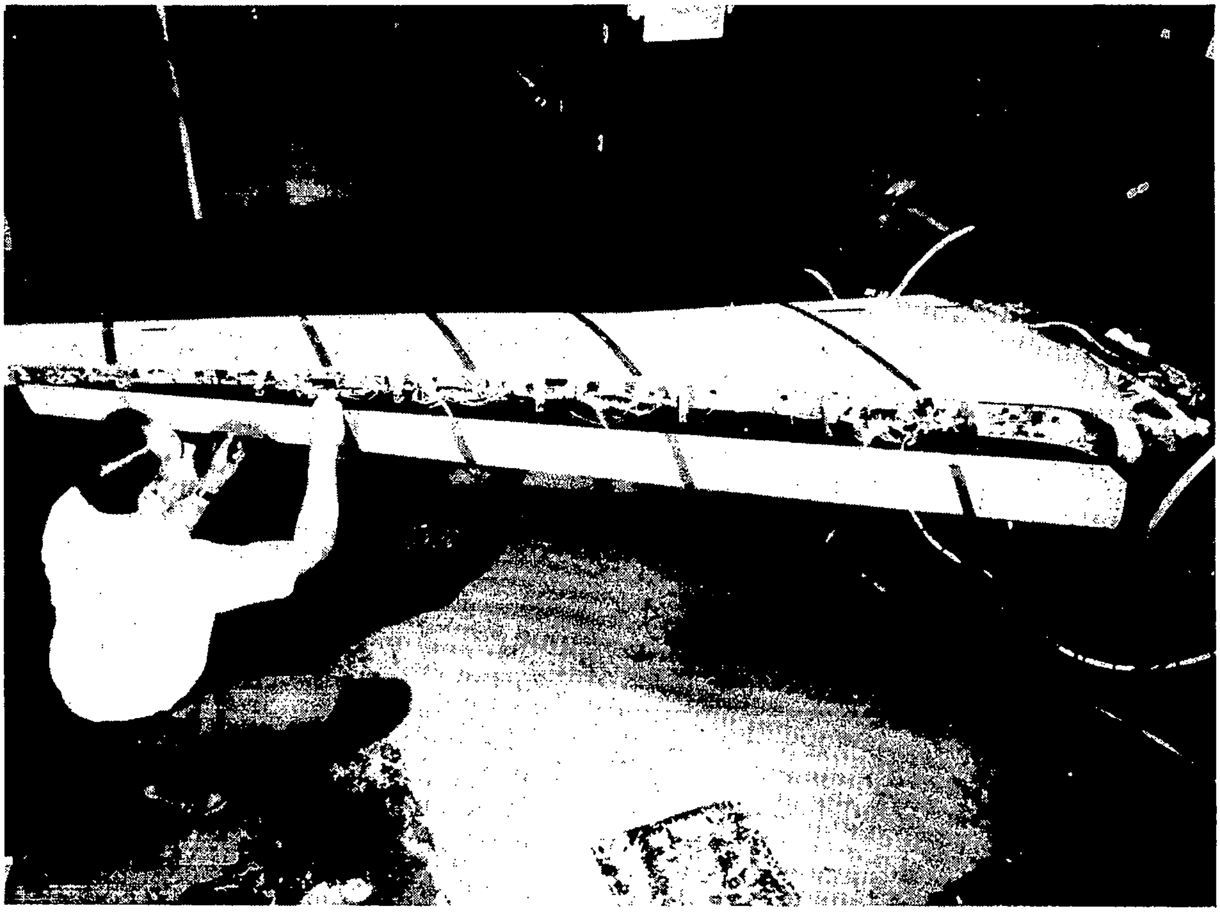
CORRELATION OF MEASURED AND PREDICTED DAMPING AND FREQUENCY VARIATIONS (ARW-1)

The frequency and damping of the dominant mode for the symmetric case are shown below. The analysis and flight test data are for a test altitude of 4.56 kilometers. The change in frequency with Mach number is predicted well for both the FSS-off and FSS-on cases. However, analysis overpredicts the damping for both the FSS-off and FSS-on cases. The experimental flutter speed is extrapolated to be approximately M = 0.80 for the FSS-off case. An actual flutter point was encountered for the FSS-on case at M = 0.82. Other data comparisons can be found in reference 17.



ARW-2 RIGHT SEMISPAN IN LAB PRIOR TO WIND TUNNEL TESTING

The ARW-2 wing panels have been fabricated and are being used to support two ground tests. The left semispan has been used to conduct a hardware-in-the-loop test of the active control system electronics. The right semispan shown in the photograph below has been tested in the Langley Transonic Dynamics Tunnel to obtain unsteady pressure distributions. This is believed to be the first measurement of unsteady pressures on a flexible supercritical wing. The pressure measurements from the wind tunnel will be compared against those measured during the flight tests. A secondary objective of the wind tunnel test is to investigate possible angle-of-attack effects on the flutter boundary at high transonic speeds.



CONCLUSIONS

A large amount of expertise has been acquired through the analytical and experimental studies conducted to date. Many lessons have been learned that help guide the future research directions. A few of these lessons are shown below. The first three lessons are technical in nature and have been or are presently receiving attention. However, even though the last lesson is nontechnical in nature, it certainly needs to receive more attention. Several of the future thrusts listed below are being researched at the present. These include the use of transonic time plane unsteady aerodynamics, applying flutter suppression methodology to other active control functions, and synthesis of multiple active control systems. The other thrusts are not presently being emphasized but are still on the list of future work.

LESSONS LEARNED

- UNSTEADY AERO THEORY NEEDS
    - CONTROL SURFACE
    - ARBITRARY MOTION
- ACCURATE DEFINITION OF ACTUATOR DYNAMICS
- ACCURATE TURBULENCE MODEL
- CLOSER COOPERATION BETWEEN AEROELASTICIAN AND CONTROLS ANALYST

FUTURE THRUSTS

- TRANSONIC TIME PLANE UNSTEADY AERO
- SYSTEMATIC METHODS FOR LOCATING CONTROL SURFACES AND SENSORS
- APPLY FLUTTER SUPPRESSION METHODOLOGY TO OTHER ACTIVE CONTROL FUNCTIONS
- SYNTHESIS OF MULTIPLE ACTIVE CONTROL SYSTEMS
- CONTROL CONFIGURED VEHICLES

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