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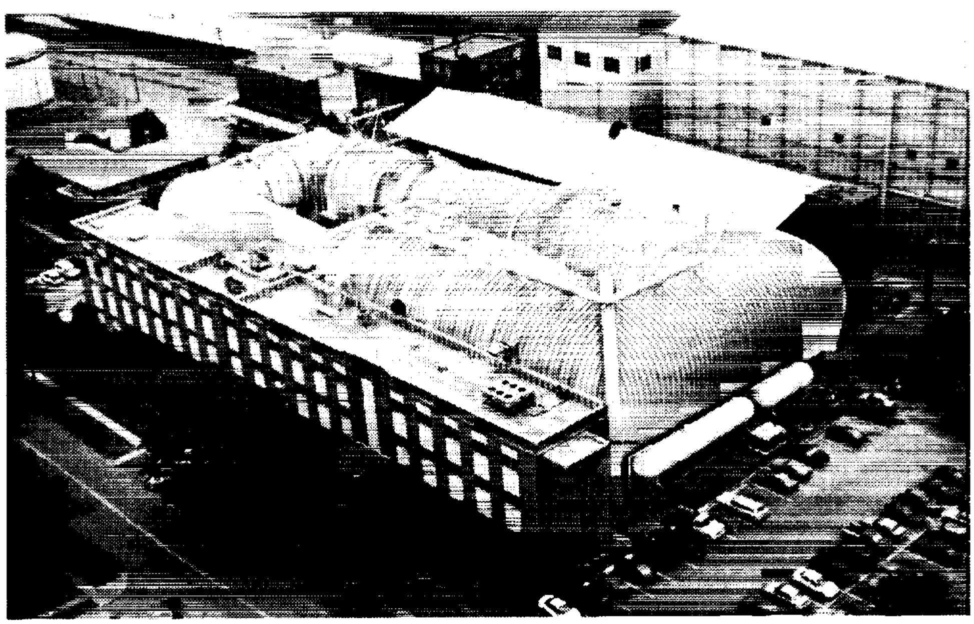

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Introduction

BY the 1960s, researchers began to investigate the feasibility of using active controls technology (ACT) for increasing the capabilities of military and commercial aircraft. Since then many researchers, too numerous to mention, have investigated and demonstrated the usefulness of ACT for favorably modifying the aeroelastic response characteristics of flight vehicles. As a result, ACT entered the limelight as a viable tool for answering some very difficult design questions and had the potential for obtaining structural weight reductions, optimizing maneuvering performance, and satisfying the multimission requirements being imposed on future military and commercial aircraft designs.

Over the past 40 years, the NASA Langley Research Center (LaRC) has played a major role in developing ACT in part by its participation in many wind-tunnel programs conducted in the Transonic Dynamics Tunnel (TDT). These programs were conducted for the purposes of: (1) establishing concept feasibility; (2) demonstrating proof of concept; and (3) providing data for validating new modeling, analysis, and design methods. This paper provides an overview of the ACT investigations conducted in the TDT.

For each program discussed herein, the objectives of the effort, the testing techniques, the test results, any significant findings, and the lessons learned with respect to ACT testing are presented.

Transonic Dynamics Tunnel

The TDT[1] shown in figure 1 became fully operational in 1960 and has served ever since as a "National Facility" dedicated almost exclusively to identifying, understanding, and solving aeroelastic problems. It is

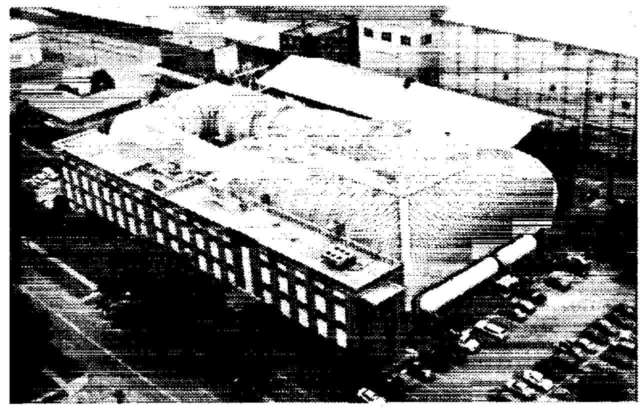

Fig. 1 Transonic Dynamics Tunnel.

the only facility in the world capable of studying a full range of aeroelastic phenomena at transonic speeds. The TDT is used by the aircraft industry to aid in clearing new designs for safety from flutter, to evaluate solutions to aeroelastic problems, and to study aeroelastic phenomena at transonic speeds. In addition to flutter clearance studies, the TDT is used by researchers to explore flutter trends and aeroelastic characteristics of new fixed wing and rotorcraft concepts, to study the use of active controls, to determine the effect of ground-wind loads on launch vehicles, and to make steady and unsteady aerodynamic pressure measurements to support computational fluid dynamic (CFD) code development.

The TDT is a closed-circuit, continuous-flow wind tunnel capable of testing at stagnation pressures from near zero to atmospheric conditions and over a Mach number range from zero to 1.2. The test section of the TDT is 16 feet square with cropped corners. Controlled variation of pressure in the tunnel simulates variations in flight altitude. One feature of the TDT which is particularly useful for aeroelastic testing is a group of four bypass valves connecting the test section area (plenum) to the opposite leg of the wind-tunnel circuit downstream of the drive fan motor. In the event of a model instability, such as flutter, these quick-actuating valves are opened, causing a rapid reduction in the test section Mach number and dynamic pressure which may result in stabilizing the model. Other features that make the TDT uniquely suited for aeroe-

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lastic and ACT testing include: good visibility of the model from the control room; a highly sophisticated computer-controlled data acquisition system; oscillating vanes upstream of the test section that can be used to generate sinusoidal gusts; a variety of model mounting and suspension systems ranging from cantilever sidewall mounts for component models to a 2-cable-suspension system for full-span "free-flying" models; safety screens that protect the tunnel fan blades from debris in case of a model failure; and state-of-the-art instrumentation and test equipment.

Tests can be performed in the TDT using air as the test medium, however, the most distinguishing feature of the tunnel is the use of a heavy gas, presently R-134a refrigerant, as the primary test medium. R-134a is about four times as dense as air, yet has a speed of sound of about half that of air. These properties of higher density and lower sonic speed have beneficial effects on the design, fabrication, and testing of aeroelastically scaled wind-tunnel models that must accurately represent their full-scale counterparts: physically larger models may be built, thereby simplifying the model fabrication process; and the scaled natural frequencies of these larger models are lower, resulting in lower flutter frequencies, thereby reducing the risk of model destruction during flutter. Other advantages resulting from the use of a heavy gas are a nearly three-fold increase in Reynolds number and lower tunnel drive horsepower.

Active Control Wind-Tunnel Tests

This section of the paper contains a summary of the tests performed in the TDT during the last 30 years that involved active contorl system demonstrations. A common thread among these projects is that each has has a significant impact on the state-of-the art of ACT.

Delta Wing Active Flutter Suppression

During the middle and late 1960s and into the early 1970s there was a growing expectation, that soon turned to a realization, that active controls technology could achieve a variety of aeroelastic benefits. After numerous analytical studies this technology found its way onto a few airplanes (references 2 and 3) and confirmed that fatigue life could be increased and that gust loads and fuselage accelerations could be reduced. These early successes led to the belief that the much more difficult and ambitious objective of active flutter suppression could, indeed, be achieved.

The very first demonstration of active controls in the TDT occurred in 1971 with active flutter suppression of a semispan model of a low-aspect-ratio clipped-delta-wing configuration (reference 4). This configuration was representative of the then-current Boeing supersonic transport design, and is shown mounted in the TDT test section in figure 2.

The model had a span of 50 inches, root and tip

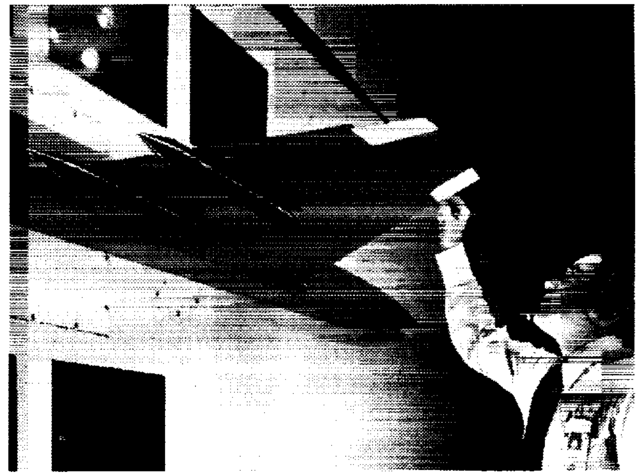


Fig. 2 Delta wing semispan model mounted in TDT.

chords of 69.4 inches and 8.8 inches, respectively, a leading-edge sweep angle of 50.5 degrees, and a circular-arc airfoil section with a thickness-to-chord ratio of 0.03. Two high-fineness-ratio bodies were mounted on the wing lower surface to simulate engine nacelles. The model was constructed of a primary load-carrying plate structure covered with balsa wood that was contoured to the desired airfoil shape. A rigid sidewall mounting block was used to simulate a fuselage fairing.

The model was equipped with both leading- and trailing-edge control surfaces centered at 78.5 percent of the wing semispan, each with a span of about 6 inches. The chord of the trailing-edge surface was about 20 percent of the local wing chord; the chord of the leading-edge surface varied from about 15 percent of the local wing chord inboard to about 20 percent outboard.

One of the significant contributions of this program to the then-emerging state of the art was the development of two miniature electrohydraulic vane actuators for mechanizing the active control surfaces. These actuators were small enough to be mounted immediately adjacent to the control surfaces and still fit within the contours of the airfoil. The importance of this proximity to the control surface was the elimination of drive shaft wind-up experienced by earlier electromechanical actuators mounted external to the model. The electrohydraulic actuators provided over 3 foot-pounds of torque output over the frequency range 0 to 25 Hz with a 1000 psi supply pressure. The actuators weighed only 2 ounces each and had angular displacement capabilities of about +/- 9 degrees.

Nissim's aerodynamic energy criterion for flutter suppression, reference 5, was employed in the design of the flutter-suppression control laws tested on this model. The criterion states that a necessary and sufficient condition for the prevention of flutter is that, for all oscillatory motions of an elastic system in an airstream, positive work be done by the system on the surrounding airstream. The mechanism by which this condition is satisfied is the inclusion of active control surfaces whose deflections are related by a control law to the plunging and pitching motions of the wing. Nissim points out that a suitable configuration is one employing both leading- and trailing-edge control surfaces, since the two working together provide independent control of lift and pitching moment.

Three different control laws were designed based on Nissim's method. The first and second used both leading- and trailing-edge control surfaces; the third used only the trailing-edge surface. In reference 5 these control laws were assigned letters, A, B, and C. Control law A was implemented and tested as designed. For the other two, modified versions of the original designs were implemented and tested and these are referred to as control law B "mod" and control law C "mod."

The flutter suppression control system consisted of the two control surfaces and their corresponding actuators, control laws implemented on an analog computer, and two accelerometers. The accelerometers were located along a chordwise strip very near the inboard edge of the control surfaces, one at about 30 percent of the local chord and the other at about 70 percent. Within the analog computer the outputs of the accelerometers were integrated once to obtain velocities, integrated again to obtain deflections, and then combined to produce normalized plunge and pitch displacements and normalized plunge and pitch rates along the strip. The control surface deflections commanded by the control law were linear combinations of these displacements and rates. Control laws A, B mod, and C mod were implemented by changing potentiometer settings.

Figure 3 presents dynamic pressure versus Mach number and summarizes the experimental results. The cross-hatch represents the open-loop flutter boundary, and clearly indicates a transonic drop in the model flutter speed. The circle, square, and diamond symbols are closed-loop results and demonstrate various increases in dynamic pressure above the open-loop flutter boundary. The solid circle symbol at 0.9 Mach number is the only closed-loop flutter point on the figure and represents a 12 % increase in flutter dynamic pressure for control law A. The open square symbol and open diamond symbols are no-flutter points and represent the highest dynamic pressures achieved before testing was terminated. Control law B "mod" demonstrated a 22% increase in dynamic pressure. Control law C "mod" demonstrated increases in dynamic pressure ranging from 11% at 0.6 Mach number to 30% at 0.9 Mach number.

Over the course of conducting this program large differences had been observed between the predicted and the actual effectivenesses of the active control system. These differences were attributed to the inability of potential theory to predict detailed aerodynamic behavior on control surfaces of such relatively small size compared to the lifting surface. It was decided that all calculations (not presented in the present paper) should try to account for these differences in some empirical manner. It was found that if the ratio of the measured-to-the-calculated static control surface hinge moments was used as an empirical correction factor on control surface aerodynamic terms (both steady and unsteady), the differences in active control system effectivenesses were greatly reduced. Today this type of empiricism is routinely used in correcting aeroservoelastic analyses.

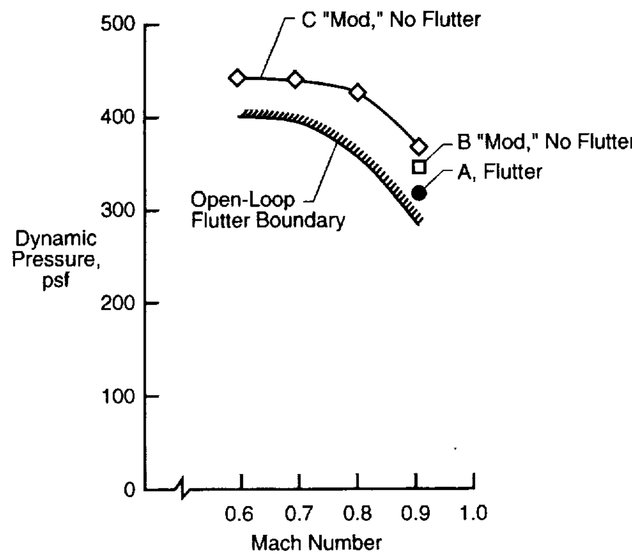


Fig. 3 Delta wing open- and closed-loop experimental results.

Another contribution of this program was the identification of the inertia coupling between the control surfaces and the main wing as the mechanism by which still-air closed-loop instabilities occurred. It was shown experimentally that this instability was driven by the rate feedback terms in the control law. The modifications in control laws B and C, referred to above, were changes to avoid these instabilities. Today this type of still air instability is a common occurrence.

C-5A Active Load Alleviation System

During the 1970s the TDT played a role in the development of C-5A Active Lift Distribution Control System (ALDCS). The then Lockheed-Georgia Company was interested in performing a correlation study of the C-5A ALDCS flight test results with the results from TDT wind-tunnel tests of a Froude-scaled aeroelastic model of the C-5A, also equipped with an ALDCS. This section of the paper is borrowed heavily from reference 6.

The C-5A airplane ALDCS was developed to reduce fatigue damage on the wing due to maneuver, gust and peak-to-peak ground-air-ground load sources.

The ALDCS was designed to reduce the inboard wing bending moment levels by redistributing the wing loads (so as to unload the wing tips) and by suppressing the airplane response in the short period and wing first-bending mode during maneuvers and in atmospheric turbulence. The system utilized wing accelerometers to form a symmetric aileron command signal through the existing C-5A Stability Augmentation System (SAS). The system also used the existing SAS pitch rate gyro and the autopilot normal accelerometer to command the inboard elevators to suppress short-period and first wing bending mode gust responses and to provide handling quality compensation.

The C-5A airplane ALDCS consisted of wing mounted accelerometers to command aileron deflection which suppressed the first wing bending mode and reduced wing bending moments for maneuver conditions. The accelerometers (two on each wing) were mounted at 89% semi-span and were located on the front and rear beams of the wing. Each pair of wing accelerometers were summed proportionally front to rear (40% to 60%) to optimize the chordwise location and were summed equally between wings to allow only vertical input signals to the ALDCS computer.

The C-5A wind-tunnel model ALDCS was implemented on an analog computer. Since the model did not have elevators, the horizontal stabilizer was commanded in pitch to duplicate the tail lift change due to inboard elevator ALDCS commands. The ALDCS response of the model stabilizer was weighted and scheduled proportionately to the elevator transfer function requirements. The tail lift generated by one degree of airplane inboard elevator deflection was approximated by 0.35 degrees of stabilizer deflection on the model. The ailerons and the stabilizer were powered by small hydraulic actuators. Position feed back from these control surfaces was programmed using operational amplifiers to give the actuators the appropriate transfer function. The actuator servo responses were measured and compared to calculated aircraft response. The total model on-board ALDCS System weighed 49.61 pounds.

The wind-tunnel model was a 1/22 geometrically scaled, aeroelastic model designed to match the airplane Froude number in the TDT heavy-gas test medium and at a density ratio of 2.65. The model was constructed of hollow and solid metal spars located along the elastic axis of each aircraft component with balsa wood fairings to achieve an aerodynamic shape. The wind-tunnel model was supported using the TDT two-cable mount system with the forward cable in the vertical plane and the aft cable in the horizontal plane. Figure 4 presents a photograph of the model installed in the TDT.

A variety of wind-tunnel model data was acquired during the 1973 wind-tunnel test. The data included independent frequency sweeps of the aileron, horizontal stabilizer, and TDT flow oscillation vanes. At comparable tunnel and flight conditions, wind-tunnel model data were compared with airplane data, with and without the ALDCS engaged. Figure 5 contains comparisons of frequency response functions (magnitudes only) of wing-tip vertical acceleration due to aileron deflection and is typical of the many comparisons in reference 6. Amplitudes for both airplane and model have been normalized by their respective ALDCS-off maximum values and the model data has been appropriately scaled to airplane frequencies. Figure 5(a) contains flight-test data; figure 5(b), wind-tunnel data. The same basic result can be seen in both parts of the figure: for the first mode (approximately 1 Hz) the ALDCS reduces the wing-tip acceleration by about 60% and broadens the peak; at all other frequencies the ALDCS produces few differences in wing-tip acceleration.

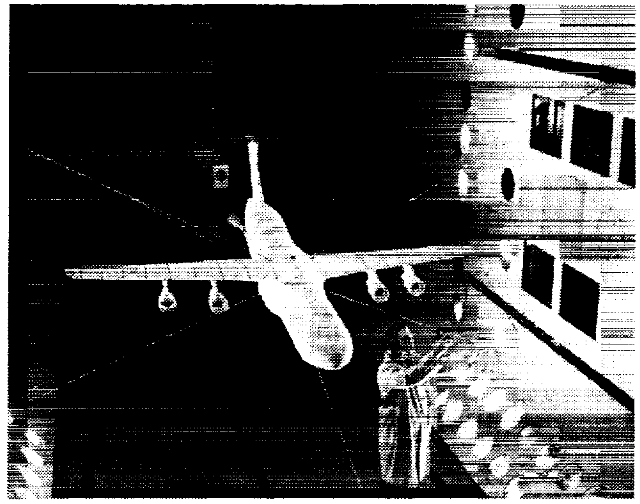
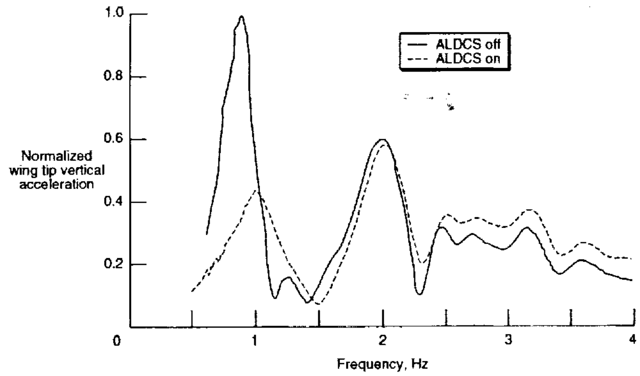


Fig. 4 C-5A model mounted in the TDT.

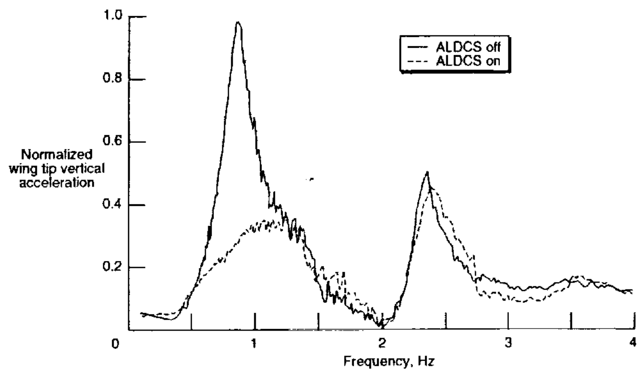
The results of this study validated the use of active control technology for the minimization of aircraft aeroelastic response and showed that scaled aeroelastic wind tunnel models can be used in developing active control technology. Both the model and airplane results showed that the desired wing load relief for the C-5A wing first bending mode was achieved with the ALDCS and the model and airplane correlated very well for this mode.

B-52 Active Control Systems

The success of flight investigations in the 1960s to reduce the dynamic response of the XB-70 and the B-52E aircraft due to gusts opened the gateway to a multitude of active control studies and applications. In conjunction with the B-52E flight investigation, a 1/30th scale, full-span, free-flying B-52 aeroelastic wind-tunnel model was constructed and tested in the TDT. The model was dynamically scaled to match the first nine symmetric elastic vibration modes of the flight vehicle (frequency range from 0 to 25 Hz). The



a) C-5A airplane response.



b) C-5A wind-tunnel model Response.

Fig. 5 Airplane and wind-tunnel model response to aileron sweeps.

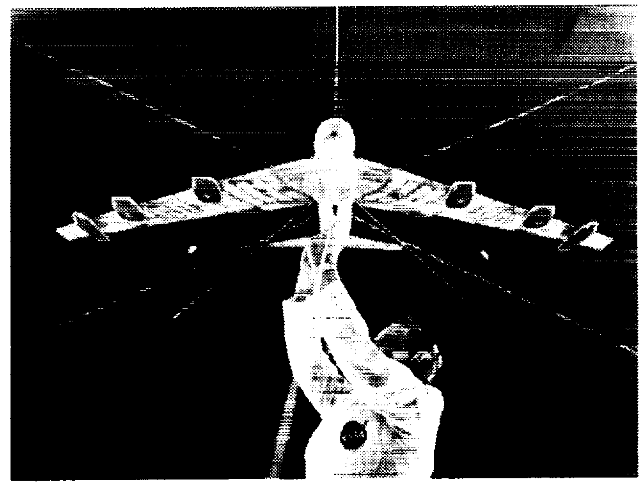


Fig. 6 B-52 model mounted on the Transonic Dynamics Tunnel's two-cable mount system.

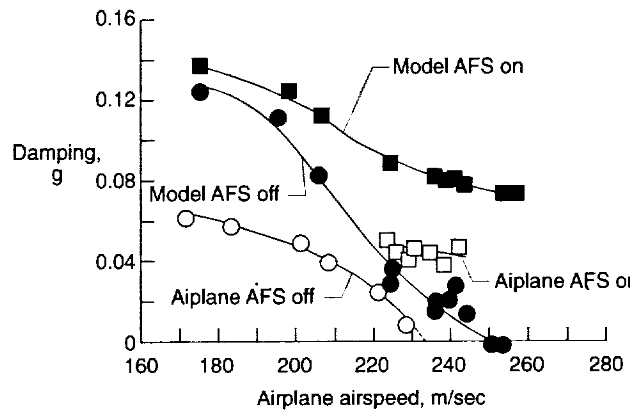


Fig. 7 Comparison of B-52 TDT and flight test results, AFS system off and on.

model was equipped with active ailerons and elevators and demonstrated, in the wind tunnel, what had already been demonstrated in flight: the ability of active controls to alleviate structural dynamic response caused by turbulence.

In parallel with Controlled Configured Vehicles (CCV) flight test program using the B-52E aircraft, an investigation[7] sponsored by the Air Force Flight Dynamics Laboratory (AFFDL) with Boeing and in cooperation with the NASA LaRC was initiated to: 1) develop active control concept evaluation techniques through wind-tunnel testing; 2) demonstrate that aircraft active control systems can be simulated with wind-tunnel models; 3) obtain experimental data for validating analysis results and methods; and 4) obtain data for correlation with the B-52E flight test results. The impetus behind this investigation was the availability of the previously-tested 1/30th scale B-52 aeroelastic wind-tunnel model.

The B-52 wind-tunnel model was modified to dynamically match equivalent changes made to the full-scale B-52E as required to produce a flutter condition within the vehicle's flight envelope. In addition, to properly represent the active flutter suppression (AFS) and the vertical ride control (VRC) systems being evaluated during the flight test program, the wind-tunnel model was further modified to include new outboard ailerons, new flap segments, and horizontal canards. These control surfaces were driven by an electromechanical system consisting of d.c. torque motors mounted within the fuselage and crank-pushrod linkages and shafting from the motors to the control surfaces. Figure 6 shows the B-52 wind-tunnel model installed in the TDT on the two-cable mount system.

The AFS system consisted of two independent feedback loops. Signals from accelerometers mounted on the ballasted external fuel tanks were compensated using an analog computer and fed back to the aileron surfaces, while accelerometer signals located near the midwing were compensated and fed back to the flap segments. Since both systems were designed to separately provide a 30 percent increase in flutter speed, they were considered redundant systems. With the exception of scaling differences, the AFS systems on the wind-tunnel model and on the B-52E aircraft were very similar over the frequency range of interest.

The wind-tunnel test data, scaled up to corresponding flight-test conditions, are compared with flight-test results in figure 7. Concentrating first on the wind-tunnel results only (closed symbols), it can be seen that the AFS-on tests were performed at velocities only slightly higher than the open-loop flutter velocity of 253 m/s. However at the highest velocity for AFS-on, the damping in the flutter mode showed a large improvement compared to that for AFS-off and also showed the potential for a significant increase in flutter speed. Comparing, now, the AFS-on wind-tunnel results (closed square symbols) with the AFS-on CCV flight-test results (open square symbols) the damping trends are seen to agree quite well.

The VRC system on the full-scale aircraft was designed to reduce, by at least 30 percent, the gust-induced vertical acceleration at the pilot's station. This system used vertical acceleration, sensed at the pilot's station and appropriately shaped with a filter, to drive the horizontal canards. The VRC system on the wind-tunnel model was a scaled-down version of the actual flight system. The performance of the VRC system was equivalent to the performance of the system on the airplane at the structural mode frequencies deemed important at equivalent test conditions. The VRC system reduced the magnitude of the 6th and 8th mode peaks on the model by about 60 percent and 75 percent respectively, and on the airplane by about 56 percent and 73 percent respectively.

The most significant finding that resulted from the B-52 CCV full-span model program was the knowledge that dynamically-scaled, actively-controlled wind-tunnel models could be extremely useful in studying and developing advanced active control concepts. From that time forward, wind-tunnel models were destined to play the following important roles in the development of active-control concepts: increase the confidence level in these concepts by providing data to verify analytical models and methods; and eliminate the risks and lower the costs associated with flight-testing these concepts.

YF-17 Wing/Store Active Flutter Suppression Program

The Northrop Corporation, under contract with the AFFDL and in cooperation with NASA LaRC, conducted a long-term wind-tunnel investigation of wing/store AFS. The objective of this program was to perform several series of tests to evaluate a multitude of control concepts based on different design philosophies. These concepts began with simple non-adaptive analog controllers and evolved into digital adaptive controllers. For this program, a 30-percent-scale, semispan, aeroelastic model of the YF-17 aircraft was designed for testing in the TDT. The wind-tunnel model consisted of a wing, a fuselage, and a horizontal tail. The sidewall mounted model was very unique in that it used cables and a set of bars and linkages to simulate rigid-body pitch and plunge degrees-of-freedom. The horizontal tail, attached to an electric motor located within the fuselage, was used for trimming the model at various tunnel conditions. The wing had leading- and trailing-edge control surfaces powered by electro-hydraulic actuators. Three different external store configurations having widely different flutter characteristics (flutter frequency, modal coupling, and flutter-mode violence) were also available. A photo of the model mounted in the TDT is shown in figure 8. .

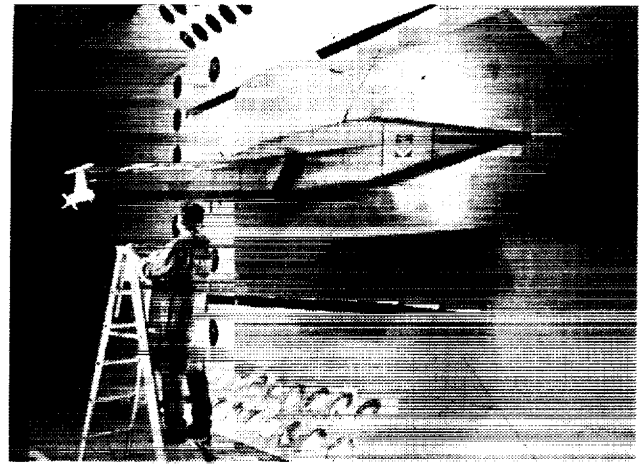


Fig. 8 YF-17 model mounted in the TDT.

The first series of wind-tunnel tests were conducted in three entries: June, August, and December of 1977. For these tests, a different AFS control law, each employing a single control surface, was developed for each external store configuration. These tests were quite successful. For the first store configuration, characterized by a lightly damped hump mode, passive flutter could not be reached within the limits of the TDT. With a control law operating that used the trailing-edge surface, a significant improvement in structural damping in the critical elastic mode was achieved. The other two store configurations were characterized by violent flutter onsets, one at about 5 Hz and the other at about 10 Hz. With control laws that used the leading-edge surface, flutter suppression was successfully demonstrated: for the configuration with the most violent flutter characteristics, the model was tested 18 percent above the unaugmented flutter dynamic pressure without incurring an instability. Based on damping trends at this condition, the model was projected to be stable up to about 29 percent above the unaugmented flutter condition.[8] This program demonstrated that active suppression of wing/store flutter was feasible. The program also demonstrated for the first time that leading-edge surfaces acting alone are viable AFS surfaces.

For the second series of tests, conducted during October 1979, the use of multiple loops with multiple control surfaces acting simultaneously was the approach for obtaining further increases in flutter speed.[9] For this series of tests only the wing/store configuration with the most violent flutter mode was used. To reduce the risk of losing the model during flutter, the store was modified to include an internal electro-mechanical system that served as a flutter stopper. This system would passively suppress flutter by moving an internal mass very rapidly, thereby changing the wing/store structural frequencies in such a manner as to decouple the critical elastic modes. Whenever an instability was encountered the system could be triggered either automatically or manually. Research organizations from three European countries were invited to participate in the second series of tests through the auspices of USAF data exchange agreements or information exchange programs. These organizations included British Aerospace and the Royal Aeronautical Establishment from the United Kingdom, the Office National d'Etudes et de Recherches Aerospatiales from France, and Messerschmitt-Bolkow-Blohm GmbH from West Germany. Control laws from each of the organizations varied greatly in their design philosophy, and in the number of sensors and control surfaces used. All control laws were highly successful in suppressing flutter.[10] One control law was tested to a dynamic pressure 70 percent above the passive flutter dynamic pressure. Post test evaluation of damping trends indicated that this control law could have stabilized the model up to about 131 percent above the passive flutter dynamic pressure boundary.

Some "firsts" demonstrated in this portion of the YF-17 semispan model program included the ability to switch from one control law to another above the unaugmented flutter condition and the ability to switch from a control law that used a trailing-edge surface to one that used a leading-edge control surface above the unaugmented flutter condition. The ability to switch control laws above flutter without experiencing any noteworthy transient motions on the model laid the groundwork for adaptive control. In addition to the test demonstrations, advancements in test procedures and measurement techniques were also accomplished. Procedures to calculate model open-loop characteristics from measured closed-loop transfer functions were demonstrated at conditions below and above flutter. Also, techniques developed and used to extract system gain and phase margins from Nyquist plots provided a measure of model stability and were useful in identifying ways to improve the control law performance.

The next step in the logical progression of AFS development in the YF-17 semispan model program was to transition from analog non-adaptive systems to digital adaptive controllers. The demonstration of an AFS digital adaptive controller was accomplished in two phases. During the first phase, several of the analog control laws tested previously were digitized and implemented on a digital controller. These control laws were then retested on the YF-17 model in the TDT during November 1981. The performance of

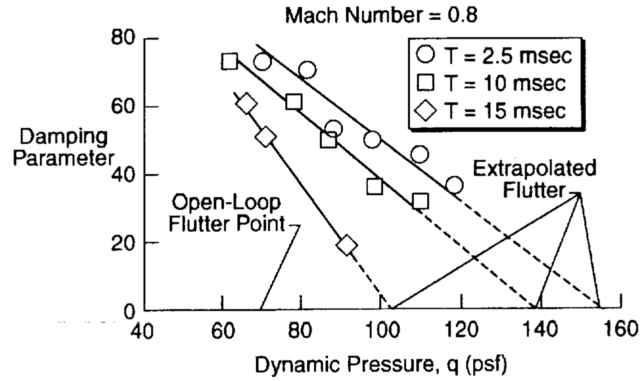


Fig. 9 YF-17 flutter suppression performance for three controller sampling times.

the digital control laws and the improvement in flutter speed demonstrated was comparable to the metrics obtained during the analog control test demonstrations. Although sampling time, T, was identified as a critical parameter (figure 9), the control laws performed adequately down to a sampling rate of 100 samples per second (T of 10 milliseconds), which was typical of sampling rates for aircraft digital control systems under development in the early 1980s.

During the second phase of these tests, a relatively simple adaptive controller was developed and tested during April 1982. The first level of adaptation consisted of discriminating between possible flutter modes (based on a priori knowledge) and selecting the appropriate control law; the second level consisted of adapting the control law to changes in flight condition. This concept was successfully demonstrated during the wind-tunnel tests.[11] In addition, the ability of the controller to adapt rapidly following a store release was demonstrated. For this unique demonstration, a wing-tip mounted store was abruptly released transforming the model from a stable condition to a violent flutter condition. The adaptive controller recognized the unstable behavior, implemented a new control law, and stabilized the model in a small fraction of a second.

DAST Wing

In the early 1970s NASA embarked on an ambitious high-risk flight-test program[12] whose primary objectives were to validate analysis and synthesis methods for the active control of aeroelastic response and analysis techniques for aerodynamic loads prediction. This program was called DAST (Drones for Aerodynamic and Structural Testing). It was conceived and implemented at NASA Langley with flight tests conducted at NASA Dryden. The flight test vehicle was an unmanned Firebee II target drone whose standard wing had been replaced with an aeroelastic research wing (ARW).

The first in a series of these wings, designated ARW-1, was designed to have both symmetric and antisymmetric classical bending-torsion flutter modes within

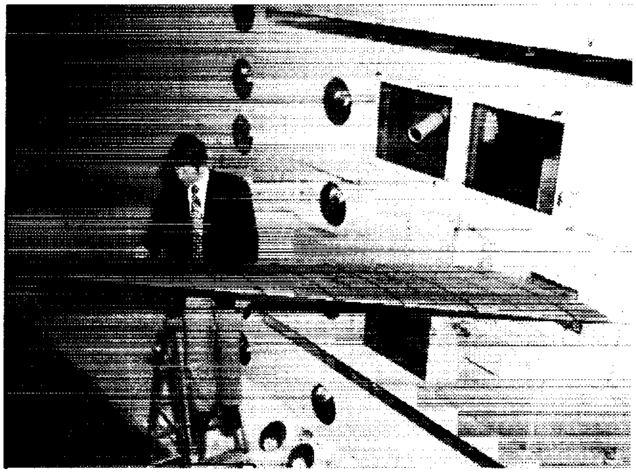


Fig. 10 DAST wing model mounted in the TDT.

the flight envelope of the DAST ARW-1 vehicle. The primary objective of the ARW-1 flight tests was to verify transonic flutter prediction techniques and to validate the predicted performance of the vehicle with an active flutter suppression (AFS) system.

As part of the DAST program, a wind-tunnel model study was undertaken to reduce the technical risks associated with implementing an AFS system on the ARW-1. A dynamically-scaled representation of the ARW-1 wing was designed such that it would flutter within the operational limits of the TDT, and a semispan wind-tunnel model of pod-spar construction was built for testing in the TDT. The model was equipped with a hydraulically actuated trailing-edge control surface, centered at 83 percent of the semispan, with a span of 13 percent of the semispan, and with a chord of 20 percent of the local wing chord. A photograph of the model mounted in the TDT is presented in figure 10.

Flutter suppression control laws,[13] based on two different methods, were designed with the objective of demonstrating a 44-percent increase in flutter dynamic pressure over the Mach number range 0.6 to 0.9. These control laws employed as feedback sensors accelerometers located near the control surface. Voltages proportional to acceleration were fed back to an analog computer upon which flutter suppression control laws were programmed. In order to demonstrate the 44-percent increase, the active control system had to operate in the presence of tunnel turbulence and within the deflection and rate limits of the actuator.

The stated objective of demonstrating a 44-percent increase in flutter dynamic pressure over the Mach number range 0.6 to 0.9 was not achieved. However, at 0.95 Mach number, both control laws did demonstrate the 44-percent increase. The major factor that prevented the 44-percent increase from being achieved was unexpectedly large (ref. 13 called them "excessive") control-surface peak deflections. These unexpectedly large deflections were, in turn, the con-

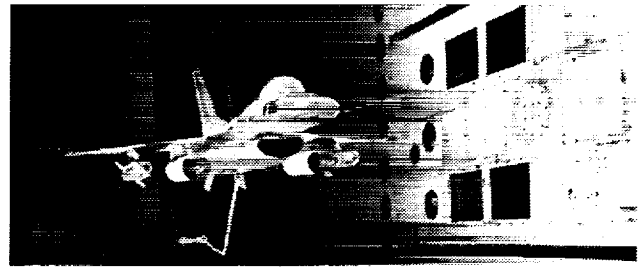


Fig. 11 F-16 wind-tunnel model on the Transonic Dynamics Tunnel's two-cable mount system.

sequence of an inaccurate description of wind-tunnel turbulence, upon which pre-test analyses and pre-test control law performance were based. The results of this test emphasized the need for a more accurate description of turbulence within the TDT test section.

F-16 Wing/Store Active Flutter Suppression Program

The F-16 aircraft carries many combinations of external stores. To assist in identifying a large number of critical wing/store flutter modes for the F-16, a 1/4 scale, full-span, free-flying flutter model was designed and fabricated for testing in the TDT. This model was tested successfully many times in the 1970s and 80s to support the USAF F-16 flutter clearance program.

Because of the large number of critical flutter modes associated with external stores, the USAF and General Dynamics became very interested in all promising flutter prevention techniques, including AFS. To investigate the potential of applying AFS to the F-16, General Dynamics took advantage of their existing 1/4-scale flutter model, by then a mature and reliable testbed, and fabricated a new set of wings equipped with accelerometers positioned at key locations and flaperon surfaces powered by hydraulic actuators. In addition, ballast in the fuselage was replaced with a hydraulic pump to power the wing servoactuators. For the next eight years the F-16 model (figure 11) with the new wings became a testbed for evaluating AFS systems that ranged from analog to complex digital adaptive concepts. This program was carried-out by a team of researchers from General Dynamics, the U.S. Air Force Wright Aeronautical Laboratories (AFWAL), and the NASA LaRC and involved three wind-tunnel test entries in the TDT.

The first test, conducted in February 1979 for a single wing/store configuration, demonstrated the suppression of an antisymmetric flutter mode at 8.6 Hz. Research issues related to AFS that were considered important included: the effects of asymmetry between left and right wing sensor signals and actuator commanded deflections; the simultaneous implementation of symmetric and antisymmetric control laws; switching of control laws above open-loop flutter; and determining if open-loop frequency response functions (FRF) could be measured accurately enough to provide useful information. The determination of accurate FRF was considered vital to the safety of the tests, ensuring that the AFS was operating as expected at subcritical speeds, and that the control law was providing the correct gain and phase to suppress flutter. The measurement of the open-loop FRF with the feedback loop physically open and closed were both successful. However, with the loop closed, tunnel turbulence caused a distortion of the FRF near the flutter frequency, and was most evident near the unaugmented flutter point. Important accomplishments from the first test included: successful modifications to control laws (gain/phase changes and sensor changes) during testing to maximize AFS effectiveness; successful switching of control laws above the unaugmented flutter condition without experiencing any threatening transient motions; and testing closed loop to a dynamic pressure 100 percent above the unaugmented flutter dynamic pressure (with flaperon displacements never exceeding 0.6 degreés).

The unaugmented flutter point for the store configuration tested in 1979 was determined from FRF derived from closed-loop system measurements, and as already stated, there was distortion, and therefore uncertainty, present in these FRF. Post-test data reduction and analysis revealed uncertainty in the actual value of unaugmented flutter point. Therefore, in October 1981 this store configuration was retested. The objectives of this test were to explicitly define the unaugmented flutter condition, to determine the accuracy of measured FRF and define approaches for improving the accuracy, and to investigate the feasibility of suppressing flutter with a single flaperon while simulating a failure in the other. In addition, a second store configuration that fluttered symmetrically at 10.6 Hz was tested to further demonstrate the usefulness of flaperons as AFS surfaces. These tests were highly successful, satisfying all their objectives.[14] The accuracy of the measured FRF was determined by actually varying gain and phase angles and measuring the gain and phase margins up to an unstable condition. Both the direct (actual measurement of open-loop data) and the indirect methods (extraction of open-loop data from closed-loop responses) of obtaining FRF were found to provide reasonable measures of model stability. The AFS was also found to perform satisfactorily with one flaperon locked out; however, the gain margin was reduced by a factor of one-half. Finally, AFS systems employing flaperons performed equally well for both symmetric and antisymmetric flutter modes. Some results from the antisymmetric AFS tests are provided in figure 12.

With successful conventional AFS wind-tunnel test demonstrations on the F-16 wind-tunnel model and successful adaptive AFS test demonstrations on the YF-17 model, the AFWAL, General Dynamics, and NASA LaRC team became directly involved in developing and demonstrating a totally digital adaptive (no prior knowledge of the aircraft configuration) system. The objectives of this investigation included: demonstrating digital adaptive flutter suppression for three different external store configurations, each having widely different flutter-mode characteristics; demonstrating a 30 percent improvement in flutter speed with the AFS operating for each store configuration; and demonstrating the suppression of flutter following the separation of a store from the wing. These tests were accomplished during December 1986 and the results are summarized in reference 15. These tests demonstrated, for the first time, the feasibility of using a digital adaptive AFS system having no prior knowledge of the wing/store configuration. Not only were significant improvements in flutter speed demonstrated for some wing/store configurations, but the system performed very well in adapting and stabilizing the model following the release of a wing-tip missile that immediately resulted in a post flutter condition. In this unstable condition, the system was able to identify the unstable plant, design a nominal control law, and suppress flutter in less than a second.

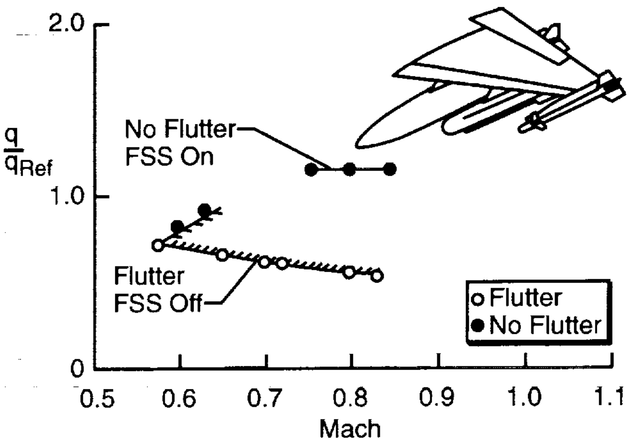


Fig. 12 F-16 open- and closed-loop flutter boundaries.

Some of the more significant accomplishments of the totally digital adaptive portion of the F-16 full-span model program included: the use of control laws developed by the adaptive controller as a backup analog safety system; the launching of missiles from a free-flying model at conditions below and above the unaugmented flutter boundary; and the successful demonstration of adaptive control. For one test run, the adaptive controller updated the control law over 2500 times without losing control of the flutter mode. In addition, the adaptive controller was successful with simulated single actuator failures and with rapidly changing test conditions.

Active Flexible Wing Program

In the early-1980s Rockwell International Corporation developed a concept it named the active flexible

Fig. 13 AFW wind-tunnel model mounted in TDT.

wing (AFW) concept,[16] and in 1985, in cooperation with the AFWAL and the NASA LaRC, Rockwell undertook a research program to demonstrate this concept. The AFW concept exploits, rather than avoids, wing flexibility by employing active leading- and trailing-edge control surfaces, up to and beyond control-surface reversal. A high-performance aircraft designed using the AFW concept achieves its high roll rates using wing control surfaces only, thereby eliminating the need for a "rolling tail," and, consequently, eliminating the additional structural weight associated with a rolling tail.

In an AFW design an active roll control (ARC) system is required to efficiently manage the rolling of the vehicle. An ARC system monitors flight conditions and, based on those conditions, chooses the most effective control surfaces to roll the vehicle, and also chooses the proper sign for control-surface deflections (one sign if below reversal, the opposite if above). In an AFW design further weight savings can also be achieved by the additional use of active controls. Taken alone or in combination, AFS, gust load alleviation, and maneuver load control all have the potential for further reductions in vehicle weight. By taking full advantage of active controls and the AFW concept, Rockwell predicted that, compared to conventionally-designed high-performance vehicles, weight savings of at least 15 percent of take off gross weight could be achieved for an advanced fighter configuration.

An AFW program grew out of the AFW concept. The testbed for the AFW program was the aeroelastically-scaled, full-span, wind-tunnel model shown sting mounted in the TDT in figure 13. The model was designed and built by Rockwell and tested on four different occasions (1986, 87, 89, and 91) in the TDT. The first two tests involved Rockwell, the Air Force, and NASA and focused on demonstrating the AFW concept. The results from these tests are reported in references 16 and 17

The second two tests involved only Rockwell and NASA and focused on the demonstration of aeroelastic control through the application of digital active controls technology. The results from these tests are reported in a special issue of the AIAA Journal of Aircraft.[18] For these tests the model was fitted with wing-tip ballast stores to lower the model flutter speed into the operational capabilities of the TDT. The model was sting-mounted utilizing an internal ballbearing arrangement, allowing the model freedom to roll about the sting. A roll degree-of-freedom brake was employed for those cases when a fixed-in-roll condition was required. The model had two leading-edge and two trailing-edge control surfaces on each wing panel driven by rotary-vane, electrohydraulic actuators powered by an onboard hydraulic system. The model was instrumented with a variety of sensors that included accelerometers, strain gages, rotary variable differential transducers, and a roll rate gyro. Active control concepts considered during the second two tests included AFS, rolling maneuver load alleviation (RMLA), and a roll rate tracking system (RRTS). These active control systems were designed to be compatible with each other such that they could be tested simultaneously, even at conditions above the passive flutter speed of the wind-tunnel model.

The design goal of AFS control laws was to penetrate the open-loop flutter boundary and proceed to the operating limit of the TDT. Requirements for minimum levels of robustness and acceptable levels of control-surface deflections and rates were specified. For the wind-tunnel model in the fixed-in-roll configuration, symmetric and antisymmetric flutter boundaries had to be penetrated to demonstrate anything more than a trivial increase in flutter dynamic pressure. Four different AFS control laws were designed, three were tested. A control law designed using a multiple-input/multiple-output (MIMO) constrained optimization technique was successful in suppressing flutter to a condition 26 percent above the antisymmetric-open-loop flutter dynamic pressure and 17 percent above the symmetric-open-loop flutter dynamic pressure.

An important goal of the AFW program was the demonstration of multiple-input/multiple-output/multiple-function control law testing. This goal was accomplished through the simultaneous operation of AFS and RMLA control laws. The design goal of RMLA control laws was to reduce or control wing loads during rolling maneuvers of 90 degrees. Important design considerations were to maintain stability, acceptable control-surface deflections and rates, and constant roll performance. These control laws were implemented with the wind-tunnel model in the free-to-roll configuration, for which only one flutter boundary (symmetric) was within the tunnel-operating envelope. Four combinations of AFS

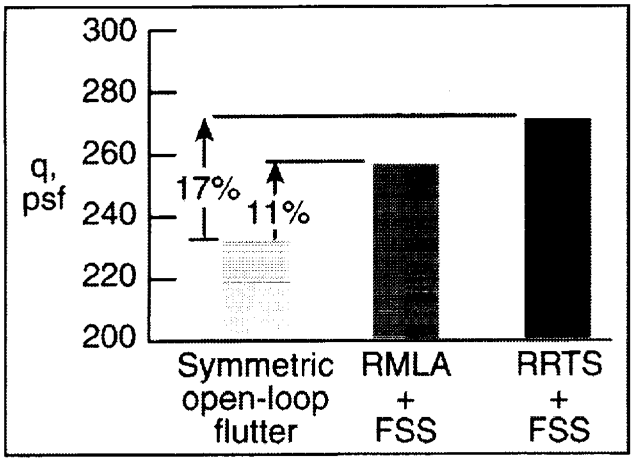


Fig. 14 AFW multi-function control law performance.

and RMLA control laws were designed and tested. Aggressive (scaled MIL SPEC) roll maneuvers were performed and wing loads were controlled 17 percent above the symmetric-open-loop flutter dynamic pressure. This data is summarized in figure 14.

Twin-Engine F-16 Derivative

Wind-tunnel models of a twin-engine F-16 derivative were tested five times in the TDT from 1988 to 1993. A flutter test program was initiated to characterize the symmetric and antisymmetric flutter modes of the aircraft.[19] A stability model and a dynamically similar model were constructed. The full-span, 2/7-scale models were designed and fabricated with a remotely moveable mass in the fuselage to allow for testing statically stable and statically unstable configurations on the TDT cable-mount system. The mass weighed 40 lbs. and could travel up to 28 inches, which moved the model center of gravity up to 12 percent of the mean aerodynamic chord.

This model is included here because it required the successful implementation of active controls in order to meet the objectives of flutter testing a statically unstable configuration. A stability augmentation system (SAS) employing pitch rate feedback to the elevons allowed the model to be tested at tunnel conditions up to a Mach number of 1.1 and a dynamic pressure of 250 psf.

Piezoelectric Aeroelastic Response Tailoring Investigation

NASA LaRC, in cooperation with the Massachusetts Institute of Technology, conducted an investigation known as PARTI (Piezoelectric Aeroelastic Response Tailoring Investigation). The objective of the PARTI project was to demonstrate in the wind tunnel the ability of strain-actuated adaptive wings to control aeroelastic response at subcritical speeds and to prevent flutter. For this demonstration, an aeroelastic semispan model with distributed piezoelectric actuators was fabricated for testing in the TDT. The model consisted of an interior composite plate to serve as the main load carrying structure and an exterior fiberglass shell to provide the proper aerodynamic contouring. The aerodynamic shell was divided into six sections. Each section was attached to the composite plate at two locations to minimize the increase in model stiffness attributed to the aerodynamic shell. The composite plate consisted of an aluminum honeycomb core with graphite epoxy face sheets. Seventy-two piezoelectric actuator patches were distributed on both the upper and lower surfaces of the composite plate. The actuators covered about two-thirds of the composite plate area and accounted for about seven percent of the total wing weight. Due to the ply orientation of the material used in the composite plate and the wing sweep, the piezoelectric actuator patches were connected in fifteen different groups chosen to affect the bending and the torsional responses of the model. During the control law development and testing these actuator groups were further combined into supergroups (several groups of piezoelectric actuator patches being activated by the same signal). Ten strain gages and four accelerometers were available as feedback sensors and for monitoring the models response during the tests. In addition to the piezoelectric actuators, the model had a trailing-edge aerodynamic control surface driven by an electric motor located in the wing root (hidden from the airstream) and an automatic flutter-stopper. Figure 15 shows a picture of the model fully assembled and installed in the TDT. Figure 16 shows the model with the external shell removed exposing some of the internal details.

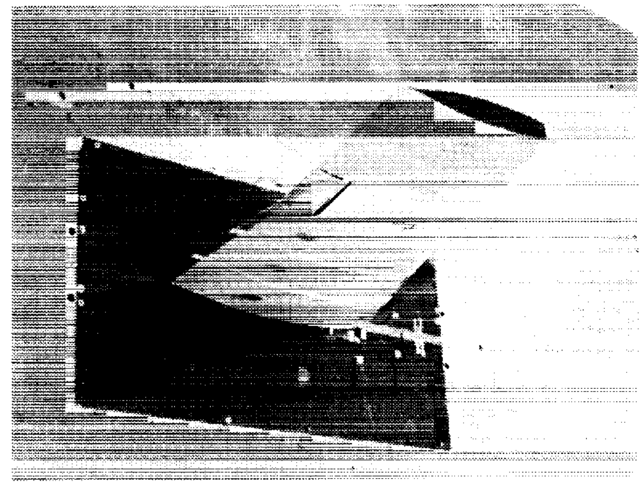


Fig. 15 PARTI model mounted in the TDT.

For this investigation two wind-tunnel test entries were performed using air as the test medium at atmospheric conditions. The first entry[20] conducted during March 1994, was used to measure the following open-loop (control law off) information: the model subcritical (below flutter) response; the basic flutter characteristics of the model in its basic configuration and with the model in a flutter-stopper configuration;

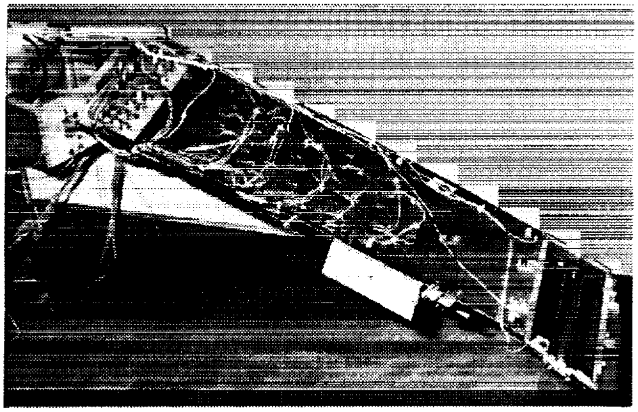


Fig. 16 Internal details of PARTI model.

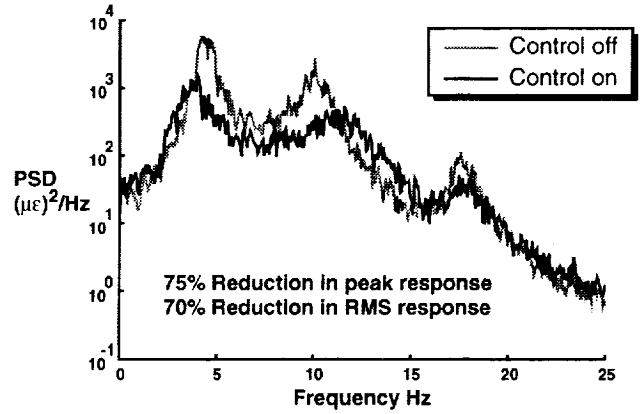


Fig. 17 PARTI turbulence response results, Mach number = 0.43, dynamic pressure = 60 psf.

and time-histories and frequency response functions for each important piezoelectric actuator group. These experimental data were useful in constructing mathematical models for designing control laws and for verifying analytical models and techniques.

The second entry[21] conducted during November 1994, was used to assess and demonstrate the capability of piezoelectric actuators to suppress flutter and to reduce aeroelastic response caused by tunnel turbulence. Many different control laws, based on different design methodologies, actuator groupings, and feedback sensors, were designed using experimentally determined state-space mathematical models and actuator transfer functions. Control law design techniques included classical frequency domain methods, the μ-Synthesis method, a Linear Quadratic Gaussian (LQG) method with loop shaping, and a sensitivity-weighted LQG method. Most of the control law designs used strain feedback rather than acceleration feedback because of the "cleaner" transfer functions provided by strain gages and the ability of the strain gages to capture the first three elastic modes of the model (1st bending, 2nd bending, and 1st torsion). Twenty-eight of these control laws were tested in the TDT and evaluated. The complexity of the control laws varied from single-input/single-output to multi-input/multi-output controllers having five sensors and nine actuator groups. The most successful control law was a single-input/single-output LQG design that used one strain gage for feedback and all fifteen actuator groups. Using this control law, an increase in flutter dynamic pressure of twelve percent was demonstrated. In addition, at dynamic pressures well below flutter, within the power spectral density function of microstrain due to tunnel turbulence, the peak value at the frequency of the first flexible mode was reduced by seventy-five percent (figure 17).

The significant contributions of this program to the state of the art were the demonstrations of flutter suppression and aeroelastic response control by distributed piezoelectric actuators on a large-scale aeroelastic wind-tunnel model.

Benchmark Active Controls Technology Model

The successful design of an active control system for controlling aeroelastic response requires overcoming numerous technical challenges. These challenges include: the current inability to accurately model control surface effectiveness, especially for spoilers; control system robustness, reliability, and sensitivity to failures; and proven analysis packages for safely testing and evaluating these systems. The Benchmark Active Controls Technology (BACT) program has been able to make contributions to all of these areas. The objectives of the BACT program were to perform wind-tunnel experiments to obtain benchmark-quality data to validate CFD 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.

The BACT program employed a rigid semispan wind-tunnel model that could be tested on either a flexible or a rigid mount. The model is a rectangular wing with an NACA 0012 airfoil, a chord of 16 inches and a semispan of 32 inches. The model was built with a conventional trailing edge (TE) control surface and one upper- (US) and one lower-surface spoiler (LS). The model was extensively instrumented with pressure transducers and accelerometers to measure surface pressures and model dynamic responses. The BACT model was the last model of NASA Langley's Benchmark Models Program.[22-25]

Each control surface on the BACT model had a span of 30 percent of the model semispan and was centered about the 60 percent semispan station. These three control surfaces could be actuated independently of each other using miniature hydraulic actuators and were, therefore, suitable for use as active control surfaces. The TE control surface had a chord of 25 percent of the model chord; the spoilers each had a chord of 15 percent of the model chord, hinged at the 60 percent chord station. The actuators allowed static control surface displacements or dynamic con-

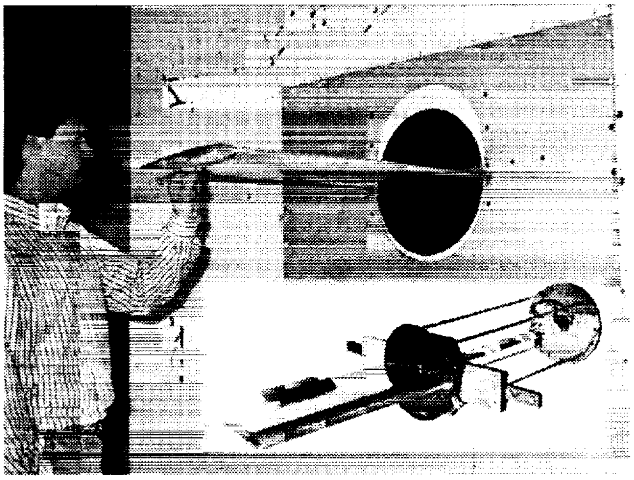


Fig. 18 BACT wind-tunnel model mounted in the TDT.

trol surface oscillations about a mean angle. The TE control surface deflection was mechanically limited to 15 degrees either up or down. Each spoiler could be deployed from its stowed position (zero degree deflection) to any angle up to 45 degrees.

During 1993, the BACT model was tested on both mount systems, flexible and rigid, and both mounts required the use of a large splitter plate. The flexible mount was the Langley Pitch and Plunge Apparatus, or PAPA,[26] a mechanism allowing model motion in those two degrees of freedom. Figure 18 shows the BACT model attached to the PAPA and shows the model and splitter plate mounted in the wind tunnel. The advantage of the PAPA mount is that the combination of rigid-wing-plus-flexible-mount results in an aeroelastic configuration that has a flutter speed. The PAPA mount was used to investigate instabilities, obtain frequency response functions, and evaluate control laws. The rigid mount consisted of a rigid strut attached to the tunnel sidewall turntable and a five degree-of-freedom balance. Results from tests on the rigid mount will not be addressed in this paper.

The active controls BACT wind-tunnel tests were performed in 1995 and 1996. Of the many accomplishments achieved within the BACT program, the following are the most significant contributions to the state of the art in active controls technology.

The BACT model offered the first opportunity to suppress flutter with a spoiler.[27] A single-input-single-output flutter-suppression control law was designed by classical techniques, implemented, and successfully tested. The control law was designed to maximize robustness over a range of dynamic pressures using a single, fixed dynamic compensator element and using fixed blending of signals from two accelerometers, one located inboard near the leading edge, the other located inboard near the trailing edge.

The BACT model offered the first successful experimental applications of multivariable robust control theory (H-∞ and μ-synthesis) to flutter suppression. Two-input-two-output flutter suppression control laws, one using H-∞ and one using μ-synthesis design methods[27] were designed, implemented, and successfully tested. These designs were obtained with weighting functions that put emphasis on keeping control activity limited to the frequencies near flutter

The BACT model offered the opportunity to use neural network based control systems to suppress flutter. Three neural network based control systems were developed and tested as part of the Adaptive Neural Control of Aeroelastic Response (ANCAR) program. ANCAR was a joint research and development effort conducted by the NASA LaRC and The Boeing Company (formerly the McDonnell Douglas Corporation) under a Space Act Agreement.

Phase I of the ANCAR program was the development and demonstration of a neural network gain scheduled flutter suppression system.[28] In this application a neural network was used to schedule control laws as a function of Mach number and dynamic pressure. The controller was tested along with a robust fixed-gain control law. The neural network scheduled system had better performance than the fixed gain controller.

Under Phase II of the ANCAR program, two adaptive neural network based control systems were developed and demonstrated. One of these systems was an implementation of model predictive control where the network was trained using experimental data to serve as the plant model.[29] The other system was an application of inverse modeling control where the network was trained using experimental data to model an inverse of the plant.[30] Both systems could adapt to plant changes by retraining the neural network using new plant input/output data. All three control systems tested under the ANCAR program successfully suppressed flutter to the limits of the testing apparatus, and represent the first experimental applications of neural networks to flutter suppression. Figure 19 shows conditions above and below the BACT open-loop flutter boundary where data was acquired for the inverse model control system.

Finally, the BACT model offered the opportunity to develop and demonstate neural network based adaptive control. This work is described in reference 31. Here, a model predictive control approach was taken and a linear plant model was employed in the wind-tunnel demonstration. This system suppressed flutter to the limits of the testing apparatus.

SST Active Controls Testbed

As part of NASAs High Speed Research (HSR) program, a 1970s Boeing-built SST model was refurbished and readied for testing on the TDT cable mount system. This model was a 1/20 scale, low-speed, full-span, dynamically-scaled model equipped with active

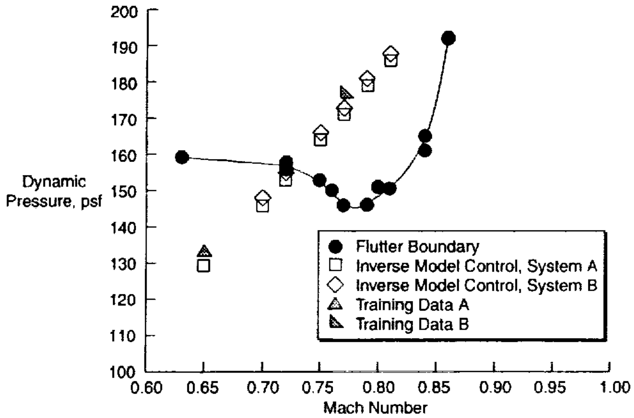


Fig. 19 BACT open-loop flutter boundary with conditions where closed-loop neural network control was implemented.

horizontal tails and active ailerons. It was selected as a testbed for developing control laws, test procedures, and analytical tools needed for an HSR wind-tunnel models program.

This model was tested in the TDT in early 1995. Two stability augmentation control laws were successfully tested closed-loop with the model on the cable mount system. These control laws featured inner and outer loops and demonstrated that additional damping could be added to the pitch and plunge flying modes and to the model first flexible mode (fuselage bending). Each of the inner loop laws, as well as the inner/outer combination, exhibited good stability robustness to errors at the plant input, errors at the plant output, and to additive plant error. Unfortunately, a third control law was unstable and caused the model to enter a cable-mount instability from which recovery was impossible. As a result, the model was damaged beyond repair. This model is shown mounted on the cables in the TDT test section in figure 20. The thick umbilical beneath the model contains instrumentation wires.

Actively Controlled Response of Buffet Affected Tails

Buffeting is an aeroelastic phenomenon which plagues high performance aircraft, especially those with twin vertical tails. For aircraft of this type at high angles of attack, vortices emanating from the wing/fuselage leading edge extensions burst, immersing the vertical tails in their wake. The resulting buffet loads cause large oscillatory stresses to be applied to the vertical tails with a consequent loss of fatigue life. There are two important parameters that determine the stress distribution of the tail in flight. The first is the angle of attack and the second is the dynamic pressure. If these stresses could be reduced by 10% the fatigue life associated with the twin vertical tails could be doubled.

A series of wind-tunnel tests were performed in the TDT beginning in 1995 and continuing into late 1999 using an existing 1/6-scale, sting-mounted F-18 model (figure 21). The first series of tests[32] were part of the ACROBAT (Actively Controlled Response of Buffet Affected Tails) project. The objectives of the ACROBAT project were twofold: first, to apply active controls technology using a variety of force producers to alleviate buffeting on twin vertical tails; and, second, to determine the spatial relationships of the differential pressures at various angle of attack conditions with the buffeting alleviation (BA) system off and on. Five new vertical tails were fabricated for these tests. Two of the tails were rigid surfaces for measuring pressures. The other three tails were flexible surfaces equipped with different control devices: a rudder surface; a tip vane configuration containing a slotted cylinder or an embedded slotted cylinder; and piezoelectric actuators. All three flexible tails were instrumented with a root strain gage aligned to measure bending moment and with two tip accelerometers located near the leading and trailing edges. The remainder of the model, namely the fuselage, the wings, and the leading edge extensions, was rigid.

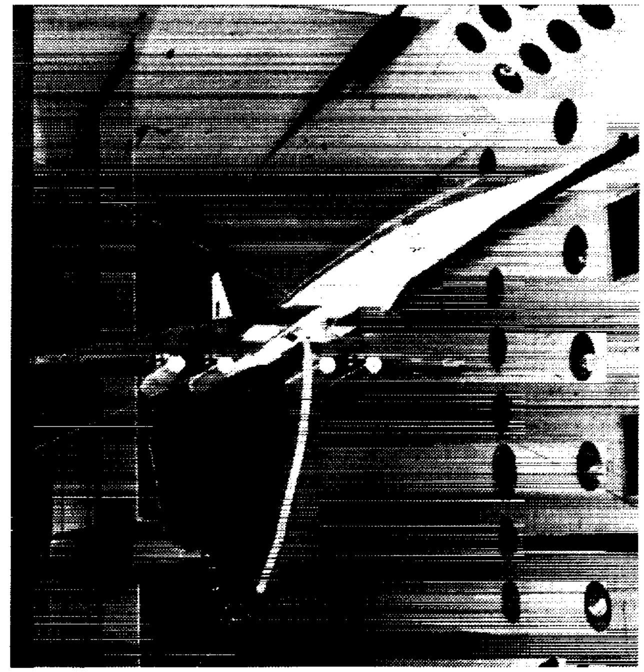


Fig. 20 SST model mounted in the TDT.

The ACROBAT wind-tunnel tests were performed with the model angle of attack varying from 20 to 37 degrees. Data were measured for several cases: open loop (no actuator commands); actuator commanded by a linear sweep; actuator commanded by constant frequency sinusoidal motion; and closed loop (control law on). It was determined that control systems using either the rudder or the piezoelectric actuators were best for suppressing the buffeting. One time-invariant, fixed-parameter, single-input/single-output (SISO) BA control law worked well to alleviate the buffeting for all flight conditions tested. This control law

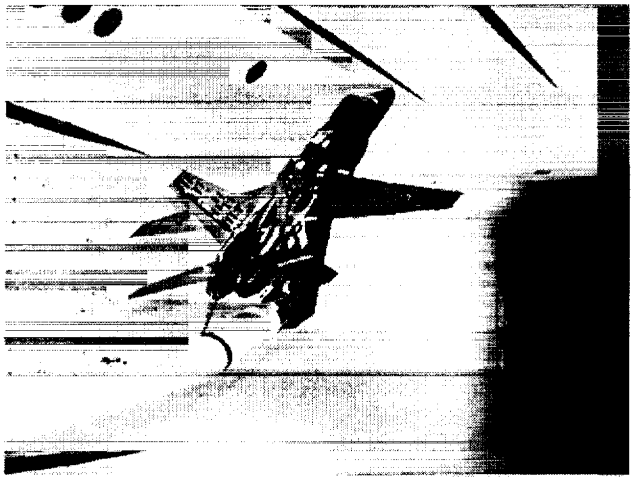


Fig. 21 ACROBAT wind-tunnel model mounted in the TDT.

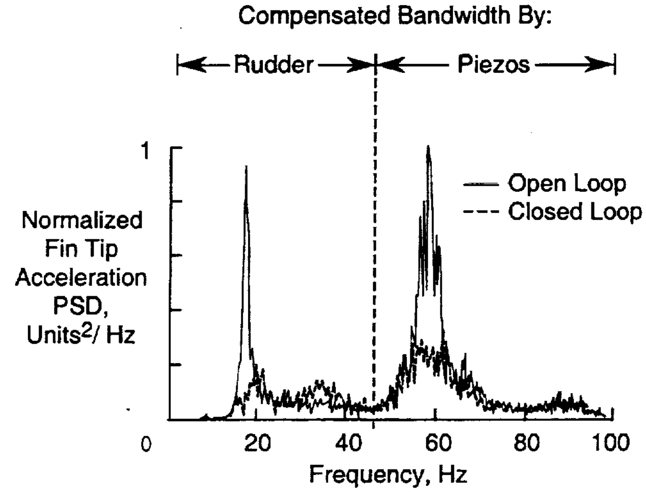


Fig. 22 ACROBAT tip accelerations, system on and off, Mach number = 0.10, dynamic pressure = 14 psf, angle of attack = 26 degrees.

was not optimized for any particular flight condition and it is thought that its performance would be improved considerably using an optimal controller or an adaptive controller. With this simple control law, the peak of the power spectral density function of the root bending moment at the frequency of the first bending mode was reduced by as much as 60% for certain angles of attack, using gains well below the physical limits of the actuator being investigated. At angles of attack up to about 30 degrees, both the rudder surface and the piezoelectric actuator control laws were nearly equally effective in alleviating buffeting. However at higher angles of attack, the rudder effectiveness was limited by degrading flow field conditions due to the separated flow around the tail while the piezoelectric actuators maintained their effectiveness regardless of flight condition.

During 1998, a second series of tests[33] were performed in the TDT using the F-18 model test bed. This project was referred to as SIDEKIC (Scaling Influences Derived from Experimentally-Known Impact of Controls). New vertical tails were fabricated for this project. These tails differed from those used previously in that continuous skin construction techniques were used and an effort was made to match the layout of the piezoelectric actuators used during a full-scale F-18 ground test at the Australian Aeronautical and Maritime Research Laboratory (AMRL).[34] In addition, the type of amplifiers used in the BA system were different. For this test, one fin employed both an active rudder for controlling responses in the first bending mode, around 16 Hz, and active piezoelectric actuators for controlling the responses in the first torsion mode, around 50 Hz. This configuration of control effectors was referred to as a blended system because two actuator technologies were combined to provide a compromise between the use of an existing control surface and a reduced number piezoelectric actuators.

A variety of control schemes were investigated during the SIDEKIC tests. Boeing, who participated in the wind-tunnel tests through a NASA Space Act Agreement, designed and tested shunt circuits and neural predictive controllers (NPC). Also. a variety of modern state-space controllers for the blended system were designed by LaRC and tested. With the blended BA system operating, the tip accelerations and root bending moments (root mean square values) could be reduced by 25 percent. At 26 degrees angle of attack and at a Mach number of 0.1, the rudder reduced buffeting in the first bending mode, around 16 Hz, while the piezoelectric actuators reduced buffeting in the first torsion mode, around 58 Hz (figure 22). Similar results were obtained for the all-piezoelectric system on the port tail. An assessment of the NPC controllers indicated that this concept performed very similar to the MIMO controller systems, but the "piezoelectric shunting" concept provided negligible reductions in the buffeting of the vertical tails.

Concluding Remarks

Over its forty-year history, more than 500 tests have been conducted in the Transonic Dynamics Tunnel (TDT) and, of these, about 35 have involved the active control of aeroelastic response. Flutter-suppression, load-alleviation (maneuver, gust, and buffeting), and stability-augmentation active control systems have been successfully demonstrated in the TDT. The TDT has contributed to the state of the art in a number of significant ways, including the following list of firsts: first wind-tunnel demonstration of flutter suppression on a large scale model; first wind-tunnel demonstration of buffeting alleviation on a large scale model; first use of piezoelectric devices for flutter suppression on a large scale model; first wind-tunnel demonstration of MIL SPEC rolling maneuvers above the flutter boundary; first use of spoilers for flutter suppression; and first use of neural networks for flutter suppression.

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