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Contributions of Transonic Dynamics Tunnel Testing to Airplane Flutter Clearance

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CONTRIBUTIONS OF TRANSONIC DYNAMICS TUNNEL TESTING TO AIRPLANE FLUTTER CLEARANCE

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ABSTRACT

The Transonic Dynamics Tunnel (TDT) became operational in 1960, and since that time has achieved the status of the world's premier wind tunnel for testing large aeroelastically scaled models at transonic speeds. The facility has many features that contribute to its uniqueness for aeroelastic testing. This paper will briefly describe these capabilities and features, and their relevance to aeroelastic testing. Contributions to specific airplane configurations and highlights from the flutter tests performed in the TDT aimed at investigating the aeroelastic characteristics of these configurations are presented.

INTRODUCTION

The Langley Transonic Dynamics Tunnel (TDT) is the world's premier wind tunnel for testing large, aeroelastically-scaled models at transonic speeds. The TDT became operational in 1960, and has provided this capability for 40 years. During this time a variety of aeroelastic investigations have been conducted ranging from flutter clearance tests to fundamental research on aeroelastic phenomena. Specific areas of work performed in the TDT have been reviewed in several prior publications.[1-10]

The purpose of this paper is to present a chronological summary of airplane aeroelastic investigations conducted in the TDT with emphasis on flutter clearance testing since the inception of the tunnel in 1960. The paper addresses contributions to specific airplane configurations and highlights the flutter tests performed in the TDT aimed at investigating the aeroelastic characteristics of these configurations that have contributed to their respective flutter clearance programs. These tests include:

1. Flutter clearance or risk reduction tests aimed at uncovering potential flutter problems and identifying potential solutions of a specific design through airplane configuration studies and tests of various components.
2. Risk reduction tests performed to obtain data through parametric variations of the airplane configuration of interest in order to use these data to guide flight tests.
3. Problem resolution tests conducted to solve or gain insight into aeroelastic problems of a particular configuration.
4. Code evaluation and code calibration tests performed as an adjunct to flutter clearance tests to obtain data for use in developing and calibrating computer codes for predicting flutter characteristics related to the airplane configuration of interest.

The airplane configurations included in this paper were chosen as a result of reviewing photographs of models tested in the TDT, reviewing the list of tests performed in the TDT, and reviewing Aeroelasticity Branch documents (internal highlights, memos and letters). Only airplanes that were flutter tested in the

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TDT, built and flown (with one exception, the A-12 configuration) are included.

The paper begins with a brief introduction to the TDT, followed by a description of the facility, its capabilities and features pertinent to flutter clearance testing. This is followed by a discussion of the airplane configurations that were flutter tested in the TDT during each decade from the 60's through the 90's. The discussion of each airplane configuration includes highlights of the tests performed in the TDT, contributions to the respective airplane flutter clearance programs and a photograph of the model. All tests were performed in heavy gas (R-12) unless otherwise noted, and all tests were conducted prior to the heavy gas conversion from R-12 to R134a in 1996.

The TDT tests did not, on their own, flutter clear these airplanes. The wind tunnel models were dynamically and aeroelastically scaled to a "theoretical" airplane configuration. However, the dynamic, aeroelastic, and other scaling laws were not specifically satisfied for each planned "as built" and "flying" airplane, hence the word "configuration" is added (or assumed added) in this paper to each airplane mentioned. Based on this "connection" between the models tested and the airplane, the results from these tests are considered experimental research that contributed to the flutter clearance of these airplane configurations.

THE TRANSONIC DYNAMICS TUNNEL

The lack of suitable facilities in the mid-1950s to study dynamic and aeroelastic problems associated with high-speed aircraft prompted NACA to convert an existing facility, the 19-ft pressure tunnel, into a facility dedicated almost exclusively to identifying, understanding, and solving these problems. The Transonic Dynamics Tunnel (TDT) became operational in 1960, and since that time has achieved the status of the world's premier wind tunnel for testing large aeroelastically scaled models at transonic speeds.

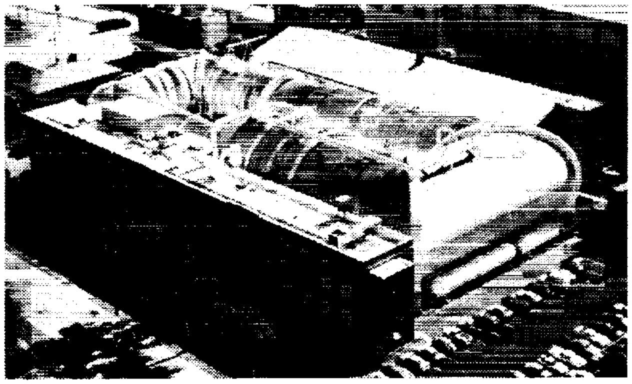

Figure 1. Aerial photograph of the TDT.

Description, Capabilities, and Features

The TDT is a large, fan-driven, continuous-flow wind tunnel capable of reaching Mach 1.2 in air or heavy gas (R-12 from 1960 to 1996, currently R134a).[11] Figure 1 shows an aerial view of the TDT. The tunnel has a variable pressure capability from near vacuum to about one atmosphere. Varying fan RPM and tunnel pressure allows gradual, and progressive increases in Mach number and dynamic pressure as the test model characteristics are carefully explored. Figures 2 and 3 show a plan view of the TDT and a cross-sectional view of the test section area. The large (16-by-16 ft) test section and the high density (compared to air) available by using heavy gas as the test medium provides great advantages in scaling and manufacture of aeroelastic models for flutter clearance. Another feature of the TDT is that the control room (from which the tunnel is operated and the wind-tunnel test is directed) is adjacent to the test section and has a large matrix of observation windows. These windows allow direct and constant visual observation and monitoring of the wind-tunnel model which is essential due to the dynamic nature of flutter clearance and aeroelastic testing. Also, collocation of the tunnel operators and the test engineers within the control room allows immediate, clear, and concise communication when model instabilities occur. Another TDT feature is the 2-cable mount system for testing full-span models in the TDT. The cable mount allows model rigid-body degrees-of-freedom to interact with model flexible modes. It is customary to first "fly" an essentially rigid or "dummy" model on the cable mount system to demonstrate the stability of the model configuration on the 2-cable mount system prior to testing the flexible flutter model of an airplane configuration. In addition to the cable mount, the typical sting, sidewall, and floor mount systems are available. Another feature of the TDT is a set of the quick-actuating by-pass valves in the tunnel circuit which, when opened, cause a rapid reduction in the test section Mach number and dynamic pressure. These by-pass valves are available for use when model instabilities such as flutter or other events occur that can damage a model. In addition to potentially saving a model from destruction, the rapid reduction in tunnel conditions reduces the driving force behind model debris heading towards the TDT drive motor fan blades. An additional feature of the TDT that contributes to the suitability for aeroelastic and flutter clearance testing is the model debris catch screen located at the wind-tunnel turning vanes just upstream of the fan blades. This catch screen has protected the TDT fan blades from model debris in the past and is considered a very valuable facility feature. These features have made the TDT a versatile and useful facility for airplane flutter clearance tests.

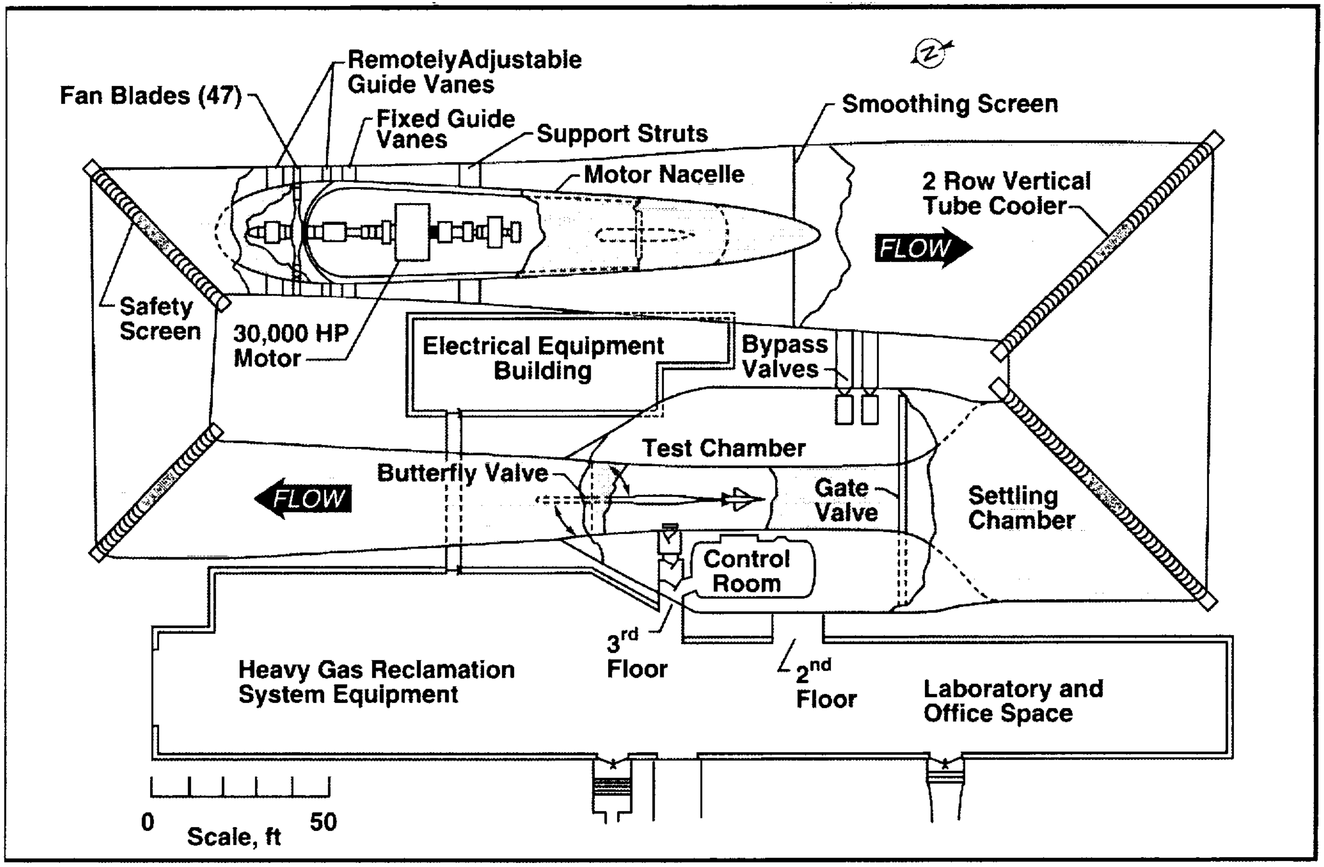

Figure 2. Plan view of TDT facility.

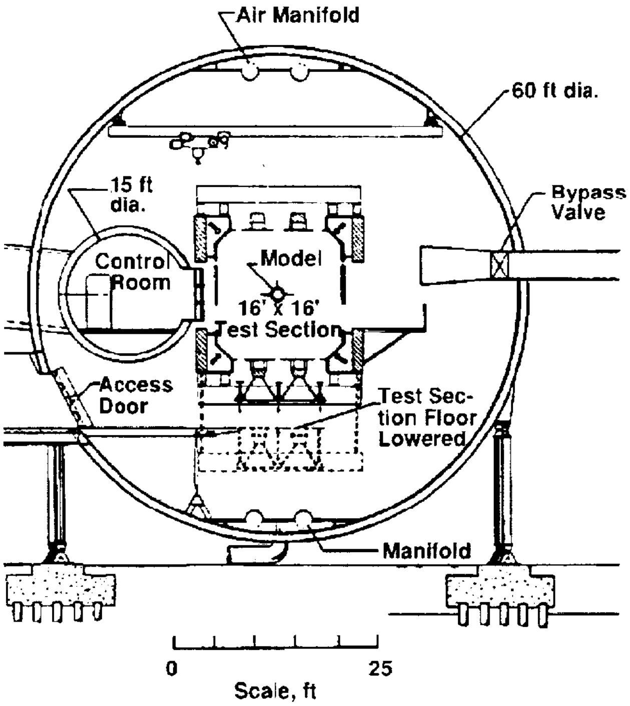

Figure 3. Cutaway view of test section area of TDT.

THE 60'S AIRPLANES

Between 1960 and 1970 flutter clearance testing was initiated for eight airplane configurations. These were the Lockheed Electra, B-58, C-141, F-111, C-5, Boeing 747, Lockheed L-1011, and DC-10. Tests were also conducted in the early 70's for some of these airplanes. In all, 51 tests in the TDT were focused on these airplane configurations.

Lockheed Electra configuration

The Lockheed Electra configuration (shown in figure 4) and engine nacelle were tested nine times for approximately 15 weeks between May 1960 and December 1961. The tests were aimed at investigating the reason for full-scale accidents[12], and conducting propeller whirl flutter research. The wind tunnel tests showed that reduced stiffness engine supports would cause the Electra to experience propeller-whirl flutter. The engine mount systems were redesigned to provide "fail-safe" redundancies such that the failure of any one component in the mount system would not cause flutter.[10]

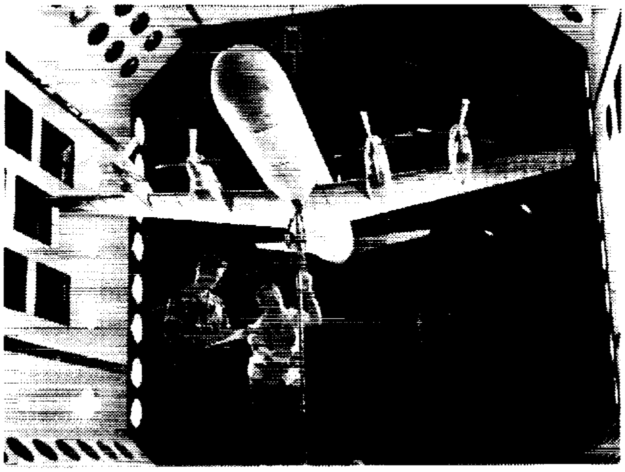

Figure 4. 1/8-scale Lockheed Electra model in TDT.

B-58 configuration

In November of 1961 a B-58 flutter model configuration spent about a week in the TDT before it was destroyed during the initial portion of wind-on testing. The photograph of the model in the calibration lab (figure 5) shows the model being prepared for testing.

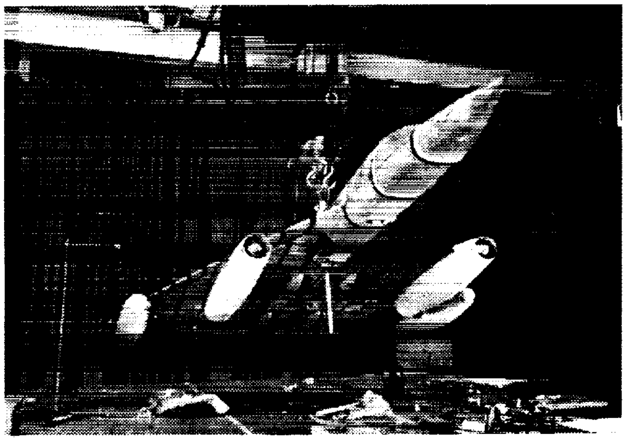

Figure 5. B-58 model in calibration lab.

C-141 configuration

Models of the C-141 airplane configuration[13, 14, 15] and its T-tail empennage configuration were tested in the TDT for a total of approximately 23 weeks between December 1961 and August 1966. The model tests showed no flutter problems with the required flutter safety margin operating boundaries. However, an early test did reveal a separated flow problem at the juncture of the horizontal and vertical tails. As a result, a new fairing was designed to alleviate the problem. Figures 6 and 7 show the C-141 model configuration and the C-141 empennage model tested.

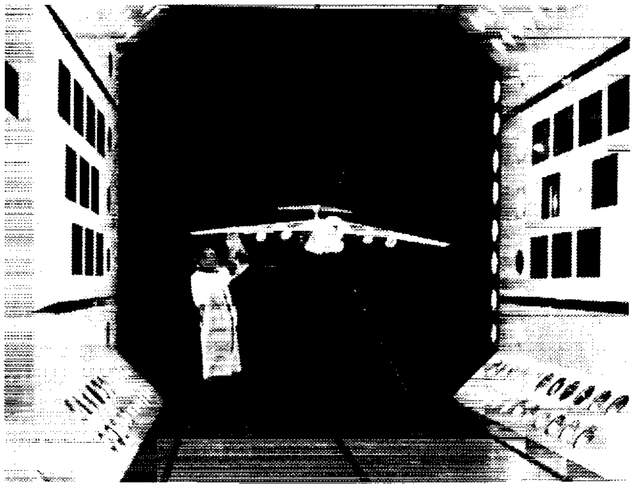

Figure 6. Full-span C-141 model in TDT test section.

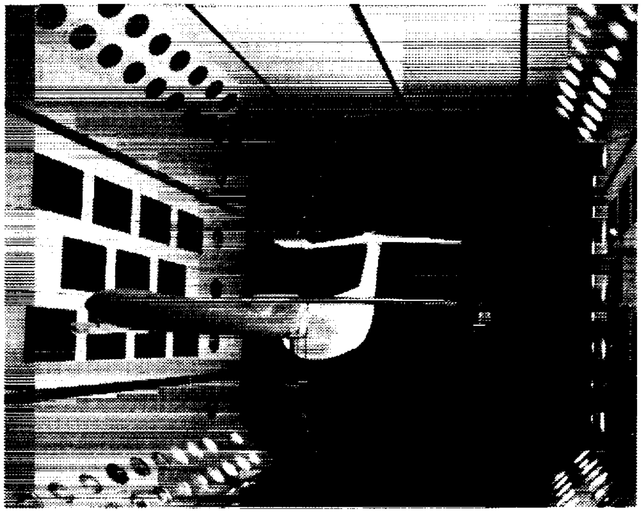

Figure 7. C-141 empennage model.

F-111 configuration

Wind-tunnel models of an F-111 configuration were tested in the TDT 15 times from mid-1963 to late-1971, with each test lasting from two to four weeks. A 1/8-scale flutter model was used to demonstrate that the F-111 had a 15 percent flutter margin of safety up to the maximum speed limits of the airplane with stores or the Mach-altitude limits of the wind tunnel and to establish the flutter boundary relative to the airplane flight boundary for use in analysis correlation.[16,17,18]

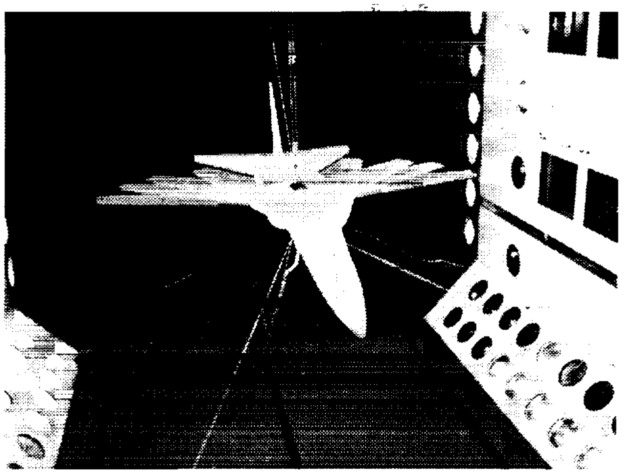
Figure 8. 1/8 scale rigid F-111 model on the 2-cable mount system.

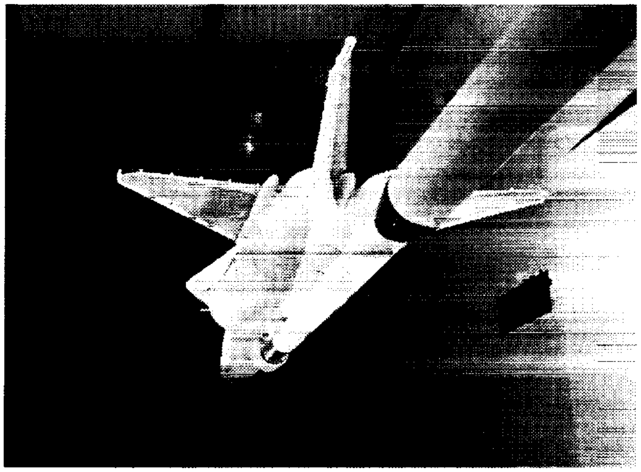
Figure 9. F-111 model with flexible empennage mounted on sting.

Figures 8 and 9 illustrate the first tests of a rigid model conducted to determine model stability on the TDT cable-mount system and to conduct flutter clearance tests of the empennage with the model mounted on a sting. The wings and fuselage of the flexible model were of a conventional spar-pod construction, with the scaled vertical, lateral, and torsional stiffness simulated using a thin-walled steel spar and lightweight fiberglass sections providing the aerodynamic shape.[16, 17, 18] Flexible wings were added for the next set of tests to flutter clear those components with the model mounted on a sting and the cable-mount system (Figure 10). The effects of various store configurations were then tested to further clear the model (Figure 11). Later tests were conducted to measure the effects of buffet loads on the empennage and determine the effects of a proposed change from a conventional to a supercritical wing on flutter of the vehicle.

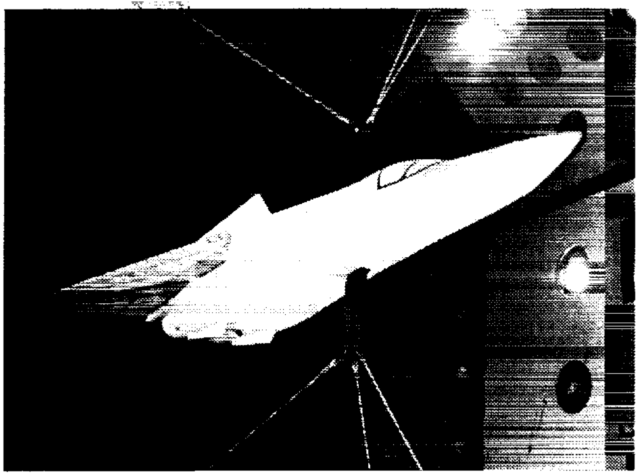
Figure 10. F-111 model with flexible wings and empennage.

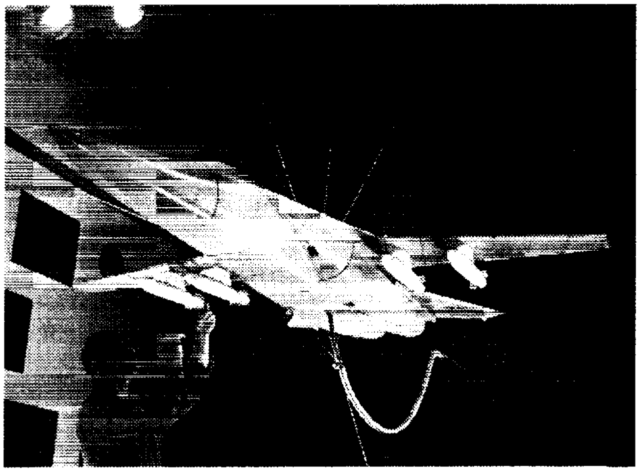
Figure 11. F-111 model with stores.

Results from the wind tunnel tests reduced the risk and cost of the flight test program. Most store configurations showed no sign of flutter occurring within the flight envelope, and store configurations where flutter could be an issue were identified for the flight test program.

C-5 configuration

Models of the C-5 transport configuration[19], and its T-tail empennage were tested on six different occasions totaling about 30 weeks between August 1966 and November of 1973. These tests included a 1/22-scale, cable-mounted, full-span flutter model (figure 12), and a cable-mounted, six degree-of-freedom, 1/13-scale empennage flutter model having a fuselage with stub wings (figure 13).

Figure 12. C-5 full-span configuration.

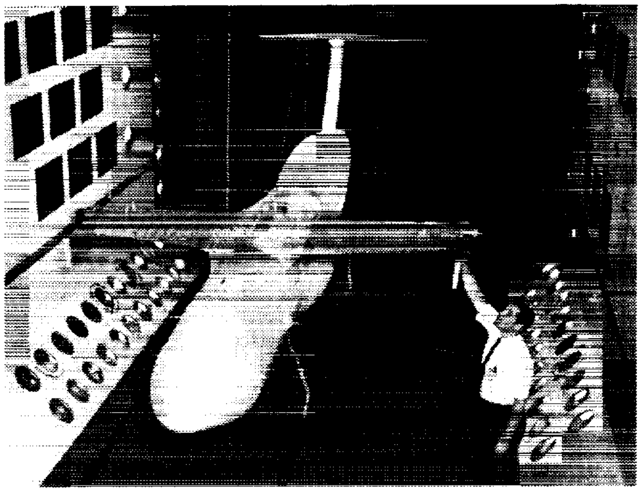

Figure 13. 1/13-scale C-5 empennage flutter model.

Tests showed that a potential vertical-tail flutter problem existed with the configuration. The vertical tail subsequently was stiffened to eliminate the problem. Tests in 1973 were devoted to demonstrating the Active Load Distribution Control System (one of the first practical applications of active controls) and demonstrating that the system did not degrade the flutter characteristics of the aircraft.

Boeing 747 configuration

A wind-tunnel model of a Boeing 747 configuration was tested twice in the TDT during 1967 - 1968. The first test was three weeks long and the second test took five weeks. The purpose of the tests was to determine the effects of the large cowls surrounding the engine fans on the flutter characteristics of the aircraft.

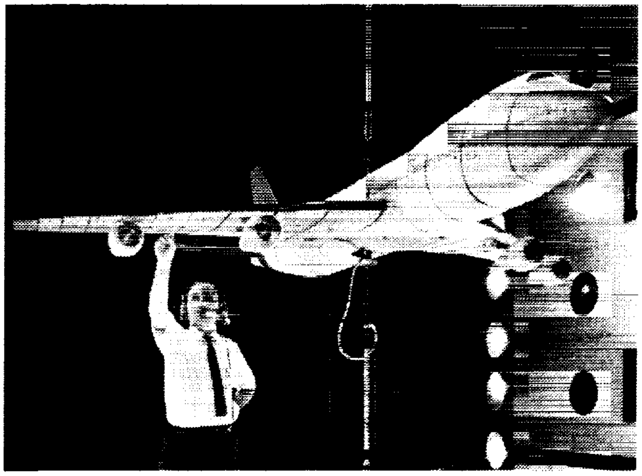

Figure 14. Boeing 747 model mounted in the TDT.

The 4.6-percent scale, full-span model was aeroelastically scaled such that the reduced frequency and mass ratio of the theoretical airplane configuration at a critical altitude were simulated when the model flew at subsonic velocities in air at sea level. The low-speed model was of conventional, single-spar construction for the fuselage and wings with the wing aerodynamic sections perpendicular to the flow. The parameters varied for the tests were 1) nacelle aerodynamics, 2) engine-pylon stiffness, 3) mount-system, and, 4) mass ratio. The nacelle aerodynamic effects on the flutter characteristics were determined by replacing the nominal engine nacelles with "pencil nacelles" that simulated the inertia and center-of-gravity characteristics of the engine nacelles. Two mount systems were used: the vertical-rod-mount system and the two-cable-mount system.[20] Figure 14 shows the model mounted in the TDT test section using the vertical-rod-mount system

Results from the low-speed investigations indicated that the nacelle aerodynamic forces for the simulated high-bypass-ratio fan-jet engines reduced the flutter-speed index about 20 percent. The flutter characteristics were greatly dependent on the outboard-engine lateral frequency. The flutter-speed index varied significantly for mass ratios below a certain value.[20] Finally, the effects on flutter-speed index due to the mount systems were small and were attributed to the differences in fuselage mass distributions for each mount system.

Lockheed L-1011 configuration

A rigid "dummy" model and an aeroelastic model of the Lockheed L-1011 were tested in the TDT in 1969.

Four tests were dedicated to the configuration. Figure 15 is a photo of the stability model on the TDT cable-mount system.

The purpose of the tests was to determine the effects of a supercritical airfoil shape on the flutter characteristics of the aircraft. The actual vehicle did not employ a supercritical airfoil, however the Lockheed Company was interested in researching the effects of such an airfoil. A photo of the aeroelastic model is shown in figure 16.

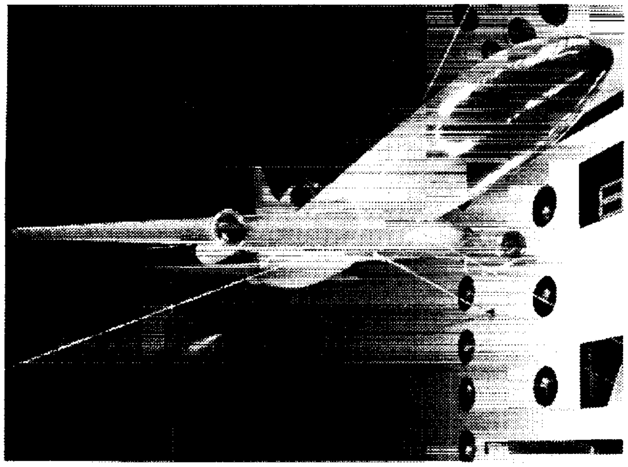
Figure 15. L-1011 Rigid "dummy" model on the TDT cable-mount system.

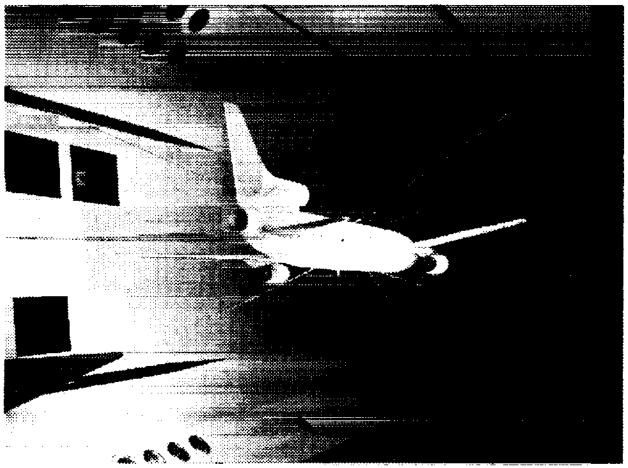
Figure 16. Aeroelastically-scaled model of the L-1011 configuration in the TDT.

DC-10 configuration

The split rudder configuration of the DC-10 vertical tail was tested in the TDT twice, once in late-1969 and again in mid-1970. These tests were to determine the effects of a split rudder versus a single large, solid rudder on the vertical tail flutter characteristics. The empennage and aft body model of the DC-10 airplane configuration showing the aeroelastically-scaled vertical tail with split rudder is shown in figure 17. Figure 18 is a closer view of the vertical tail of the model. Transonic wind-tunnel tests showed that the split rudder had a beneficial effect on flutter by reducing the required stiffness to prevent flutter of a similar-sized solid rudder.

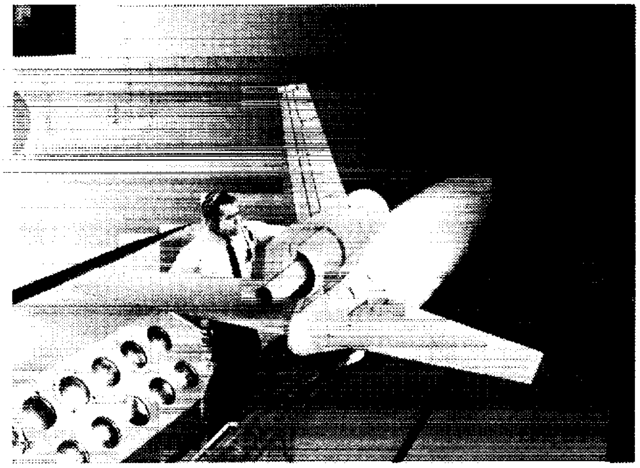
Figure 17. Sting mounted DC-10 empennage and body model.


Figure 18. Aeroelastically scaled vertical tail with split rudder.

THE 70's AIRPLANES

Between 1970 and 1980 flutter clearance testing was initiated for 7 airplane configurations. These were the F-14, S-3A, F-15, B-1, F-16, Gulfstream III, and Boeing 767. Tests were also conducted in the early 80's for some of these airplanes. In all, 56 tests in the TDT were focused on these configurations.

F-14 configuration

Between January 1970 and June 1975 the F-14 fighter configuration (figure 19) was tested 10 times (for a total of 14 weeks) in the TDT for flutter and buffet loads at high angles of attack.

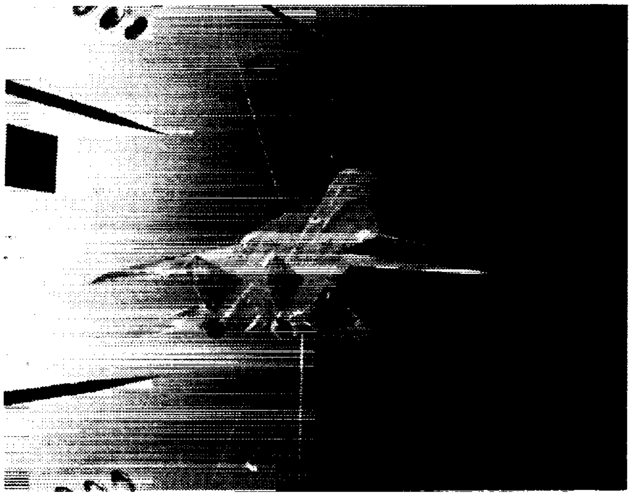

Figure 19. F-14 model tested in TDT.

During the tests it was discovered that the flow over the "over-wing" fairings caused the fairings to deform and oscillate. These fairings were essentially cantilevered from a point near the swing-wing hinge. Several potential fixes were evaluated and an acceptable solution demonstrated. Also, at high angles of attack the model indicated significant buffet loads on the vertical tails, giving forewarning to vertical tail vibrations that were later experienced in flight.

S-3A configuration

From September 1970 to July 1971 approximately 12 weeks and four tests were devoted to flutter studies of the S-3A anti-submarine warfare aircraft configuration in the TDT (figure 20). During these tests a problem with aileron buzz was encountered. An increase in control actuator stiffness solved the problem.

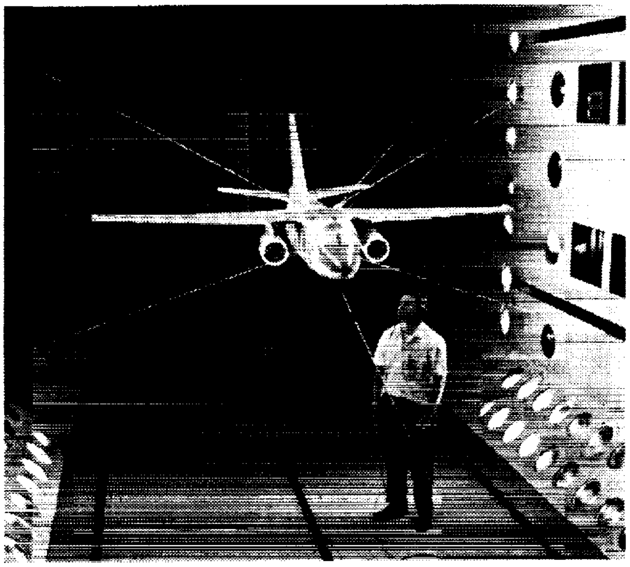

Figure 20. Cable mounted S-3A model in TDT.

F-15 configuration

Wind-tunnel models of the F-15 were tested in the TDT four times in 1971, with each test lasting from one to four weeks. A full-span, 13-percent dynamically and aeroelastically scaled model of the F-15 was used to determine the flutter boundaries for various model components.

Figure 21 shows the first test of a rigid model conducted to determine stability on the TDT cable-mount system and to aid in the future flutter clearance tests of the aeroelastically-scaled full-span model. However, no records of flutter clearance tests for the full-span, aeroelastically-scaled model on the cable mount system were found. The model was mounted on the sting for flutter clearance tests of the empennage and wings. Figure 22 is a photo of the model mounted on the sting with horizontal and vertical tails only.

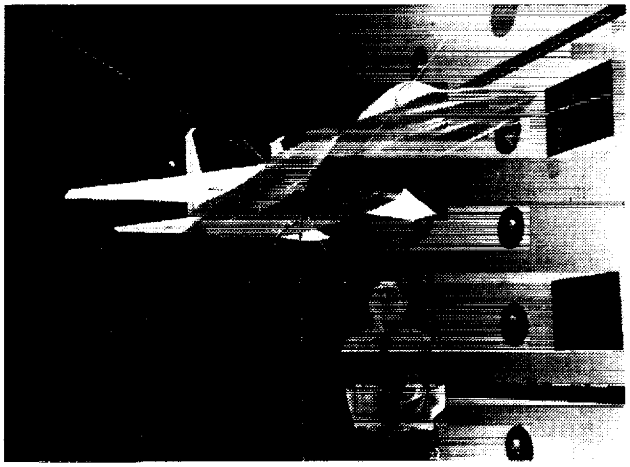

Figure 21. Rigid stability model of F-15 on cable mount system.

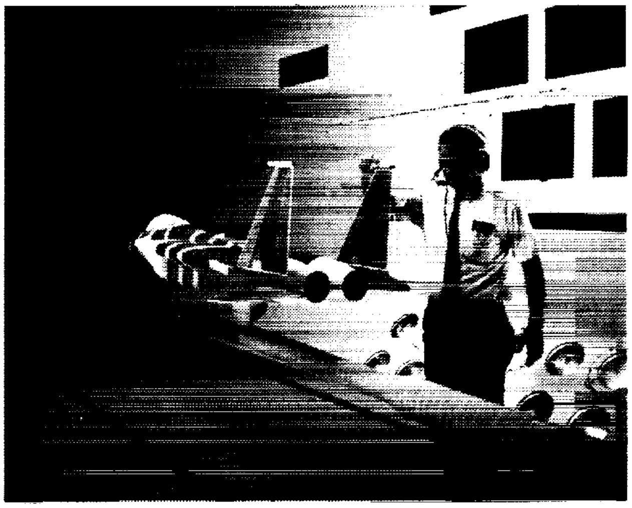

Figure 22. Aeroelastically scaled F-15 empennage model on sting.

Results from the empennage flutter studies showed that flutter was encountered for the basic horizontal stabilator and vertical tail design within the required flutter margin. The flutter boundary involving the horizontal stabilator is shown in figure 23. Modifications to the empennage were examined experimentally to increase the flutter speed of these components. The flutter speed was raised above the required flutter margin by stiffening the stabilator actuator and adding mass to the stabilator and vertical tails. In addition to flutter clearance work on the empennage, flutter clearance studies were conducted to that ensure the aircraft wings did not flutter within the required flutter margin (figure 24).

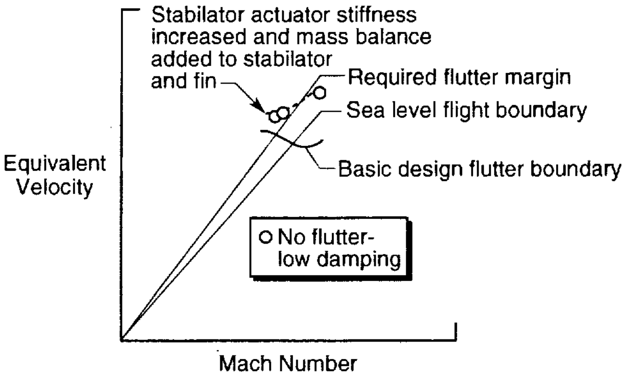

Figure 23. Effect of modifications to F-15 empennage.

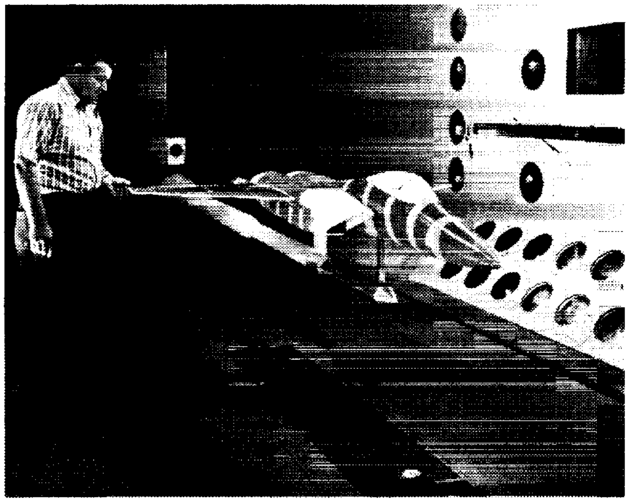

Figure 24. F-15 wing and fuselage model in TDT.

B-1 configuration

From August 1972 to April 1976, approximately 18 weeks of test time were devoted to testing the B-1 configuration in the TDT. No flutter problems were encountered during these. As an adjunct to these tests, the model (figure 25) was tested until flutter was obtained (outside the scaled flight envelope) to evaluate analytical procedures being used.

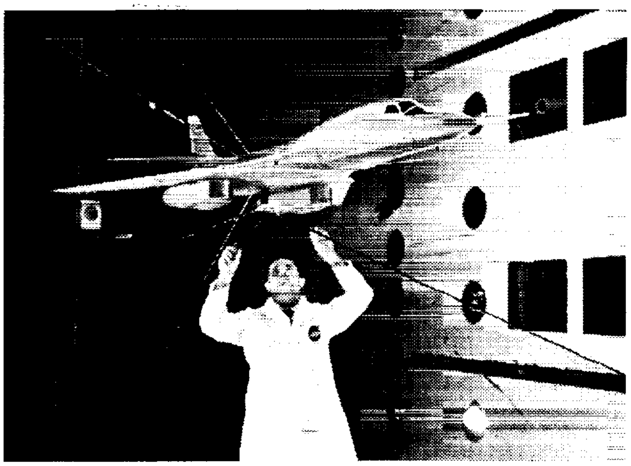

Figure 25. Cable mounted B-1 configuration in TDT.

Additional tests in the TDT were conducted between September 1978 and April 1983 to investigate limited amplitude wing oscillations encountered in flight, at high altitude, under maneuver load conditions. In these tests, attempts were made to simulate the load factor and flight conditions for which the B-1 encountered the wing oscillations. The oscillations occurred near critical Mach number conditions for the airfoil and only at high positive angles of attack. The instability was demonstrated in the tunnel, although at slightly different conditions than in flight.

F-16 configuration

From January 1973 to September 1987, 24 flutter tests were devoted to the F-16 fighter configuration. During these tests a full-span, one-quarter-scale F-16 flutter model (figure 26) was used on both sting and cable mount systems to identify potential flutter problems and to guide flight tests. The TDT data was also used in concert with analytical methods to develop and evaluate solutions to the flutter problems that were identified as reported by Foughner and Bensinger.[21]

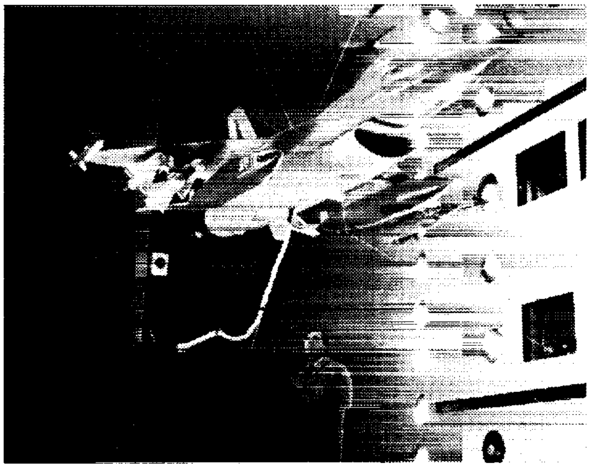

Figure 26. F-16 fighter configuration in TDT.

Gulfstream III configuration

A scaled flutter model representative of a Gulfstream III configuration with a proposed supercritical wing was tested twice in the TDT in 1978. The 1/6.5-scale semispan model was sidewall mounted and was used to investigate three wing configurations: (1) with a normal wingtip, (2) with a wingtip with a winglet, and (3) with a normal wingtip ballasted to simulate the winglet mass properties.

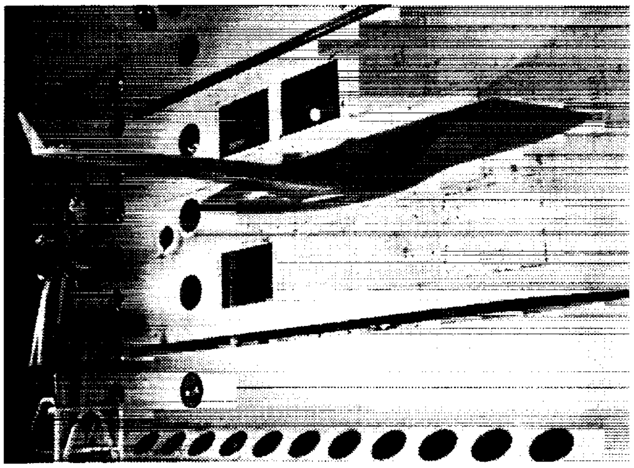

Figure 27. Gulfstream III model mounted in TDT.

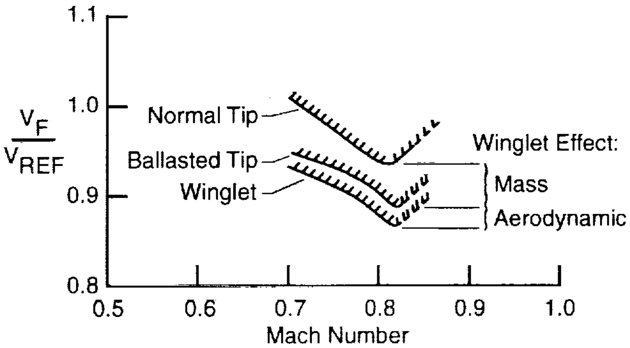

Figure 28. Effect on measured flutter boundary.

Figure 27 is a photo of the model mounted in the TDT test section. The objectives of the tests were to, 1) determine winglet effects on the flutter characteristics of a realistic supercritical wing, 2) compare these measured results with analyses, 3) investigate possible angle-of-attack induced flutter issues, and 4) examine the effects of aeroelastic deformations on the aerodynamic characteristics of the supercritical wing. Transonic flutter boundaries were measured for each wingtip configuration for a Mach number range of 0.6 to 0.95. Results from the TDT tests showed 1) the wingtip configuration did not effect the typical boundary shape, with the minimum flutter speed occurring near M = 0.82, 2) the winglet effect on flutter was more a mass effect than an aerodynamic effect, 3) doublet-lattice unsteady aerodynamic analyses correctly predicted the flutter boundaries up to M = 0.82. Figure 28 is a plot illustrating the effects of the wing tip configurations on the measured flutter boundaries.[22]

Boeing 767 configuration

Two Boeing-built, 1/10-scale semispan flutter models of a twin-engine transport type wing representative of the Boeing 767 configuration were tested in the TDT in August 1979; a low-speed model, and a high-speed model.

The objectives of the low-speed model test were to investigate mass-density ratio effects at low-speeds and to show that mass-density ratio effects for a winglet-configured wing could be predicted at low Mach numbers. Two configurations were tested: (1) the wing with nominal nacelle, and (2) the wing with nominal nacelle and winglet. The low-speed model was of conventional, single-spar construction with wing sections perpendicular to the spar.

Figure 29. Photo of Boeing 767 configuration model in TDT.

The high-speed model, shown in figure 29, was constructed using fiberglass sandwich components with ribs, spars, stringers, and skin simulating a modern transport wing. The high-speed model was tested in heavy gas (R-12) over a Mach number range of 0.6 to 0.91 and dynamic pressures up to 200 psf. Three configurations were tested: (1) wing with nacelle and nominal tip, (2) wing with nacelle and ballasted tip, and (3) wing with nacelle and winglet. The main objectives for the high-speed wing tests were to determine the effects of Mach number on flutter characteristics, determine experimentally the effects of winglets on flutter for various configuration parameters, and correlate these results with analysis.[23]

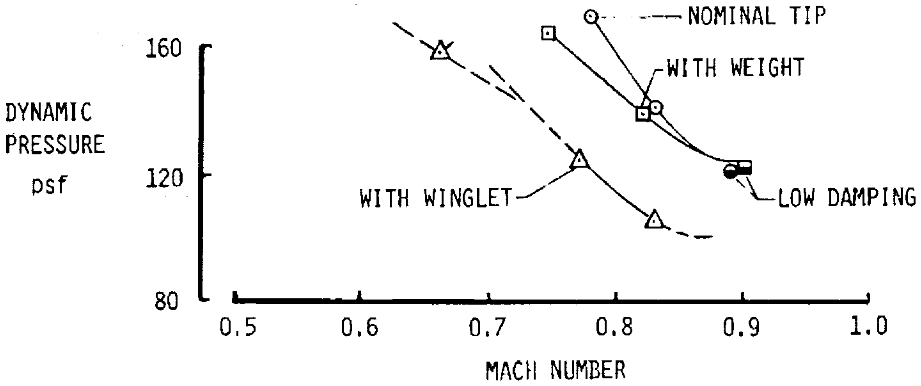

Figure 30. Effects of winglets on large twin engine transport type wing.

Results from the low-speed model flutter tests showed reasonably good correlation with analysis, although the change in the flutter mode occurred at a higher mass-density ratio in the test. Transonic flutter boundaries were measured with the high-speed model in each of the three wing tip configurations and the following parameters varied: empty fuel, full fuel, and empty fuel with softened engine nacelle mounts. Figure 30 is an example of the test results showing the winglet effects on the flutter dynamic pressure for the empty fuel configuration. The winglet aerodynamic effect was much greater than its mass effect and lowered the wing flutter dynamic pressure as much as 20 percent at the minimum flutter dynamic pressure. These wind-tunnel tests provided an excellent basis for the evaluation of analytical methods for the configuration with or without winglets.[23]

THE 80's AIRPLANES

Between 1980 and 1990 flutter clearance testing was initiated for six airplane configurations. These were the X-29, F-16E, C-17, JAS-39, A-6 (advanced composite replacement wing), and A-12. For some of these, tests were also conducted in the early 90's. In all, 17 tests in the TDT were focused on these airplane configurations.

X-29 configuration

Several concepts of an X-29A configuration were tested in the TDT in 1979 and in 1983. In late 1979, models of two concepts of an aeroelastically-tailored, forward swept wing airplane configuration, one from Grumman Aerospace Corporation and one from Rockwell International Corporation, were tested for two weeks each.

The Grumman concept model was a half-scale, semispan forward swept wing and fuselage fabricated from advanced composite materials to simulate the design of a full-scale demonstrator airplane having a supercritical wing section.[24] Figure 31 is a photo of the Grumman model installed in the TDT test section.

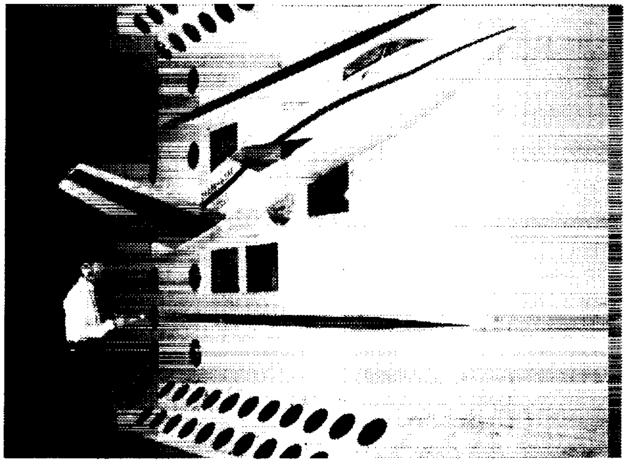

Figure 31. Semispan model of the Grumman X-29A concept in the TDT.

The Rockwell concept models were dynamically scaled 0.6-size wing models with a splitter plate. Three 0.6-size models were tested in the TDT to determine divergence and flutter characteristics.[25]

The primary objectives of the wind-tunnel tests for both concepts were to determine the divergence speed and evaluate the accuracy of the analytical tools for predicting divergence. The Grumman model test results showed a reasonably good overall correlation of divergence speed with predicted values, although the linear aerodynamic theory used was unusually conservative for both subsonic and supersonic Mach numbers. Some light buffet was encountered at transonic speeds, and extreme variations in the wing loads were measured due to minor angle of attack changes near the divergence boundary.[24]

The divergence boundaries of the Rockwell models were measured over a Mach number range of 0.6 to 1.15. Results from the tests verified the suitability of then current analytical methods available for forward swept wing applications, although nonlinear aerodynamic effects produced a small dependence of the divergence speed on wing load levels in the test wing. Figure 32 illustrates the effect of wing load level on the predicted divergence point. This behavior was due to a nonlinearity in the measured wing bending moment versus angle-of-attack observed in the test data.[25]

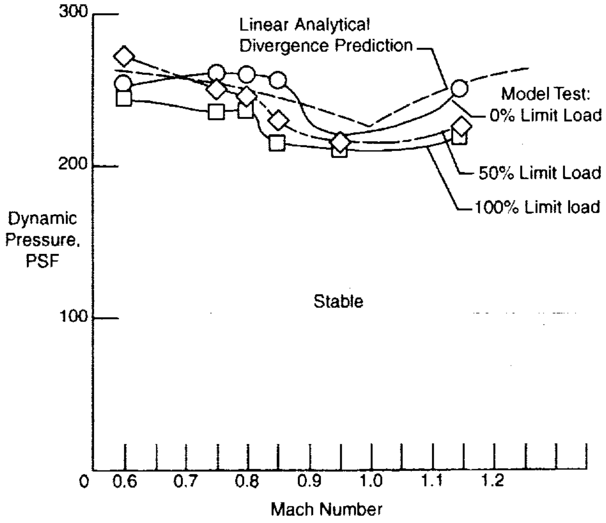

Figure 32. Rockwell concept model divergence results.

In 1983, the Grumman model was tested on a new mount system designed to provide rigid-body degrees of freedom (figure 33) to allow for the study of body-freedom flutter. Body-freedom flutter is a phenomenon which often occurrs on forward swept wing aircraft and is caused by the adverse coupling of rigid-body pitching and wing bending motions. Figure 34 shows the measured and calculated aeroelastic stability results in terms of Mach number and dynamic pressure. The calculated values predicting body-freedom flutter are unconservative when compared to the measured data. Additionally, a subcritical response technique used to predict the dynamic pressure at which static divergence would have occurred based on data acquired below the flutter boundary produced a result 40 percent above the measured flutter boundary.[26]

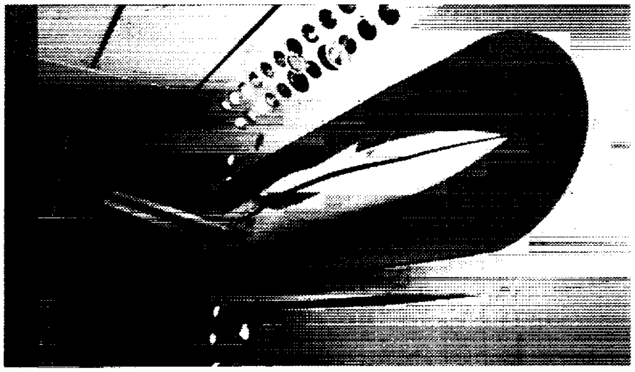

Figure 33. Grumman X-29A concept on sidewall rigid-body D.O.F. mount.

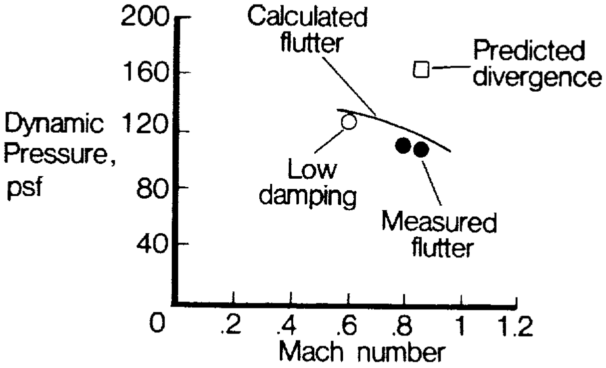

Figure 34. Comparison of measured and calculated results.

F-16E configuration

Three wind tunnel tests were performed using a 1/4 scale model representative of the F-16E configuration.[27] The F-16E configuration (figure 35) featured an advanced technology wing that offered improved aerodynamic performance over the conventional F-16 airplane. The TDT tests were performed to provide experimental flutter data to support the flight demonstration tests.

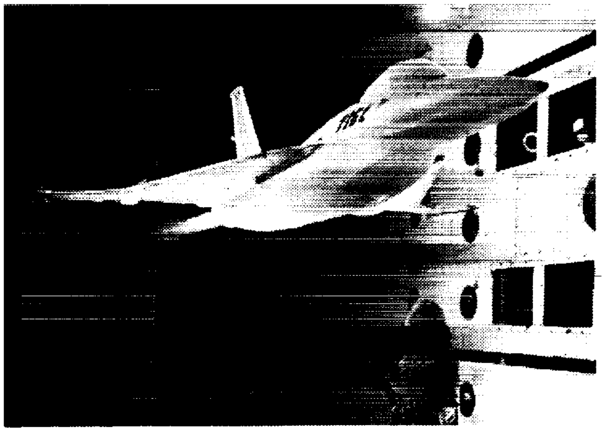

Figure 35. Sting mounted F-16 E model in TDT

C-17 configuration

In December 1983 a semi-span scaled flutter model of a four-engine transport supercritical wing with winglets (figure 36) was tested in the TDT.[28] The model was tested in heavy gas at Mach numbers up to 0.88. This test provided experimental data for use in the verification and modification of C-17A flutter analysis methods

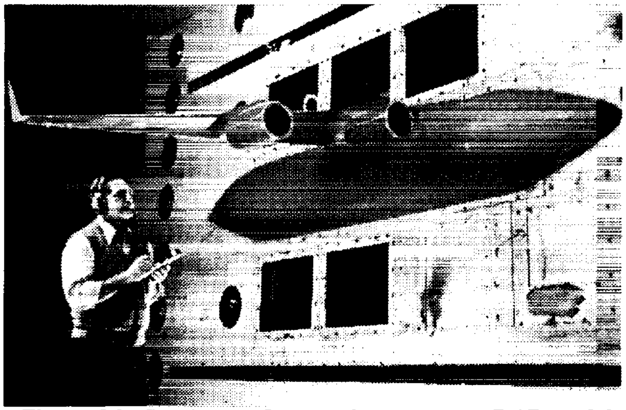

Figure 36. Semi-span four engine transport C-17 model in TDT.

JAS-39 configuration

A 0.23-scale model of the JAS-39 airplane configuration (figure 37) was tested on two occasions in the TDT during 1985 -1986. The configurations tested included the basic airplane with no external stores, and different combinations of wing mounted external stores such as fuel tanks and air to air missiles. The store configurations studied were selected from those expected to be used most frequently and most flutter critical. The wind tunnel tests showed that all these configurations were flutter free throughout the airplane operational envelope simulated. In addition buffet data was obtained for several configurations to provide a basis for predicting the buffet loads for the airplane.

Figure 37. Cable mounted JAS-39 model in TDT test section.

A-6 (Advanced composite replacement wing)

Between February 1986 and July 1987 two tests were conducted in the TDT using 1/4-scale semi-span aeroelastic models of the A-6 with an advanced composite wing. These tests were to determine the transonic flutter characteristics of the advanced composite wing with and without external stores. Tests of the clean wing, both with and without pylons showed the flutter boundary was well outside the airplane planned operating envelope. However during the first test it was found that the flutter characteristics of the wing with external stores were unsatisfactory and quite different from what had been predicted by analysis. To aid in understanding these experimental results and lack of correlation with analysis, a pencil store configuration was tested. During these runs the model was lost to flutter. Although sufficient data were obtained during the first test to understand the flutter characteristics and provide guidance to modify the structural design of the wing, a second model (figure 38) was built and tested. This served to verify that modifications incorporated to the new design (based on the results of the first test) had acceptable flutter characteristics. During the second test, 37 configurations were tested at transonic Mach numbers. These test results, in conjunction with analyses, indicated that the full-scale airplane would be flutter free. In addition, the large amount of flutter data obtained contributed to the available information on the effect of store configuration variables on flutter.[29]

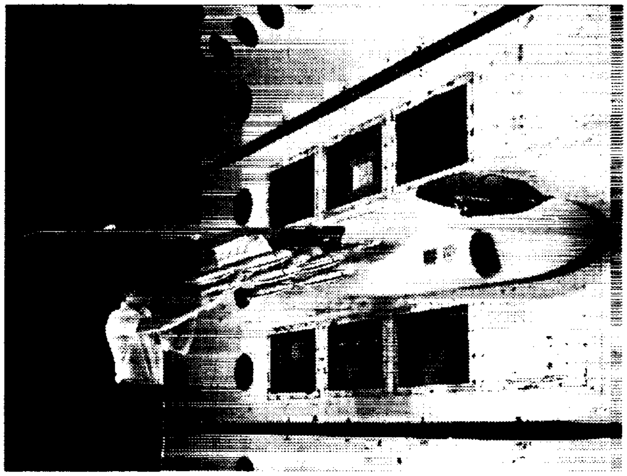

Figure 38. A-6 replacement-wing model with external wing stores.

A-12 configuration

Four wind tunnel tests were performed using a dynamically scaled aeroelastic model (figure 39) of the A-12 configuration between July 1989 and August 1990 as part of the flutter clearance program.[30] The objective of the program was to verify that the airplane would have the required flutter margin of safety throughout its flight envelope. Initial testing was conducted using an overly stiff model to determine stability of the cofiguration on the cable mount system. In addition, model configurations that were considered most likely to flutter were first tested on a sting mount to establish their flutter characteristics prior to testing on the cable mount.

In all, 41 model configurations were tested in the TDT. Some configurations were tested to determine the influence on flutter of free-play effects and flexibility in the wing fold joints and wing control surfaces. In addition, fuel-mass effects on flutter was also studied. All configurations tested were shown to have the required flutter margins of safety throughout the vehicle flight envelope.

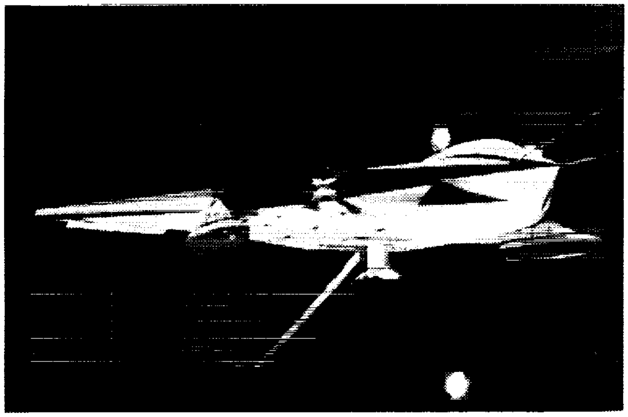

Figure 39. Cable mounted A-12 configuration.

THE 90's AIRPLANES

Since 1990 flutter clearance testing has been conducted for five airplane configurations. These were the Boeing 777, Gulfstream V, Cessna Citation X, F-18E/F, and the Learjet Model 45. In all, 14 tests in the TDT were focused on these configurations.

Boeing 777 configuration

A dynamically scaled semispan aeroelastic model of the Boeing 777 wing was tested in 1992 at the TDT. Four weeks of testing were conducted in order to explore the flutter characteristics of this configuration and assess analytical prediction methods. The model had a rigid half-body fuselage to simulate the effect of the fuselage on flow over the wing (figure 40).

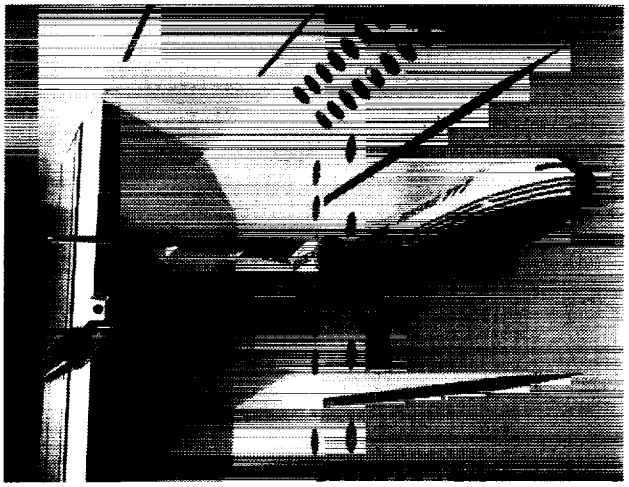

Figure 40. Boeing 777 configuration model.

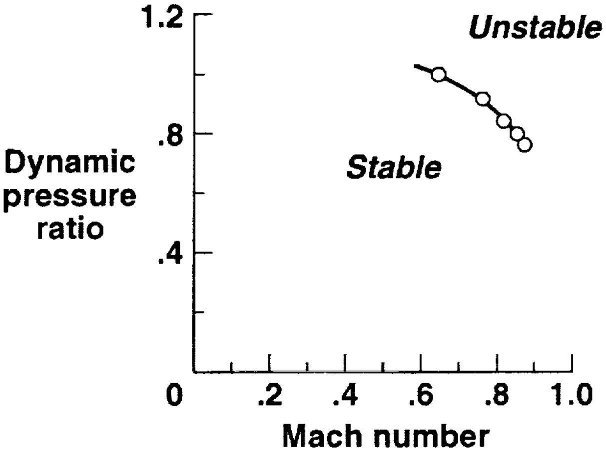

Figure 41. Stability boundary for model with additional tip mass.

The engine nacelles were designed to provide similar mass flow to the engine nacelles on the airplane. Engine pylon stiffness and wing fuel were also remotely adjustable. Results from the ten configurations tested showed no flutter problems with the scaled flight envelope. The model wing tip was ballasted to obtain flutter within the TDT operating boundary for use in assessing the accuracy of analytical flutter prediction methods. Figure 41 shows the flutter boundary obtained for this configuration. The tests results were used to calibrate analytical flutter codes used in the flutter safety certification of the 777 airplane.[31]

Gulfstream V configuration

A simple model (figure 42) representing a Gulfstream V configuration was tested three times in the TDT from early-1993 to mid-1994. The objectives of the tests were to determine the effects of winglets on flutter of a business-jet class wing and to validate aeroelastic codes for use in the full-scale aircraft.

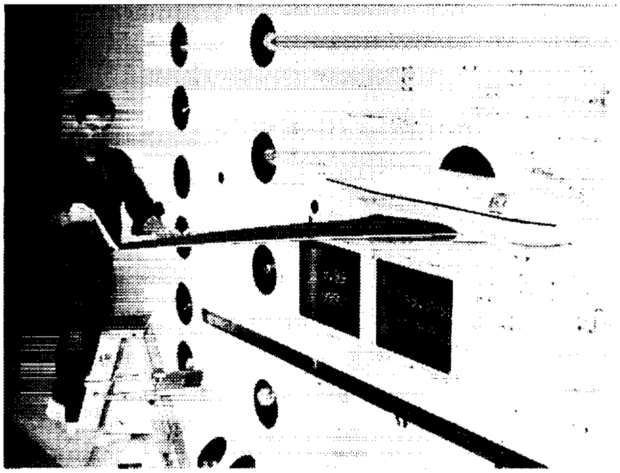

Figure 42. Photo of simple business-jet model.

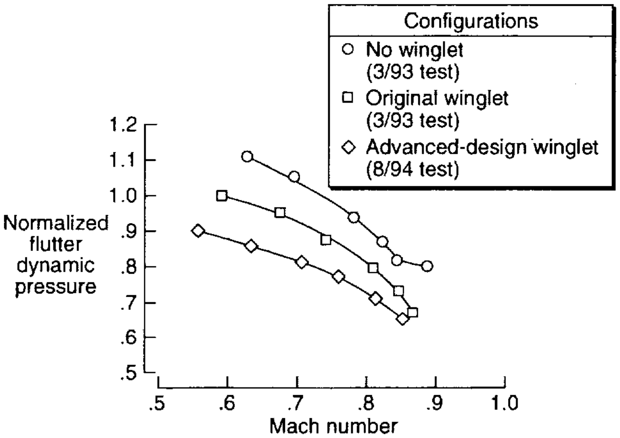

Figure 43. Winglet effects on flutter characteristics.

The simple, 1/10-scale, semispan model was constructed from an aluminum plate simulating the bending stiffness of the scaled wing. Balsa wood was bonded to the plate and contoured to form a supercritical airfoil.[32] The configurations tested included a nominal wing tip, a ballasted wing tip matching the mass of a proposed winglet, and a wing tip with the proposed winglet. A final test was conducted to determine the effects of an advanced-design winglet on the flutter characteristics of the model. Figure 43 contains a plot showing the effects on the flutter characteristics of the model with a nominal wing tip, the proposed winglet, and the advanced-design winglet. Tests results showed that the winglet effects on flutter were mostly due to mass of the winglets rather than an aerodynamic effect.[32]

Cessna Citation X configuration

Flutter models of a Cessna Citation X business-jet configuration were tested a total of three times in the TDT in 1993 and 1994. The objectives of the test program were to demonstrate that the aeroelastically-scaled model of a Citation X was flutter free throughout the scaled flight envelope plus a 15 percent flutter safety margin and to obtain flutter data for use in calibrating aeroelastic codes. The first test was of a semispan, flutter clearance model with surface orifices to measure unsteady pressures. The final two tests used a full-span model mounted to a sting. Figure 44 is a photo of the full-span model mounted on a sting in the TDT test section. Results from the tests were used by Cessna engineers for guidance during the aircraft flight envelope expansion tests.

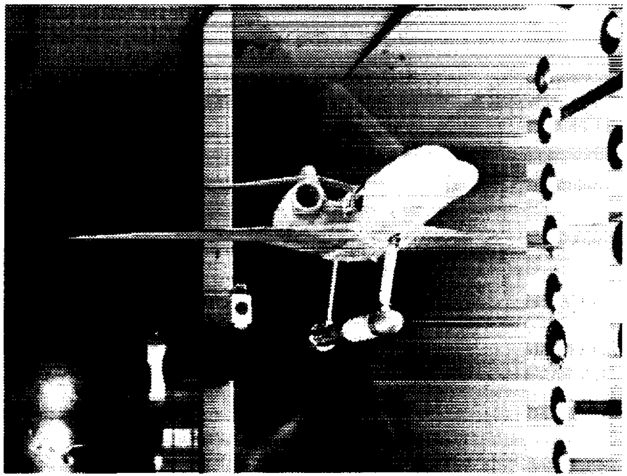

Figure 44. Cessna Citation X business jet configuration in the TDT.

F-18E/F configuration

A series of five wind tunnel tests were conducted as part of the flutter-clearance wind-tunnel test program of the F-18 E/F configuration. The model is shown on the cable-mount in the TDT test section in figure 45. The tests consisted of multiple entries that built upon one another. Initial testing was conducted using an overly stiff model to determine dynamic stability of the configuration on the cable mount system. In addition, some model configurations that were considered most likely to flutter were first tested on a sting mount to reduce risk to the model when on the cable mount.

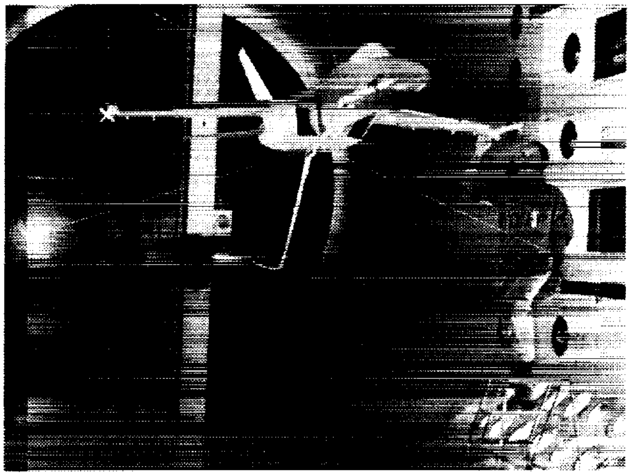

Figure 45. Cable mounted F-18E/F configuration.

The test program was completed in March 1995 with several significant accomplishments:

1. Flutter clearance and boundaries were established for the 18-percent full-span model with and without underwing stores on the cable mount system. These were used to guide initial flight tests.
2. The TDT tests verified stability of the all-moveable stabilators with mil-spec free play, and investigated the effect on aeroelastic stability due to repair weight on trailing-edge flaps and rudders.
3. Parametric studies were conducted in the TDT to obtain transonic correction factors for contractor analytical codes. The variations included stabilator free-play, wing and fuselage fuel, wing-tip and wing-pylon mounted stores, and control-surface actuator stiffness.

Learjet Model 45 configuration

A Learjet Model 45 (M45) configuration was tested twice in the TDT in 1995. The full-span, 1/6-scale flutter model was sting-mounted with flexible lifting surfaces and a rigid fuselage (figure 46). The wind-tunnel tests were conducted to 1) ensure flutter would not occur within the scaled flight envelope of the model with a 20-percent flutter safety margin, 2) evaluate free-play and jammed-control-surface effects on the model flutter characteristics, 3) measure the transonic flutter conditions for a modified wing configuration, and 4) obtain data to validate linear flutter prediction codes for Mach numbers greater than 0.8.

The nominal model configuration was shown to be flutter free within the required flight envelope. All configurations including mass balance variations, freeplay, and jammed control surface conditions were also flutter cleared. Transonic flutter characteristics of a modified wing configuration were measured (figure 47) and correlated with linear flutter prediction code results. These comparisons showed the codes to be approximately 10 percent conservative. The data from the wind-tunnel tests of the scaled model were used to minimize the risk of the flight flutter test of the Learjet M45.

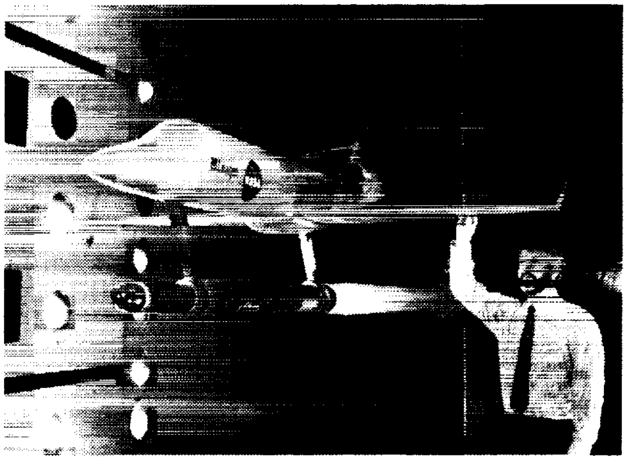

Figure 46. Photo of Learjet M45 configuration in TDT.

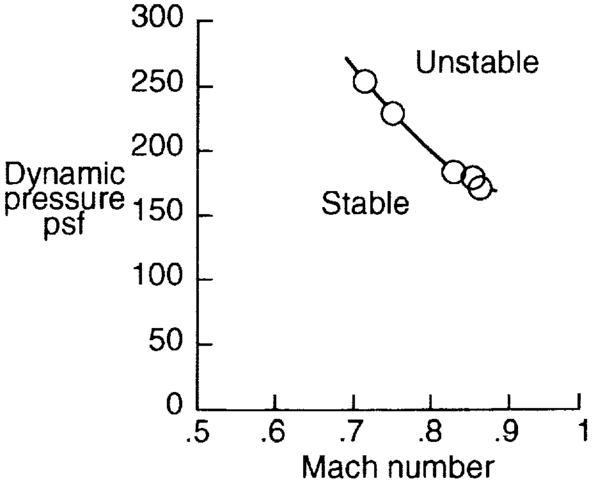

Figure 47. Flutter points for modified wing configuration.

CONCLUDING REMARKS

Flutter clearance tests have been performed in the TDT for numerous airplane configurations since it became operational in 1960. The contributions to the flutter clearance program of the airplane configurations highlighted in this paper have been presented.

These tests contributed to, and were aimed at, uncovering potential flutter problems and solutions of a specific design through airplane configuration studies and tests of various components. In addition to flutter clearance testing, the tests performed in the TDT on the following airplane configurations obtained data to guide flight tests. These were the F-111, F-16, F-16E, A-6 composite replacement wing, Citation X, F-18E/F, and Learjet M45.

In addition to contributing to their flutter clearance program, tests were conducted in the TDT for the following configurations to solve or gain insight into the aeroelastic problems of the particular configuration. These were the F-14, S-3A, F-15, B-1, and F-16.

Additional TDT testing contributions to airplane flutter clearance for the following configurations have been through code evaluation and calibration tests. These tests were performed in conjunction with TDT flutter tests to obtain data for use in developing (or evaluating) computer codes to predict flutter characteristics related to the airplane configurations. These were (primarily the 80's and 90's airplanes) the F-16, B-767, X-29, C-17, A-6 replacement wing, B-777, Gulfstream V, Citation X, F-18E/F, and Learjet M45.

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