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Transonic Dynamics Tunnel Aeroelastic Testing in Support of Aircraft Development

Stanley R. Cole, Thomas E. Noll, and Boyd Perry, III
NASA Langley Research Center, Hampton, Virginia 23681-2199

Introduction

Historical Perspective on Aeroelasticity

ALTHOUGH this paper is about the NASA Langley Research Center's Transonic Dynamics Tunnel, to a very large extent the TDT is about aeroelasticity. To this end, an historical perspective on aeroelasticity is offered as a method of introducing the TDT and to shed a great deal of light on the past importance and potential future contributions of the TDT. Aeroelasticity is a field of aeronautics that deals with the interaction of vehicle structural components, in terms of elastic and inertial characteristics, and aerodynamic loads that develop over the vehicle in flight. Aeroelasticity encompasses dynamic phenomena, such as buffet and flutter, and static phenomena, such as aileron reversal and wing divergence. Dynamic phenomena are highly undesirable and can result in a catastrophic instability if not eliminated during the design and development process. Aeroelasticity is predominantly thought of in terms of detrimental dynamics. However, static phenomena such as the deformation of an elastic wing under steady aerodynamic loads are also important considerations in vehicle design. Such deformations

Stanley R. Cole is Branch Head of the Aeroelasticity Branch, Structures and Materials Competency at the NASA Langley Research Center. He received his B.S. degree in aerospace and ocean engineering from Virginia Polytechnic Institute in 1982 and continued further graduate studies in mechanical engineering at George Washington University and Old Dominion University. Since 1982, Mr. Cole has worked in the field of aeroelasticity at NASA Langley with a strong emphasis on experimental studies. Prior to 1995, Mr. Cole led, assisted, or had oversight responsibilities in 56 wind-tunnel tests at the Langley Transonic Dynamics Tunnel (TDT), 0.3-m Transonic Cryogenic Tunnel, Unitary Plan Wind Tunnel, Mach 20 Hypersonic Helium Tunnel, and National Transonic Facility. In 1995, Mr. Cole became the manager of the High Speed Research program aeroelasticity task leading work performed by NASA Langley, Boeing, McDonnell-Douglas, and Northrop-Grumman. Mr. Cole was selected as the Facility Manager of the Transonic Dynamics Tunnel in 1997 and was selected for his current position in 2003. He has published extensively and has taught several NATO and AIAA short courses on experimental aeroelasticity. Mr. Cole is an Associate Fellow of the AIAA and a member of the American Helicopter Society. E-mail: stanley.r.cole@nasa.gov.

Dr. Thomas Noll received a B.S. in mechanical engineering from the University of Cincinnati in 1967. Upon graduation, he was employed by the Air Force Flight Dynamics Laboratory in the Aeroelastic Group of the Vehicle Dynamics Division at Wright–Patterson Air Force Base. In 1972 he received an M.S. in aerospace engineering from the Ohio State University and in 1983 obtained a Ph.D. in aeronautical engineering from the University of Dayton. In 1987 Dr. Noll was selected as the Assistant Head of the Aeroservoelasticity Branch at the NASA Langley Research Center, and in 1988 became Head of the branch. In 1993 Dr. Noll became Head of the Aeroelasticity Branch, which includes the Transonic Dynamics Tunnel (TDT) and the Rotorcraft Hover Test Facility. He was responsible for the technical direction and administration of the branch research program which involves: performing analyses and tests to determine the aeroelastic characteristics of fixed and rotary wing commercial, general aviation, and DOD aircraft; developing, implementing, and validating advanced concepts that employ smart materials or aerodynamic control surfaces for alleviating or exploiting aeroelastic response; developing and validating advanced computational aeroelastic algorithms for predicting transonic aeroelastic phenomena; and performing wind-tunnel experiments to obtain aeroelastic and aerodynamic data to validate the new and improved analysis and design methodologies. In addition, the branch provided technical support for NASA projects to insure that the flight envelope of these vehicles was free of unstable aeroelastic phenomena or adverse structural response. In 2001, Dr. Noll was appointed as the Associate Director of the Structures and Materials Competency at the NASA Langley Research Center, and in 2003 he was selected as the Deputy Director of the Competency. Dr. Noll also serves as the NASA representative on The Technical Cooperation Program (TTCP) AER-4 international panel, which is concerned with structural and dynamics issues of aerospace vehicles. He is an Associate Fellow of the AIAA, and is a registered Professional Engineer. Dr. Noll is the author or coauthor of over 75 technical reports, and has recently been awarded the NASA Outstanding Leadership Medal. E-mail: thomas.e.noll@nasa.gov.

Boyd Perry, III is Assistant Head, Aeroelasticity Branch, Structures and Materials Competency. He received a B.S. in aeronautical engineering from Rensselaer Polytechnic Institute in 1969. Immediately after graduation he went to work at the NASA Langley Research Center in Hampton, Virginia in the Aeroelasticity Branch. In 1975 he received an M.S. in aerospace engineering from The George Washington University. During his career Mr. Perry specialized in the fields of gust loads and active controls, co-developing Matched Filter Theory as a gust loads analysis tool and leading the NASA portion of the Active Flexible Wing project. In 1992 Mr. Perry was selected as the Assistant Head of the Aeroservoelasticity Branch at NASA Langley and, since 1993, Mr. Perry has served as the Assistant Head of the Aeroelasticity Branch at NASA Langley. During the past decade Mr. Perry co-led the conduct of pioneering experimental aeroelastic research in the Langley Transonic Dynamics Tunnel (TDT) and co-led the development of methodologies for the analysis and synthesis of active control systems capable of improving aeroelastic stability and alleviating undesirable structural responses of fixed wing vehicles. Mr. Perry is the author of over 50 technical papers and is a Member of AIAA.

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might or might not be catastrophic. Even if the deformations are not catastrophic, they can degrade desired lift and drag properties. The field of aeroelasticity also deals with methods to prevent instabilities, such as through aeroelastic tailoring or through active control methodologies. For the reader with an interest in learning more about aeroelasticity, References 1–3 are three classic textbooks on the subject.

Aeroelastic behavior has been important with respect to many technological advancements for a very long time. Reference 4 briefly describes some early, unusual encounters with aeroelasticity. Two examples of these early aeroelastic effects are problems in windmills that were empirically solved four centuries ago in Holland and some 19th century bridges that were torsionally weak and collapsed from aeroelastic effects. Many other examples of aeroelastic problems exist in civil engineering; however, the widest attention given to aeroelasticity has been in the field of aeronautics. Virtually from the beginning of flight, aeroelasticity has played a role in the design or flight readiness process of new vehicles. One of the earliest examples of conscientious and beneficial use of aeroelasticity was the Wright Brothers' application of wing warping to take advantage of wing flexibility for the purpose of lateral control of their aircraft.[5]

As flight capabilities progressed rapidly in the early 20th century, aeroelasticity continued to play an important part in aircraft design. Aeroelasticity was generally looked upon as a problem, and aeroelasticians were usually consulted to fix these problems rather than being invited to join the design team early in the process to anticipate and make beneficial use of aeroelastic characteristics. This led to many expensive vehicle redesigns, as well as the loss of flight vehicles and human lives along the way. While theoretical developments progressed so that there was a continually improving understanding of aeroelasticity, the drive to achieve faster flight forced vehicles in the direction of ever-lighter structures and thinner, more flexible lifting surfaces. This trend continued to make aeroelasticity an important technical field for flight. As vehicles approached and exceeded transonic speeds, the need for experimental assessment of aeroelastic behavior grew substantially because of the pronounced effect of transonic aerodynamics on phenomena like wing flutter. At the time that the transonic flight regime was being conquered, the ability to theoretically determine unsteady aerodynamics for use in the prediction of flutter did not exist. This inability to handle transonic aeroelastic effects was one of the major considerations that led to the idea of the NASA Langley Transonic Dynamics Tunnel (TDT).

History of the TDT

As the flight capabilities of aircraft advanced, wind-tunnel testing capabilities were also advancing to satisfy the need. By the early 1950s several transonic wind tunnels were available. Aeroelastic experiments could then be conducted at transonic conditions, which tended to be the critical flight regime for many aeroelastic issues. A significant early effort to specifically address this need was the conversion of a 4-ft heavy gas tunnel at the NACA Langley Memorial Aeronautical Laboratory to a 2-ft continuous flow transonic tunnel for the purpose of flutter testing.[4] However, the lack of a particularly suitable facility in which to determine the aeroelastic behavior of new high-speed aircraft designs led A. A. Regier in 1951 to propose building a large-scale, transonic facility dedicated to aeroelastic testing. Reference 4 lists the original requirements stated by Regier: 1) the facility should be as large as feasible to enable accurate simulation of model details, such as control surfaces; 2) the facility should be capable of operating over a wide range of density to simulate various altitude conditions; 3) the facility should use Freon gas (dichlorodifluoromethane, which is often referred to as R-12) as the test medium, which, based on previous experience, enables the use of heavier, less expensive models, results in higher Reynolds number, and allows more efficient power usage; and 4) the facility should be capable of operating at Mach numbers up to 1.2.

NACA's answer to Regier's request for a new facility was the conversion of the Langley 19-ft Pressure Tunnel to the Transonic Dynamics Tunnel. The new wind tunnel would have all of the features proposed by Regier: a 16×16-ft test section that could operate at Mach numbers up to 1.2 with variable pressure conditions in either air or a heavy gas. The design and conversion process began in 1954, and the TDT became operational in early 1960. At the time the TDT represented a significant advancement in aeroelastic testing capabilities, primarily because of its large size, heavy-gas test medium, and transonic speed capabilities.

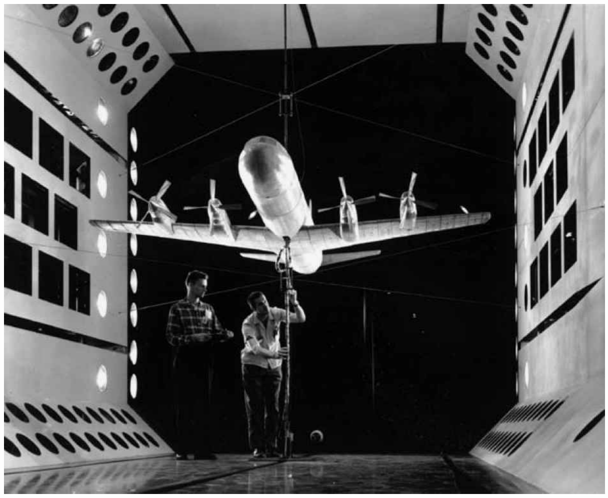

Fig. 1 Lockheed Electra model mounted in the TDT.

Right from the beginning, the TDT was to play a critical role in solving a severe aeroelastic problem. In late 1959 and early 1960 the Lockheed Electra aircraft experienced two catastrophic crashes. Evidence from these crashes pointed in the direction of violent wing flutter. In an attempt to rapidly solve the Electra problem, a 1/8-scale aeroelastic model was assembled for testing in the TDT. A photograph of this first-ever, flight-vehicle flutter model tested in the TDT is shown in Fig. 1. By the time the TDT test occurred, a Lockheed engineer had identified the possibility that the Electra was experiencing a coupling between the wing structure, engine gyroscopic torques, and aerodynamic forces in a phenomena referred to as propeller-whirl flutter. The TDT wind-tunnel tests showed that reduced stiffness engine supports on the outboard engines would cause the Electra to experience propeller whirl flutter. Based on these findings, the engine mounts were strengthened on the flight vehicles to prevent stiffness reductions that could potentially develop from mount-system failures caused by operational loads. Following the modifications, the aircraft never experienced a catastrophic flutter incident again. An unsubstantiated story has circulated over the years that the money saved by the aircraft industry in quickly solving the Electra propeller-whirl flutter in itself more than equaled the facility conversion costs in constructing the TDT. Reference 6 includes a detailed summary of the flight vehicle story of this Electra whirl-flutter problem.

Over its 42-year history, the TDT has served as a workhorse for experimental aeroelastic research and vehicle clearance testing. Testing has included such varied aeroelasticity concerns as buffet, divergence, gusts loads, flutter, limit-cycle oscillations, and other types of dynamic response. In addition to testing for these phenomena, many passive and active control studies have been carried out in the TDT to demonstrate methods of overcoming aeroelastic obstacles to flight. References 7–15 provide overviews of testing that has occurred in the TDT over the years. Most military fighters and commercial transports developed in the United States have been tested in the TDT at some time in their development history. Today, the TDT is still a very unique facility dedicated to aeroelastic testing. Reference 16 describes the general features, characteristics, and capabilities of the TDT. This paper also describes the heavy gas [Tetrafluoroethane (CH_2FCF_3), which is also identified as R-134a] that is presently used in the tunnel and the various model mount systems available for use including a very unique high-frequency, large displacement oscillating turntable.[17]

Contributions of the TDT to Aircraft Development

The TDT has contributed to many research and development efforts for aircraft throughout its history. The remainder of this paper will emphasize such contributions. For simplification, the TDT's contributions have been grouped into three categories. The first category is aircraft flutter-clearance studies. To a large degree, this type of testing represents the basic investigation type for which the TDT was initially developed and accounted for a large portion of the testing during its first several decades of operation. The second category of testing is active aeroelastic control demonstrations. This category essentially represents a substantial advancement in the field of aeroelasticity as the phenomena became understood well enough to control it and to potentially beneficially exploit it in designing more efficient aircraft. The final category of testing that will be discussed is unsteady aerodynamics measurement programs. The measurement of unsteady aerodynamics represents another substantial advancement in the field of aeroelasticity in that it contributes to a better understanding of the dynamic flowfield surrounding and interacting with a deforming vehicle during flight.

Flutter-Clearance Tests

This section of the paper presents a representative selection of flutter-clearance tests conducted in the TDT and draws heavily upon Ref. 15 by Rivera and Florance, which documents 138 such tests in the TDT. The present selection of flutter-clearance tests contains examples from each decade of the TDT's history as well as tests from each major category of such tests identified by Rivera and Florance. For conciseness, a particular configuration type was selected for discussion in each decade. However, many more tests in each configuration type have occurred through each decade in the history of the TDT. The major categories identified by Rivera and Florance are as follows: 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; and 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.

Only airplanes that were flutter tested in the TDT, built, and flown are included herein. The TDT tests did not, by themselves, 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 section 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.

Jumbo Jet Configurations (1960s)

All three wide-body jet transports (known originally as jumbo jets) designed during the 1960s to carry passengers (Boeing 747, Lockheed L-1011, and McDonnell-Douglas DC-10), as well as a wide-body military cargo transport (Lockheed C-5), were tested in the TDT during the 1960s.

C-5

Models of the C-5 transport configuration[18] 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 and a cable-mounted, six-degree-of-freedom, 1/13-scale empennage flutter model having a fuselage with stub wings. Tests showed that a potential vertical-tail flutter problem existed with the configuration. The vertical tail subsequently was stiffened to eliminate the problem.

Fig. 2 Boeing 747 model mounted in the TDT.

Boeing 747

A wind-tunnel model of a Boeing 747 configuration was tested twice in the TDT during 1967 and 1968 for a total of eight 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. Two mount systems were used: the vertical-rod-mount system and the two-cable-mount system.[19] Figure 2 shows the model mounted in the TDT test section using the vertical-rod-mount system.

Lockheed L-1011

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 this configuration. The purpose of these 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.

McDonnell-Douglas DC-10

The split rudder configuration of the McDonnell-Douglas 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 vs a single unsplit rudder on the vertical tail flutter characteristics. 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 unsplit rudder.

Selected Fighter Configurations (1970s)

Grumman F-14

Between January 1970 and June 1975 the F-14 fighter configuration (Fig. 3) was tested 10 times (for a total of 14 weeks) for flutter and buffet loads at high angles of attack. During the tests, it was discovered that the flow over the overwing 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.

McDonnell-Douglas F-15

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% dynamically and aeroelastically scaled model of the F-15 was used to determine the flutter boundaries for various model components. The model was mounted on the sting for flutter-clearance

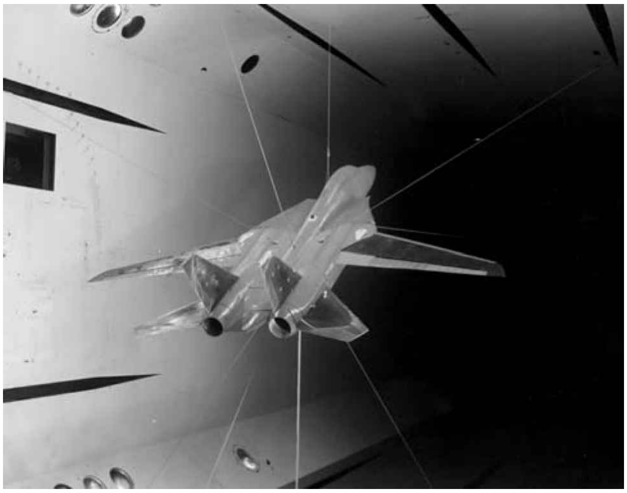

Fig. 3 F-14 model tested in TDT.

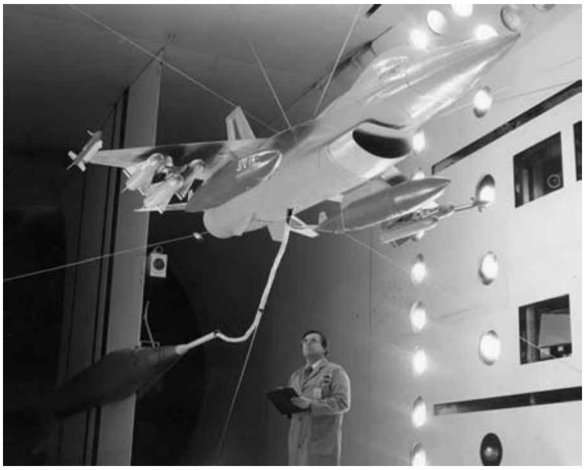

Fig. 4 F-16 fighter configuration in TDT.

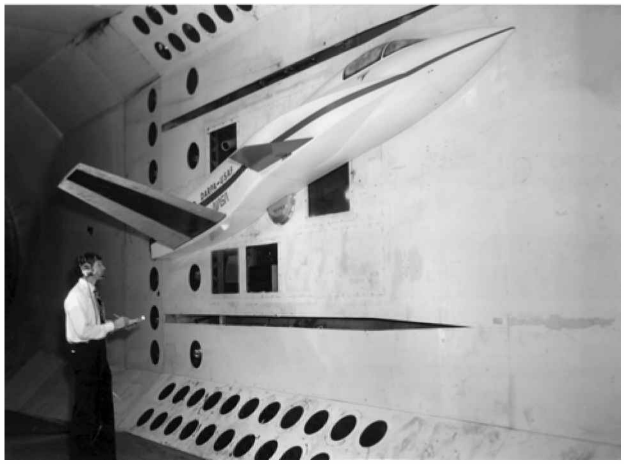

Fig. 5 Grumman X-29 model mounted to TDT sidewall support system.

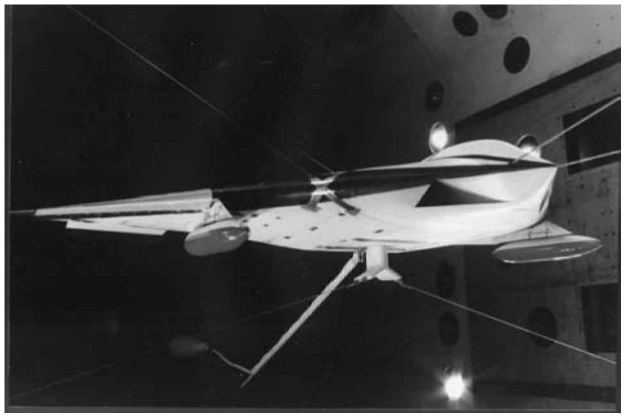

Fig. 6 Cable-mounted A-12 configuration.

tests of the empennage and wings. Results from empennage flutter studies showed that flutter was encountered for the basic horizontal stabilator and vertical tail design within the required flutter margin. 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 ensure that the aircraft wings did not flutter within the required flutter margin.

General Dynamics F-16

From January 1973 to September 1987, 24 flutter tests were devoted to the F-16 fighter configuration. During these tests, a full-span, 1/4-scale F-16 flutter model (Fig. 4) was used on both sting and cable mount systems to identify potential flutter problems and to guide flight tests. The TDT data were 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.[20]

Novel Configurations (1980s)

X-29

Several concepts of an X-29 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.[21] Figure 5 is a photo of the Grumman model installed in the TDT test section. 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. Results from the tests verified the suitability of then current analytical methods available for forward-swept wing applications. In 1983, the Grumman model was tested on a new mount system designed to provide rigid-body degrees of freedom to allow for the study of body-freedom flutter, a phenomenon that often occurs on forward swept wing aircraft and is caused by the adverse coupling of rigid-body pitching and wing bending motions.

A-12

Four wind-tunnel tests were performed using a dynamically scaled aeroelastic model (Fig. 6) of the A-12 configuration between July 1989 and August 1990 as part of the flutter clearance program.[22] 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 configuration on the two-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 were also studied. All configurations tested were shown to have the required flutter margins of safety throughout the vehicle flight envelope.

Business Jet Configurations (1990s)

Gulfstream V

A simple model 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. Tests results showed that the winglet effects on flutter were mostly caused by mass of the winglets rather than an aerodynamic effect.[23]

Cessna Citation X

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% 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 (Fig. 7). Cessna engineers used the results from the tests to guide the aircraft flight envelope expansion tests.

Learjet Model 45

A Learjet Model 45 (M45) configuration was tested twice in the TDT in 1995. The full-span, 1/6-scale flutter model (Fig. 8) was sting-mounted with flexible lifting surfaces and a rigid fuselage. The wind-tunnel tests were conducted to 1) ensure flutter would not occur within the scaled flight envelope of the model with a 20% flutter safety margin; 2) evaluate freeplay 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 and correlated with linear flutter prediction code results. These comparisons showed the codes to be approximately 10% 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.

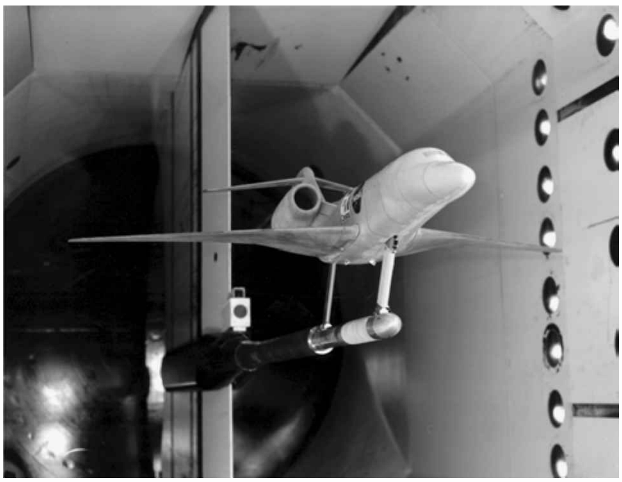

Fig. 7 Cessna Citation X business jet configuration in the TDT.

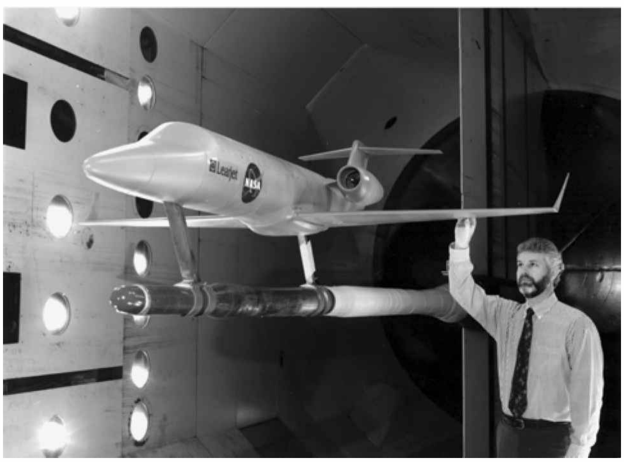

Fig. 8 Photo of Learjet M45 configuration in TDT.

Active Control Tests

During the middle and late 1960s and into the early 1970s, there was a growing expectation that soon turned to a realization: active controls technology (ACT) could achieve a variety of aeroelastic benefits. After numerous analytical studies this technology found its way onto a few airplanes 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 (AFS) could, indeed, be achieved. 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. More than 560 tests were completed in the TDT since 1960, and, of these, about 10% involved the active control of aeroelastic response either on fixed-wing or rotorcraft flight vehicles. Reference 13 by Perry et al. documents many of these tests. This section of the paper draws heavily upon this reference. In addition, for each ACT test described next a reference is provided so that the reader will have access to more detailed information if desired.

Delta Wing Active Flutter Suppression (AFS) Program

The very first demonstration of active controls in the TDT occurred in 1971 (Ref. 24) and involved AFS of a semispan model of a low-aspect-ratio, clipped-delta-wing configuration representative of the Boeing supersonic transport design. Several different control laws were designed for flutter suppression and implemented on an analog computer. With the AFS operating, increases in flutter dynamic pressure ranging from about 11 to 30% were demonstrated across the Mach-number range from 0.6 to 0.9. Other significant contributions to ACT that evolved from this program included the development and first use of miniature electrohydraulic vane actuators for driving control surfaces; observations of large differences between the predicted and the actual effectivenesses of the active control system, which was attributed to the inability of potential aerodynamic theory to predict the behavior on small control surfaces; and the identification that inertia coupling between control surfaces and the main wing is the mechanism by which still-air closed-loop instabilities occurred. Today the use of hydraulic actuators in wind-tunnel models and applying empirical corrections to control surface aerodynamic terms (both steady and unsteady) are routine when investigating aeroservoelastic phenomena.

C-5A Active Load Distribution Control System (ALDCS) Program

During the 1970s, the TDT played a role in the development of C-5A ALDCS.[25] The Lockheed–Georgia Company was interested in comparing the C-5A ALDCS flight-test results with data from tests in the TDT using a 1/22-scale, full-span, aeroelastic model designed to match the airplane Froude number in a heavy-gas test medium. A photograph of the model attached to the TDT's two-cable-mount system is shown in Fig. 9. The model ALDCS was implemented on an analog computer, and small hydraulic actuators powered the ailerons and the stabilizer. The C-5A airplane ALDCS

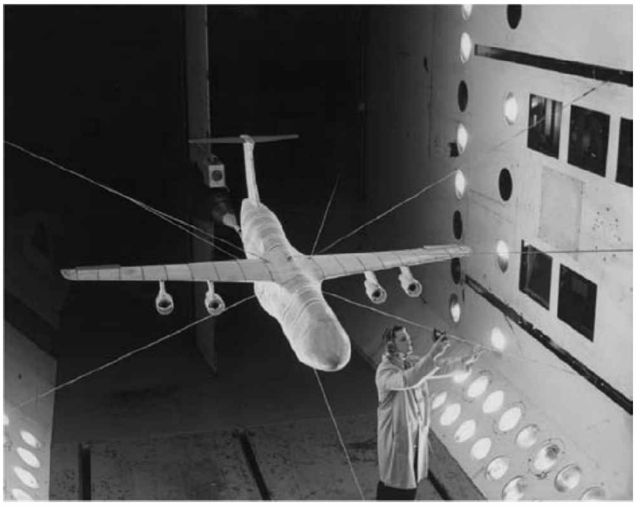

Fig. 9 C-5A model on two-cable-mount system.

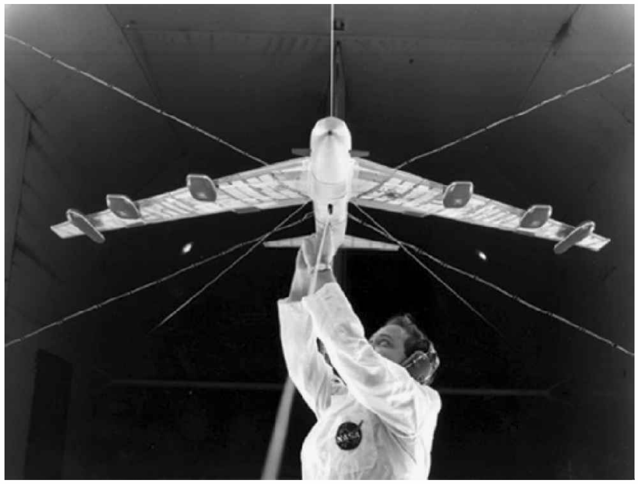

Fig. 10 B-52 model mounted on two-cable-mount system.

was developed to reduce fatigue damage on the wing caused by maneuver, gust, and peak-to-peak ground-air-ground load sources. This was to be accomplished by redistributing the wing loads to reduce the inboard wing bending moments and by suppressing the airplane response in the short period and wing first-bending mode during maneuvers and during atmospheric turbulence. The system utilized compensated wing accelerometers to drive the ailerons symmetrically for redistributing wing loads and the existing stability augmentation system pitch rate gyro and the autopilot normal accelerometer to drive the inboard elevators for suppressing short-period and first wing-bending-mode gust responses and for providing handling quality compensation. Because the model did not have elevators, the horizontal stabilizer was commanded in pitch to duplicate the tail lift change caused by inboard elevator ALDCS commands. The ALDCS response of the model stabilizer was weighted and scheduled proportionately to the elevator transfer function requirements. For both the airplane and the model the test results showed the desired wing load relief with the ALDCS operating, thus validating the use of ACT for the minimization of aircraft aeroelastic response and the potential use of flexible wind-tunnel models for ACT development.

B-52 Model Program

In the early 1970s the Air Force Flight Dynamics Laboratory (AFFDL) initiated the Control Configured Vehicle flight-test program to investigate AFS and ride control (RC) concepts using a B-52E as the testbed. In parallel with the flight program, the AFFDL sponsored another investigation with the NASA Langley Research Center (LaRC) to further develop wind-tunnel model technology and to obtain data for validating emerging analysis methods. The wind-tunnel model was a 1/30th scale, full-span, free-flying aeroelastic wind-tunnel model of the B-52E with active ailerons, flaps, and canards driven by electric motors mounted in the fuselage. Figure 10 shows the model installed in the TDT on the two-cable-mount system. The AFS systems consisted of two independent feedback loops designed separately to provide a 30% increase in flutter speed. The aileron loop fed back compensated accelerometer signals from ballasted external fuel tanks while the flap loop fed back compensated accelerometer signals from near the midwing. The wind-tunnel data[26] scaled up to flight conditions compared well with flight-test results. The RC system was designed to reduce the gust-induced vertical acceleration at the pilot's station by at least 30% using the canards commanded by a compensated vertical acceleration sensed at the pilot's station. The RC system reduced modal response in the critical modes of vibration on both the airplane and the model by about 60 to 75%. The most significant finding that resulted from the model program was the knowledge that dynamically scaled, actively controlled wind-tunnel models were extremely useful in studying and developing advanced active control concepts. From the time forward, wind-tunnel models were destined to play important roles in the development of active-control concepts.

YF-17 Wing/Store AFS Program

The Northrop Corporation, under AFFDL sponsorship and in cooperation with the LaRC, conducted a long-term program beginning in 1977 to develop and demonstrate in the wind-tunnel wing/store AFS capabilities. A multitude of AFS concepts that began with simple, single-loop, nonadaptive, analog controllers and evolved into multiloop, digital, adaptive controllers were evaluated using a 30%-scale, semispan, aeroelastic model of the YF-17 aircraft and three different external store configurations having widely different flutter characteristics (flutter frequency, modal coupling, and flutter-mode violence). The model, which consisted of a wing, a fuselage, and a horizontal tail, was uniquely mounted to the sidewall of the TDT using cables and a set of bars and linkages to simulate rigid-body pitch and plunge degrees of freedom. The horizontal tail driven by an electric motor located within the fuselage was used to trim the model at various tunnel conditions. Leading-edge (LE) and trailing-edge (TE) control surfaces powered by electrohydraulic actuators were available for use as AFS effectors. The program[27] was also unique in that researchers from British Aerospace and the Royal Aeronautical Establishment (United Kingdom), the Office National d'Etudes et de Recherches Aerospatiales (France), and the Messerschmitt-Bolkow-Blohm GmbH (West Germany) participated in the test. Besides increasing the flutter dynamic pressure by over 70% with the AFS operating, some "firsts" demonstrated during this program included switching from one control law to another above the unaugmented flutter condition, switching from a control law that used a TE surface to one that used a LE control surface above the unaugmented flutter condition, employing a digital controller, discriminating between possible flutter modes and adapting to the appropriate control law (based on a priori information), adapting the control law to changes in flight condition, and adapting the controller to rapid changes in store configuration (store release). For the latter 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 ARW-1 Program

In the early 1970s NASA embarked on an ambitious high-risk flight-test program 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 Drones for Aerodynamic and Structural Testing (DAST). The flight-test vehicle was an unmanned Firebee II target drone whose standard wings were replaced with new aeroelastic research wings designated as ARW-1. As part of the DAST program, a wind-tunnel model study[28] in the TDT was undertaken to reduce the technical risks associated with implementing an AFS system on the DAST. A dynamically scaled, semispan model of the ARW-1 wing with a hydraulically actuated trailing-edge control surface was designed to flutter within the operational limits of the TDT. Flutter suppression control laws were designed with the objective of demonstrating a 44% increase in flutter dynamic pressure over the Mach-number range 0.6–0.95. These control laws used accelerometers located near the control surface as the feedback sensor. Voltages proportional to acceleration were fed back to an analog computer upon which flutter suppression control laws were programmed. At 0.95 Mach number a 44% increase in flutter dynamic pressure was demonstrated. However, this goal was not achieved at other Mach numbers because large control-surface peak deflections were encountered. These unexpectedly large deflections were the consequence of an inaccurate description of wind-tunnel turbulence, upon which pretest analyses and pretest 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 AFS Program

In 1979 General Dynamics, under Air Force Wright Aeronautical Laboratories (AFWAL) sponsorship and in cooperation with the LaRC, began an eight-year investigation (Ref. 29) that involved three entries in the TDT to assess the feasibility of applying AFS to the F-16 aircraft carrying external stores. An existing 1/4-scale, full-span, free-flying flutter model was modified to include a new set of flexible wings and new flaperon surfaces driven by actuators using an onboard hydraulic system. Highlights of these tests included closed-loop testing to dynamic pressures 100% above the unaugmented flutter dynamic pressure with flaperon displacements never exceeding 0.6 degs; ability to suppress both symmetric and antisymmetric flutter modes using flaperons; simultaneous operation of symmetric and antisymmetric AFS control laws; satisfactorily AFS performance with one flaperon locked out; 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; the use of control laws developed by the adaptive controller as a backup analog safety system; and the use of advanced computer architecture employing multiple processors and multitasking to permit high speed asynchronous parallel processing. In addition, 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. For one test run the adaptive controller updated the control law over 2500 times without losing control of the flutter mode. The controller also performed satisfactory during simulated single actuator failures, with rapidly changing test conditions, and following the release of a wing-tip missile that immediately resulted in a postflutter 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.

Active Flexible Wing (AFW) Program

In 1985 Rockwell International, in cooperation with the AFWAL and NASA, initiated a research program to demonstrate in the TDT a concept that exploits wing flexibility to achieve high roll rates. The AFW concept consists of an active control system, which based on flight conditions selects the most effective combination of control surfaces to aerodynamically deform the flexible wing for rolling the vehicle. The payoff, besides improved maneuvering performance, is reduced structural weight because a "rolling tail" is no longer required. The AFW testbed was a full-span, aeroelastically scaled model (Fig. 11) of an advanced fighter configuration having two LE and two TE control surfaces driven by electrohydraulic actuators. The model was sting mounted utilizing an internal ball-bearing arrangement that allowed the model the freedom to roll about the sting; a brake was also available when fixed-in-roll conditions were tested. The model was tested on four different occasions in the TDT. The first two tests were successful in demonstrating the basic AFW concept. The second two tests, requiring a model modification to include wing-tip ballast stores for lowering the model flutter speed into the operational capabilities of the TDT, focused on demonstrating AFS, rolling maneuver load alleviation (RMLA), and roll-rate tracking systems in combination with the AFW concept. These concepts were designed to be compatible with each other because an important goal of the program was the demonstration of multiple-input, multiple-output, multiple-function digital control laws. For the model in the free-to-roll configuration and using a combined AFS/RMLA control law, aggressive roll maneuvers through 90 deg were performed, and wing loads were controlled at conditions 17% above the open-loop flutter dynamic pressure. The results of these tests are summarized in Ref. 30.

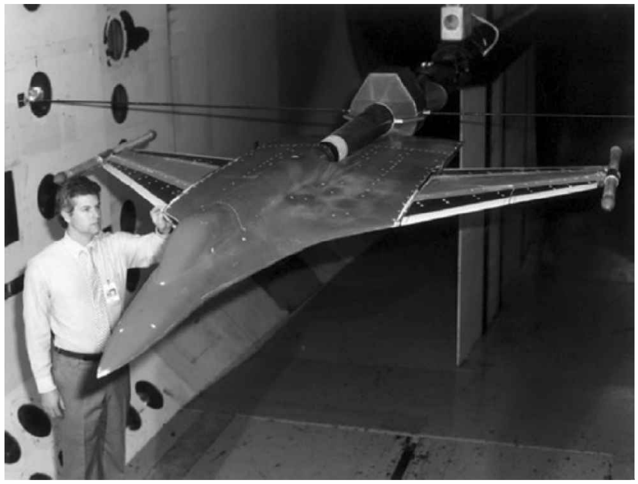

Fig. 11 AFW model mounted on free-to-roll rig.

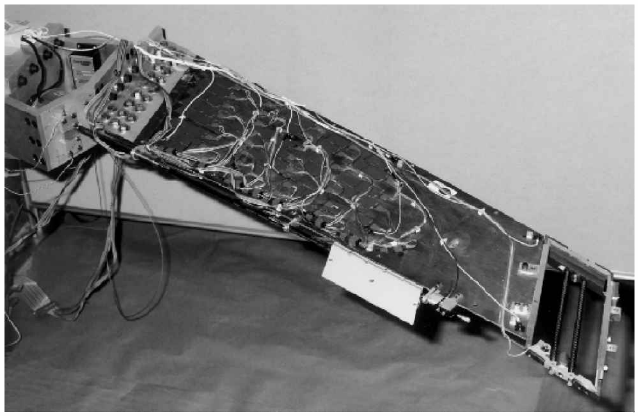

Fig. 12 Internal details of the PARTI model.

Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI) Program

The NASA LaRC, in cooperation with Massachusetts Institute of Technology, conducted an investigation to demonstrate the ability of a strain-actuated adaptive wing to control structural response caused by turbulence and prevent flutter. A flexible semispan model consisting of a composite plate that served as the main load-carrying structure and a segmented exterior fiberglass shell that provided the aerodynamic contouring was used. Seventy-two piezoelectric actuator patches were distributed on the upper and lower surfaces of the composite plate (Fig. 12). Because of the ply orientation of the material used in the composite plate and the wing sweep, the piezoelectric actuator patches were connected in 15 different groups chosen to affect the bending and the torsional responses of the model. Two wind-tunnel test entries were performed; during March 1994 the open-loop aeroelastic characteristics were measured, and during November 1994 the capability of piezoelectric actuators to reduce the model's response caused by turbulence and to suppress flutter was assessed. Several control law design methodologies were evaluated during the tests with the most successful providing a 12% increase in flutter dynamic pressure and a 75% decrease in the peak value of the power spectral density of microstrain as a result of turbulence at the frequency of the first flexible mode. This study[31] was the first large-scale demonstration of the use of smart materials to alleviate undesirable aeroelastic response and led to later TDT demonstrations that used smart materials to alleviate buffeting, to reduce rotorcraft loads and vibrations, and to improve the flight vehicle aerodynamic performance.

Benchmark Active Controls Technology (BACT) Program

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 objectives of the BACT program[32] were to perform wind-tunnel experiments in the TDT to obtain benchmark-quality data to validate computational fluid dynamics and computational-aeroelasticity codes, to verify the accuracy of current aeroservoelastic design and analysis tools, and to provide an active controls testbed for evaluating new and innovative control methodologies. The testbed was a pressure-instrumented, rigid semispan rectangular wing with three active control surfaces, a trailing-edge aileron surface, and upper and lower wing spoiler surfaces, powered by independent miniature hydraulic actuators. To obtain aeroelastic instabilities using a rigid surface, the model was attached to a pitch-and-plunge apparatus (PAPA) mount system (Fig. 13) that provided the bending and torsion degrees of freedom needed for classical flutter. During the initial TDT entry, wing and control surface steady and unsteady aerodynamic characteristics were measured, and the open-loop flutter boundary was defined across the TDT's Mach range. During follow-on tests, active flutter suppression systems based on multivariable robust control theories (H-infinity and μ-synthesis) and neural-network-based adaptive control schemes were evaluated using aileron and spoiler effectors separately and in combination. The most important accomplishments resulting from this program included first-time demonstration of flutter suppression using spoilers or combined aileron/spoiler control surfaces, first-time demonstration of a neural-network-based system for adaptive flutter suppression, and the development of a very extensive aerodynamic database for computational unsteady aerodynamic and aeroelasticity code validation.

Supersonic Transport (SST) Active Controls Program

In the mid-1990s as part of NASA's High Speed Research (HSR) program, a 1970's 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 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 Fig. 14. The thick umbilical beneath the model contains instrumentation wires.

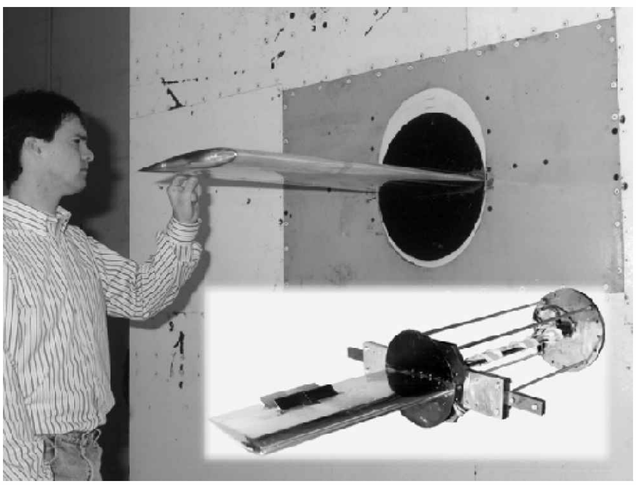

Fig. 13 BACT semispan model on the PAPA mount.

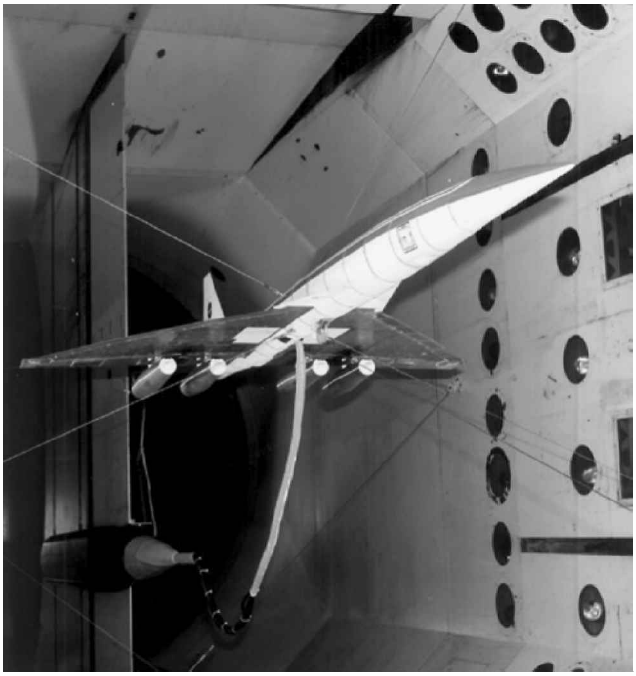

Fig. 14 SST model mounted on the two-cable-mount system.

Buffet Load Alleviation (BLA) Program

Buffeting is a phenomenon, which plagues high-performance aircraft, especially those with twin vertical tails. At high angles of attack, vortices emanating from the wing/fuselage leading-edge extensions burst, immersing the vertical tails in their wake. Buffet loads cause large oscillatory stresses to be applied to the vertical tails with a consequent loss of fatigue life. Beginning in 1995 and continuing into late 1999, a series of wind-tunnel tests were undertaken to determine the feasibility of applying piezoelectric actuators, active rudders, or other embedded aerodynamic vane devices for controlling structural buffeting. The testbed for this investigation, a rigid 1/6-scale, full-span, F-18 model with flexible vertical tails, is shown in Fig. 15 mounted to the TDT's centerline sting. Initial wind-tunnel tests performed at angles of attack up to 37 deg demonstrated that BLA concepts using either the rudder or piezoelectric actuators could significantly reduce the tail's response during buffet. At angles of attack up to about 30 deg, both systems were nearly equally effective in alleviating buffeting. However at higher angles of attack, the rudder effectiveness was limited by degrading flow-field conditions caused by the separated flow around the tail while the piezoelectric actuators maintained their effectiveness regardless of flight condition. Improved piezoelectric actuator devices, more efficient amplifiers, and blended concepts were evaluated during

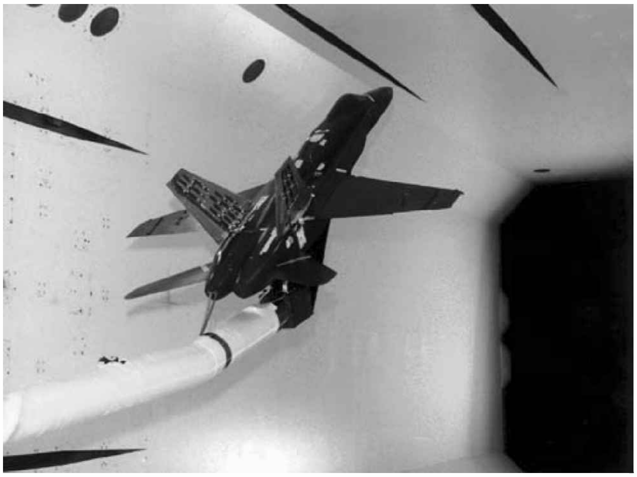

Fig. 15 BLA F-18 testbed on the TDT centerline sting.

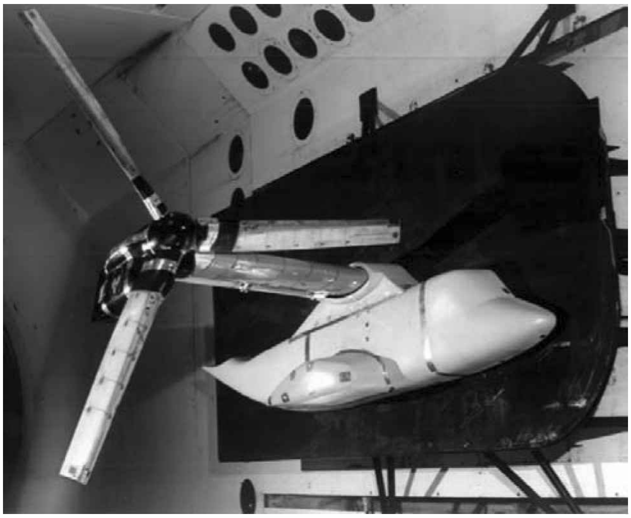

Fig. 16 WRATS tilt-rotor testbed in the TDT.

follow-on tests. The blended concept used an active rudder to control buffeting in the first bending mode, and piezoelectric actuator devices were used to control buffeting in the first torsion mode. Based on the findings of these test,[33] full-scale ground tests are now underway, and follow-on flight tests are being planned to further develop the BLA concept.

Wing and Rotor Aeroelastic Test System (WRATS) Program

In the mid-1990s an aggressive wind-tunnel test program was conceived and implemented to address tiltrotor aeroelastic research issues as identified by 1) the NASA Short-Haul Civil Tiltrotor Program, 2) U.S. rotorcraft industry with regard to the development of marketable tilt-rotor technologies, and 3) the U.S. Army with regard to the development of high-speed rotorcraft capabilities. A key to improving the marketability of current tilt-rotor systems is to reduce noise and weight and to improve aerodynamic performance. Such reductions and improvements generally result in an associated detrimental impact on the loads, vibrations, and aeroelastic stability of the vehicle. The objectives of the WRATS program are to validate improvements in aeroelastic stability using tailored composite-wing technology and to demonstrate the feasibility of using active control concepts to reduce fuselage and wing vibrations. The testbed for this activity was a 1/5-scale, refurbished, V-22 aeroelastic tiltrotor model (Fig. 16) on loan to NASA by the U.S. Navy. In collaboration with Bell Helicopter Textron, multiple tests that focused on a range of aeroelastic technical areas that have the potential for enhancing the commercial and military viability of tiltrotor aircraft were performed in the TDT. Emphasis was placed on the development of active and passive techniques for vibration control, stability augmentation, and increased aerodynamic performance. All tests were highly successful. During one test (Ref. 34), a load/vibration alleviation system that commanded the swashplate and an active flaperon simultaneously reduced the three-per-revolution wing beam, chord, and torsion loads, at multiple tunnel conditions, by 89 to 99%. The WRATS program is still ongoing and is expected to play an even greater role in the development of future tilt-rotor aircraft.

Smart Wing Program

In January 1995 the NGC (Northrop–Grumman Corporation) under a Defense Advanced Research Projects Agency-funded contract and with cooperation from the Air Force Research Laboratory and the LaRC initiated the Smart Wing program to address the development of smart technologies and to demonstrate novel actuation systems for improving the aerodynamics and aeroelastic performance of flight vehicles. This program was conducted in two phases, with two wind-tunnel entries per phase in the TDT. In Phase 1 two 16%-scale semispan models of an F-18 wing were tested. One wing utilized nickel-titanium shape-memory-alloy (SMA) torque tubes to twist the wing from root to tip and SMA wires or tendons to create hingeless control surfaces. The other wing incorporated conventional control surfaces to be used as a baseline for comparing the traditional and smart designs. During the tests, a maximum of 5 deg of wing twist was achieved using the SMA torque tube concept, resulting in an approximate 15% increase in rolling moment and 11% increase in lift relative to the untwisted conventional wing. For Phase 2 (Ref. 35) a full-span, 30%-scale, flexible model based on a NGC Unmanned Combat Air Vehicle concept (Fig. 17) was tested on the TDT sting. This model had hingeless control surfaces on the starboard wing and conventional control surfaces on the port wing. This test demonstrated that smart control surfaces, deformed using eccentuator arms driven by piezoelectric ultrasonic motors at high rates, had a very promising future and could provide a more effective means of achieving aerodynamic and aeroelastic control while improving the low observable characteristics of future air and space vehicles.

Unsteady-Pressure-Measurement Tests

A number of unsteady-pressure-measurement tests have been conducted in the TDT, and Ref. 14 by Schuster et al. documents 40 such tests. This section of the paper draws heavily upon this reference. Included in this section are unsteady-pressure-measurement tests supporting configuration research conducted in the 1970s and 1980s and benchmark model tests, high-speed research tests, and twin tail buffet tests conducted in the 1990s.

Clipped Delta Wing

This test is one example from a large number of unsteady-pressure-measurement tests that supported research of specific

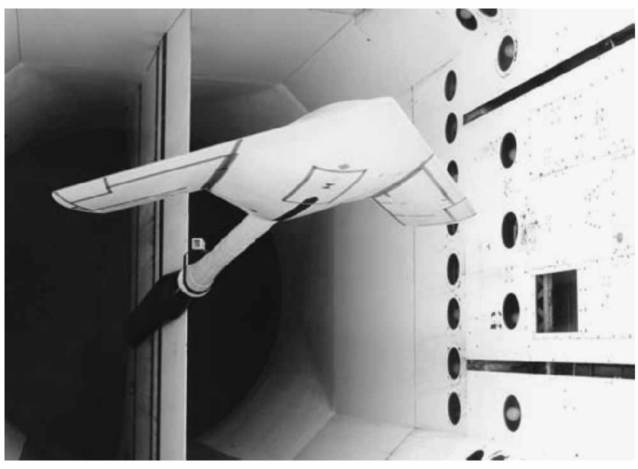

Fig. 17 Smart-wing UCAV model mounted on TDT sting.

vehicle configurations. Four test entries of a clipped delta-wing configuration were tested in the TDT over the five-year period beginning January 1976. The wing planform was derived from a proposed design of a supersonic transport known as the Boeing 2707-300. The leading-edge strake was removed from this configuration, as were all camber and twist. The wing thickness was also increased to 6% chord from the typical 2.5 to 3% chord to accommodate instrumentation. The clipped delta-wing wind-tunnel model had a circular-arc airfoil profile. This investigation involved the measurement of unsteady pressures while the wing underwent rigid-body pitching and TE control-surface oscillations. It was mounted to a splitter plate that was offset from the TDT wall, and the root of the wing was attached to an endplate that moved with the wing during pitching oscillations. The model was oscillated in pitch using a large, hydraulically driven, spring-system mounted behind the TDT wall. The mean angle of attack and the amplitude and frequency of pitch oscillation could be varied using this device. A miniature hydraulic actuator located in the wing drove the TE control surface. Pressure instrumentation for this wing was located in four well-populated rows of transducers located at the 34, 54, 69, and 84% span locations. A fifth, less-populated row, at 59% span, was included to improve the resolution of data near the edges of the control surface. All tests were performed in heavy gas with Mach number ranging from 0.40 to 1.12 and with static angles of attack ranging between 0.0 and 5.5 deg. All data for the static and first harmonic unsteady pressure distributions are provided in Ref. 36.

Aeroelastic Research Wing No. 2(ARW-2)

Two tests of the DAST ARW-2 wing were conducted in the TDT in the mid-1980s. These tests are additional examples of unsteady-pressure-measurement tests that supported research of specific vehicle configurations. Figure 18 shows the wing installed on the tunnel sidewall on a half-body fuselage. Both the fuselage and the wing were mounted on the remotely controlled turntable mechanism located on the tunnel sidewall. The wing was equipped with three hydraulically driven control surfaces, two inboard surfaces and one outboard aileron. The inboard surfaces were held fixed at 0 deg, and only the aileron was deflected statically and dynamically. The wing contour was formed from three different supercritical airfoil shapes located at the wing-fuselage junction, the wing planform break, and the wing tip. The wing was instrumented with 191 pressure transducers arranged in six chordwise rows and 10 accelerometers. Both steady and unsteady pressures were obtained using differential pressure transducers referenced to the tunnel's static pressure. Among the many investigations performed during the TDT tests of the ARW-2 wing were the measurement of unsteady pressures at several combinations of dynamic pressure and Mach number while the outboard aileron control surface was oscillated. These data are reported in Ref. 37.

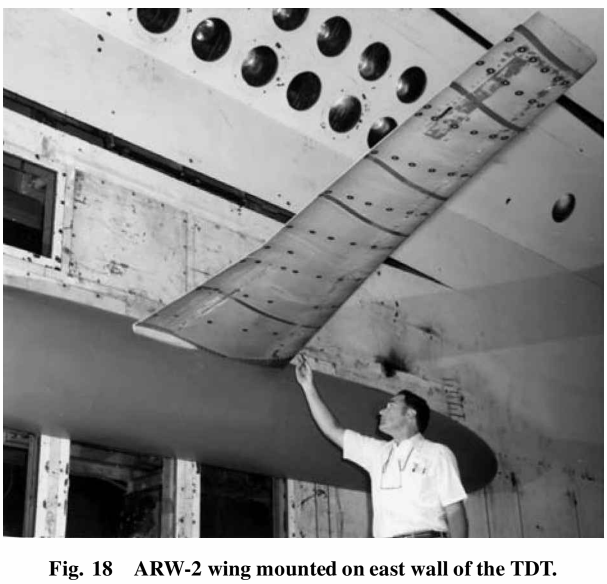

Fig. 18 ARW-2 wing mounted on east wall of the TDT.

Benchmark Models Program

The NASA Langley Benchmark Models Program (BMP)[38] was undertaken in the late 1980s and extended into the 1990s to provide experimental unsteady aerodynamics data, particularly at flutter conditions, for computational method validation, verification, and evaluation. The BMP program focused on making very high-quality unsteady pressure measurements on a geometrically simple wing so as to simplify modeling in the computational methods and to facilitate the interpretation of results. Three wings with the same rectangular planform were tested on PAPA at transonic flight conditions. Each wing had a different airfoil profile with different transonic performance characteristics. One model was built using a NACA 0012 airfoil, the second used a NACA 64A010 airfoil, and the third used a NASA SC(2)-0414 supercritical airfoil. The three wing models were constructed and instrumented similarly, with slight differences in detail. Each had a rectangular planform with a span of 32 in. plus a tip of revolution. The chord each was 16 in., giving the wings a panel aspect ratio of two. They were machined of aluminum to a very smooth finish. Detailed geometry measurements were performed for each of the wings along several sections so that as-tested geometries could be accurately modeled in computational methods. For each BMP model there were 40 unsteady pressure transducers located along the chord at 60% span and 40 located at 95% span. The models were tested both in air and in heavy gas at Mach numbers ranging from Mach 0.30 to 0.90 at angles of attack between -3 and $+5$ deg. A fourth benchmark model, the BACT model, was also tested in the TDT and also involved the measurement of unsteady pressures. The BACT model was described in the Active Controls section of this paper.

High-Speed Research Rigid and Flexible Semispan Models

Under the NASA High-Speed Research (HSR) program, a pair of models was developed to acquire static- and dynamic-pressure data for configuration and computational code evaluation. These models, known as the HSR Rigid Semispan Model (HSR-RSM) and the HSR Flexible Semispan Model (HSR-FSM), were virtually identical in geometry and instrumentation suites. The HSR-RSM was a very stiff model to minimize aeroelastic deflections, whereas the HSR-FSM was designed with a flexible structure aeroelastically scaled to expected flight vehicle specifications. The wings for these models were patterned off an existing High Speed Civil Transport planform known as Reference H. The models were constructed using composite materials that consisted of, for the RSM, a foam wing core with graphite epoxy skins, and for the FSM, fiberglass skins bonded to the core. Rigid fuselage fairings were constructed for the models. Each model had 131 in situ unsteady pressure transducers distributed in chordwise bands at the 10, 30, 60, and 95% span stations. Each model could also be tested with or without a pair of flow-through nacelles, and both had a hydraulically actuated inboard control surface that could be oscillated to generate unsteady aerodynamics data. The wings also had 14 accelerometers distributed throughout the wing planform, and the rigid fuselage fairing was instrumented with 120 steady pressure orifices at seven fuselage stations. Because the HSR-FSM was a structurally flexible wing, it included one torsion strain gauge and three bending strain gauges in its instrumentation suite, and photogrammetric deflection measurements were also performed on the wing tip. The models were mounted to a turntable located behind the east wall of the TDT that was used to control the model angle of attack. A variety of attachment devices was used to mount the models to the turntable. Both models were tested on a balance. The HSR-RSM was also tested on a pitch- and-plunge apparatus to simulate rigid-body, two-degree-of-freedom dynamics on the model. The HSR-FSM was only tested on the balance for subcritical conditions. A rigid strut replaced the balance for flutter testing. The HSR-RSM as it was mounted in the TDT is shown in Fig. 19. These two models were tested in the TDT a total of six times from 1994 to 1998, using both air and heavy gas as test mediums. Large steady and unsteady force and pressure

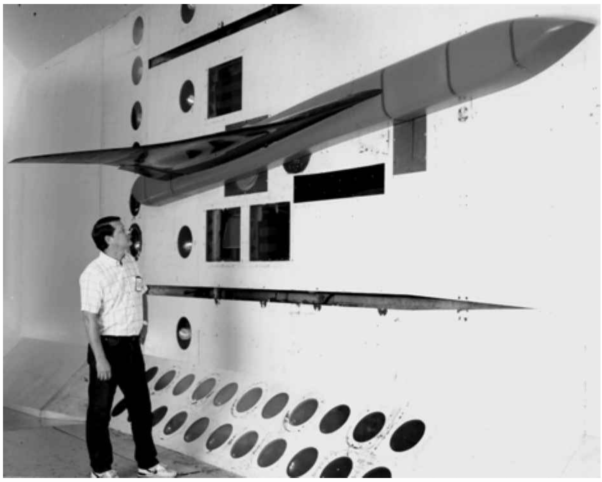

Fig. 19 HSR-RSM model mounted in the TDT.

databases[39] were obtained on these models in the form of angle-of-attack polars, steady control-surface deflection polars, and forced dynamic response caused by control-surface deflections.

Conclusions

The Transonic Dynamics Tunnel has made significant contributions to a better understanding of aeroelastic phenomena throughout the facility's 43-year history. Capabilities of the TDT that make it particularly suited to accomplishing successful aeroelastic testing have been described in this paper. The fundamental early contribution of the TDT was the provision of a capability for flutter-clearance testing of the (then) latest advanced vehicle concepts, particularly at transonic conditions. This paper has reviewed a selected sampling of flutter-clearance test projects for several key vehicle types grouped by decades for ease of presentation and conciseness. The paper further examined advances in the field of aeroelasticity through active control applications and unsteady aerodynamic measurements, again with selected examples of aircraft and research test projects conducted in the TDT over the years. It is anticipated that the TDT, with its heavy gas-testing capability, will continue to provide unique opportunities for carrying out and advancing the state of the art in experimental aeroelasticity into the foreseeable future. NASA remains committed to maintaining and improving the TDT as best as possible within the constraints of ever-changing political and administrative pressures.

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