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Aeroelasticity Research at Wright–Patterson Air Force Base (Wright Field) from 1953–1993

Terry M. Harris and Lawrence J. Huttsell
U.S. Air Force Research Laboratory, Wright–Patterson Air Force Base, Ohio 45433

Introduction

THE research and development facilities of Wright–Patterson Air Force Base (WPAFB, known earlier as Wright Field) have played a substantial part in the initiation, direction, development, and transfer of technologies related to flight vehicle aeroelasticity. The connection between WPAFB and aeroelasticity research began in the 1920s and has continued into the 21st century. This paper is not intended to be an inclusive review of the history of developments in aeroelasticity. The historical reviews by Garrick and Reed,[1] Bisplinghoff,[2] and Collar[3] are excellent accounts of developments in aeroelasticity. Early encounters with problems of static aeroelasticity, flutter, and dynamic loads are also documented in the book by Flomenhoft.[4] The WPAFB-sponsored research contributed significantly to advancements in aeroelasticity, and an attempt is made herein to summarize this research.

Pre-1953

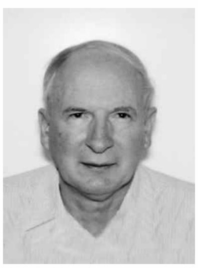
Work in prediction and prevention of aeroelastic instabilities was being accomplished in the 1920s at McCook Field, Dayton, Ohio, the predecessor of WPAFB.[5,6] By the late 1930s a Flutter and Vibrations Section had been established within the Aircraft Laboratory at what was then known as Wright Field.[6] This office was active through the WWII years and beyond in a hands-on approach to assisting the aircraft manufacturers with the many flutter and vibration problems starting to occur in higher-performance aircraft. Much of the aeroelastic testing in these early years had to be done in flight because the authorities that controlled wind-tunnel operation would not permit the testing of flexible models that ran the risk of damaging the tunnels upon breakup.[7]

One of the most important products of this team was the 1942 in-house technical report by Lt. Ben Smilg and Lee Wasserman commonly known as "4798," that is, "Application of Three-Dimensional Flutter Theory to Aircraft Structures."[8] This report provided nondimensional aerodynamic coefficients as functions of reduced frequency and were tabulated for various values of commonly used flutter parameters. The employment of these tables greatly decreased the labor and time required for flutter computations. "4798" helped transition the theory of Theodorson, Garrick, and Kussner into production-line engineering analysis methods needed to prevent flutter. Industry used the tables extensively, expanded the method to include modal degrees of freedom, and employed the report as a manual to train new aeroelasticians. The application of the 4798 method significantly reduced the occurrences of aileron, elevator, and rudder flutter problems. Tab flutter analysis was addressed in another in-house report.[9] This report contained elaborate tables of aerodynamic coefficients for control surfaces and, again, was used widely in the aircraft industry. Cases addressed included spring-controlled tabs, geared tabs, and trim tabs. "5153" was particularly timely and useful in determining the causes and remedies for the rash of spring tab flutter cases that occurred in the late 1940s and early 1950s.

The 1950s

The late 1940s and 1950s saw the de facto training by the Flutter and Vibrations Section of many of the nationally known aeroelasticians. [Raymond L. Bisplinghoff, the distinguished authority and

Terry M. Harris is the Chief of the Design and Analysis Methods Branch, Structures Division, Air Vehicles Directorate, Air Force Research Laboratory at Wright–Patterson AFB, Ohio. He received a B.S. in aeronautical and astronautical engineering from Purdue University in 1972 and an M.S. in aerospace engineering from the University of Dayton in 1979. As an engineer in the Directorate's Design and Analysis Group in the 1970s and the Aeroelasticity Group in the 1980s, Mr. Harris gained considerable experience in aeroelasticity and aeroservoelasticity. He was the Air Force program manager for numerous programs for the development of flutter optimization methods and wind tunnel tests involving active and adaptive flutter suppression for aircraft carrying external stores. As Leader of the Aeroelasticity Group from 1987 to 1997, Mr. Harris oversaw the development of many aspects of aeroelasticity-related technologies. Mr. Harris has authored or coauthored over thirty publications, including seven national and international conference papers and two *Journal of Aircraft* articles. He is a Senior Member of AIAA.



Lawrence J. Huttsell is the Aeroelasticity Team Leader in the Design and Analysis Methods Branch, Structures Division, Air Vehicles Directorate, Air Force Research Laboratory at Wright–Patterson AFB, Ohio. He received a B.S. in mechanical engineering from the University of Louisville in 1967 and an M.S. in aeronautical and astronautical engineering from the Ohio State University in 1972. Mr. Huttsell has considerable experience in unsteady aerodynamic, aeroelasticity, and aeroservoelasticity. He has led several national and international programs: unsteady pressure measurement programs with the Netherlands, active flutter suppression wind tunnel tests (Germany, France, England, and Israel) and a USAF/German flight test demonstration, and a joint AF/NASA NASP government work package for panel flutter. He has served on Executive Independent Review Teams and consulted on system problems in the area of unsteady aerodynamics, aeroelasticity, buffet, and aeroservoelasticity. He is currently leading an in-house team for computational aeroelasticity. Mr. Huttsell has over 70 publications, eight of which are in archival journals. He is an Associate Fellow of AIAA.

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educator in aeroelasticity, served as a consultant in the Wright Field Flutter and Vibrations Section in 1941–1943 (Ref. 2).] Ray Peloubet, for many years the leader of the General Dynamics, Fort Worth, Texas, structural dynamics team, spent his formative years in the Flutter and Vibrations Section, as did Henry Katz of the McDonnell Corporation, Leon Tolve of Lockheed, and Herb Voss of Boeing. Furthermore, at about this time Lee Wasserman departed U.S. Air Force service and formed his own flutter model design company, Dynamic Devices, in itself a valuable asset to aeroelasticity research for many years.[10] Wasserman's flutter models and engineering support significantly helped in avoiding flutter and assuring flight safety.

During the 1950s, the Flutter and Vibrations Section sponsored a large number of wind-tunnel tests, especially in the investigation of transonic phenomena. These tests provided valuable research data needed to support the new systems in the absence of dependable analysis methods. 1952–1956 saw transonic flutter trends established by flutter model tests on a wide variety of wing planforms in investigations into the effects of sweep, aspect ratio, tip pods, and engine location. Flutter tests were also conducted to investigate control surface flutter and trim tab flutter. Results from this series of wind-tunnel tests were used in the design of the F-100, F-105, F-106, B-52, and B-58 (Cooley, D. E., "Major Milestones in Flutter Prevention Technology," unpublished document). In the period 1952–1960, all-moveable stabilizer flutter characteristics were established through model testing. (Transonic results are documented in Ref. 11.) Results were used in the design of the F-100, F-101, F-105, F-4, and C-141 (Cooley, D. E., "Major Milestones in Flutter Prevention Technology," unpublished document). This research originated as an in-house activity and continued as a contract with Bell Aircraft. Tests, and analyses specifically for T-tail flutter were run from 1952–1960; results were applied to the design of the Matador missile, F-104, C-141, DC-9, and Boeing 727 (Cooley, D. E., "Major Milestones in Flutter Prevention Technology," unpublished document).[12,13]

In 1956, the Flutter and Vibrations Section sponsored a series of transonic flutter model tests with Cornell University for 45-deg swept wings, straight wings, and 60-deg delta wings.[14–16] These tests provided a set of flutter data for a wide range of nondimensional flutter parameters, which formed a valuable database for aeroelastic design and analysis.

In the mid-1950s the loss of an F-101 fighter in an incident of panel flutter resulted in a series of investigations that continued through 1967. The objective of these efforts was to develop suitable prediction methods, to produce reliable and repeatable experimental data, and to develop design criteria.[17,18]

The 1960s

The 1960s saw an emphasis on supersonic and hypersonic aeroelastic wind-tunnel testing—both for lifting surface flutter and for panel flutter—pushed by the need for technology development for the Dyna-Soar orbiting aerospace plane, the XB-70 supersonic bomber, and the X-24 lifting-body vehicles. In March of 1963, the WPAFB aeroelasticity research office became part of the newly established U.S. Air Force Flight Dynamics Laboratory (AFFDL). Much hypersonic research was accomplished through the AFFDL Project ASSET (Aerothermodynamic/elastic Structural Systems Environmental Tests), which employed Thor and Thor-Delta boosters to fire glide models down the Eastern Test Range.[7] The ASSET gliders were flat-bottomed, 69-in. (1.7526 m) long test articles with 70-deg delta wings. Included in the major goals of ASSET were the obtaining of panel flutter data and oscillatory pressure data at high Mach numbers.

Unsteady aerodynamics research and design for aeroelastic prediction methods was a key research area throughout the 1960s.[19–26] The importance of interference effects had been shown for T-tails. In 1966 subsonic flutter model tests by Boeing[27] showed the serious deficiency in the state of the art for configurations with variable sweep wings. One of the first experimental programs in the transonic regime was defined in 1966 by the AFFDL and was performed by the Cornell Aeronautical Laboratory.[28] In 1968 the AFFDL conducted an in-house test program to further explain the mechanism of wing-tail flutter.[29,30] The wind-tunnel model is shown in Fig. 1 with various wing/tail positions. These tests provided more complete trends with systematic variations of controlling parameters, defined flutter prevention criteria, and provided experimental data for code validation.

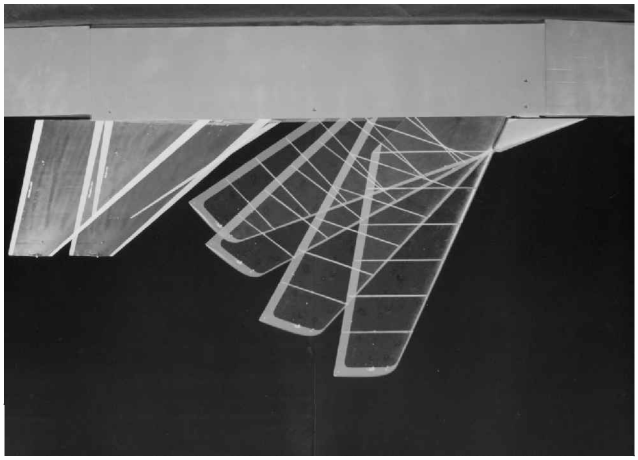

Fig. 1 Subsonic wing-tail flutter model with various wing/tail positions.

Also during these years, the AFFDL first began its development of finite element analytical methods, such MAGIC,[31] a displacement method approach developed through Bell Aerospace. Aeroelasticians became interested in the development of these programs when it was shown that the stiffness matrices generated, coupled with eigenvalue solvers and mass information, gave reasonable mode shape and frequency results that could be employed in flutter and dynamic response analyses.

The 1970s

During the 1970s, major improvements in linear unsteady aerodynamic prediction tools were made. Based on the success of the planar doublet-lattice code developed by Albano and Rodden,[32] the AFFDL sponsored the development of a doublet-lattice code for nonplanar surfaces through the Douglas Corporation. The H7WC doublet-lattice code[33] was a preliminary version of the method, which accounted for body/lifting surface interference by direct application on nonplanar lifting surface elements, whereas N5KA,[34] the "final" version, used an image system and an axial singularity system to account for the effects of the body. However, demand for a viable unsteady aerodynamic tool was so great that the AFFDL distributed H7WC in advance of N5KA. By happenstance, H7WC became probably the most widely distributed unsteady aero code of all time and, further, was incorporated into structural analysis and design tools (FASTOP, NASTRAN, etc.). In the area of supersonic code development, the AFFDL sponsored through Boeing the development of an improved Mach Box code for nonplanar wings and wing-tail configurations.[35,36]

There was a rapid development of numerical methods for computing aerodynamic forces for small-disturbance transonic flows about oscillating airfoils and planar wings. Based on the procedure first introduced for steady flows by Murman and Cole,[37] Traci et al. and Farr et al. developed computer programs (STRANS and UTRANS)[38,39] for two-dimensional small-disturbance steady and unsteady transonic flows about oscillating airfoils. The finite difference relaxation method was extended to oscillating planar wings[40,41] and applied in a transonic flutter analysis of a rectangular wing in Ref. 42. During this period, Ballhaus and Goorjian[43] developed a computer code, LTRAN2, which solves the two-dimensional, nonlinear, low-frequency, small-disturbance transonic flow equation by an alternating-direction-implicit algorithm. This popular two-dimensional code was used by many investigators and improved for unsteady aerodynamic and aeroelastic applications. Some of the AFFDL-sponsored applications are discussed in Refs. 44–46.

Wind-tunnel testing was performed to validate the various unsteady aerodynamic prediction methods. The AFFDL and the U.S. Air Force Armament Test Laboratory sponsored unsteady aerodynamic testing of an F-5 wing model with and without external stores in the Dutch National Aerospace Laboratory (NLR) tunnel in Amsterdam.[47–50] The store represented an AIM-9J missile and was successively mounted at the wing tip and on an underwing pylon. These test results quickly became an international standard for validation of the newly developing computational unsteady aeroprediction methods.

Automated tools were being developed, which combined fully stressed strength design with other, namely, flutter, constraints. The AFFDL sponsored the development of FASTOP (Flutter and Strength Optimization Procedure)[51] through the Grumman Aerospace Corporation in 1975. This program contained a doublet-lattice (subsonic) routine and a Mach-box (supersonic) routine for iterative, converging flutter and strength design of metallic structure. By 1978, FASTOP-3 (Ref. 52) was released, which extended the method to composite structure.

The application of advanced filamentary composites to aircraft structures in the 1960s, such as the proposed composite wing for the F-111 Transonic Improvement Program, later called TACT (Transonic Aircraft Technology) emphasized the need for automated preliminary design tools. The first method to address this need was tailoring and structural optimization (TSO), developed by General Dynamics under AFFDL sponsorship. TSO incorporated aeroelastic tailoring as its primary objective, that is, "the embodiment of directional stiffness into aircraft structural design to control aeroelastic deformation, static and dynamic, in such a fashion as to affect the aerodynamic and structural performance in a beneficial way."[53] The AFFDL sponsored numerous improvements to TSO and validated the program through several series of wind-tunnel tests and design studies extending into the early 1980s, both in-house and on contract.[54,55]

At this time AFFDL aeroelasticians were participating in the TACT program and assisting in the design of the Highly Maneuverable Aircraft Technology (HiMAT). The HiMAT remotely piloted vehicle, built by Rockwell for testing at the NASA Dryden Research Center, Edwards, California, was the first modern aircraft to fly with aeroelastically tailored lifting surfaces.

A major application of aeroelastic tailoring was in the design of forward-swept wings, in which, for example, low divergence speeds could be eliminated through proper orientation of the wing's composite fibers. The design aspects of forward-swept wings were being addressed in house through analytical studies and wind-tunnel tests while the AFFDL oversaw for DARPA (Defense Advanced Research Projects Agency) feasibility studies with General Dynamics, Grumman, and Rockwell, followed by wind-tunnel demonstration programs conducted by Grumman[56] and Rockwell.[57] These investigations formed the confidence base for the X-29, a forward-swept wing fighter-size flight demonstrator (Fig. 2), the development of which was monitored for DARPA by an AFFDL advanced development program office in the 1980s. Aeroelastic tailoring and flutter optimization methods were used extensively in the design of the X-29 to preclude divergence and body-freedom flutter.

One of the most prevalent aeroelastic problems facing the U.S. Air Force over the years was the reduction in flutter speeds suffered by wings carrying external stores. During this period, the AFFDL attacked the problem of predicting wing/store flutter, with the knowledge that many aircraft (F-4, F-16, etc.) were capable of carrying many thousands of store combinations. With the Air Force Seek Eagle Office (responsible for stores clearance) as the primary customer, the AFFDL sponsored the development by Northrop of perturbation methods[58] and by McDonnell Douglas the computer code FACES (Flutter of Aircraft with External Stores).[59,60] The perturbation technique was developed to expedite flutter clearance of many store combinations by rapidly screening out the major stores combinations in a typical stores flutter study. Significant flutter characteristics are singled out by the method, and relatively few new baseline analyses were needed to allow this perturbation study to complete the flutter trend in a new range. The FACES computer program was

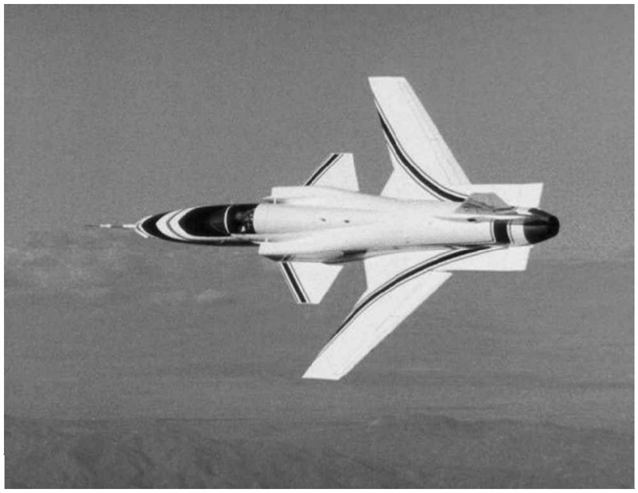

Fig. 2 X-29 flight demonstrator aircraft.

Fig. 3 YF-17 flutter suppression model in the wind tunnel.

developed especially for simplified and efficient aircraft/external store flutter analyses.

Another approach to the wing-store flutter problem was through active flutter suppression, that is, the commanding of control surfaces, through a control law, to oscillate at a counteracting force and phase. The first of AFFDL's analytical investigations was with McDonnell Douglas, in which flutter suppression methods were applied to the F-4.[61] Soon thereafter, the AFFDL commissioned Northrop with the design of a wing-store flutter suppression system for a half-span, wall-mounted model of the YF-17 fighter shown in Fig. 3. The model was built by Dynamic Devices and was used in a long series of experiments in the NASA Langley Research Center's 16-ft Transonic Dynamic Tunnel (TDT).[62,63] The YF-17 international flutter suppression wind-tunnel test program sponsored by the AFFDL involved the development of control laws and verification testing, again in the NASA Langley TDT. Under this international cooperative program, MBB (Messerschmitt-Bölkow-Blohm) under German sponsorship, the French ONERA (Office Nationale d'Etudes et de Researches Aerospaciales), the Israeli Technion Institute under a NASA grant, Northrop Corporation under AFFDL contract, British Aerospace under Royal Aeronautical Establishment sponsorship, and in-house AFFDL researchers designed and evaluated control laws for testing.[64] The control laws for active suppression of an explosive wing-store flutter case were tested in October 1979. Results were very promising and demonstrated substantial potential for this technology.

Other active flutter suppression contracts were awarded to Rockwell International for developing control laws for the HiMAT unmanned vehicle[65] and to General Dynamics to develop flutter suppression methods for the F-16.[66] The first American flight test (Fig. 4) of active flutter suppression occurred earlier when the

Fig. 4 B-52 CCV flight-test aircraft.

Fig. 5 F-4 active flutter suppression flight-test aircraft.

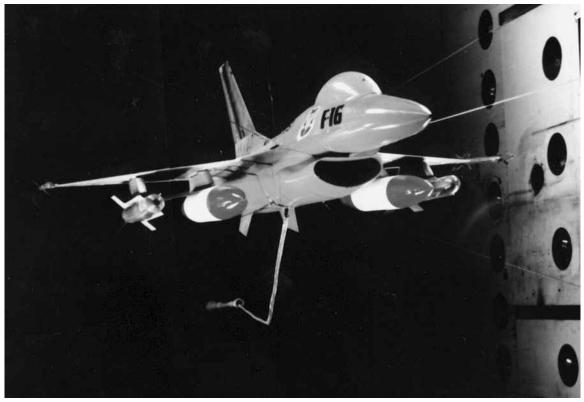

Fig. 6 F-16 flutter suppression model in the wind tunnel.

AFFDL sponsored the implementation of such a system during the B-52 control-configured-vehicle (CCV) flight tests.[67,68]

Adverse aeroelastic interaction with the flight vehicle control system led the U.S. Air Force to perform research in the prevention of these aeroservoelastic instabilities.[69] The AFFDL sponsored a number of efforts with McDonnell Douglas[70] and General Dynamics[71] in an effort to find efficient ways to predict and prevent these occurrences. In-house efforts to achieve a viable, efficient aeroservoelasticity (ASE) prediction tool for both analog and digital control systems continued into the 1980s.[72]

1980–1993

By the early 1980s, the research arm of the U.S. Air Force was called by then AFWAL (Air Force Wright Aeronautical Laboratories), and, as of October 1988, it was called WRDC (Wright Research and Development Center). As just described the AFFDL portion of AFWAL was performing in-house validation tests of aeroelastic tailoring techniques and wind-tunnel tests of forward-swept wing designs, in parallel with the X-29 development.[73,74] The X-29 demonstrator brought together the following advanced technologies: forward-swept wing, close-coupled canard, aeroelastic tailoring, advanced structures and composites, relaxed static stability, fly-by-wire digital flight control, and advanced integrated subsystems.

In January 1980 the AFFDL portion of AFWAL was redesignated the Flight Dynamics Laboratory (FDL). In that year another international effort in flutter suppression reached its culmination. The FDL, with McDonnell Douglas as its contract support, in cooperation with the German Ministry of Defense designed and implemented a flutter suppression system that was flight tested on a German Air Force F-4F (Fig. 5) with external stores.[75]

In the early 1980s the FDL continued its development of flutter suppression techniques, through Northrop and the YF-17 model, and through General Dynamics employing a quarter-scale, full-span, cable-flying F-16 model designed for testing in the Langley TDT (Fig. 6). By the mid-1980s the FDL changed its emphasis in active flutter suppression to adaptive flutter suppression, that is, control laws that would automatically adjust themselves for changing flight condition and store configuration. Northrop Corporation again was contracted to design a flutter control system for the YF-17 model.[76,77] During the related series of tests, a wing-tip store was released, which resulted in a low flutter speed configuration. The control system detected the changed dynamics and implemented a new control law that successfully suppressed the flutter response. Later that decade General Dynamics was contracted for a series of adaptive flutter suppression investigations for their F-16 wind-tunnel model. These developments culminated in the testing of a near fully adaptive flutter suppression system for the F-16 model.[78]

In addition to ASE instabilities and active flutter suppression research, a third area of investigation into control system/aeroelastic interaction started in the early 1980s and continues today. On the basis of a Rockwell International proposal to the FDL, the active-aeroelastic-wing (AAW, at the time called active flexible wing) concept was developed and wind tunnel tested in the NASA Langley TDT. This concept employs multiple control surfaces as tabs, using the power of the airstream to shape the wing to achieve the desired effect, such as improved roll rates or efficient cruise. Several contracted investigations, plus tests on a subsonic wind-tunnel model designed and fabricated by FDL aeroelasticians and based on the F-16 Agile Falcon,[79] showed total aircraft takeoff weight, depending on configuration, could be reduced substantially using this technology. AAW technology was shown to be so promising that the FDL initiated a flight demonstration program with Boeing implementing the concept on a modified F/A-18.[80]

Throughout this later period the FDL (later called the Flight Dynamics Directorate) researchers were concerned with investigating ways to predict and control buffeting of the twin tails of fighter-type aircraft at high angles of attack and of preventing damage caused by this phenomenon. The FDL sponsored investigations in the 1980s and 1990s, including numerous wind-tunnel tests[81,82] to obtain buffet data. The eventual goal will be a flight demonstration of active suppression systems actuating either the existing rudders or piezoelectric panels integral to the skin of the vertical tails (or both concepts combined).

Another area of investigation involved large amounts of wind-tunnel testing under a joint effort with NASA. This program included the design, fabrication, and test of NASP (National Aerospace Plane) components. The FDL designed and sponsored the fabrication of both all-moveable wing/stabilator and vertical tail aeroelastic models,[83] and a panel flutter model.[84] The lifting surface models were tested in the NASA Langley TDT, and the panel flutter model was tested in the Unitary Tunnel at NASA Langley.

In the field of unsteady aerodynamics, the FDL sponsored numerous investigations involving the transonic small disturbance (TSD) theory. This research (1978–1982) resulted in the development by Boeing of the XRAN3S computer code.[85] It was the first operational code to incorporate both the effects of unsteady flow and structural flexibility in a three-dimensional aerodynamic solution of a nonlinear potential equation, specifically the inviscid transonic modified small disturbance equation. XTRAN3S demonstrated the advantage of the TSD formulation in terms of relatively inexpensive computational cost, gridding simplicity, and the potential for realistic aircraft configurations.

Also during this time, the FDL sponsored a number of wind-tunnel tests to obtain unsteady pressure data for validating the new unsteady aerodynamic codes. Unsteady transonic pressure measurements were performed on a semispan model of a transport type supercritical wing, oscillating in pitch.[86] The tests of this Lockheed, Air Force, NLR, and NASA (LANN) model were conducted in the NLR wind-tunnel. In addition, the FDL and the Dutch Ministry of Defense sponsored a wind-tunnel program in 1992 to investigate the unsteady aerodynamic aspects of transonic high-incidence flows over a simple straked-wing model.[87–90] The model was oscillated sinusoidally in pitch at various amplitudes and frequencies for mean angles of attack from 4 to 48 deg. In addition, maneuver-type transient motions of the model were tested. Both the LANN and simple straked-delta-wing models were tested in the NLR wind tunnel in Amsterdam. The data from both of these tests have been selected by Research and Technology Organization (formerly AGARD) as a standard for validating unsteady aerodynamic computations.[91]

The FDL went on to sponsor the Lockheed–Georgia Company in the development of the Euler/Navier–Stokes three-Dimensional Aeroelastic (ENS3DAE) method.[92,93] ENS3DAE solves the full three-dimensional compressible Reynolds averaged Navier–Stokes equations, the thin-layer approximation to these equations or the Euler equations using an implicit approximate factorization algorithm. A linear generalized mode shape structural model is closely coupled with the aerodynamic method to analyze structurally flexible vehicles. A series of improvements has been made by Lockheed, the FDL, NASA Langley, and Georgia Tech to enhance the code's capabilities and computational efficiency.

Building upon the structural optimization codes of the 1970s, the FDL went on to sponsor through Northrop the development of the ASTROS (Aerospace Structural Optimization System) code.[94] This extensive program made use of the most modern programming methods of the time to provide for the design of air vehicle structures in the presence of static loads, aeroelastic, deflection, and buckling constraints. ASTROS has been independently judged as an excellent research tool and has been distributed to over 100 companies, universities, and laboratories.

Summary

In an effort to help solve existing problems and preclude future surprises, the research arm of the U.S. Air Force, housed at Wright–Patterson Air Force Base, has stood in the forefront of aeroelasticity research and design, through contracted and in-house investigations, "paper" studies, wind-tunnel experiments, and flight tests. The individuals involved in this research also contributed to the military specifications, safety reviews, and accident investigations. The research efforts flow beyond the 40-year span of this report and continue today. The organization (currently known as the Air Vehicles Directorate of the Air Force Research Laboratory, AFRL) serves as the office of primary responsibility in developing advanced technologies to predict and prevent adverse aeroelastic problems and in employing aeroelastic concepts to enhance future designs.

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The authors wish to thank Dale E. Cooley and Michael H. Shirk—the "old hands" of the Aeroelasticity Section at Wright–Patterson Air Force Base—for their long memories, and especially Walter J. Mykytow, whose career in aeroelasticity at Wright–Patterson Air Force Base began in 1939 and extended (as a consultant) into the 1980s. Others with long memories who deserve our thanks include Ed Pendleton, Jim Olsen, Ken Griffin, and Max Blair.

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