USB applications. Another interesting concept currently under study is the use of many small "distributed" propulsion units that spread out the induced circulation lift across the wing span. It is expected that many small engines would generate noise at high frequencies, which typically mix with entrained flow much faster and might further reduce the noise for powered-lift systems.

A currently emerging NASA interest in developing the technology required for futuristic runway-independent fixed-wing transport aircraft addresses the benefits that can accrue by the operation of STOL aircraft. If, as predicted by the FAA, commercial air traffic continues to increase in the new millennium, a fresh look at the ability of STOL technology to relieve limitations of the future transportation system will be in order. Thanks to research conducted by NASA and its partners over three decades ago, the technology appears to be ready for applications.

Control of Aeroelastic Response: Taming the Threats

Concept and Benefits

The flexible characteristics of aircraft structures can result in dramatic, sometimes catastrophic, behavior of civil and military aircraft. When the inherent structural flexibility of an airplane interplays with the aerodynamic, gravitational, and inertial forces and moments acting on it, steady or dynamic deflections or oscillatory motions of aircraft components can result. Such interactions can cause reduced structural life of airframe components, undesirable coupling with control systems, severe reductions in ride quality, and even abrupt and violent structural failures. The three most important aeroelastic phenomena for aircraft designers are loads (static and dynamic), flutter, and buffet. The subject of loads is concerned with the a structural airframe's ability to accommodate external loads encountered during the flight envelope, with emphasis on the airplane's performance, stability, control, and structural integrity. Flutter is a dynamic aeroelastic

Photographs of B-52 airplane on the ground and in flight graphically show the structural flexibility of the wing.

phenomenon that involves the interactions of a structure's elastic and inertia characteristics with the aerodynamic forces produced by the airflow over the vehicle. It is a self-excited oscillation of the aircraft structure involving energy absorbed from the airstream. When an aircraft's elastic structure is disturbed at speeds below flutter speed, the resulting oscillatory motions decay. However, when the structure is disturbed at speeds above flutter speed, the oscillatory motions will abruptly increase in amplitude and can rapidly lead to catastrophic structural failure. In some instances, flutter oscillations are limited to just a single airplane component such as the wing, while in other instances the oscillations may be considerably more complex, involving coupling of natural structural modes of wing, fuselage, and empennage motions. Buffet is a randomly varying structural response often triggered by intense and chaotic aerodynamic forcing functions associated with stalled or separated flow conditions. Fluctuating pressures present during buffet conditions can cause highly undesirable responses from wings, fuselages, pod-mounted engine nacelles, and empennages. Dynamic loads experienced during buffet can lead to pilot fatigue or structural fatigue, resulting in serious reductions in the anticipated structural life of airframe components.

The traditional solution to these aeroelastic issues has been primarily to stiffen the airframe structure, thereby either eliminating undesirable excitation of structural characteristics or ensuring that the undesirable phenomena occur only at conditions beyond the flight envelope. Unfortunately, this "passive" approach involves adding additional structure to stiffen that which is already sufficiently strong to carry normal flight loads. These weight penalties adversely affect manufacturing and acquisition costs, mission performance, and add to operational costs throughout the life of the airplane.

The state of the art in aeroelasticity has steadily advanced to the point that, by the 1960s, many fundamental physical phenomena, predictive methodologies, and processes for the resolution of problems had been identified for conventional airplanes. Researchers began turning attention to the use of "active" controls technology (ACT) to favorably modify the aeroelastic response characteristics of aircraft to permit structural weight reduction, optimal maneuvering performance, and multimission capability. As the name implies, ACT uses aircraft control surfaces that are linked to a computer and sensors in a manner to automatically and immediately limit any unwanted motions or aerodynamic loads on the aircraft structure.

The potential benefits of active control of aeroelastic response are significant. For example, if the stiffening requirements for wings can be reduced, the weight reduction could be absorbed in additional passengers and payload revenues for commercial transports. If an active flutter suppression system was incorporated in the design of an advanced configuration, such as a highly

swept supersonic transport, the substantial weight savings translates into increased range or payload, with a significant reduction in airplane direct operating costs. Active control of tail buffet for highly maneuverable fighter aircraft could result in weight savings, increased structural service life, and reduced maintenance and cost.

The transition of technology for effective control of aeroelastic response from laboratory experiment to extensive fleet applications has involved a few success stories, but the general application to aircraft to date is relatively limited. For example, gust load alleviation using active control laws on commercial transports has only been implemented on aircraft such as the Lockheed L-1011 and the Airbus A320, and active flutter suppression has not achieved operational status on any civil aircraft. In the early 1970s, the first practical demonstration of active flutter suppression was carried out by the U.S. Air Force in its Load Alleviation and Mode Stabilization (LAMS) Program. A Boeing B-52 bomber was equipped with an active flutter suppression system that was demonstrated during flight tests to increase the airplane flutter speed by at least 10 kts. As will be discussed, another success story has been the development and application of an active system by McDonnell Douglas (now Boeing) to suppress an unacceptable limit-cycle structural oscillation exhibited by preproduction F/A-18 aircraft with certain external store loadings. The system was subsequently incorporated into the production control system for fleet F/A-18 aircraft.

Challenges and Barriers

Disciplinary Challenges

The primary disciplinary challenges for active control of aeroelastic response are requirements for highly accurate predictions of critical aerodynamic and structural phenomena at test flight conditions of interest; reliable prediction and analysis methods for the aeroelastic interactions that occur; and the design of robust, redundant control systems that are tolerant to parametric uncertainties. The consequences of inadequate or invalid design methods are not acceptable, and concepts such as active flutter suppression are viewed as inherently high risk.

Active control of aeroelastic response is dependent on the specific configuration and flight condition under analysis. For example, design of an active flutter suppression system for a commercial transport, with a typical high-aspect-ratio wing, may focus on the interactions between the first few structural vibration modes of the wing, usually relatively simple combinations of bending and twisting of the structure. However, flutter mechanisms of a low-aspect-ratio fighter design will be more complicated because the structural vibration modes are more complex, including interactions of basic wing motions with the motion of a variety of different pylon-mounted external stores.

Paramount to all these design challenges is the difficulty of precisely predicting the complex, steady and unsteady, aerodynamic characteristics present at the high subsonic or transonic conditions where the onset of flutter becomes most critical.

Operational and Economic Challenges

Operational issues pose special challenges for active control systems. Clearly, systems used for flutter suppression must be reliable and designed to be totally failsafe, with requirements similar to those for automatic control systems used in the automatic stabilization and control of highly unstable airplanes. The design of such systems clearly calls for redundancy, and multiple systems will be required for safety. Other concerns for active controls include manufacturing and maintenance costs and additional complexity. The active control system will have to be as reliable as the structure that it replaces.

As is the case for any advanced technology, the use of active control for tailoring aeroelastic response will be successful only if the potential benefits are feasible from a cost/benefit perspective. The requirements for robust, redundant sensors, maintenance schedules and costs, environmental protection, and certification compliance and costs must be favorably addressed before widespread application of the technology can occur.

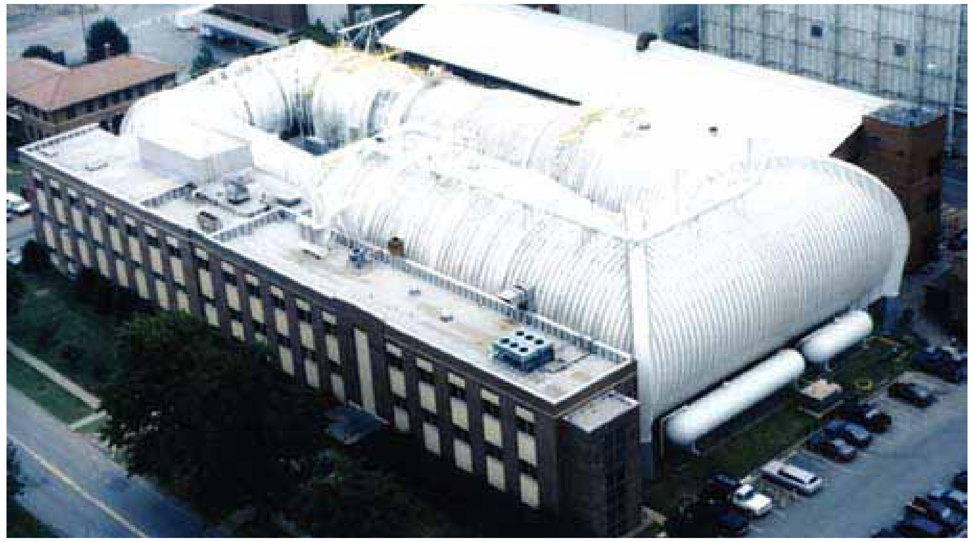
Langley Activities

Langley Research Center is the lead NASA Center for research in structures and materials, and it is internationally recognized as a world leader in aeroelastic research. This reputation stems from a rich legacy of contributions in technology, cooperative research, consultation and problem solving, and unique experimental facilities. Langley's efforts in structures, materials, and loads as an NACA laboratory prior to 1958 are well documented and will not be discussed herein. Rather, several major contributions and research activities since the early 1960s are highlighted as examples of the critical role Langley researchers and facilities played in advancing the state of the art in active and passive control of aeroelastic response. Although Langley's research accomplishments have included both fixed-wing and rotary-wing vehicles, the discussion is limited to research on fixed-wing aircraft. Two areas of activities are overviewed: contributions and ongoing aeroelastic research over the last 35 years by the staff and facilities of the Langley 16-Foot Transonic Dynamics Tunnel (TDT); and the NASA ACT Program of the late 1970s. The discussion draws extensively on the excellent summaries of Boyd P. Perry, III, and Ray V. Hood, Jr. (see bibliography).

The 16-Foot Transonic Dynamics Tunnel

Without question, the centerpiece facility for Langley's research in aeroelasticity is the Langley TDT. Converted from an existing 19-Foot Pressure Tunnel, with operations commencing in 1960, it is the only facility in the world capable of studying a full range of aeroelastic phenomena at transonic speeds. Research in aeroelasticity in the TDT ranges from flutter clearance studies of new vehicles using aeroelastic models to the development and assessment of new concepts to control aeroelastic response, and to the acquisition of unsteady pressures on wind-tunnel models for providing experimental data to validate unsteady theories. Analytical methods are developed and validated to solve the aeroelastic problems of fixed- and rotary-wing vehicles, including the control of instabilities, loads, vibration, and adverse structural response.

The TDT is a closed-circuit continuous-flow wind tunnel capable of testing with either air or R-134a refrigerant as the test medium over a Mach number range from 0 to 1.2. The R-134a gas is very attractive for use in wind-tunnel studies of aeroelastic phenomena because, as compared with air, it has a low speed of sound and high density. Since the first test was conducted in 1960, the tunnel's testing capabilities have been continuously expanded by introducing a number of new features, such as airstream oscillators, sophisticated data acquisition systems, a variety of model mounting and suspension systems (including a two-cable suspension system for full-span "free-flying" flutter models), and excellent model-monitoring visual systems. Many very significant contributions of the tunnel and its staff to military and civil aircraft programs are summarized in NASA SP-2000-4519 *Partners in Freedom* and NASA SP-2003-4529 *Concept to Reality* (see bibliography).



The Langley 16-Foot Transonic Dynamics Tunnel.

After almost 45 years of operations and over 500 tests, the TDT staff has led the way as experimental aeroelasticity reached relative maturity. This progress has involved an intense coupling of experimental and computational research including the use of advanced CFD and advanced control theory. However, the research required to mature and extend the use of active controls for aeroelastic response has not diminished. Understanding and predicting the effects of transonic aerodynamic phenomena such as shock waves, flow separation, viscosity, and the interactions of these complex aerodynamic features with active control systems in controlling aeroelastic response are still major challenges.

Flutter Suppression

Delta Wing Flutter Suppression Study

The first practical demonstration of an active flutter suppression system was accomplished during the early 1970s in TDT tests. This effort was fueled by flutter concerns of large SST aircraft. Most studies had shown that large SST configurations, such as those of interest in the United States, had relatively severe flutter problems, requiring the addition of thousands of pounds of structural weight to provide the stiffness needed to ensure that flutter occurred well outside the operating envelope. Conceptually, an active flutter suppression system would require the addition of perhaps only a few hundred pounds of added weight as opposed to the thousands of pounds of a passive system. Because there was little information available on the design, implementation, and operation of active flutter suppression systems, a delta wing flutter suppression study was undertaken. The research team was lead by Langley's Maynard C. Sandford with critical support provided by a number of other Langley researchers (especially Irving Abel and David C. Grey) and from Boeing-Wichita under contract.

In the benchmark 1971 experiments, a simplified 1/17-scale semispan model representative of the Boeing SST (2707-300) wing configuration was mounted to the wall of the TDT with a rigid sidewall-mounting block used to simulate the fuselage faring. The model was equipped with both leading- and trailing-edge control surfaces as well as high-fineness-ratio bodies on the wing lower surface that were used to simulate the mass properties of engine nacelles. The model also incorporated advanced, miniaturized hydraulic actuators to move the active control surfaces. The development of these actuators was a significant advance in the state of the art for model construction and surface actuation at that time.

The flutter suppression systems implemented were based on the aerodynamic energy concept developed by Elihu Nissim, who worked at Langley as a postdoctoral research fellow. Three control laws were studied, including Nissim's basic method and two variations developed by Langley researchers. Two of the systems used both leading- and trailing-edge control surfaces, whereas the third system used only the trailing-edge surface. The control laws were implemented on an analog computer located in the wind-tunnel control room. Response of the model was sensed by two accelerometers located at the same outboard station as were the control surfaces. Model response signals were routed to the analog computer for processing through the control laws. The processed signals were then routed to servo valves that provided hydraulic power to the actuators and caused them to move in such a way that the aerodynamic forces generated by the motion of the surfaces added damping to the wing, thus preventing flutter from occurring.

When the "open-loop" flutter characteristics of the model with the suppression control system off were compared with results obtained with the suppression control activated, it was found that all three active control systems demonstrated significant increases in the dynamic pressure for flutter onset at transonic speeds (Mach = 0.9). The increase in flutter dynamic pressure ranged from 11 to 30 percent for the systems.

In addition to dramatically demonstrating the potential of active control systems to extend flutter speeds, this investigation made major contributions to the fundamental understanding of aerodynamic prediction methods for complex transonic flows and the understanding of inertial coupling between the control surfaces and the main wing. In retrospect, this particular investigation is widely regarded as a landmark study and a major contribution to subsequent advances made in active control of aircraft aeroelastic responses.

Wing-Store Flutter Suppression

YF-17 Program

High-performance military attack aircraft typically carry vast arrays of air-to-air or air-to-ground weapons on wing-mounted pylons. The substantial weight and aerodynamic characteristics of these external stores can dramatically change the aeroelastic characteristics and structural response characteristics of wings, resulting in unacceptable flutter constraints or airplane motions. Each of the literally hundreds of different combinations of external store configurations is a new dynamic system with its own set of flutter characteristics. In particular, the onset of flutter can occur at lower airspeeds than the baseline aircraft, thus restricting the aircraft's operating envelope and limiting military operations. It appeared that active control techniques might be applicable to the wing-store flutter problem. Initial U.S. efforts to develop active wing-pylon-store flutter suppression systems were begun by the military with the F-4 airplane in the early 1970s. Langley has participated extensively in domestic and international research programs to advance and validate store-induced flutter design methods, including assessments of active control systems for wing-store flutter suppression.

In 1977, Langley researchers began a cooperative program with Northrop and the Air Force Flight Dynamics Laboratory (AFFDL) to conduct long-term wind-tunnel investigations in the Langley TDT of several concepts for wing-store flutter suppression. The program's focus was a 30-percent scale semispan, aeroelastic model of the YF-17 Lightweight Fighter prototype consisting of a wing-fuselage and horizontal tail. The model was mounted on a special support system that provided rigid-body pitch and plunge freedoms. In addition to having powered leading- and trailing-edge control surfaces, the model was equipped with three different external store configurations that produced widely different flutter characteristics (flutter frequency, coupling of structural modes, and relative violence of the flutter mode).

Moses G. Farmer led the cooperative test team during the TDT test program. During initial testing in 1977, results demonstrated that active flutter suppression could be achieved for the significantly different aeroelastic characteristics of the wing-store configurations tested and that, for the first time, the use of only leading-edge control surfaces could achieve suppression. In a second series of TDT tests conducted in 1979, more sophisticated multiple control loops were conceived and assessed for further expansion of the flutter-free envelope. Concentrating on the store configuration with the most violent flutter mode, researchers developed an innovative "flutter stopper" electromechanical internal system to rapidly change the distribution of store mass in such a manner as to decouple the critical elastic modes. This unique system proved a valuable tool in suppressing flutter of the model during the tunnel test.

Through the auspices of an Air Force data exchange agreement with certain European nations, an international assessment of control laws developed by individual organizations was conducted using the YF-17 model in the TDT. European participants included British Aerospace and the Royal Aeronautical Establishment (RAE) from the United Kingdom, the Office National d'Etudes et de Recherches Aerospatiale (ONERA) from France, and Messerschmitt-Bolkow-Blohm GmbH (MBB) from Germany. Substantial information was mutually shared on the effects of suppression system design, including the number of sensors and control surfaces used. Some concepts produced extremely effective flutter suppression, including one that was tested to a dynamic pressure 70 percent above the passive flutter dynamic pressure. Many notable firsts were achieved in this international program, including demonstrations of the ability to switch between flutter-suppression control surfaces above flutter speeds without undesirable transients, and the validation of design procedures and techniques.

Members of the international active store flutter suppression team pose with the YF-17 model in the Transonic Dynamics Tunnel.

The initial collaborative wing-store flutter suppression activities in the TDT had been based on the use of analog controllers, but the advances and application of digital controllers in an adaptive manner was the next target of researchers. During 1981, some control laws previously implemented on an analog computer were converted to a digital computer and retested. In 1982, another phase of investigations of digital controllers was conducted with the objective of demonstrating adaptive flutter suppression. In this approach, the controller was required to discriminate between flutter modes and select the appropriate control law with changes in flight condition. The tests were highly successful and proceeded to the point of demonstrating the release of a wingtip-mounted store designed to transform the model configuration from a stable condition to a violent flutter condition. The adaptive controller rapidly recognized the unstable behavior, implemented a new control law, and stabilized the model in a fraction of a second.

The highly successful YF-17 store flutter suppression program extended through seven different entries in the TDT and is known as a critical NASA accomplishment in the field of aeroelasticity.

F-16 Program

The General Dynamics YF-16, winner of the Air Force's Lightweight Fighter Program, was initially conceived as a highly agile, lightweight fighter with emphasis on close-in air-to-air combat maneuverability. As the Air Force developed the airplane into today's F-16, mission requirements for the aircraft changed to emphasize the air-to-ground mission, thereby leading to an extensive application of external stores to the configuration. Early in the airplane's development program, the Air Force requested Langley to support the flutter clearance requirements for flight testing by conducting traditional flutter tests in the Langley TDT. Subsequently, over 18 different TDT test entries were conducted for the F-16 to cover flutter characteristics of the basic airplane and the airplane with external stores. With the very large number of potential external stores and aeroelastic characteristics to be encountered with the F-16, a cooperative program on active flutter suppression was established between Langley, the Air Force Wright Aeronautical Laboratories (AFWAL), and General Dynamics. Langley's lead researchers for the program were Moses G. Farmer, Raymond G. Kvaternik, Jerome T. Foughner, Frank W. Cazier, and Michael H. Durham. Using a 0.25-scale flutter model of the F-16, the team investigated a range of potential control concepts from analog-type systems to digital adaptive systems.

Tests of a single wing-store configuration were led in 1979 by Foughner to investigate the suppression of flutter for that specific configuration. Study results demonstrated that an antisymmetric flutter mode could be suppressed with an active control system, and detailed research data and analyses of the details of mechanizing such systems produced vital information for further developments. Test program highlights included a demonstrated ability to switch control laws on above the unaugmented flutter condition without undesirable transients and demonstrated flutter suppression to a dynamic pressure 100 percent above the unaugmented flutter dynamic pressure.

Jerome T. Foughner with F-16 model in Transonic Dynamics Tunnel during flutter tests with external stores.

Further testing of the F-16 model by Cazier in 1981 introduced a second store configuration with successful demonstrations of flutter suppression. Additional information on the dynamic response requirements for the control system was determined, and assessments of the effectiveness of individual control surfaces to suppress flutter were made.

Based on YF-17 test program successes and the F-16 demonstrations, the joint F-16 research team pursued the goal of developing and demonstrating a totally digital, adaptive suppression system. The work tasks included developing a suppression system for three different external store configurations, demonstrating a 30-percent improvement in flutter speed for each configuration, and demonstrating the suppression of flutter following the separation of a store from the wing. Conducted in 1986 by Cazier and Moses Farmer, these TDT tests contributed critical technology to the development of adaptive digital suppression controls. By demonstrating the feasibility of a digital adaptive system that required no prior knowledge of the wing-store configuration, coupled with successful simulated launching of missiles from a free-flying model at conditions below and above the unaugmented flutter boundary, this highly successful cooperative research project has been recognized as a benchmark event for adaptive control technology development.

In 1999, the Air Force designed and tested a prototype active flutter suppression system (AFSS) designed to suppress the F-16's tendency to oscillate when flying at high speeds while carrying certain combinations of fuel tanks and different types of weapons. The motion is known as limit cycle oscillation, or LCO. Although the oscillations are not serious enough to damage an F-16, they can affect a pilot's ability to precisely fulfill his mission, such as accurately launching a missile during air-to-air combat. Referred to as being "like driving a car with an out-of-balance tire," the phenomenon is caused by the antisymmetric flutter mode discussed earlier. Due to this mode's excitation, the pilot experiences a side-to-side rolling motion in the cockpit. The F-16 active flutter suppression system was designed by Lockheed Martin Tactical Aircraft Systems and uses ailerons for flutter suppression. The flight tests included flights with the F-16 configured in five different store loadings, including heavy air-to-ground weapons under the wings, AIM-9 Sidewinder missiles attached on the wingtips, and wing-mounted fuel tanks. The program successfully suppressed LCO at the desired speeds and altitudes for each combination of loadings. The test team flew 21 flights with the system totaling more than 48 flying hours.

Despite the improved characteristics experienced in the flight test evaluations, the AFSS has not been implemented in operational F-16s at this time.

F/A-18 Application

A remarkable accomplishment in the suppression of wing-store limit cycle oscillations occurred in the early 1980s during the development and deployment of the F/A-18 aircraft by McDonnell Douglas. As an attack aircraft for the U.S. Navy, the F/A-18 is required to carry a wide variety of air-to-ground stores up to transonic speeds. During pre-production flight tests of certain external store configurations, the aircraft exhibited an unacceptable LCO of about 5.6 Hz during flutter testing. The resulting lateral accelerations at the pilot's station greatly exceeded allowable levels, with values of as much as 1.0 g peak to peak experienced in the cockpit. The oscillations typically occurred only at altitudes less than 12,000 feet and at speeds greater than Mach 0.8.

The specific store loading susceptible to LCO involved wing store combinations which included high pitch inertia stores on the outboard wing pylons along with wingtip-mounted AIM-9 missiles. The fundamental structural contributor to the LCO mechanism was an outboard pylon/store antisymmetric pitch structural mode. Extensive flight testing demonstrated that the oscillations were not due to classical flutter and were not reinforced by coupling with the flight control system. Testing further demonstrated that the wing oscillation amplitude was not sufficient to cause a structural integrity or fatigue problem. However, the accelerations at the pilots station were of sufficient magnitude to create a very uncomfortable ride and thereby degrade pilot performance. A flight test program was initiated to solve the LCO problem, with an initial focus on potential mechanical passive solutions. The testing results indicated that a practical wing reconfiguration could not be found to satisfactorily reduce the oscillations over the flight envelope.

McDonnell Douglas engineers were aware of the research being conducted at Langley on wing/store flutter for the YF-17 and the F-16, and the promising results of that research gave the company additional confidence that an active system might provide a feasible solution to the F/A-18 problem. The program was in a situation requiring a rapid and reliable solution which led to development of a solution from flight testing. One of the major issues encountered by the McDonnell Douglas team was the fact that the LCO phenomenon had not been predicted by flutter analyses conducted at that time. The LCO had been experienced almost 200 knots below the speed predicted by linear flutter analysis.

An Active Oscillation Suppression (AOS) system was subsequently developed under the programmatic constraint of only using the existing F/A-18 flight control system components and interfaces. After extensive analysis and flight test evaluations, an effective AOS system was developed and implemented using feedback from an existing lateral accelerometer to actuate the aircraft's ailerons via the flight control computer. During other flight testing, it was found that certain outboard pylon store configurations would not require engagement of the AOS. Thus, logic to interrogate the type of store configurations carried was implemented within the AOS system. Since the LCO was not regarded as a classical flutter problem and therefore not a safety of flight consideration, the use of a single string AOS concept did not violate any redundancy requirements. However, if more serious flutter is encountered for future aircraft requiring active flutter suppression, redundancy will have to be considered from a flight safety perspective.

McDonnell Douglas successfully developed and applied an active control system to suppress wing/store limit cycle oscillations in production F/A-18 aircraft

Following the highly successful development of the AOS system by McDonnell Douglas, the system was applied on all production F/A-18A/B/C/D aircraft and has been extremely effective for over 20 years. Although NASA was not an active participant in the development of the solution to the F/A-18 problem, the precursor research that had been conducted by Langley played an important role in establishing confidence and risk reduction in this critical activity.

Decoupler Pylon

In concluding the discussion of wing-store flutter suppression, it is appropriate to mention an innovative "quasi-passive" concept conceived by Langley's Wilmer H. (Bill) Reed, III, in the early 1980s. As an alternative to conventional passive methods of incorporating additional structure to increase stiffness or to use advanced active control methods, Reed devised a spring-mount system for external stores called a decoupler pylon, which isolates or decouples the external store's pitching vibratory motions from those of the wing, thereby increasing the flutter speed. The concept was substantiated by analysis, demonstrated in TDT tests, and validated at full-scale conditions through flight test using an F-16 airplane. Langley participants in studies of this revolutionary concept, in addition to Reed, were Frank W. Cazier, Jr., Moses G. Farmer, and Harry L. Runyon, Jr.

Reed's decoupler pylon concept was relatively simple yet very effective. It consisted of soft-spring and damper components that, in combination, isolated the wing from the pitch inertia effects of the external store. A low frequency, automatically controlled alignment system was provided to keep the softly supported store properly positioned relative to the wing during maneuvers. The decoupler pylon could be made robust in that a variety of different stores could be mounted on the same decoupler pylon without changing the overall wing flutter characteristics.

Following some carefully crafted analytical studies, and after highly successful wind-tunnel studies in the TDT using YF-17 and F-16 flutter models demonstrated increases in flutter speeds of over 100 percent could be obtained by using the decoupler pylon versus the same store mounted on a conventional pylon, a flight demonstration program was initiated. The plan was to design, build, and flight test a decoupler pylon on an F-16 airplane. A pair of decoupler pylons was designed, fabricated, and ground tested by General Dynamics (now Lockheed Martin) under contract to NASA. The flight tests were conducted on an F-16 from the Joint Task Force at Edwards Air Force Base, California. Langley's Frank W. Cazier, Jr., served as Project Manager for the flight test in a joint activity with NASA Dryden Flight Research Center, the Air Force, and General Dynamics.

The chosen test configuration was an asymmetric loading of AIM-9J wingtip missiles, a GBU-8 bomb near midspan, and a half-full 370-gallon fuel tank inboard. That particular configuration exhibited the well-defined limited-amplitude antisymmetric flutter when the bomb is carried on a standard F-16 pylon. Analyses and wind-tunnel tests indicated that mounting the bombs on decoupler pylons in place of standard pylons would appreciably increase the airplane's flutter speed. The flight test objectives were to demonstrate an improvement flutter speed of at least 30 percent over the conventional pylon flutter boundary, assess the requirements for the alignment system, and demonstrate that store separation from the decoupler pylon was satisfactory.

Flight tests for the F-16 in 1985 with a standard pylon-store configuration were first conducted at an altitude of 10,000 ft and for Mach numbers above 0.7. This configuration experienced the antisymmetric LCO discussed previously. Pilots described the oscillation as a "continual pounding oscillation that was of sufficient amplitude to cause visual blurring of the cockpit displays." With the decoupler pylon, the LCO that had been experienced with the standard pylons was suppressed throughout the flight envelope tested. The investigation expanded in scope to develop methods to reduce friction in the pylon mechanisms, as well as assessments of the effectiveness of the alignment system. During one flight test, a GBU-8 was ejected, demonstrating that weapons separation from the decoupler pylon was satisfactory. Flight tests, including maneuvers, demonstrated an increase in flutter speed of 37 percent over the standard F-16 pylon configuration.

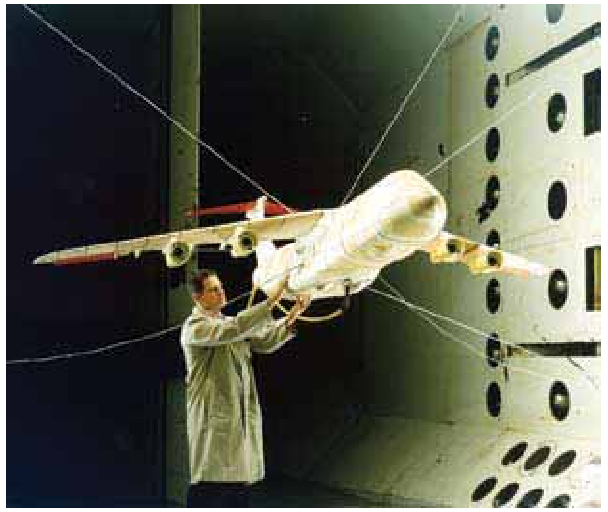
As was the case for the F-16 AFSS, technical success in the decoupler project did not lead to applications to the F-16 fleet.

Load Alleviation

The reduction of loads imposed on aircraft by maneuvers, gusts, and turbulence has been explored extensively by Langley researchers during in-house studies and cooperative programs with their partners from industry and DoD. The range of airplane configurations studied has included general aviation airplanes, commercial transports, military transports, and bombers. Although some activities were based on passive control that did not include elements of active control systems, they are included herein for background and completeness.

C-5A Active Lift Distribution Control System

Lockheed-Georgia was awarded an October 1965 Air Force contract for a C-5A heavy transport with a specified wing fatigue life of 30,000 flying hours. The first flight of the new transport was in June 1968 and, unfortunately, static fatigue testing of a wing test specimen revealed wing structural cracks in July 1969. Although a structural modification program was immediately begun to reinforce the critical wing stations, structural modifications turned out not to be an acceptable long-term solution to the problem. After the C-5A had been in service for several years, a wing tear-down inspection on one aircraft revealed cracks in the structure that projected to a fatigue life of less than 8,000 flying hours, approximately one quarter of the desired life. Lockheed proceeded to explore solutions, including an active aileron system to alleviate gust loads on the wing, local structural modifications to improve fatigue life, and redistribution of fuel within the wing to reduce bending moments. Active ailerons were retrofitted to C-5As during 1975 to 1977 as part of an active lift distribution control system (ALDCS) that increased fatigue life by symmetric



C-5 model mounted in the Transonic Dynamics Tunnel.

deflections of the ailerons in response to gusts and maneuvers. The concept also used an automatic elevator deflection to null out pitching moments caused by the aileron deflections. Additional redesign of the center wing and wing box sections was also incorporated in the modification program, and by 1987 all surviving C-5As had been modified. Also, in 1982 the decision was made to have Lockheed build 50 C-5Bs, which incorporated the wing improvements of the C-5A.

Wind-tunnel tests conduced in the Langley TDT during 1973 were a key component of the successful development of the ALDCS. A full-span cable-mounted 1/22-scale C-5A model was tested to experimentally verify the effectiveness of the ALDCS system in reducing loads. Langley's Charles L. Ruhlin and Maynard C. Sandford led the NASA-Lockheed team that conducted this first-ever scaled model study of an ALDCS.

The C-5 test was very successful. The results showed that the ALDCS was very effective in reducing both wing dynamic bending and torsion loads. Bending moments at the frequency of the wing first bending mode were reduced by more than 50 percent across the wing span. Although the reduction for torsion loads was less, it was still substantial. Later correlation of results from airplane flight tests and the aeroelastic wind-tunnel model tests were in very good agreement for the critical low frequency bending mode. Once again, this study validated the use of active control technology to reduce aircraft aeroelastic response and further demonstrated the valid application of aeroelastic wind-tunnel models for developing active control technology.

Passive Gust Load Alleviation

The ride quality for passengers in light general aviation airplanes in turbulent weather is characteristically rough and uncomfortable. Particularly offensive are the large up-and-down heave motions encountered because of relatively light wing loadings of such aircraft. Researchers at Langley have investigated the human response to typical accelerations encountered in flight, and have identified the critical frequencies that lead to highly undesirable effects on humans, including airsickness. An extensive investigation into the subject of ride quality was led by Langley's D. William (Bill) Conner during the 1970s.

Although these highly undesirable passenger accelerations could theoretically be alleviated by an automatic control system using appropriate sensors, computers, and rapid-actuation controls, the complexity, costs, and maintenance of such systems are beyond the capabilities of typical airplane owners. Despite the long-term interest of designers in reducing the effects of turbulence on ride quality, and the continuing dissatisfaction of public passengers with undesirable accelerations due to turbulence, no current general aviation aircraft are equipped with gust-alleviation systems. As part of a long-term research in aircraft response to gusts, Langley Research Center has investigated several concepts for gust alleviation for this class of aircraft.

In the late 1940s Langley's W. Hewitt Phillips was exposed to an earlier French gust-alleviation concept by René Hirsch wherein the horizontal tail surfaces were connected by pushrods to flaps on the wing. On encountering an upward gust, the tail surfaces would deflect up, moving the wing flaps up and thereby offsetting the effects of the gust. The system had been analyzed and designed to minimize adverse interactions on other airplane characteristics, such as pitching moments. (Phillips later traveled to France in 1975, met Hirsch, and inspected some of the aircraft that he had designed.) Intrigued by the possibility of achieving gust alleviation with automatic controls rather than the complex aeromechanical interconnects of Hirsch's design, Phillips began studies of airplane response characteristics to sinusoidal gusts and the character of control inputs required to alleviate accelerations. After studying several systems, he arrived at the idea of using a gust-sensing vane mounted on a boom ahead of the nose to operate flaps on the wing through a hydraulic servomechanism.

Following analytical studies, a flight demonstration project was conceived to demonstrate gust alleviation in flight. A Navy C-45 twin-engine airplane was modified to include a nose boom to hold an angle-of-attack vane; the wing flaps, which normally deflected only downward, were modified for deflections in both up and down directions; the elevator was split into three sections with two sections being linked to the flaps for gust alleviation; and small segments of the wing flaps near the fuselage were driven separately from the rest of the flap system so that they could be used in either the same or opposite directions as the rest of the flaps. Following these NACA tests at Langley, jet transports were introduced into commercial service and the higher wing loadings, higher cruise altitudes, and the use of weather radar to avoid storms resulted in less likelihood that passengers might become airsick. Also, the problem of active gust alleviation was made more difficult because the structural flexibility of jet transports placed structural frequencies closer to the range of interest for gust alleviation. Thus, the interest and momentum for gust-alleviation systems waned.

Following a visit to France and meeting with Hirsch in 1975, Phillips revisited the aeromechanical approach to gust alleviation and initiated a Langley study of the concept. Eric C. Stewart, L. Tracey Redd, and Robert. V. Doggett, Jr., led analytical and experimental studies of a 1/6-scale model of a typical general aviation airplane equipped with an aeromechanical gust alleviation system.

Nose boom with angle of attack vane on C-45 transport used for gust alleviation research.

The project was designed as a cooperative venture between NASA, Cessna, and the Massachusetts Institute of Technology (MIT). The gust alleviation system consisted of two auxiliary aerodynamic surfaces that deflected the wing flaps through mechanical linkages to maintain nearly constant airplane lift when a gust was encountered. The dynamic model represented a four-place, high-wing, single-engine light airplane, and was rod mounted in the Langley TDT for tests. The effects of flaps with different spans, two sizes of auxiliary aerodynamic surfaces, single and double-hinged flaps, and a flap-elevator interconnect were studied. Investigation results showed that the gust-alleviation system reduced the model's root-mean-square normal acceleration response by 30 percent in comparison with the response in the flaps-locked condition. Despite these promising results, the aeromechanical concept was not pursued and has not been applied to production aircraft.

About 10 years later, Langley briefly pursued a concept for an active, computer-based gust-alleviation system for general aviation aircraft. Teamed with Cessna and the University of Kansas, Langley researchers conducted analytical studies of the application of computer-driven controls with a view toward flight demonstrations using a Cessna C-402 twin-engine research airplane. The analysis included the use of advanced modern control theory to develop the control architecture. Unfortunately, the response characteristics required of the control actuators could not be accommodated within the budget and time allotted for the project, and the activity was terminated.

Combined Aeroelastic Control Concepts

Although some studies examined the effectiveness of a single active control concept, others emphasized more than one: for example, the simultaneous application of active flutter suppression and active load control. Some of these latter studies are described in this section.

B-52 Control Configured Vehicles Program

The B-52 Control Configured Vehicle (CCV) Program was the first in a number of studies addressing multiple applications of active controls. It was a natural follow-up to work of the 1960s in applying flight controls systems to attenuate the structural response (especially cockpit accelerations) of large military airplanes such as the B-52E and the XB-70.

During the early 1970s, AFFDL sponsored the B-52 CCV Program at The Boeing Company to demonstrate the benefits of applying advanced flight control technology to a large flexible airplane. The effort was initiated in July 1971 and was completed in 1974. A highly modified Boeing NB-52E bomber was used to investigate four active control concepts: ride control, flutter mode control, maneuver load control, and augmented stability. The existing elevators and rudder of the B-52 were not sufficient to implement the control systems, so it was necessary to add additional control surfaces consisting of three-segment flaperons, outboard ailerons, and horizontal and vertical canards. On August 2, 1973, the B-52 CCV test aircraft made aviation history by flying 10 kts faster than its flutter speed. Although the flight tests were halted at this point, there was no indication of a decrease in damping in the structural vibration mode important to flutter, so the actual flutter speed was considerably higher. This event was the first time that an aircraft had been flight tested above its flutter speed relying solely on an active flutter control system to augment the structural damping.

At Langley, an investigation sponsored by AFFDL with Boeing and NASA participation was conducted for correlation with flight results. The objective was to demonstrate that wind-tunnel models and testing techniques could be used to design and assess active control concepts. An existing 1/30-scale, full-span, free-flying B-52 aeroelastic wind-tunnel model was modified and tested in the TDT. Although capability to study all four active control concepts was incorporated into the model, only active vertical ride control (VRC) and active flutter suppression (AFS) were actually tested during three separate wind-tunnel tests in 1973 and 1974. The Langley Project Managers for the wind-tunnel studies were Jean Gilman, Jr., and L. Tracy Redd.

The airplane VRC system was designed to reduce the gust-induced vertical acceleration at the pilot's station by at least 30 percent. This system processed vertical acceleration signals sensed at the pilot's station through a computer implemented control law to drive horizontal canards. The performance of the model's VRC closely matched the performance of the full-scale airplane system, resulting in a dramatic reduction in vertical accelerations at the cockpit location

The AFS consisted of feedback loops using signals from accelerometers mounted on the model's external fuel tanks (fed back to the aileron control surfaces) and from accelerometer signals located near the midwing (fed back to the flap segments). Wind-tunnel tests results demonstrated that, with the AFS on, the damping in the flutter mode showed a large improvement over that displayed with the AFS off, verifying the full-scale flight results and indicating the potential for a significant increase in flutter speed.

Follow-up AFS tests with yet another modification to the B-52 model were conducted by Robert V. Doggett, Jr., Rodney H. Ricketts, and Maynard Sandford in 1978. For this study, the model was converted from a free-flying model to a sting-mounted model. In this case, the digital-computer-implemented control laws had to simultaneously deal with two distinct flutter modes, one involving antisymmetric wing motion and the other involving symmetric wing motion. Because the control laws were implemented on three separate computers, it was possible to evaluate the effects of system failures on the effectiveness of the AFS. This study provided the first successful demonstration of multimode, digital active flutter suppression, including considerations of redundancy management.

From a research viewpoint, the most significant result of B-52 CCV experiments in the TDT was validation that dynamically scaled, actively controlled wind-tunnel models could be used to study and demonstrate advanced active control concepts. Based on the proven success of this pioneering effort, wind-tunnel models in the TDT are now used routinely to increase the confidence level in active control concepts by providing data to verify analytical models and methods used in design and to eliminate the risks and lower the costs associated with flight testing such concepts.

The Aircraft Energy Efficiency Active Controls Technology Program

In 1976, NASA initiated its ACEE Program in response to the dramatic increase in fuel prices that began in the early 1970s. The program included several elements of technology in aerodynamics and active controls with an emphasis on concepts that traded cruise speed for increased fuel efficiency. A major part of ACEE activities was the EET Program. Langley's leaders in the active controls element of the EET Program were Ray V. Hood (Program Manager) and David B. Middleton (Deputy Program Manager). A detailed program summary and bibliography of the EET activities has been prepared by Middleton, Bartlett, and Hood (see bibliography). One element of the EET Program included in-house research activities and cost-shared contracts with Boeing, Douglas, and Lockheed-California for the analysis, preliminary design, testing, and in-depth assessments of selected advanced concepts for ACT for improved mission efficiencies. Because higher aspect-ratio wings quickly became a focal point for aerodynamic efficiency, control of aeroelastic responses became a vital segment of the program.

Active wing flutter suppression concepts were pursued that increased the damping of wing structural modes important to flutter to the extent that the flutter placard speed was increased beyond the airplane's expected maximum operating speed without adding any structural weight. In addition, maneuver load control concepts that reduced wing-bending moments during maneuvering flight were conceived, as well as active gust load alleviation systems that reduced structural loads during encounters with vertical gusts. Collectively, these two load alleviation systems comprised an active control function called wing-load alleviation.

Douglas pursued the design and assessment of active systems for flutter suppression and load alleviation on a derivative of the DC-10 configuration that had an increased wing span. Wind-tunnel testing to determine dynamic wing loads was conducted in industry tunnels, and control laws derived by Douglas using conventional methods increased flutter speed by up to 19 percent and significantly decreased wing-bending accelerations. Within this coordinated effort, Langley supplied alternate control laws based on advanced design methods. Both NASA control system designs increased flutter speeds by more than 25 percent.

The Lockheed L-1011-500 was the first commercial transport to use active load control.

Lockheed studies involved extending the wing span of its existing Lockheed L-1011 transport configuration and providing a load alleviation system using symmetric operation of outboard ailerons at high speeds. Outboard ailerons on most conventional transports are designed to be inoperative at high speeds because of adverse aeroelastic issues, and inboard ailerons are used for roll control. The load alleviation system for the L-1011 redistributed the wing lift and thus eliminated the need for significant structural redesign and increase in structural weight to support the extended wing span. This configuration was ultimately implemented by Lockheed with company funds and flight tested on Lockheed's L-1011 research airplane, demonstrating a 3-percent fuel savings. Based on these very favorable results, Lockheed immediately pursued FAA certification of the active control system and later incorporated the system in its derivative long-range Advanced TriStar L-1011-500 transport in 1980, representing the first significant application of active controls to a modern wide-body transport.

The ACEE Program's EET element greatly accelerated the state of the art in active control of aeroelastic response, and the resulting application by Lockheed to the L-1011 was a major event in the acceptability and certification of such systems.

Drones for Aerodynamic and Structural Testing Program

In keeping with its mission for conducting high-risk research, Langley conceived and initiated a flight test project known as Drones for Aerodynamic and Structural Testing (DAST) in the early 1970s to validate analysis and synthesis methods for active control of aeroelastic response and analysis techniques for aerodynamic loads prediction. Flight tests provided the opportunity to simulate characteristics that could not be accurately simulated or properly accounted for in wind-tunnel tests, such as maneuvering flight. Because of the inherent risks in flight testing advanced active control concepts, an unmanned, remotely controlled Teledyne-Ryan BQM-34 Firebee II was chosen as the test vehicle, with the flight test to be conducted at NASA's Dryden Flight Research Center. Langley's Harold N. Murrow was the Project Manager and headed a virtual "who's who" team of Langley aeroelasticians, aerodynamic and structural analysts, and control theory specialists. Some key Langley researchers were Irving Abel, William M. Adams, Jr., Clinton V. Eckstrom, Jerry R. Newsom, Boyd Perry, III, Maynard C. Sandford, and Vivak Mukhopadhyay. An equally competent team was assembled at Dryden to conduct the flight tests.

NASA F-8 research airplane with supercritical wing used as basis for design of ARW-1 wing.

The plan was to fit the Firebee with two aeroelastic research wings (ARW). Both wings were to be representative of advanced subsonic transonic transport configurations. ARW-1 was to have the same planform as the research wing that had been used in Dryden flight demonstrations of the supercritical airfoil section on the NASA F-8 research airplane. The ARW-1 test evaluated two active flutter suppression systems that had been carefully selected from a number of proposals. The objective was to demonstrate in transonic flight at least a 20-percent increase in flutter velocity. Wind-tunnel tests in the TDT were conducted using a simplified model of the ARW-1 to add confidence that the proper choices had been made.

The ARW-2 wing was an even more ambitious activity, including three active control systems: flutter suppression, gust load alleviation, and maneuver load alleviation. The ARW-2 had a higher aspect ratio than ARW-1. The wing configuration was chosen to represent a design derived during a NASA-contracted Boeing study of EET configurations. Fabrication of the ARW-2 began while the ARW-1 portion of the program was still in progress. Part of the ARW-2 plan was to test one of the flight test wing panels in the TDT as opposed to building a separate simplified model, as was done for ARW-1. TDT testing of the ARW-2 wing by Maynard Sandford began in 1978.

The flight-test approach involved launching the test drone from a wing-mounted pylon on NASA's B-52B launch aircraft, conducting the active control experiments, then recovering the test vehicle by deploying an onboard parachute that was "air-snatched" by an Air Force helicopter/aircrew during descent. During the free-flight portion of the experiment, a NASA pilot controlled the drone from a remote ground-based cockpit while researchers monitored flight data transmitted via telemetry. In case the telemetry link between the drone and the ground was lost, the Firebee could also be flown to the recovery site using a backup control system in a NASA F-104 chase airplane.

Drone with standard Firebee wing mated to B-52 in 1977 captive flight at NASA Dryden.

Drone during flight with ARW-1 research wing on June 12, 1980, before catastrophic flutter occurred.

Research flights for the DAST program at Dryden were conducted from 1977 to 1983. Initial fight tests were conducted with the Firebee fitted with an instrumented standard wing (also called the "Blue Streak" wing) to (1) develop test procedures and experience to be used during assessments of the flutter-suppression concepts for the ARW-1, and (2) to obtain wing data on surface pressures and bending moments using strain gauge instrumentation. The wing had been designed for a predicted flutter speed of Mach 0.95 at an altitude of 25,000 ft.

Unfortunately, the DAST project was fraught with operational problems, so only a few flights were completed successfully. Research studies of ARW-1 were halted unceremoniously when the test vehicle crashed on June 12, 1980. A programming error in implementing the active flutter suppression control law went undetected, despite careful review by all participants. This error resulted in the system gain being only one-fourth the desired value, and the wing fluttered unexpectedly at flight conditions where it should have been well safe from flutter. This catastrophic flutter resulted in the breakup of the wings and subsequent crash of the test vehicle.

The ARW-1 wing was rebuilt after the crash and again prepared for testing with the control law error corrected. On June 1, 1983, the ARW-1's misfortune continued when, following launch from a Navy DC-130 airplane routinely used to launch military drones such as the Firebee, the recovery parachute system malfunctioned and the parachute inadvertently disconnected from the drone, resulting in a second crash.

Following this second crash, the DAST project was terminated for several reasons. The program's initially planned 5-year lifetime had elapsed, and a combination of reduced funding and resource demands for other emerging high-priority unmanned airplane projects at Dryden made additional flight tests unlikely. However, the planned TDT testing of the ARW-2 wing was completed prior to the program's final termination.

Some view the DAST project as a technical disappointment because the program's original objectives were not attained. However, all the program's inherent research and active control law development considerably advanced the overall state of the art in applying active control techniques to favorably modify aeroelastic response. Perhaps the program's most important legacy was the dramatic experience with the challenges and difficulty of achieving some of these advanced concepts in practice.

Active Flexible Wing Program

In the early 1980s, engineers at Rockwell International Corporation conceived and studied analytically an active control concept that became known as the active flexible wing (AFW). Rockwell's early work was so promising that a cooperative research program involving Rockwell, the U.S. AFWAL, and NASA Langley was initiated in 1985 to further develop the concept and demonstrate it in tests in the TDT.

In the AFW concept, an active roll control system was used to optimize the airplane's rolling response while minimizing maneuver loads. This was achieved by taking advantage of inherent flexibility characteristics of the wings in a carefully controlled manner in conjunction with actuating leading- and trailing-edge control surfaces. The system monitored both flight conditions and wing structural deformations. Using this information, the system selects the best control surfaces to produce the desired rolling motion and commands those surfaces to deflect accordingly. An active roll control system offers the potential for significant savings in structural weight. For example, because the system works effectively at angles of attack above the control-surface reversal condition, it would eliminate the need for the "rolling horizontal tail" and render unnecessary the structural weight required by the rolling tail. If the AFW incorporates other active control applications, such as active flutter suppression, gust load alleviation, and maneuver load control, additional weight savings are possible. Rockwell predicted that by taking full advantage of the AFW concept, a weight savings of at least 15 percent of takeoff gross weight was possible for advanced fighter configurations.

Testing of the AFW concept in the TDT was conducted between 1986 and 1991. Langley's leading researchers for the AFW investigations included Boyd Perry, III, Carol D. Wieseman, Jennifer Heeg, Jessica A. Woods-Vedeler, Anthony S. Pototzky, Sherwood T. Hoadley, Vivak Mukhopadhyay, Maynard C. Sandford, Stanley R. Cole, William M. Adams, Jr., Carey S. Buttrill, Jacob A. Houck, and Martin R. Wazak.

The AFW TDT study used an aeroelastically scaled, 1/6-scale, full-span wind-tunnel model of an advanced fighter concept that was fabricated by Rockwell and tested during four different tunnel entries. The model featured eight separate active control surfaces with two leading and two trailing edges on each side of the wing. As per the name, the wing of the AFW model was designed to be extremely flexible and lightweight. The model test set up included a novel single-degree-of-freedom internal bearing arrangement, which permitted the model to roll freely about the wind-tunnel sting mount. Extensive instrumentation and sensors were also implemented in the model, including accelerometers, strain gauges, and a roll-rate gyro. Because the flutter speed of

the basic configuration was too high, it was reduced by the addition of a specially designed wing tip mounted store. A remotely controlled weight within the store could be rapidly moved to raise the flutter speed should violent flutter be encountered unexpectedly.

The investigation included two distinct research parts. In the first part, the Air Force, Langley, and Rockwell coordinated efforts to demonstrate the effectiveness of the basic AFW concept during TDT tests in 1986 and 1987. In the first of these tests, a data base of static forces and moments produced by control surface deflections was determined. These data were required to provide accurate values of the control surface effectiveness needed to design the active roll control system. After several active roll control laws were synthesized by using this data base, the different control was implemented on the wind-tunnel model system and each successfully evaluated during the second wind-tunnel test. All the digital-computer implemented control laws performed well, with the experimental results being in good agreement with theoretical predictions. The test results clearly showed that the AFW concept worked as advertised and, therefore, offers a viable means of improving the maneuver and roll control characteristics of advanced fighter type airplanes.

The second part of the AFW study was considerably more complex than the first. The objective was to demonstrate multi-input/multi-output (MIMO) single function and multifunction digital control of aeroelastic response. Three active control capabilities were incorporated into the wind-tunnel model system: active flutter suppression, the roll rate tracking system (RRTS), and rolling maneuver load alleviation (RMLA). The RRTS was designed to limit loads only when loads reach a predetermined level. The RMLA was designed to reduce loads during rolling maneuvers up to 90 degrees in amplitude. The control laws were implemented on a digital computer. Single function MIMO studies were conducted for each control system. Multifunction studies were conducted for active flutter suppression in combination with each of the two roll control systems

Key accomplishments of this sophisticated investigation included successful demonstrations of single- and multiple-mode flutter suppression, load alleviation and load control during rapid roll maneuvers, and MIMO active-control demonstrations above the open-loop flutter boundary. Rolling maneuvers representative of goals defined by military specifications were performed, and wing loads were controlled at dynamic pressures 24 percent above the open-loop flutter condition. In addition to significantly advancing active controls technology, this study also provided significant advances in the wind-tunnel test methodology needed to evaluate active control of aeroelastic response.

The Benchmark Active Controls Technology Project

The analysis and accurate prediction of aeroelastic phenomena is one of the most difficult challenges facing aerospace engineers. Not only are the phenomena affected by complex interactions of aerodynamic and structural forces, but they often are most troublesome in nonlinear flight regimes, such as transonic speeds. The addition of active controls to the technology poses even new challenges to aeroelasticians. In the late 1980s, Langley initiated the Benchmark Models Program (BMP), with goals of providing high quality experimental data that could be used to the evaluate the accuracy of advanced CFD codes applicable to aeroelastic analysis and to study the effects of new aerodynamic concepts on aeroelastic phenomena. The basic idea was to conduct relatively simple experimental studies where it would be possible to isolate the effects of key parameters, such as airfoil shape. Although active control technology was not included in the initial program plan, such studies were added after the program was initiated.

The BMP Program was a collaborative effort among several working groups of the Structural Dynamics Division and was supported by the entire Langley infrastructure. The Configuration Aeroelasticity Branch, the Unsteady Aerodynamics Branch, and the Aeroservoelasticity Branch all participated in the research activities, which were based on about two tests in the TDT per year over the program's 5-year duration. TDT researchers Robert M. Bennett, Clinton V. Eckstrom, Jose A. Rivera, Jr., Bryan E. Dansberry, Moses G. Farmer, Michael H. Durham, David A. Seidel, and Walter A. Silva collaborated in early benchmark studies. Researchers David M. Schuster, Robert C. Scott, and Sherwood T. Hoadley joined the team as the program evolved.

The program used a basic benchmark active controls technology (BACT) model, which was a rigid semispan configuration that had an NACA 0012 airfoil section. The unswept rectangular-planform model could be mounted on either rigid or flexible supports. The relatively simple, flexible support system provided for pitch and plunge motion of the model, the two most important motions to aeroelastic response. This system greatly simplified the structural aspects of the experiment and allowed the focus to be on aerodynamics and active controls. The model was well instrumented, with a number of pressure transducers to determine aerodynamic pressures and accelerometers to measure model motion. The model had a remotely controlled trailing-edge aerodynamic control surface that could be positioned either statically or dynamically. Remotely controlled upper and lower surface aerodynamic spoilers were also provided. The trailing-edge control and the spoilers were driven by miniature hydraulic actuators similar to those developed during the delta wing flutter suppression study.

The BACT model offered the opportunity to conduct a number of pioneering active control studies. Many of these are very technical and can be fully appreciated only by those well versed in controls theory, whereas others are relatively easy to understand. A couple of the latter studies will be cited here. Although it had been shown previously by another investigator that statically deflected spoilers were effective in increasing flutter speeds, BACT model tests represented the first time that actively controlled spoilers were effectively used as flutter suppressors. The second example was application of artificial intelligence (neural network) concepts to active flutter suppression. Artificial intelligence systems learn based on experiences and, depending on the application, may actually improve themselves as they are used or gain experience. This effort was part of the Adaptive Neural Control of Aeroelastic Response Program, which was a joint effort between NASA Langley and McDonnell Douglas Corporation (now part of The Boeing Company). A number of control systems, both adaptive and nonadaptive, were developed using neural network concepts implemented on the BACT model and successfully demonstrated in TDT tests.

The BACT model provided an opportunity not only to learn more about the characteristics of different aeroelastic phenomena, but also to evaluate very advanced active control techniques during an experiment that is easily managed as compared with many active controls studies conducted heretofore. Although the model system might be relatively simple, the phenomena being studied were not.

Piezoelectric Aeroelastic Response Tailoring Investigation

Before discussing the details of the Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI) some introductory comments are in order. Previous active control studies to favorably change aeroelastic response of airplanes had focused on the use of traditional aerodynamic control surfaces to effect the changes in excitation forces needed to accomplish the desired performance improvements. As advances were made in structural and other technologies, it became apparent that the use of "structural actuators" might be viable alternatives to "aerodynamic control surface" actuators. Piezoelectric materials appeared to offer much promise. When electric voltages are applied to these materials, internal strains develop that cause the material to change shape. By controlling the applied voltages to piezoelectric actuators either embedded in or mounted on a structure, it is possible to deform the structure in a desirable manner.

Inspired by graduate student Robert C. Scott's (later a TDT staff member) thesis in 1990, Jennifer Heeg designed and implemented an exploratory wind-tunnel experiment to assess the use of piezoelectric actuators in active flutter suppression. Following the detailed development of a candidate control law, a wind-tunnel experiment of a simple, free to pitch and plunge, aeroelastic wing model was conducted in the Flutter Research and Experiment Device (FRED), which was a small open-circuit wind tunnel with a 6- by 6-in. test section. The experiments, which included open-loop and closed-loop flutter testing, demonstrated that the use of piezoelectric control could increase flutter speed of the test wing by about 20 percent. Almost simultaneously, Heeg expanded her study to include active control of buffeting response. A modified version of the model was used for additional tests in FRED. This study resulted in the first successful application in the United States of active controls to attenuating buffeting response.

The favorable results of Heeg's early work and of studies performed elsewhere led Langley to establish a cooperative research program with MIT. The program's purposes were to further evaluate the ability of distributed strain actuators to control aeroelastic response and to demonstrate selected concepts on a research model wing to be tested in the Langley TDT. The principle used for control in the investigation involved the use of piezoelectric actuators. The piezoelectric actuator concept consists of a series of electrical strain-gauge patches (potentially hundreds per wing) wired for a low-current, high-voltage electrical charge. Wing response measurements, either static or dynamic, are fed back through control laws that output voltages to these actuators, either individually or in selected combinations. These voltages produce internal actuator strains that cause the wing to deform either statically or dynamically in a desired manner.

The PARTI project used an aeroelastic semispan model with 72 distributed piezoelectric actuator patches on the upper and lower surfaces of the wing. (An actual airplane application may require hundreds of actuator patches.) Various groups of actuator patches were oriented to facilitate bending and torsional responses of the model. In addition to the piezoelectric actuators, the model had a trailing-edge aerodynamic control surface driven by an electric motor located in the wing root. Extensive research activities were allocated to the development of instrumentation, control law development, and experimental demonstrations of flutter suppression.

During the first TDT entry in early 1994, the open-loop characteristics of the model were determined, including supercritical (below flutter) response, basic flutter characteristics of the model, and time-dependent response functions for each important piezoelectric sensor group. These data provided the foundation for the Langley-MIT research team to construct mathematical models of candidate control laws and validate analysis techniques prior to additional wind-tunnel testing.

Objectives of the second TDT entry in late 1994 included an assessment and demonstration of the capability of piezoelectric actuators to suppress flutter and to reduce aeroelastic response caused by tunnel turbulence. Several control laws, based on different design techniques, were implemented

to assess input-output control effectiveness for various sensor and actuator groups. For the most successful control law, an increase in flutter dynamic pressure of 12 percent was demonstrated, and the peak value of strain measured by the instrumentation was significantly reduced for dynamic pressures below flutter.

The PARTI project successfully completed its primary objective of demonstrating flutter suppression and aeroelastic response control by using distributed piezoelectric actuators on a large-scale aeroelastic wind-tunnel model. Key Langley researchers for PARTI included Anna-Maria R. McGowan, Jennifer Heeg, Donald F. Keller, and Renee C. Lake.

Control of Aeroelastic Response of Vertical Tails

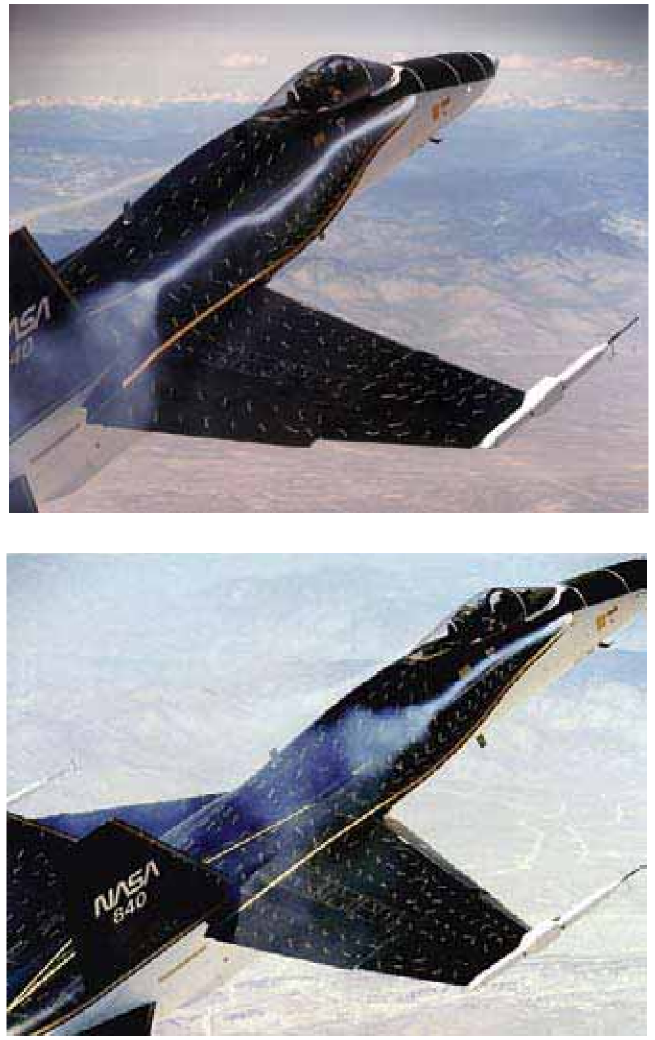
During the 1970s, the operational doctrine of U.S. military air forces began to focus on highly maneuverable fighter tactics. Extensive advancements in aerodynamics, propulsion, and structures—coupled with effective digital flight controls that provided "carefree" maneuvering—resulted in significant operations at high angles of attack. Many recently developed advanced U.S. fighter configurations have used vortex-control techniques for enhanced lift during strenuous maneuvers, as well as twin-tail configurations to provide satisfactory stability and control during these conditions. A number of these configurations, including the F-14, F-15, F-18, and F-22, have experienced problematic buffeting loads and oscillatory stresses to the vertical tails at high angles of attack (above about 25 degrees) because the tails were immersed in high-intensity turbulence and chaotic airflow caused by phenomena, such as stalled wing wakes or vortex "bursting." The resulting randomly varying structural response of the tails caused by the applied buffet loads severely degrades the fatigue life of these components. Tail buffet loads have necessitated structural modifications for some airplanes, or even mandated maneuver limitations for others. In addition to structural modifications, special and costly inspections are required to check for damage due to buffet loads. Analysis based on available usage history of two aircraft configurations suggests that the tail surface fatigue life could be doubled if the tail stresses could be reduced by only 10 percent.

In the case of the F/A-18, an aggressive problem-solving exercise by industry, DoD, and NASA over a period of years had resulted in a passive approach to the fin buffet issue. Specifically combined modifications consisting of structural cleats at the bottom of the vertical tails and small fences on the wing leading-edge extension (LEX) were incorporated on operational aircraft to meet fatigue requirements. The effects of different LEX lengths on tail buffet loads were examined on an F/A-18 model in the Langley 30- by 60-Foot Full-Scale Tunnel by researcher Gautam H. Shah. McDonnell Douglas (now Boeing) also examined other passive techniques to increase fatigue life of its aircraft. Because these types of passive techniques do not solve the buffeting problem for all flight conditions, an active tail buffet alleviation study was initiated. With active control techniques offering so much promise for solving other aeroelastic problems, it was only natural that research would be initiated to reduce the buffeting response of vertical tails. Except for some work in France and the aforementioned efforts of Heeg, little research had been conducted previously on the active control of buffeting response.

Langley and its DoD, industry, and international partners have conducted extensive research on the fundamental aeroelastic phenomena associated with tail buffet and have conducted several studies to assess and demonstrate active control to reduce the loads and stresses encountered. Led by Robert W. Moses, a series of wind-tunnel tests have been performed in the TDT since 1995 to develop and mature active control concepts. The initial activity, known as the Actively Controlled Response of Buffet Affected Tails (ACROBAT) project, focused on the F/A-18 configuration that had experienced significant operational tail buffet loads due to vortex bursting at high angles of attack.

A 1/6-scale, sting-mounted model of the F/A-18 served as the ACROBAT study workhorse. Objectives of the project were to apply active controls technology using various force producers, such as aerodynamic control surfaces and piezoelectric structural actuators, to alleviate buffeting for twin vertical tails; and to determine detailed unsteady aerodynamic data at high angles of attack with the buffet alleviation controls on and off. A variety of vertical tail surfaces was fabricated for the tests, including rigid (nonflexible) as well as flexible surfaces. Extensive instrumentation, including strain gauges and accelerometers, was used to obtain steady and unsteady characteristics during the tunnel tests. The investigated angle-of-attack range varied from 20 to 40 degrees. Early results of the ACROBAT studies indicated that control systems using either the rudders or piezoelectric actuators worked best for suppressing the buffeting loads and for angles of attack up to about 30 degrees, both approaches were equally effective in buffet alleviation. Exhibiting a strong interest in applying the rudder and piezoelectric actuators to reduce tail buffet loads, Daimler Benz Aerospace of Germany participated in the tests through a set of international agreements in aeroelasticity research.

Through an interagency agreement, NASA joined forces with the Air Force Research Laboratory (AFRL) to develop buffet scaling techniques by comparing the ACROBAT unsteady pressure data with full-scale, low-speed pressure measurements on an F/A-18 aircraft tested in the 80- by 120-Foot test section of the National Full-Scale Aerodynamics Complex (NFAC) Facility at NASA Ames. The scaling technique was later demonstrated by Moses and Shah through comparisons with unsteady pressures measured on a vertical tail of the NASA High Angle of Attack Research Vehicle F/A-18 aircraft at NASA Dryden while the airplane was flying at high angle-of-attack conditions. In addition to the scaling technique, the spatial correlation of the buffet, a random process, was demonstrated by Moses for the ACROBAT pressure data and comparisons with limited aircraft data. This information subsequently proved vital to modeling unsteady buffet pressures on the F-22 configuration for evaluating active control system models or minor changes to the tail structures and materials.

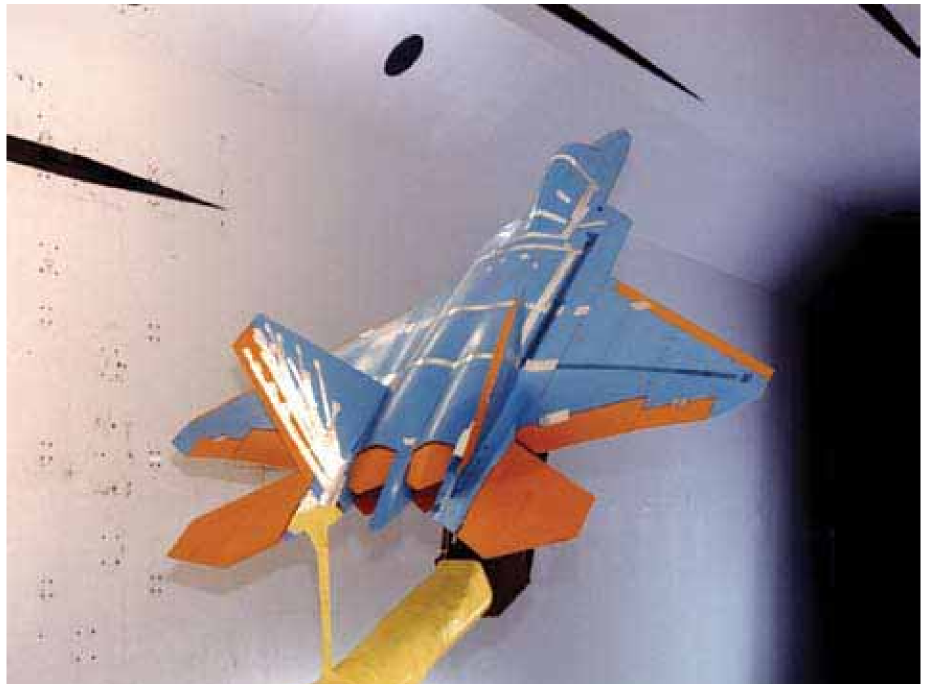


NASA's F/A-18 High Angle of Attack Research Vehicle uses smoke injected into vortex flow to illustrate vortex breakdown position for angles of attack of 20 degrees (top) and 30 degrees (bottom).

Building upon the successful ACROBAT Program, the collaborative F/A-18 tail buffet suppression studies were later expanded to include participation by Australia and Canada (operational users of the F/A-18). The research program was coordinated by AFRL and was conducted under the auspices of The Technical Cooperation Program (TTCP). The collaborative program involved tests of a full-scale F/A-18 empennage, including assessing the use of commercially available patch piezoceramic actuators to provide buffet alleviation. This ground test program used the International Follow-On Structural Testing Program (IFOSTP) facility located at the Australian Defence Sciences & Technology Organisation. The purpose of this collaborative program was to investigate the feasibility of piezoceramic actuators to withstand and control severe buffet loads applied to the F/A-18 vertical tails. Open- and closed-loop tests of the concept's effectiveness were completed successfully during ground tests in 1997 and 1998, respectively. This highly successful cooperative program has served as a pathfinder for future buffet loads alleviation research.

In 1998, another test entry of the F/A-18 model in the TDT involved a project known as Scaling Influences Derived from Experimentally-Known Impact of Controls (SIDEKIC). In this study, Bob Moses and his team cooperated with the Australian Aeronautical and Maritime Research Laboratory (AMRL) to correlate data during mutual investigations of the F/A-18 configuration. Because the F/A-18 is also flown by Australian military forces, mutual sharing of data and technology on tail buffet alleviation was especially valuable to the participants. New vertical tails were fabricated for the TDT F/A-18 model, and an effort was made to match the arrangement of piezoelectric actuators used during full-scale airplane ground tests at AMRL. One of the model's vertical tails used both an active rudder and active piezoelectric actuators for controlling responses over specific frequency ranges. This approach to providing buffet alleviation was referred to as a "blended" system because two different actuator technologies were combined by Bob Moses. Several other control schemes were evaluated during these tests, including one contributed by Boeing.

The F/A-18 research program's contributions and other studies of the F-15 configuration resulted in extensive studies using flow visualization, flow velocity measurements, pressure transducers, and response gauges. The state of the art for predicting buffet loads and fatigue life has rapidly matured and has been updated with tests of additional configurations. In 1999, Langley and AFRL conducted a cooperative TDT investigation of vertical tail buffeting characteristics of an early model of the F-22 fighter. Led by Bob Moses, the investigation used a 13.3-percent-scale model of the F-22 equipped with various types of instrumentation and sting-mounted in the TDT for testing at low Mach numbers (up to 0.12) and high angles of attack. A variety of measurements, including flow visualization techniques, was used to identify key features of the buffet-inducing flows. Model configuration variables such as wing leading-edge flap deflection were also assessed, and the general results obtained for the F-22 model were compared with the F/A-18 results for correlation and general conclusions. A rudder on the starboard-side vertical tail was actively controlled using feedback of buffet-induced accelerations near the tip of that tail. This approach proved quite effective in reducing buffet-induced responses.



F-22 model mounted in Transonic Dynamics Tunnel for tail buffet studies.

Highly successful demonstrations of the blended control system in the TDT, under the SIDEKIC Program presented earlier, led to full-scale actuator development, including systems-level considerations of cost and operational environmental conditions for electronic components. To validate the latest technologies in piezoceramic actuators and piezo drive amplifiers on an F/A-18, another international ground test program was formed in 2002 under the auspices of the TTCP. A series of ground tests were conducted in the Australian IFOSTP facility, as before; however, this test concentrated the piezo actuators near the vertical tail tip to control buffet-induced responses there and near the rudder to reduce vibratory response in the bending mode. Completed in 2004, this ground test program successfully demonstrated the feasibility of the "blended" control system to alleviate buffet loads as designed for an aircraft.

The success of international collaboration has peaked interest in the next generation of vertical tail active buffet suppression systems and the capability to predict systems performance. This interest was especially intense in 2001, when an early version of the Lockheed Martin X-35 Joint Strike Fighter aircraft experienced high tail buffet loads when attempting to fly at high angles of attack. Bob Moses was contacted by Lockheed Martin for consultation and assistance in the development of an in-house capability to design for tail buffet. Together, this team implemented an aggressive wind-tunnel test and tool development program that benefited from Langley's experience in model instrumentation, data acquisition and analysis, and predictive tool development. Within

15 months of the initial consultation, this team had scaled and implemented wind-tunnel pressure measurements into design methods not only to predict the buffet loads on existing designs, but also to redesign the tails to mitigate buffet-induced fatigue. Plans are underway to implement similar capabilities at Boeing to augment its current buffet loads design capabilities.

Status and Outlook

The challenges inherent in active control of aeroelastic responses have been the target of research at Langley Research Center for over 35 years. Progress in defining the complex transonic aerodynamic flow fields of importance has increased tremendously, as has the ability of CFD methodology to predict these phenomena. Experimental demonstrations in the TDT and in flight have been impressive and provided confidence in the ability of technology to alleviate aeroelastic problems using active control techniques.

Nonetheless, there has been very little application of active control for fixed-wing aircraft in the civil or military sectors. Significant widespread application barriers remain, especially issues regarding the additional complexity and cost of active controls. As yet, the cost-benefit consideration has not been in favor of such systems. More importantly, the critical safety-related margins comfortably enjoyed today for aeroelastic issues such as flutter are the result of years of experience in worldwide operational scenarios.

Using active controls for control of aeroelastic response within the U.S. commercial transport industry has not significantly advanced beyond Lockheed's early application to the L-1011 configuration in the 1970s. Meanwhile, the European Airbus Industrie Consortium has explored numerous areas using active controls for drag reduction, active center-of-gravity control, active-load control, variable-camber control, and active sideslip control. Airbus has subsequently applied the early principles derived from the Lockheed efforts by designing a wing load alleviation system into its A-320 transport from its early design, thereby reducing wing weight and improving passenger ride quality in turbulence by actively controlling wing bending moments. The A-320 entered commercial operations in 1988. Military applications of the technology have now progressed to in-depth assessments and flight evaluations for control of vertical tail buffet concerns at high angles of attack and for limite-cycle flutter alleviation for wing/store combinations. The successful application of active controls by McDonnell Douglas to production versions of the F/A-18 prior to the F/A-18E/F represents a milestone in the technology.

The Joined Wing: Diamond in the Sky

Concept and Benefits

One of the most attractive aircraft design areas for innovators has been the challenge of optimizing trade-offs among aerodynamic efficiency, structural effectiveness, and aircraft weight. Although requirements for aerodynamic performance may stimulate the designer to consider wings with very high aspect ratios, the attendant structural weight penalties and requirements for strength and rigidity for such configurations limit the geometric approaches that may be used for a feasible design. For conventional configurations, which use cantilevered-wing arrangements, the loads that must be safely accommodated by the wing-fuselage structure include critical bending moments induced by the aerodynamic and weight loads on the wing panels. Such loads always play a critical role in the aerodynamic and structural integration of new aircraft. Since the advent of heavier-than-air flight, the aeronautical community has continually investigated unconventional and innovative schemes to optimize these trades.

One approach used by designers has been to lay out configurations that use tandem fore-and-aft wings that are joined to form a diamond-type shape when viewed from above and from the front or rear. Depending on the specific geometry involved, potential reductions in structural weight or improved aerodynamic characteristics may be generated. Early designs included a glider, designed by Reinhold Platz in Europe in 1920, and a rudimentary multijoined-wing airplane built by Ben Brown of the University of Kansas in 1932. A more recent joined-wing configuration is the "box plane" concept designed by Luis R. Miranda of the Lockheed-Georgia Corporation in the early 1970s. The box plane concept has been proposed by Lockheed Martin for potential applications for commercial transports, freighters and military tankers.

Also in the 1970s, Julian Wolkovitch of ACA Industries advanced a joined-wing concept wherein the root of the rear wing was intentionally designed to be at a higher elevation than the front wing. With this arrangement, the fore-and-aft wings form a truss structure that relieves some of the loading from the front wing and significantly stiffens the structure. This joined-wing concept is obviously a highly integrated approach to aerodynamic and structural design.

For aircraft applications, the principal benefit of this particular joined-wing configuration is that the rear wing acts as a strut brace to support some of the wing bending moments. This loading feature can be exploited as a reduction in wing weight or as an increase in wing span (aspect ratio), or a combination of both. A secondary benefit of the joined-wing configuration is that the nonplanar arrangement of lifting surfaces can theoretically result in lower induced drag for a given span and weight.

Boeing concept for a joined-wing flight demonstrator.

In addition to these fundamental considerations, the joined-wing configuration offers other potential benefits that are unique to its unconventional geometry. For example, because of the wings' diamond-shaped arrangement when viewed from above, the lifting surfaces can be used to support various types of radar antennas to provide a 360-degree azimuth coverage with little or no aerodynamic penalty. Equipped with wing conformal electronically scanned array radars, a joined-wing research aircraft could offer a substantial increase in radar capability and improved range and endurance. The multiple lifting surfaces result in a compact configuration, requiring less deck space for shipboard military naval applications. In another potential military application, the relatively stiff outer wing of a joined-wing tanker (with a forward/rear wing joint at about 70 percent of the semispan) could accommodate refueling booms on fairing pods at the two outer-wing joints. This capability would enable simultaneous air-to-air refueling of two aircraft, which is not currently possible with today's tanker configurations.

An interesting potential application of the joined-wing configuration would be for advanced aircraft designed for aerial applications, such as crop treatment and seeding, or for fire fighting. In these potentially hazardous missions, structural robustness and crashworthiness can be more important than aerodynamic efficiency or structural weight. The rigidity and structural strength afforded by the joined-wing geometric arrangement offers the promise of significantly enhanced safety and reduction of fatalities. In another civil application, the use of the joined-wing layout with its inherent rigidity might significantly increase the flutter speed encountered by conventional high-altitude sensor vehicles, such as those used to monitor earth environmental and resource characteristics. These vehicles conventionally have been configured with very high-aspect-ratio wings that can result in undesirably low flutter speeds.

Yet another potential application of the joined-wing concept involves the design of supersonic aircraft configurations with relatively low sonic boom levels. The intensity of sonic booms is a strong function of vehicle length, and a joined-wing configuration has a greater "effective length" because of the elevated rear wing junction to the vertical fin. Additionally, current concepts for engine nacelles that reduce takeoff and landing noise have rather long silencers extending aft from the wing trailing edge. These nacelles provide a natural location for the wing-tail joint and may provide some bending or torsional moment relief to the wing.

Challenges and Barriers

The joined-wing concept has faced many challenges and barriers from technical considerations in the areas of structures, aerodynamics, and stability and control. NASA, industry, DoD, and universities have addressed many of these issues with analytical and experimental studies.

The greatest structural benefit of the joined-wing configuration occurs when the front- and rear-wing joints are all fixed cantilever connections. Unfortunately, this arrangement results in a structure that is more difficult to analyze (referred to as statically indeterminate) and can result in counterintuitive characteristics. Another major challenge results from the fact that typical joined-wing configurations are designed with the root of the rear wing above the front wing, so the rear wing is loaded in combined bending and compression. The rear wing, which acts as a compression strut, must be designed with enough stiffness not to buckle. Typical low-fidelity structural weight-estimation tools used during early conceptual and preliminary design are not capable of determining realistic loads, moments, stresses, or weight of a joined-wing structure.

The necessity for more sophisticated structural design methods and capability—early in the vehicle conceptual development—is a powerful economic barrier for companies that might otherwise consider a joined-wing configuration. Because of the lack of detailed design experience with such an unconventional structure, the potential advantage of lower structural weight is regarded as a significant technical risk. Companies are reluctant to make the investment in design tools and training, and they have neither sufficient funding nor schedule margin to allow longer design evolution/iteration to occur in the detailed design. Any nontraditional structural arrangement will encounter similar barriers when the groups performing detailed structural design within the companies are faced with such a radical departure from established methods and procedures.

In the area of aerodynamics, the most dominant challenge to the joined-wing configuration is the minimization or elimination of separated flow at wing and fuselage junctures and aerodynamic component interference effects across the flight envelope, including cruise, takeoff, and landing. With the added component juncture formed by the wing joint, the joined wing provides added challenges to the aerodynamicist. If the configuration experiences unacceptable juncture-flow characteristics (particularly at high subsonic cruise conditions), overall drag levels may be significantly higher than those of conventional transports.

The joined-wing configuration may also exhibit unique challenges in the critical area of propulsion integration. For some applications, engine nacelles may have to be located on lateral stubs on the fuselage near the configuration's center. Aerodynamic interference effects from the forward wing/fuselage components (particularly for high angles of attack or sideslip) may result in unsatisfactory engine inlet flow characteristics or inefficient propulsion performance at cruise. In addition, the engine efflux may cause interference effects on the aft wing or vertical tail.

Finally, inadequate design of the rear wing or vertical tail juncture may cause flow separation, which can result in a significant increase in drag and a large impact on stability and control. In addition, the overall consideration of trimmed lift for operational conditions across the envelope must be analyzed and the vehicle configured to ensure satisfactory characteristics. The relatively short moment arm of the aft wing control surfaces of most diamond-wing type joined wing aircraft aggravates the classical problem of longitudinal trim or lift trades at low-speed landing conditions. For a stable aircraft, the short-coupled rear wing may have to produce excessive download to trim the pitching moments experienced during various phases of flight, resulting in a significant loss of lift. Other approaches to joined-wing configurations, such as an auxiliary aft-mounted tail surface, might be employed to alleviate unacceptable levels of lift loss due to trim.

Many joined-wing configuration wind-tunnel models have exhibited a nosedown ("pitch down") characteristic at moderate angles of attack below wing stall, thereby limiting the maximum lift of the configuration to less than desirable values. The phenomenon is attributed to stalling of the front wing, resulting in loss of lift on the forward wing and a reduction in downwash onto the rear wing, which increases the pitch-down contribution of the rear wing. Although this effect is favorable as a natural stall-prevention mechanism for the airplane, it can severely limit the magnitude of attainable lift. Thus, longitudinal stability of the joined-wing design requires a careful integration of individual wing stall characteristics.

Operational challenges specific to joined-wing configurations are relatively unknown because of the lack of applications and flight experiences with aircraft other than personal sport vehicles. Issues such as icing characteristics, detailed handling quality assessments, and other real world issues have not been assessed at the current time.

Langley Activities

NASA's participation in research on joined-wing aircraft has involved Langley Research Center, Ames Research Center, and Dryden Flight Research Center. The following discussion highlights critical activities at the participating Centers, with an emphasis on activities that have occurred at Langley. More detailed information on activities at Ames and Dryden is provided in references listed in the bibliography.

Exploratory Study of Aerial Applications Aircraft

In 1979, Julian Wolkovitch approached Joseph L. Johnson, Assistant Head of the Dynamic Stability Branch, with a request for a cooperative wind-tunnel test of an advanced joined-wing general aviation airplane designed for aerial applications. The configuration, which the legendary Elbert L. (Burt) Rutan had designed, featured a tractor-propeller-driven, joined-wing layout with the rear wing joined at the mid-span location of the forward wing, which had winglets. The pilot was located in the 18-percent thick vertical tail of the vehicle. Wolkovitch had crash resistance in mind as a primary design objective when he first pursued the joined wing as a sport glider in 1974, and he and Rutan believed that the proposed agricultural plane design would offer significant safety improvement over conventional designs.

Because of its interest in providing data for advanced configurations, NASA fabricated a scale model of the design and conducted a cooperative test in a 12-foot low-speed subsonic tunnel at Langley. Lead engineer for Langley during the exploratory tests was E. Richard White. The tests were regarded as exploratory and limited because of the low Reynolds number of the test conditions, and all participants had expected premature flow separation on the wings and junctures due to lack of simulated flight conditions. Nonetheless, it was felt that any aerodynamic data on stability and control characteristics of this remarkable configuration would be of great interest to the engineering community.

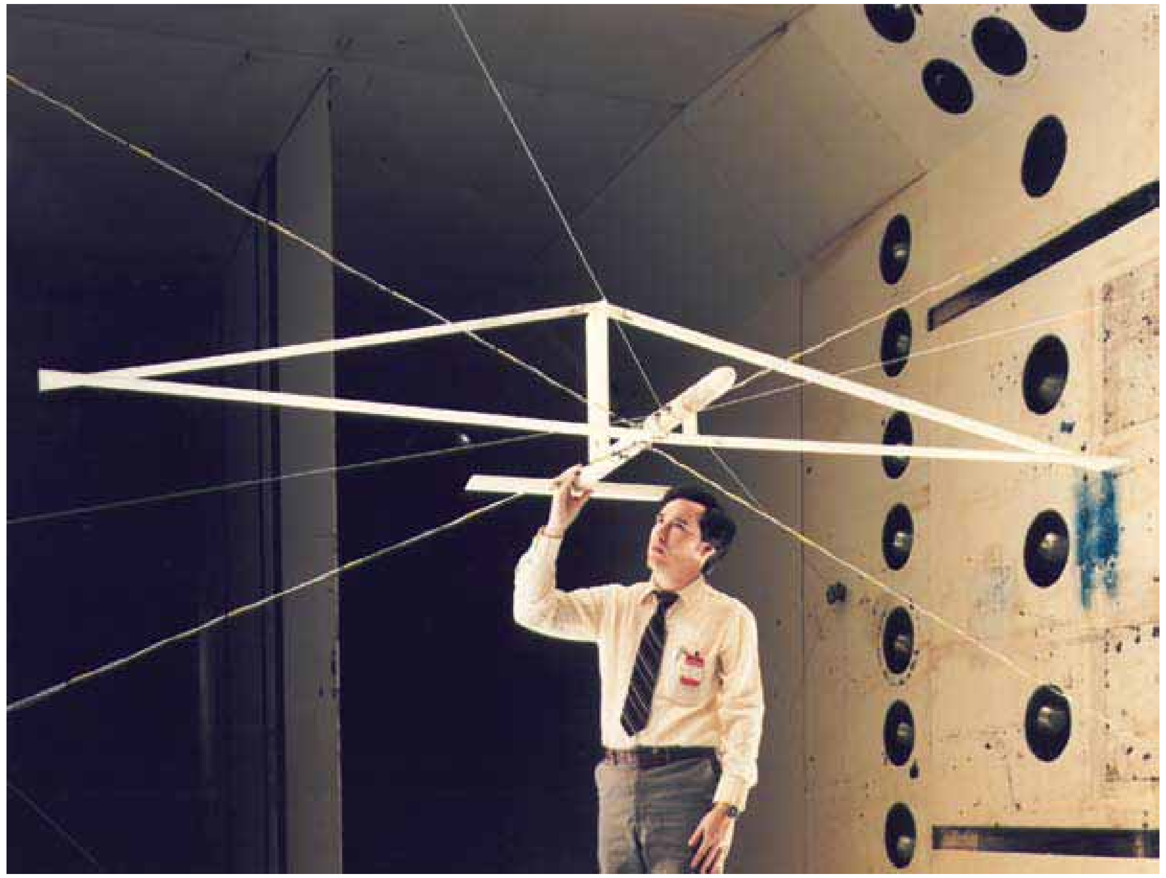
Advanced agricultural airplane model tested at Langley.

The results of the test verified the expected flow separation regions, especially at the wing-joint locations at moderate and high angles of attack. Of more concern, however, was the impact of flow separation at the rear wing-vertical tail juncture, which resulted in a loss of directional stability contributed by the thick, short-span vertical tail. Although the design was not subsequently pursued for a commercial product, this early test identified a number of performance, stability, and control issues that have resurfaced as challenges throughout later studies of joined-wing vehicles.

High Altitude Vehicle Flutter

Aircraft flying above 100,000 ft must operate near the drag-divergence Mach number while generating high lift coefficients. For such flight conditions, thin supercritical airfoils are desirable. Cantilever wings employing these thin airfoils tend to be heavy or excessively flexible. For joined wings, however, reducing thickness-chord ratio gives only small penalties in structural weight and rigidity. The net effect is that the joined wing can potentially increase the altitude and payload capabilities of very high altitude aircraft. A key consideration of this benefit is the joined wing's impact on potentially catastrophic flutter.

In 1984, Langley's Michael H. Durham and Rodney H. Ricketts of the Aeroelasticity Branch teamed for an analytical and experimental study of the joined-wing configuration's benefits on flutter characteristics of very high-aspect-ratio (21.6 and 42) vehicles. In the investigation, they studied two types of joined-wing models in the Langley TDT at Mach numbers of 0.4 and 0.6. Durham and Ricketts investigated semispan wall-mounted models of conventional and joined-wing designs, as well as full-span flutter models, on the unique free flying cable-mount system used for flutter testing in the TDT. Results obtained with the sidewall-mounted models compared characteristics of joined wings with conventional cantilevered wings of equal span, weight, and projected area. For each Mach number tested, Durham and Ricketts found the dynamic pressure for onset of flutter for the joined-wing configurations to be about 1.6 times higher than that of cantilever wings, verifying the joined wing's expected benefits. Testing the cable-mounted full-span models provided more excitement and some unexpected results. The lower aspect-ratio (21.5) full-span joined-wing model experienced an aerodynamic instability and was destroyed in the ensuing out-of-control motions. In addition, the cable-mounted high-aspect-ratio full-span joined-wing model exhibited a symmetric flutter mode that was remarkably unconventional. In this flutter mode, the model displayed fore-and-aft motion as well as vertical motion. Observers noted that the model appeared to be performing a "butterfly stroke" similar to a swimmer. Durham studied the motion and developed an approach for analysis that correlated well with the experimental results for both flutter speed and mode. He subsequently disseminated the investigation's results at specialists meetings.



Researcher Mike Durham with flutter model of joined-wing high-aspect-ratio configuration.

Joined-Wing Studies at NASA Ames Research Center

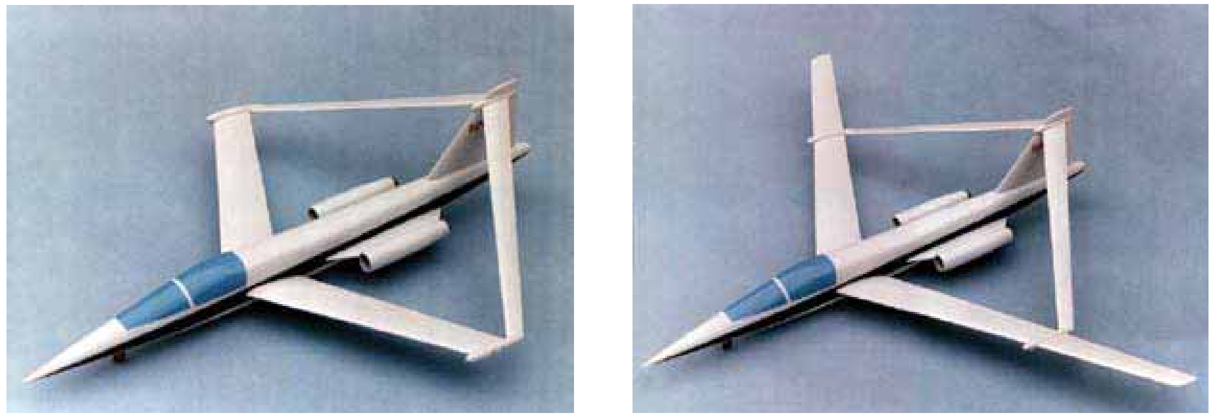
While Langley was engaged in assessing the benefits of joined-wing vehicles for civil and military applications, similar efforts were underway at NASA Ames Research Center, including investigations of civil transport applications. Although not directly coordinated with Langley, this work mentions these studies for completeness and perspective on the scope of studies at Ames.

As researchers at Ames began studying the joined-wing concept, they recognized that more sophisticated design and analysis tools would be required to properly assess performance trends that are dependent on structural weight and trimmed-drag prediction. In 1986, work began on a combined structural and aerodynamic analysis code that would be appropriate for conceptual design. Stephen C. Smith at NASA Ames and Ilan M. Kroo and John W. Gallman at Stanford University collaborated on this work. They based the aerodynamic model on a vortex-lattice representation of the configuration and included a coupled optimization routine to find optimum twist distribution and tail incidence to minimize induced drag and achieve pitch trim with fixed static stability. The structural model was based on a finite beam-element method with a coupled optimization to determine the minimum structural weight with maximum-stress and minimum-gauge constraints. These tools allowed parametric studies of the effects of various configuration changes on structural weight and cruise drag. Smith, Kroo, and Gallman published the study results in 1987.

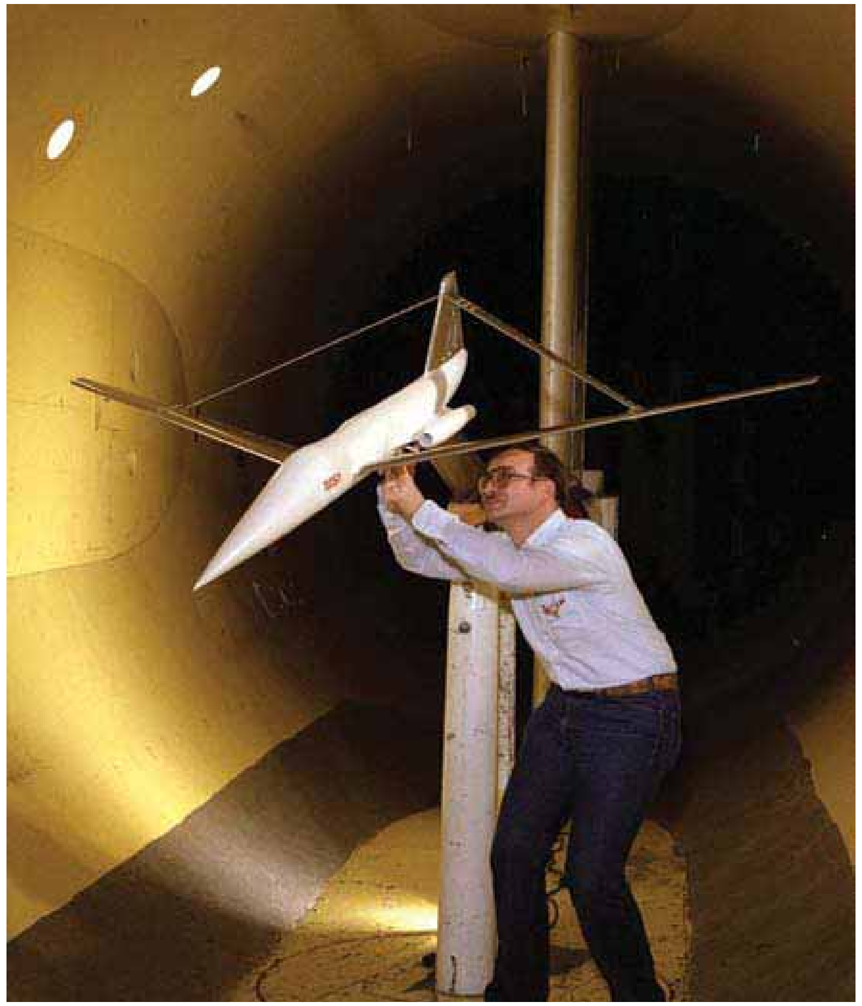
Ames subsequently hired Gallman, and he incorporated these models into a full mission-synthesis model that performed a complete vehicle optimization subject to real world constraints, such as takeoff and landing field length, engine-out climb requirements, internal fuel volume and cruise range with IFR fuel reserves, static stability and trim over allowable center of gravity range, positive weight on nose wheel, structural loads and weights in compliance with FAR 25, and many others. Improvements to the analysis models included maximum trimmed lift capability, buckling margin, and flutter prediction.

In parallel with the conceptual design efforts, Ames supported Julian Wolkovitch's company, ACA Industries, in designing and developing a manned flight demonstrator aircraft to develop a representative joined-wing structural arrangement and demonstrate satisfactory flying qualities. SBIR phase I and phase II awards funded this effort. A wind-tunnel test was conducted to measure the aerodynamic characteristics of a joined-wing research aircraft (JWRA), which was designed to use the fuselage and engines of the existing NASA AD-1 research aircraft. The AD-1 had completed a very successful piloted flight program to demonstrate oblique-wing technology. The JWRA was designed to have removable outer-wing panels to represent three different configurations with the interwing joint at different fractions of the wing span. A 1/6-scale model of all three configurations of the JWRA was tested in the Ames 12-Foot Pressure Tunnel to measure aerodynamic performance, stability, and control characteristics. These test results indicate that the JWRA had very good aerodynamic performance and acceptable stability and control throughout its flight envelope. Although the wind-tunnel results showed satisfactory performance, stability, and control, with no adverse interference drag using well-designed fairings at the wing-tail joint, the funds available for research were exhausted before the flight demonstrator vehicle could be fabricated.

Ames design study results of commercial civil transports indicated that, for the specific mission application chosen, the joined wing had a few percent higher direct operating cost. However, they also showed that several adverse characteristics of the design could probably be mitigated with further design. Chief among these was the larger wing size required because of poor trimmed maximum lift, a consequence of high tail downloads required to trim. Alternative high-lift systems that produce less pitching moment and longer fuselage layouts may have improved the trimmed lift enough to make the joined wing competitive with conventional configurations. At the same



Model of the Ames Joined-Wing Research Aircraft concept shows two of the three wing arrangements.



The 1/6-scale model of the Joined-Wing Research Aircraft in the Ames 12-Foot Pressure Tunnel.

time, tailored composite tail structures may have increased stiffness and buckling margin with less weight penalty, again improving the joined-wing performance relative to the conventional airplane arrangement. Alternatively, exploiting the wing strut bracing's structural benefit while retaining the efficient trimming capability of a conventional horizontal tail may be an even more efficient configuration. Each potential design fix was regarded as beyond the scope of the Ames studies, which were concluded in 1993. Such approaches, however, could potentially make the joined wing attractive and successful. The Ames experience shows that the joined wing, more than most other vehicle concepts, requires a well-established multidisciplinary design approach throughout the vehicle development process, from conceptual and preliminary design through detailed design.

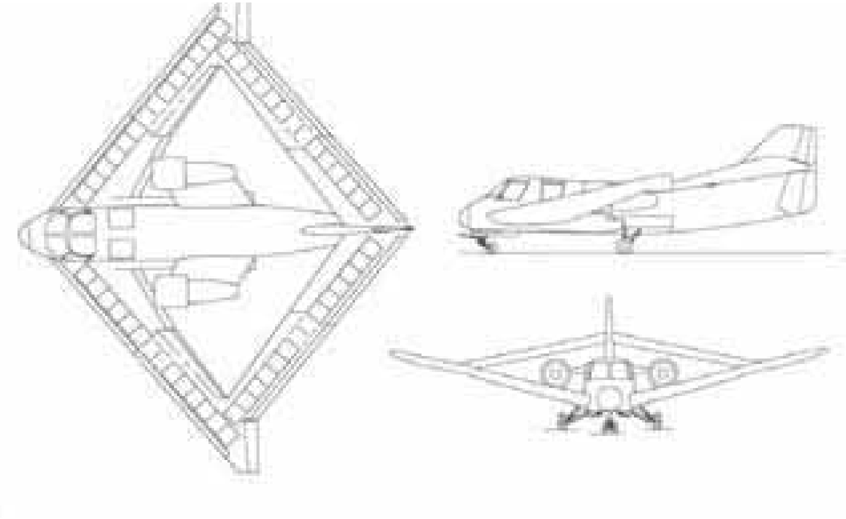
Participation in Boeing's EX Program

The safety of U.S. Navy carrier battle groups depends strongly on an early warning of incoming aircraft and missiles launched by beyond-the-horizon enemies. For over 30 years the responsibility for providing early warning has been assigned to the Navy E-2C Hawkeye aircraft, which uses a 24-ft rotodome atop the vehicle to enclose its radar antenna. Anticipating the need for a more capable replacement surveillance aircraft as the E-2C reaches the end of its lifetime in the fleet, the Boeing Defense and Space Group's Military Airplane Division embarked on studies of a radical new joined-wing surveillance aircraft design in response to a new Navy program known as the Electronics Experimental (EX) Program in 1990. The EX Program achieved Milestone 0 definition in 1992, but the Navy did not pursue the program because of defense funding reductions.

The Boeing EX aircraft concept incorporated advanced active-aperture radar arrays in each joined-wing segment to create an ideal arrangement for the radar arrays and a more aerodynamically effective design than the conventional E-2C. The joined-wing EX concept was only about 80 percent the size of the larger E-2C, yet it incorporated four 31.5-ft wing-mounted radar apertures, compared with the single 22-ft aperture carried by the E-2C.

In the early 1990s, the Navy E-2C Program Office approached NASA Langley researchers for discussions of a cooperative study of the EX configuration in the Langley 16-Foot Transonic Tunnel. In accordance with NASA's mission to explore advanced configurations of interest, Division Chief William P. Henderson and Branch Head Bobby L. Berrier agreed to Langley participation in the project, and researchers Richard J. Re, Jeffery A. Yetter, and Timmy T. Kariya served as key Langley engineers on the Boeing-NASA team. In July 1993, the team tested a model of the EX design to evaluate longitudinal and lateral aerodynamic characteristics and the effectiveness of various control surfaces. Measurements were also made to determine the effects of the wings and fuselage on engine inlet fan-face total pressure distortions at angles of attack and sideslip. The test program's results showed that the initial EX configuration exhibited several regions of separated flow for all values of Mach number investigated, including cruise conditions.

Artist's concept of the Boeing EX joined-wing aircraft.



Three-view sketch of the Boeing EX configuration.

Guided by the results of this first tunnel entry, Boeing modified the configuration's wings, and a second entry in the tunnel occurred during October 1998. E. Ann Bare led Langley's participation and was assisted by Wesley L. Goodman. Early test results indicated that undesirable flow separation still existed on the modified configuration. Langley's Steven E. Krist and Boeing provided additional analysis and guidance by conducting CFD analyses. One of the configuration's more challenging flow separation areas was the juncture of the aft-wing root and the vertical tail. Aerodynamic drag caused by massive separation in this area resulted in large performance penalties for the configuration. Responding in an extremely timely fashion, Krist quickly analyzed the flow field at the critical junction area using the OVERFLOW code and designed a leading-edge modification ("bump") for the vertical tail that minimized the separation phenomenon. Technicians quickly fabricated the tail modification for the model and provided quick turn around for testing of the modification. Test results for the revised model showed that the new tail configuration dramatically reduced drag. Krist's valuable contribution to the joint investigation was widely recognized and appreciated by all members of the Boeing-NASA team.

In addition to the pioneering information provided on the aerodynamic characteristics of joined-wing configurations, and the EX in particular, the test entries in the 16-Foot Transonic Tunnel and the interactions of the Langley and Boeing staffs provided the foundation for a follow-up NASA RevCon project to be discussed in a later section.

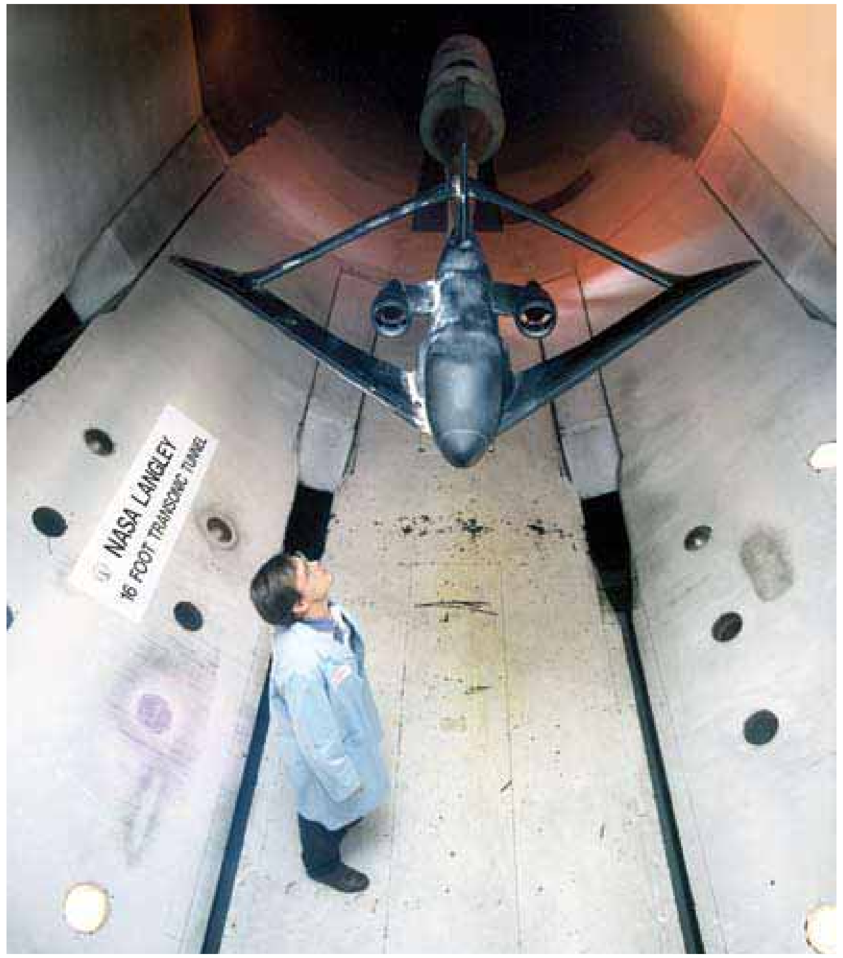
Other Langley CFD efforts were also directed at the unconventional joined-wing EX configuration operating at transonic, separated-flow conditions. Neal T. Frink, Shahyar Pirzadeh, and Paresh Parikh calibrated an unstructured Navier-Stokes capability within NASA's Tetrahedral Unstructured Software System (TetrUSS) to demonstrate the system's ability to predict the shock-induced trailing-edge flow separation observed on the fore and aft wings. The surface-flow patterns obtained with TetrUSS were in good agreement with experimental oil-flow data obtained in the tunnel tests. Computed pressures were also in good agreement with the experimental data. This study represented a significant contribution toward a broader goal of validating a next-generation CFD methodology for rapid and cost effective Navier-Stokes analysis and design of complex aerodynamic configurations.

The NASA RevCon Program

As previously discussed within the topic of the blended wing body concept, in 1997 Darrel R. Tenney, Director of the Airframe Systems Program Office, and Joseph R. Chambers, Chief of the Aeronautics Systems Analysis Division, formulated and proposed a new research program based on the selection of precompetitive advanced configurations that would be designed, evaluated,

fabricated, and test flown using remotely piloted vehicle technology at Dryden. The program, known as RevCon, would be based on a 4-year life cycle of support for concepts selected. Initial reactions to the proposed program from NASA Headquarters and Dryden were favorable, and following intercenter discussions with the additional participation of Ames and Glenn, a formal NASA RevCon Program was initiated in 2000 that was to be led by Dryden. Robert E. McKinley led the RevCon activities at Langley under the RACRSS element of Airframe Systems.

In June 2000, NASA's Office of AeroSpace Technology selected nine aeronautical concepts in its initial RevCon Program, including a teamed effort by Langley (team lead) with partners from Dryden, Boeing (Phantom Works), Naval Air Systems Command (NAVAIR), and AFRL for the design, development, fabrication, and flight testing of a joined-wing integrated structures demonstrator. The Air Force involvement in the program came about due to rapidly growing interest in surveillance unmanned air vehicles (UAVs). The project would receive approximately

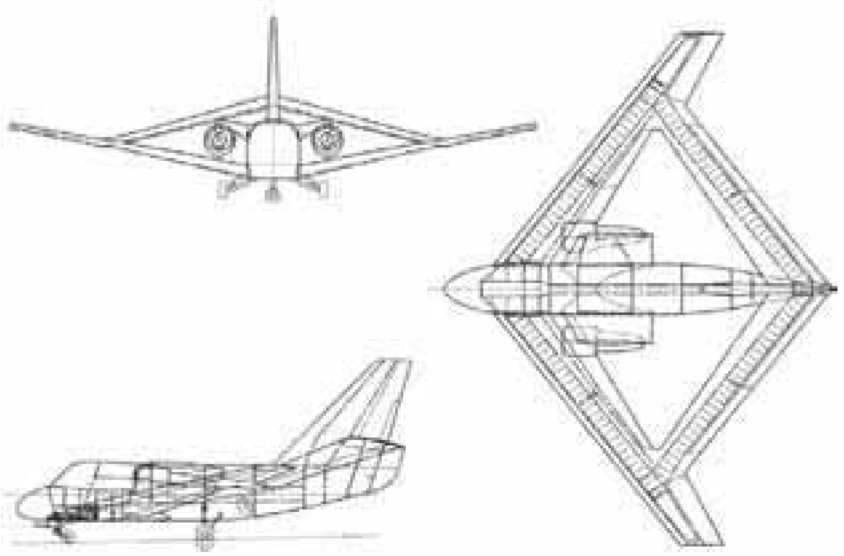


Jeff Yetter inspects the EX model in the Langley 16-Foot Transonic Tunnel in 1993.

$300,000 from NASA for phase I research, and the industry-DoD partners were expected to commit similar levels of funding. Objectives of the 4-plus-year project were to (1) enable the integration of large radar apertures into smaller aircraft for improved detection range and resolution, (2) reduce drag and weight for improved aircraft speed and endurance, and (3) reduce system costs. Flight experiments would be conducted with a full-scale piloted research aircraft using a modified U.S. Navy S-3 Viking fuselage with new joined wings.

In an 8-month phase I activity, the team explored demonstration alternatives, conducted risk-reduction experiments and analyses, and planned phase II details and costs. The primary research and technology objectives of the Joined-Wing Flight Demonstrator (JWFD) Project fell into three broad categories: (1) aerodynamics, flight controls and flight characteristics; (2) multifunctional structures, and (3) wing-integrated RF apertures. During phase II, the demonstrator aircraft would be fabricated and flight tested. Within the RevCon Program, flight testing would focus on aircraft performance, flying qualities, flight-envelope expansion, and validation of structural behavior. Following the RevCon phase II flight test activities at Dryden, plans included U.S. Navy flight testing at Patuxent River, Maryland, to evaluate carrier suitability and the radar aperture performance.

Langley's Program Manager for the teamed phase I effort was Jeff Yetter, manager of the Advances through Cooperative Efforts (ACE) Program of the Aerospace Vehicles Systems Technology Office. The research Integrated Product Team (IPT) leaders at Langley were Phillip B. Bogert (structures), Steve Krist (aerodynamics), and James W. Johnson (electromagnetics). The phase I and phase II plans identified the use of several unique Langley facilities, including tentative entries in the Langley 16-Foot Transonic Tunnel, the Langley 14- by 22-Foot Low Speed Tunnel, the Langley 20-Foot Vertical Spin Tunnel, the Langley Electromagnetics Test Facilities, the Langley Structures and Materials Laboratory, and the Langley Nondestructive Test Laboratory.



Three-view sketch of the Joined-Wing Flight Demonstrator configuration.

The project would make extensive use of existing Navy flight vehicle hardware and new joined-wing hardware. The 35,000-pound (takeoff gross weight) JWFD would be assembled from new joined wings adapted to an existing Navy S-3 aircraft fuselage. The forward and aft wings of the JWFD would contain integrated phased array antennas. The forward fuselage, aft fuselage, and vertical tail would be modified to accept the new wings. The S-3's existing wing would be terminated outboard of the fuselage sides and new wing stubs would be added to accommodate the pylon/engine installations. The engines would be TF-34 turbofans (existing S-3 engines) provided from the Navy inventory.

The phase I aerodynamic design of the JWFD expanded upon knowledge gained from Boeing-Navy-NASA studies of the earlier Boeing EX configuration. The JWFD's forward and aft wings were essentially identical to those for the EX, with supercritical airfoil sections and slightly different sweep and dihedral angles. The JWFD's wing span was increased from that of the EX in order to provide adequate aileron area for desired roll control authority. This change, together with the minor sweep change, increased total span from 63 ft on the EX to 72 ft on the JWFD. The JWFD planform, like that of the EX, permitted the integration of 31.5-ft conformal apertures into each of the four wings.

Model of the Joined-Wing Flight Demonstrator in the Langley 14- by 22-Foot Tunnel.

The JWFD was designed to have 13 flight control surfaces consisting of inboard and outboard trailing-edge flaps on the forward wing, inboard trailing-edge flaps on the aft wing, upper and lower split trailing-edge flaps on the outer-aft wing, trailing-edge flaps on the wing tips, and the rudder. Leading-edge flaps were provided on the forward wing for high lift during takeoff and landing. This robust suite of flight controls made the JWFD an excellent platform for further control system development and optimization of handling qualities for joined-wing aircraft.

The project started its phase I risk reduction and phase II planning activities on September 1, 2000, rapidly advancing the definition of the JWFD. In aerodynamics activities, an exploratory low-speed test of the JWFD configuration was immediately formulated, a model prepared, and tests conducted in the Langley 14- by 22-Foot Tunnel during February 2001 to determine performance of the high-lift system, static longitudinal and lateral-directional stability, control effectiveness, inlet flow qualities, and ground effects. Langley's JWFD test leaders were Richard J. Re and Harry L. Morgan. The configurations tested, including takeoff, approach, landing, and patrol configurations, determined the effects of various control surface deflections (individually as well as in combinations) on stability and control. The leading- and trailing-edge flaps of the forward wing were evaluated for high-lift capability, as were the wing-tip ailerons. On the aft wing, the effects of elevator, outboard flap, and speed-brake deflections were investigated. Data were also obtained for maximum rudder deflection. Runs were conducted with, and without, the landing gear and gear doors extended, and a limited number of flow visualization runs were conducted using tufts mounted on the wing tip and outboard portions of the forward and aft wings. Test results showed that the JWFD configuration had adequate stability and control characteristics for use as a flight demonstrator.

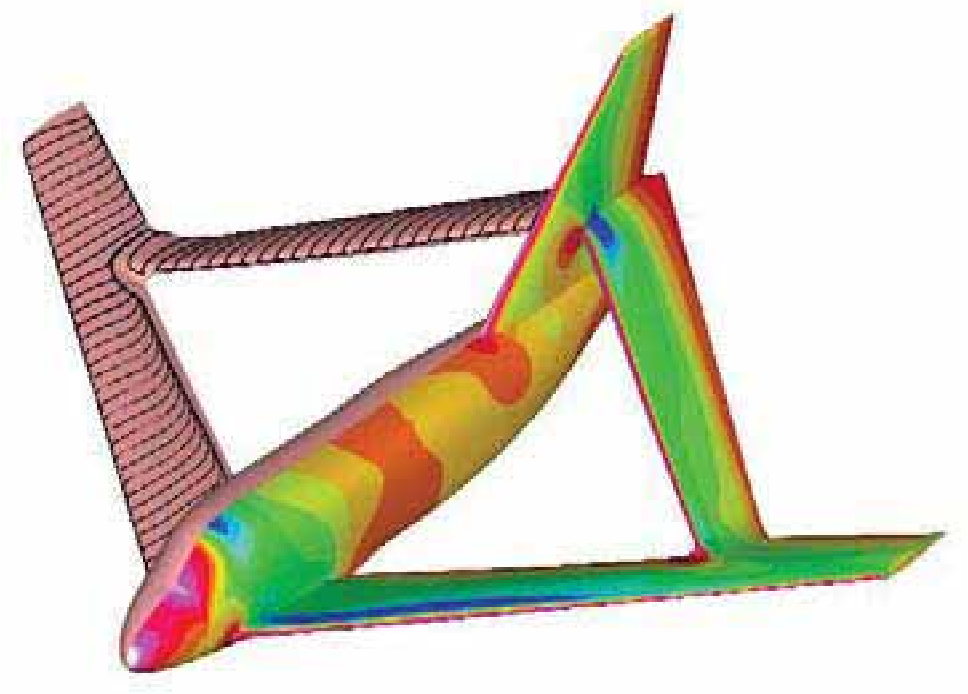
One potential aerodynamic issue of the JWFD that concerned the research team was the possible existence of significant jet effects on the rear wing and vertical tail. In a head-on view, the engine nacelles of the JWFD were about evenly placed above the forward wing and below the aft wing, mounted close in to the fuselage on stubs. The possibility therefore existed that the jet efflux could cause interference effects on the aft wing and tail, particularly at high angles of attack. The AFRL initiated a limited CFD investigation of powered effects using COBALT, a Navier-Stokes flow solver for unstructured grids, but none of the cases involved high angles of attack and the results were inconclusive relative to the suspected critical conditions.

Steve Krist's IPT team conducted CFD analyses with OVERFLOW, a Reynolds Averaged Navier-Stokes code for overset structured grids. CFD analyses of the joined-wing configuration were performed across the operating speed range, flow characteristics for the wing-body, wing vertical tail and fore/aft wing junctures were examined, and estimates of air loads were generated. Optimal engine inlet orientations were defined for good inflow to the fan face, and drag-rise characteristics were calculated to verify the aerodynamic efficiency of the joined wing design. Flow separation at the aft wing-vertical tail juncture of the JWFD was considerably improved over that discussed for the earlier EX configuration. This improvement resulted from the juncture of the aft-wing leading edge with the vertical tail being much further aft on the JWFD than on the EX. Flow visualizations at Mach numbers ranging from 0.4 to 0.81 indicated that extensive separation on the lower portion of the vertical tail appeared as early as Mach 0.6 on the EX, but not until Mach 0.78 on the JWFD.

Computational results indicated that the two areas on the JWFD providing the greatest potential for reduction in drag were the forward-wing/aft-wing juncture and the aft-wing/vertical tail juncture. Flow separation at the forward wing/aft wing juncture occurred primarily at high angle-of-attack subsonic conditions where the compressive effect of the aft-wing leading edge resulted in significant spanwise flow on the upper surface of the outboard forward wing and the wing tip. Procedures were developed for redesigning this juncture using OVERDISC, a computational design tool that couples the CDISC inverse design method developed by Richard L. Campbell of Langley with the OVERFLOW flow solver. Initial attempts at CFD designs at Mach 0.45 experienced great difficulty in controlling the local surface shape while meeting geometry constraints in this unconventional juncture.

Problems at the aft wing/vertical tail juncture arose at transonic conditions, resulting in a sharp drag rise at Mach 0.81. On the upper surface, a shock developed at the juncture and strengthened with increasing Mach number. On the lower surface, the separation at the trailing edge migrated forward with increasing Mach number until, at Mach 0.81, the flow on the lower portion of vertical tail separated just behind the aft wing leading edge. Procedures for using OVERDISC to design a fillet for this juncture—to mitigate the upper surface shock—are well developed, having been validated with Steve Krist's studies on the EX configuration. However, there was insufficient time in the JWFD project to fully explore this procedure.

The NASA-Boeing team made substantial progress in the structural definition and design of joined wings. A general structural arrangement for composite joined wings with integral radio frequency apertures was prepared, side-of-body connections for the engine nacelles were defined, and the required structural modifications to the S-3 airframe were identified. The team also generated detailed static and dynamic finite element models, performed loads and stress analysis of critical load cases to verify the wing-fuselage attachment concept, and performed initial structural element sizing. A conceptual design for an innovative fiber optic wing-shape sensing system was



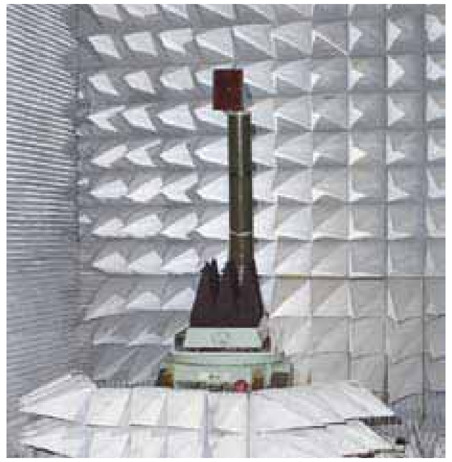
CFD predictions of pressures, streamlines, and flow over the Joined-Wing Flight Demonstrator for a Mach number of 0.7 and an angle of attack of 0 degrees.

Computational simulation of power-induced flow on the RevCon Joined-Wing Flight Demonstrator.

also developed. The system would have computed in-flight wing deformations from fiber optic measured strains, thereby providing information needed for the phased-array application. The system would also have been a key building block for future in-flight health monitoring systems for other applications.

Boeing and NASA continued efforts to define the analytically redundant fly-by-wire control system of the JWFD, and simulations showed that the flight control system was robust. Boeing used the simulation to assess sensitivity to actuator sizing and rates.

In the area of electromagnetics, single array element models were built and tested, while analytical tools were developed and validated. A full-scale working model of the probe-fed element was built and chamber tested. Conceptual designs were completed for the flight control actuation, high lift, hydraulics, electrical, ECS, and fuel systems. The designs focused on using existing S-3 subsystems and components available from the existing inventory. In addition to component parts, the Navy identified a specific S-3 airplane for use by the JWFD project. Finally, the flight-test team developed a draft test plan that identified all required preflight qualification testing, indicated necessary flight-test instrumentation, and outlined an approach for obtaining airplane flight qualities, low-speed performance and flight-envelope expansion.



Brassboard testing of Joined-Wing Flight Demonstrator array element at Langley

The team submitted the final report on the phase I JWFD study results in April 2001. Unfortunately, funding priorities within the participating government agencies were directed elsewhere following the initiation of the RevCon Program. The Navy and the Air Force were unable to meet their shares of the required funding commitments, and NASA's portion of the funding was redirected to providing a return-to-flight capability for the NASA X-43A (Hyper X) Program following the X-43A accident on June 2, 2001. NASA terminated its RevCon Program on September 30, 2001.

Although the RevCon Program was terminated before phase II could be undertaken, the NASA-DoD-industry team significantly advanced the definition of a joined-wing aircraft system and developed a practical conceptual design for a manned flight demonstrator. Progress was made in a variety of risk reduction areas and the team developed a viable project plan, cost estimates, work breakdown structure, and definition of responsibilities between the partners. Because of this activity, the technical community now has a much better understanding of what it would take to design, build, and fly a joined-wing technology demonstrator of this type.

Status and Outlook

Joined wing aircraft application remains centered on surveillance, providing a means for integration of large apertures into compact aircraft for reduced cost and increased sensor performance. Current funding for concept development is being provided by the Air Force Research Lab (AFRL) as a part of its SensorCraft initiative. A series of contracts have been awarded to Boeing that focus on the viability of the joined wing concept as a sensor platform. The contracts include systems studies for concept refinement and for defining an advanced technology demonstration (ATD) of the concept; a contract for Aero Efficiency Improvements (AEI) that addresses the aerodynamic design of the joined wing sensor platform and the aero-elastic characterization of the joined wing structure; a contract that is part of the Very Affordable Advance Technology Engine (VAATE) program that addresses energy management, including secondary power, electrical power generation and thermal management; and a contract (a cooperative AFRL/Boeing program) that addresses the development of a structurally integrated X-band aperture and a full-scale wing conformal UHF aperture.

The Vortex Flap: Efficiency and Versatility

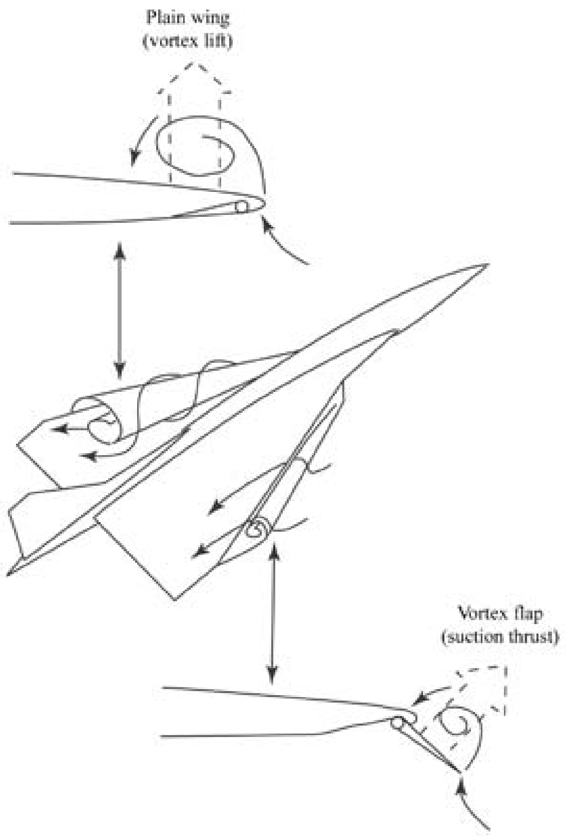
Concept and Benefits

Highly swept wings or other surfaces exhibit strong vortical flow over their upper surfaces during flight at moderate or high angle-of-attack conditions, such as those associated with takeoff, landing, or strenuous maneuvers. The vortical flow's beneficial influence on the integrated wing aerodynamic behavior results in greater lift for takeoff and maneuvers, better control of the aerodynamic center's location, and relatively similar flow fields over a wide range of angle of attack and Mach number. Many contemporary aircraft, including the Concorde supersonic transport and highly maneuverable fighters such as the F-16 and F/A-18, use vortex flows to enhance aerodynamic behavior through the mechanism of "vortex lift" across the range of operational conditions.

The F-16 (left) and the F/A-18 (right) use vortex lift for improved maneuverability.

Unfortunately, the generation of vortex lift by wing leading-edge flow separation also results in a very undesirable byproduct: a loss of aerodynamic leading-edge thrust (or leading-edge suction) that results in a dramatic increase in drag for a typical highly swept configuration. In contrast, wings of conventional aircraft having lower sweep exhibit leading-edge thrust produced by attached flow over the wing, thereby reducing aerodynamic drag. Rather than producing thrust, the leading-edge force for highly swept wings at high angles of attack is redirected to a position normal to the wing surface where it augments normal force, but no longer has a beneficial impact on drag.

The vortex-flap concept involves the use of specially designed wing leading-edge flaps that modify undesirable leading-edge flow separation behavior. This approach provides the aircraft designer with options to design highly swept wings with geometric features that recover a portion of the lost leading-edge thrust without compromising other aerodynamic characteristics, such as stability and control. Using this concept, the designer can reorient part of the vortex-force vector forward instead of directly normal to the chord plane.



The vortex-flap concept.

The primary mechanism of the vortex flap is depicted in the sketch. Vortical leading-edge flows are depicted for a representative highly swept configuration having a conventional leading edge (left-wing panel) and a specially designed vortex flap that is deflected from underneath the wing leading edge about a pivot point on the lower surface (right-wing panel) at a high angle of attack. As indicated in the sketch, flow separates over the conventional left leading edge, inducing the previously discussed vortex-lift force component normal to the wing surface. On the right wing panel, the vortex flap reduces the vortex core's strength and size because of the leading-edge deflection (camber effect) and leads to a vortex path that is redirected along the leading edge. The result is a suction force that acts on the deflected flap in a forward, drag-reducing direction. Furthermore, the vortex also functions as a rotating fluid cylinder to turn the flow around the leading edge onto the wing upper surface, thereby promoting a smooth transition to attached flow on the wing.

Both civil and military aircraft can use the vortex-flap concept's potential benefits. For example, a supersonic transport or supersonic business jet that uses a wing with high leading-edge sweep for efficient supersonic cruise capability could use the improved L/D ratios provided by the flap for enhanced takeoff performance, thereby permitting the use of lower engine thrust settings and resulting in lower levels of community noise. Military aircraft could use the vortex flap's beneficial effects for significant improvements in maneuvering performance, particularly at transonic conditions where improvements in turning performance during high angle-of-attack maneuvers in close-in combat are extremely significant.

In addition to the vortex-flap concept's performance-enhancing potential, innovative applications of other vortex-flap configurations, such as upper-surface flaps, wing apex flaps, and differentially deflected leading-edge vortex flaps (for aircraft roll control), offer the potential for additional improvement of performance, stability, and control characteristics.

Challenges and Barriers

Before designers can apply this revolutionary concept for vortical flow control to production aircraft, numerous issues need to be addressed and resolved. Perhaps the most constraining barrier to the general application of the vortex flap is its inherent limitation for use on highly swept wings. Some of the other more important challenges and barriers involve aerodynamics, structural design and operational deployment issues, impacts on aircraft flying qualities, weight penalties, maintenance issues, and full-scale flight demonstrations of technology readiness.

Aerodynamic issues that have inhibited the application of vortex-flap technology begin with a fundamental understanding of the flow physics involved in the concept. Factors such as the sensitivity of vortical-flow physics to geometric wing design variables, including the effects of wing-sweep angle and leading-edge radius, must be defined and incorporated in robust design procedures. Relative stability of the vortical-flow pattern produced by the vortex flap must be predictable and consistent across the operational range of candidate aircraft. Thus, the aerodynamic maturity of the vortex flap concept must be ensured from the perspectives of fluid physics and operational applications at full-scale conditions involving large changes in the values of Mach and Reynolds number.

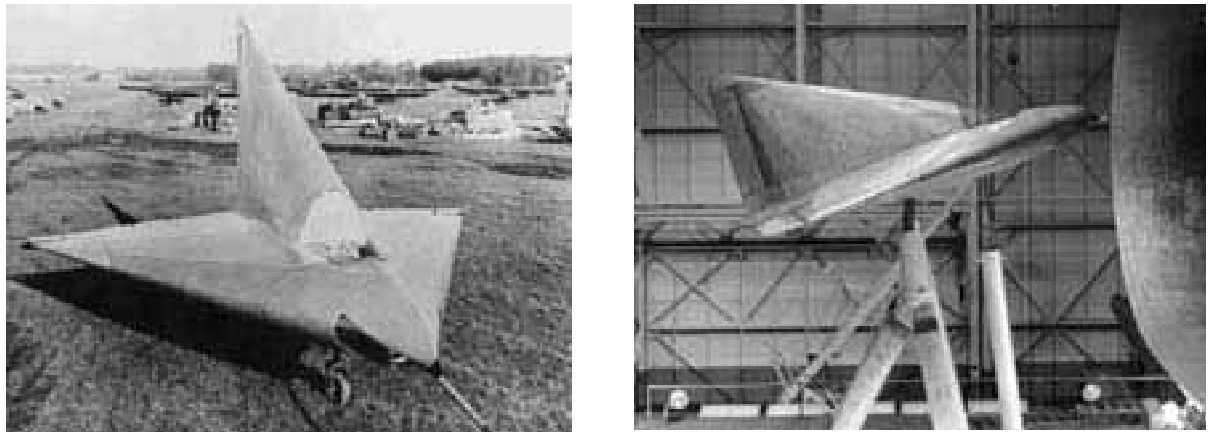
The vortex-flap concept's impact on aircraft stability, control, and handling qualities also demands in-depth research to ensure that undesirable behavior is not encountered in terms of changes in aircraft trim requirements, stability variations, control effectiveness, and aircraft maneuverability. For example, the use of differentially deflected leading-edge vortex flaps for roll control would not be acceptable if large amounts of adverse yawing moments (yawing moments that result in degraded roll response) are encountered. In addition, the potential for degradation of handling qualities because of vortex bursting or vortex instability due to aircraft dynamic motion effects must be evaluated.

Structural design barriers for the vortex flap include providing acceptable levels of complexity and weight for flap hinges, actuation devices, and structural loads. In particular, comparisons of results of performance or penalty trade studies between deflectable vortex flaps and other approaches, such as the use of fixed conical wing leading-edge geometries that do not use leading-edge devices (e.g., design approaches used by the F-106 and F-15), must be resolved in favor of the vortex-flap concept. Other associated challenges for military applications include the impact of leading-edge structural discontinuities and details on aircraft signature characteristics, such as radar cross section.

Langley Activities

Langley Research Center has a rich legacy of expertise in vortex-flow technology. Researchers at Langley had conducted brief studies of low-aspect-ratio delta wings in the 1930s; however, the prediction of extremely poor low-speed flying characteristics and the absence of propulsion systems for high-speed flight resulted in a loss of interest within the Center's research thrusts. During the latter stages of World War II, international research rapidly increased on the beneficial impact of wing sweep on aircraft performance at transonic speeds. By the war's end, renewed efforts of the NACA, industry, and military organizations were initiated and focused on the advantages and problems of swept-back and delta wings. As expected, major challenges ensued at takeoff and landing conditions because of the wing flow separation problems encountered as wing sweep was increased. Langley's research on the aerodynamics of swept and delta wings began to accelerate and intensify, leading in turn to pioneering research on vortical flows.

One interesting example of some early research being conducted at Langley on vortical-flow effects occurred during 1946 when the characteristics of the German Lippisch DM-1 glider were explored in the Langley 30- by 60-Foot (Full-Scale) Tunnel. This delta-wing research aircraft, which was captured by Allied forces and brought to the United States for analysis, had been designed to explore the low-speed handling characteristics of delta configurations. Langley's wind-tunnel testing indicated highly nonlinear lift variations with angle of attack, and studies of surface flows using wool tufts revealed peculiar swirling patterns that were ultimately attributed to the impingement of vortical flow fields on the wing's upper surface. Researchers found that the lift increase exhibited by the airplane at high angles of attack could be attributed to vortical flow actions, and that the lift augmentation could be intensified by modifying the relatively large leading-edge radius with a sharp-edged leading edge. This project was one of the first full-scale aerodynamic studies of delta wings at Langley.



The Lippisch DM-1 glider captured by the Allies (left) and undergoing tests in the Langley 30- by 60-Foot (Full-Scale) Tunnel (right).

Aerodynamic research on swept and delta wings at Langley reached a peak during the 1950s, with extensive efforts conducted in many wind tunnels at speeds from low subsonic conditions to supersonic speeds. These efforts were augmented by analytical studies, flight testing, and vastly increased intellectual knowledge of the flow physics associated with vortical flows. The Center attained international recognition for its expertise in this area, and when the Nation turned its attention to supersonic civil and military aircraft in the late 1950s, Langley was poised to make valuable contributions in the design and application of vortex flows.

Langley's participation in the U.S. SST Program of the 1960s and the NASA SCR Program in the 1970s provided additional opportunities to optimize highly swept configurations and advance the state of the art of vortex-flow technology.

In the late 1970s, the growing lethality of surface-to-air missile systems and the danger of deep-strike mission requirements led to intense interest in the U.S. Air Force for the development of supersonic cruise ("supercruise") fighter configurations. The Air Force awarded several industry contracts for studies of supercruise fighter designs. Stimulated by these contracts and the obvious application of highly swept configurations to the mission requirements, industry interacted with the Langley staff to share in the expertise and experiences gained by NASA with highly swept wing designs during the civil supersonic programs. Langley's staff had developed a research program known as the Supersonic Cruise Integrated Fighter (SCIF) Program under the leadership of Roy V. Harris, Jr., to extend its technology to this class of military aircraft. Langley researchers designed and tested several in-house supercruiser fighters across the speed ranges in Langley facilities. The objectives of SCIF were to focus in-house Langley aerodynamic and flight dynamic research toward feasible configurations for supercruiser applications and to provide coordinated activities with

Model of a Langley-designed supersonic-cruise fighter concept (SCIF-IV) in the Langley Full-Scale Tunnel in 1977.

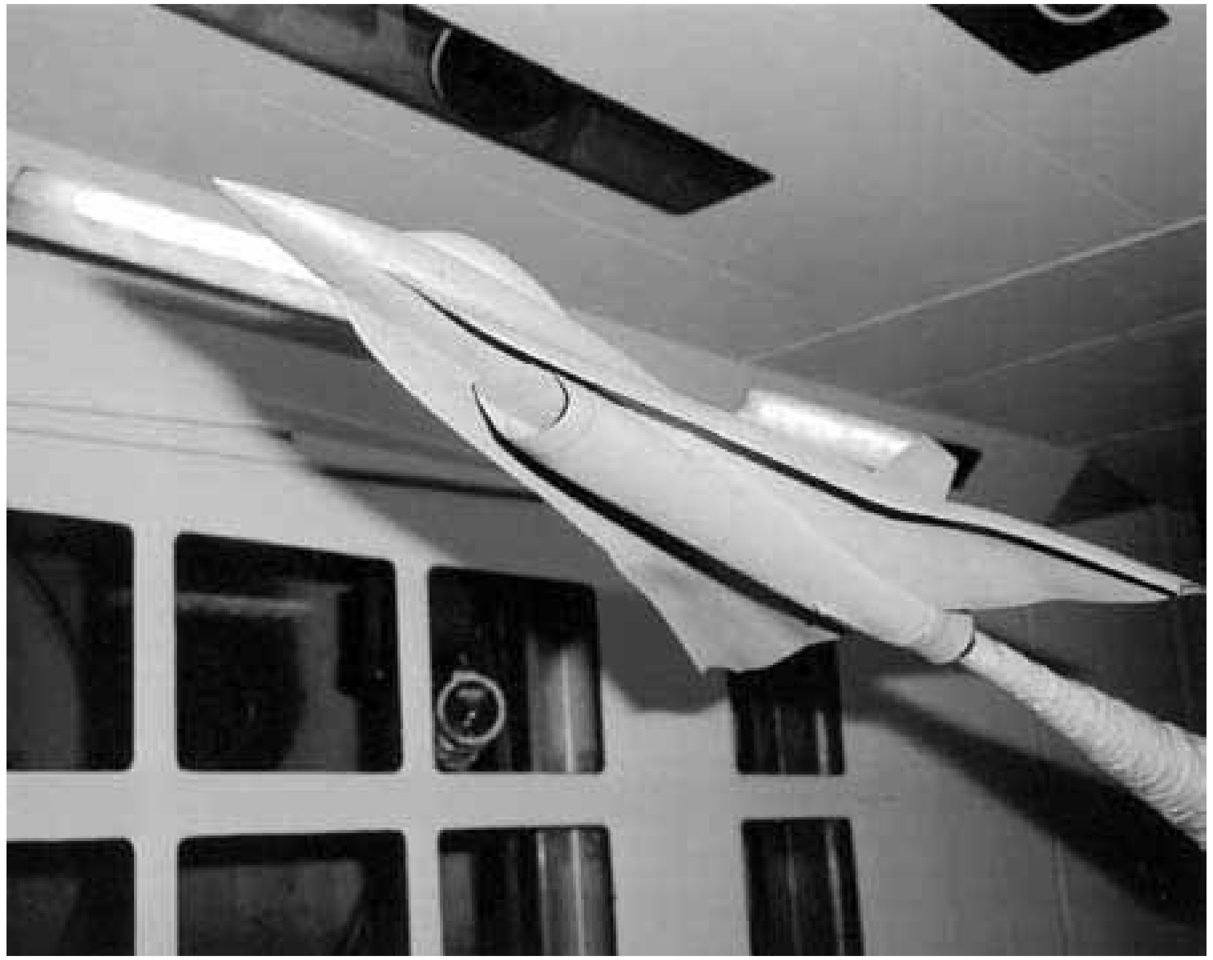
industry teams competing for leadership in supercruiser technology. Subsequent to the initiation of its SCIF program, Langley joined several industry partners in cooperative, nonproprietary studies of supercruiser configurations.

One of the earliest meetings to promote a cooperative supersonic wing design occurred in March 1977 when General Dynamics (now Lockheed Martin) met with Langley researchers to discuss a joint design effort involving several advanced supersonic wing candidates to be designed with NASA and tested in the supersonic Langley Unitary Plan Wind Tunnel and the transonic Langley High-Speed 7- by 10-Foot Tunnel. As part of the effort, General Dynamics assigned two engineers in residence at Langley for 4 months to interact in wing design methodology. Tests of new wing designs in 1978 indicated a supersonic performance improvement of about 30 percent compared with the basic F-16. At subsonic speeds, the modified configurations achieved the same performance as the F-16. Encouraged by these positive results, General Dynamics had committed to a Supersonic Cruise and Maneuver Prototype (SCAMP) concept that used a highly swept "cranked" (double-delta) wing planform for supersonic cruise efficiency. Refinement of this SCAMP concept later led to the development of the F-16XL prototypes by General Dynamics.

During the development of the final SCAMP configuration, several cooperative projects used the configuration as a focus. A wide range of topics was studied, including supersonic store carriage concepts, low-speed stability and control of highly swept configurations, and spin characteristics. One highlight of the 1978 research efforts was a study to provide transonic maneuvering lift at low drag. The research efforts focused on concepts to alter the drag produced by forming leading-edge vortices. Edward C. Polhamus led Langley's vortex research program, and his research group was within the Transonic Aerodynamics Division led by Percy J. (Bud) Bobbitt. Polhamus' group had gained industry's respect and close working relationships by making several significant contributions in cooperative programs as well as in specific aircraft development programs, such as the F-16 and the F/A-18. In a keynote activity, John E. Lamar, James F. Campbell, and their associates joined in a cooperative study with General Dynamics.

During the Langley tests, the NASA-General Dynamics team focused on wing design requirements for a 4-g transonic maneuver with a highly swept wing. Lamar conducted wind-tunnel and computational analyses to define the "optimum" camber and shape for such a wing, but his experiences with vortex flows suggested that a simpler, more versatile solution might be provided by vortex-control concepts. In exploratory testing, the team found that certain combinations of deflected full-span leading- and trailing-edge flaps on a planar (no camber) wing produced almost the same drag improvements at transonic speeds as a specially designed and transonically cambered wing. This early application of vortex-flap principles also produced nearly the same supersonic L/D as a supersonic designed wing (also better than the F-16), a subsonic cruise L/D nearly as good as the value for the F-16 (and better than the supersonic design), and transonic maneuver L/D was midway between that of the F-16 and the fixed supersonic wing. Results obtained with these simple flaps were very attractive from a practical design and fabrication standpoint and stimulated numerous other NASA studies. In-house and NASA-contracted projects included efforts that were focused on developing and validating the design methodology for the vortex-flap concept, as well as exploratory assessments of other innovative applications of vortex-control concepts using deflected flaps.

Neal T. Frink of Langley and his associates conducted extensive pioneering wind-tunnel tests to evaluate the effects of wing-sweep angle and other geometric characteristics on vortex-flap effectiveness. Frink's study provided a matrix of performance information for delta wings having sweep angles from 50 to 74 degrees with constant-chord vortex flaps and formed the key basis for an approach to the design process. Frink initiated and pursued complementary theoretical studies that led the way for predicting overall forces and moments as well as detailed pressures for vortex-flap configurations. His efforts culminated in development of a leading-edge vortex-flap design procedure in 1982.

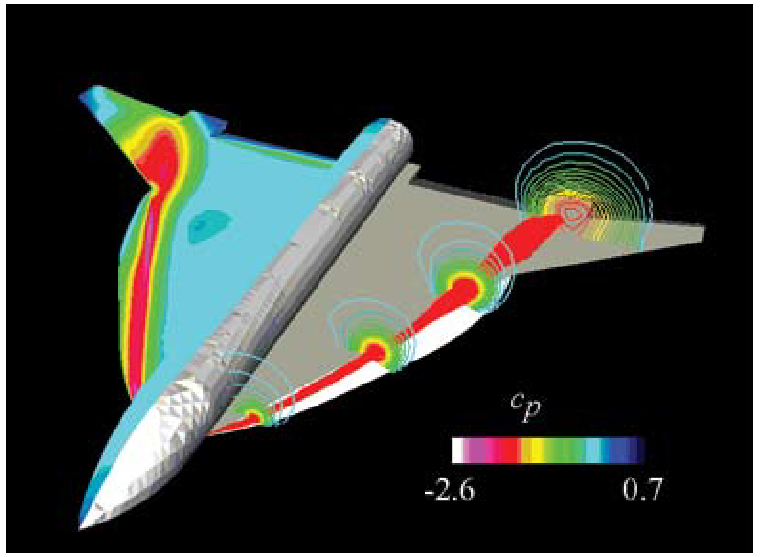


Camber study model used to develop optimum camber.

Meanwhile, other NASA researchers and their industry peers pursued innovative applications of vortex-control technology based on lessons learned with the vortex-flap concept. NASA contractor Dhanvada M. Rao (initially of Old Dominion University and later ViGYAN Research Associates, Inc.) was particularly active in vortex-flap research. Rao demonstrated that reducing inboard length improved the flap's efficiency and that shaping the flap along the span improved flap efficiency and vortex formation. Rao and an independent team led by W. Elliott Schoonover, Jr., of Langley and W. E. Ohlson of Boeing showed that increasing the flap size delayed inboard movement of the vortex and reduced drag. Additional contributions by Rao included the use of flap segmentation to reduce flap area while achieving the same L/D as without segmentation. He also was the first to explore using vortex flap deflections on individual wing panels to produce roll control.

In 1981, Langley researchers Long P. Yip and Daniel G. Murri conducted studies of the effects of vortex flaps on the low-speed stability and control characteristics of generic arrow-wing configurations in a 12-ft low-speed tunnel at Langley. Although improved lateral stability and

L/D were obtained in the tests, an unacceptable nose-up pitching moment was caused by the flaps. The researchers investigated geometric modification impacts on the vortex-flap configuration, including the flap's spanwise length and the leading-edge geometry. A modified flap concept, which included a deflected "tab" on its leading edge, was found to alleviate the pitching-moment problem, and the flap configuration was then applied to SCAMP configuration models during the aircraft development program. Yip and Murri installed the tabbed vortex flap on a 0.18-scale free-flight model of the SCAMP (which had by then transformed into the F-16XL prototype) and conducted free-flight tests in the Langley 30- by 60-Foot (Full-Scale) Tunnel in 1982. Results indicated that the flap's performance benefits could be obtained with no degradation in flying characteristics or pitch problems.



Computational fluid dynamics study of vortex flap on a representative high-speed civil transport.

The vortex-flap concept's civil applications have centered on supersonic transports and supersonic business jets. As part of the NASA SCAR technology program, Paul L. Coe led several wind-tunnel studies of vortex flap effects on aerodynamic performance, stability, and control of representative supersonic transport designs. Coe also contributed vortex-flap studies during the NASA High-Speed Research Program, which focused on providing improved L/D for take-off operations of supersonic transports. During the program, improved low-speed aerodynamic performance was a major research focus, and the research team evaluated vortex-flap configurations in several Langley tunnels, including the 30- by 60-Foot Tunnel and the 14- by 22-Foot Tunnel. Kenneth M. Jones, Kevin Kjerstad, and Victor Lessard conducted computational studies of the aerodynamic characteristics of attached-flow leading-edge flaps and vortex-flap concepts at subsonic takeoff and landing conditions. Using the USM3D computer code developed at Langley, they obtained results that accurately predicted the primary vortex's reattachment line in good agreement with experimental flow visualization. Forces, moments, and surface pressures compared well with the experimental data.

Flight Research

F-106B

By 1983, research on the vortex-flap concept by Langley and its partners had progressed to the point that the next major step in technology maturation was required. Subscale models of generic aircraft configurations with vortex-flaps had been extensively evaluated in wind-tunnel and analytical studies; however, reliable extrapolation of model results to full-scale conditions and evaluations of potential effects of the concept on aircraft handling qualities were required. Following a review of vortex-flap technology progress, a joint NASA-AFWAL steering panel recommended a feasibility study for conducting a full-scale flight experiment using either an F-106, F-16XL, or the Advanced Flight Technology Integration (AFTI) F-111 research aircraft. James F. Campbell led a study team that examined the options and chose an F-106B airplane because of its wing geometry, flight characteristics, and accessibility to NASA researchers. NASA had used a two-place F-106B as a research aircraft for a variety of prior programs, including engine testing at NASA's Lewis (now Glenn) Research Center and severe storms and lightning assessments at Langley. At that time, the aircraft was based at Langley where engineering staff and fabrication shops could be used for aircraft modifications. With a wing leading-edge sweep of 60 degrees and transonic maneuver capability, as well as a second cockpit seat for observation of flow phenomena, the aircraft was ideally suited for an initial full-scale aerodynamic vortex flap flight assessment. The advocacy efforts of Joseph W. Stickle, Chief of the Low-Speed Aerodynamics Division at Langley, were also instrumental in the selection process.

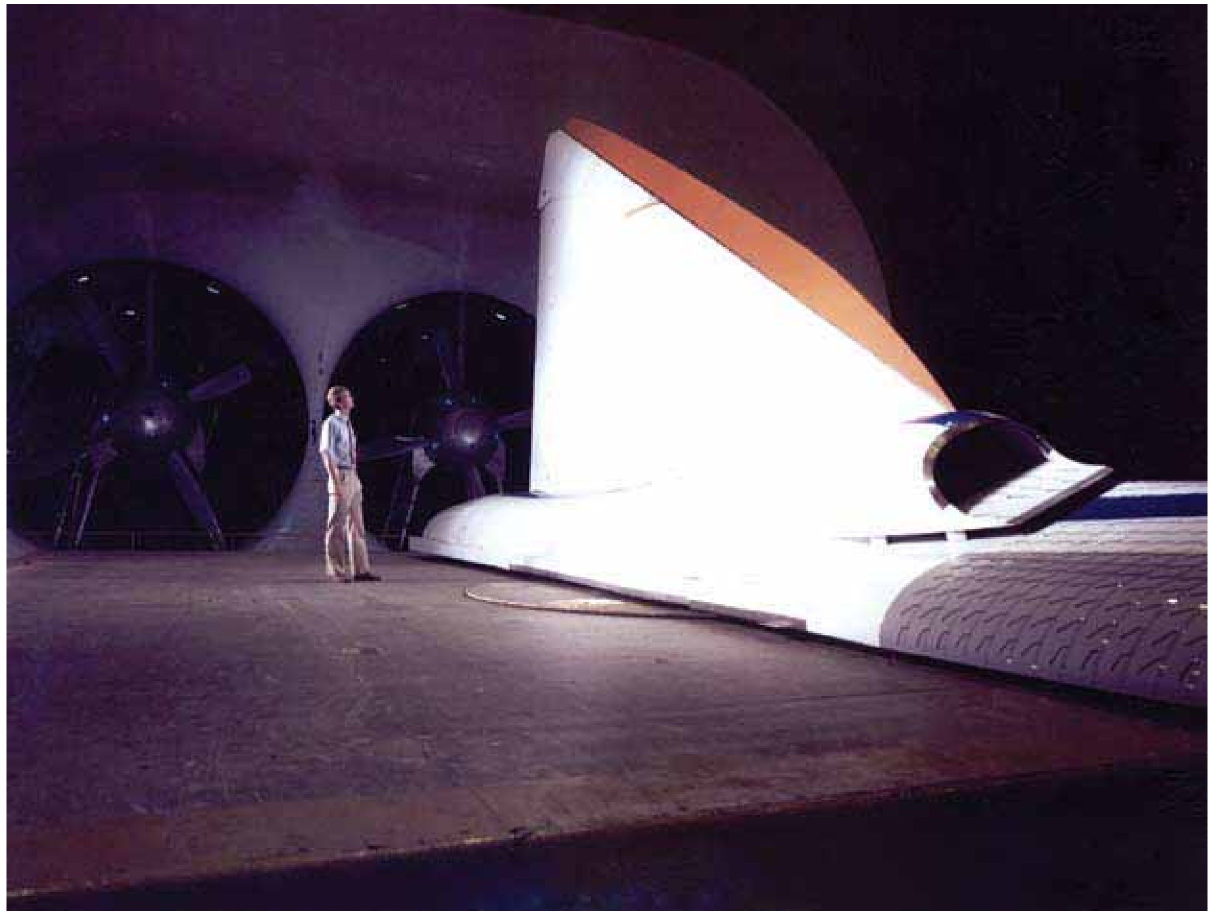
In 1985, Langley held a national Vortex Flow Aerodynamics Conference to review the state of the art in vortex-flow technology under the joint sponsorship of NASA and AFWAL. At that meeting, several papers were presented on study results of vortex-flap applications to specific configurations, including the F-106.

The scope of studies required to implement and flight test the vortex flap on the F-106B included aerodynamic design (including wind-tunnel tests and analytical design), structural design and development of instrumentation, fabrication of flight hardware in Langley shops, installation of hardware and instrumentation by Langley aircraft technicians, development of simulation software, piloted simulator evaluations of aircraft handling qualities prior to flight, and flight tests of the modified aircraft at NASA's Wallops Flight Facility on Virginia's Eastern Shore. A particularly valuable aspect of the flight program was the use of unique on-surface and off-surface flow visualization techniques that the Langley staff developed and implemented.

Neal Frink led a team on the design of the vortex flap for the F-106B. Using his own design process, Frink arrived at the specific design to be flight tested on the airplane. An immediate project challenge was working with an existing old airframe design with specific load carrying capabilities. One critical result of the loads situation was that the vortex flap had to have a smaller chord than desired. If loads had permitted, a larger flap would have been used, resulting in improved performance. Researchers conducted numerous wind-tunnel tests to verify the flap design's effectiveness and obtain loads information prior to fabrication. A major problem for the austere project (Roy V. Harris, Jr., Director of Aeronautics, reprogrammed funding to accomplish this multiyear effort) was the unavailability of existing wind-tunnel models for the aged F-106 configuration. Following a nationwide search, Jim Campbell located a 1/20-scale high-speed test model of the F-106B that had been retired to the Smithsonian Air and Space Museum. Langley engineering support and brought the model out of mothballs, restoring it to testing condition.

James B. Hallissy, Jarrett K. Huffman, and Frink led the initial testing and analysis of the model in Langley's 7- by 10-Foot Tunnel. Unfortunately, for angles of attack of interest with the vortex flaps installed, the F-106B model was load limited in the wing leading-edge area and could only be tested up to Mach numbers of 0.5 in the atmospheric 7- by 10-Foot Tunnel. To obtain the necessary data, Langley researchers would have to conduct testing in a tunnel with reduced pressure and lower loads. The Langley 8-Foot Transonic Pressure Tunnel, with its capability to run at reduced pressures, would have been the obvious choice for this work, but was not available as it was heavily committed to Langley laminar-flow tests (discussed in a previous section). The Langley 16-Foot TDT was the only other transonic tunnel at Langley with the capability to test at stagnation pressures below atmosphere. Hallissy, Charles H. Fox, Michael H. Durham, and W. F. (Bill) Cazier took on a major challenge in this endeavor because the TDT was not set up for performance testing. The researchers confirmed that a significant performance increment could be achieved transonically, although the optimum flap deflections were different and the magnitude of the increment was somewhat reduced relative to the subsonic conditions. Hallissy further extended the data by conducting additional tests in the Ames Research Center 6- by 6-Foot Supersonic Tunnel.

While high-speed tunnel testing assessed transonic performance of the F-106B vortex-flap configuration, a team led by Long P. Yip conducted low-speed tests of a full-scale airframe in the Langley Full-Scale Tunnel. Because a full-scale F-106B could not be accommodated within the



Neal Frink inspects full-scale semispan model of F-106 equipped with his vortex-flap design.

tunnel's 30- by 60-ft test section dimensions, Yip and his team acquired a second, nonflightworthy F-106B aircraft and proceeded to physically slice the airplane down its centerline to create a semispan, full-scale F-106B test article. Referred to as the F-53 (half an F-106!), the semispan article was tested for flap loads and stability effects in 1985. Results of the tests indicated an apparent vortex-flow instability on the flap's inner portion near the fuselage intersection. In view of these results and additional guidance from CFD computations, the team increased the inner flap's local chord length.

The F-106B flap system's structural design was led by Joseph D. Pride, Garland O. Goodwin (Kentron Technologies, Inc.), and a team of in-house engineering personnel. The system consisted of a simplified ground-adjustable "bolt-on" flap that could be installed at different fixed deflection angles from 20 to 50 degrees. The flap was designed and constructed in spanwise segments to comply with structural loading and deflection issues. The actual fabrication included access straps that bridged leading-edge access areas between major segments located ahead of the wing spar. Langley's fabrication shops constructed the vortex-flap components.

Free-flight model of the F-106B modified with a vortex flap (left) and in flight in the Langley Full-Scale Tunnel (right).

Prior to flight test planning, no information on potential effects of a vortex flap on stability, control, and flying qualities of the F-106B was available. To assess this issue and to prepare pilots for the flight tests, Langley staff conducted a series of static and dynamic stability assessments and a piloted simulator study. Long P. Yip led dynamic stability testing in the Langley Full-Scale Tunnel, which included dynamic model force tests to obtain aerodynamic data for analysis of dynamic stability and for inputs to piloted simulators. Yip also led free-flight tests of the 15-percent scale model to assess the impact of vortex flaps on stability and control characteristics. One of the major concerns prior to these free-flight model tests was whether the leading-edge vortices on the vortex flaps would lift off the surface abruptly or discontinuously, causing undesirable aircraft responses. Assisted by Sue B. Grafton and Jay Brandon, Yip obtained free-flight model results demonstrating that vortex flaps did not significantly affect the damping characteristics of the configuration; and, with the exception of an acceptable reduction in longitudinal stability, the flaps did not degrade flying qualities.

Jay Brandon led a Langley team in gathering the necessary aerodynamic data for the development of a piloted simulator of the modified F-106B for pilot assessment and training using the Langley Differential Maneuvering Simulator (DMS). Langley research pilot Philip W. Brown was selected to be the primary evaluation pilot for the flight test program as he had accumulated significant flight time in the basic F-106B in previous Langley flight programs. Brown conducted several simulator assessments and concluded that the F-106B vortex-flap configuration would be expected to have satisfactory flying characteristics.

Project Manager for the F-106B flight-test program was Ronald H. Smith, who was assisted by James B. Hallissy. In addition to his managerial responsibilities, Hallissy was Principal Investigator for determining the flow-field characteristics and performance increments achieved with flaps on the airplane. Together with W. Elliott Schoonover, Hallissy contributed extensive efforts to prepare the airplane for performance measurements and postflight data analysis. The tasks were particularly challenging because the airplane lacked conventional instrumentation for performance tests (such as a calibrated engine) and pressures had to be obtained by upper-surface belts rather than pressure ports. Jay Brandon and Thomas D. Johnson (PRC-Kentron, Inc.) accompanied project pilot Phil Brown on flow-visualization flight tests.

A most informative aspect of the F-106B vortex-flap flight test program was the unique vapor-screen flow-visualization technique used to visualize details of the leading-edge vortex structure during actual flight tests. The visualization concept, which John E. Lamar conceived, involved a flight adaptation of an existing vapor-screen method for flow visualization commonly used in wind tunnels. During aircraft flight maneuvers, high relative humidity and low pressures in the flow around an aircraft will sometimes cause moisture to condense, providing a natural visualization of aerodynamic flow patterns. The Langley vapor-screen technique obviated the need for natural humidity by seeding the air stream with a heated propylene glycol vapor pumped from a missile-bay pallet and expelled through a probe placed under the left wing panel's leading edge. When exposed to cold temperatures, the clear glycol vapor became white, allowing for visualization of the flow field. In the first flight experiments, conducted in 1985 before the aircraft was modified, the vapor entrained by the vortices was illuminated by a thin light sheet that was projected across the wing in a fixed plane by a mercury-arc lamp behind a narrow slit in an apparatus mounted on the fuselage's side. Onboard video cameras were used to record flow patterns of the vortical flow within the fixed light sheet on the wing upper surface. The unmodified wing's flow-visualization flights began in February 1985 and were conducted on moonless nights to provide contrast and optimize the images produced. Joseph D. Pride and Tom Johnson were key members of Lamar's flow visualization team, which obtained detailed flow information from Mach 0.4 to Mach 0.9 during maneuvers for the basic F-106B.

Initial results from the visualization experiments showed the complicated flow field on the wing upper surface. Single leading-edge vortices were observed on each F-106B wing panel at angles of attack above about 20 degrees as expected, but at lower angles of attack, between 17 and 20 degrees, multiple leading-edge vortices appeared along the wingspan. This unexpected phenomenon warranted additional visualization studies (to be discussed later), which were conducted after the vortex-flap performance testing was completed.

In 1987, after nearly 3,000 hours of wind-tunnel model testing and computational studies, the Langley research team evaluated the vortex-flap concept in flight on the F-106B. Flight tests of the unmodified airplane were first conducted to establish a baseline for performance measurements, then the production wing leading edges were removed and the ground-adjustable vortex flaps installed. The right wing panel was instrumented to measure surface pressures, and the left wing was instrumented with accelerometers and strain gauges to monitor structural loads and deformation. The team made the first flight with the vortex flap on August 2, 1988, and continued testing for 93 research flights over the next 2-plus years. The flight program's primary objectives were to document detailed aerodynamic flow characteristics and compare them with wind-tunnel and computational predictions, and to assess the vortex flap's impact on aircraft performance and handling qualities, including takeoffs, landings, and transonic maneuvers. The research team designed the extensive pressure measurements and flow visualization tests to provide a database for design and analysis tool calibration for vortex-flap technology as well as generic experimental, computational, and flight test technology. Flights were conducted for vortex-flap angles of 30 and 40 degrees for Mach numbers from 0.3 to 0.9 and for altitudes up to 40,000 ft. Results were obtained in the form of incremental performance measurements from the basic F-106B, and parameter identification techniques were used to extract aircraft stability and control information. Tom Johnson and Jay Brandon flew as flight test engineers for all the performance flights and in the chase airplane for photos and coordination.

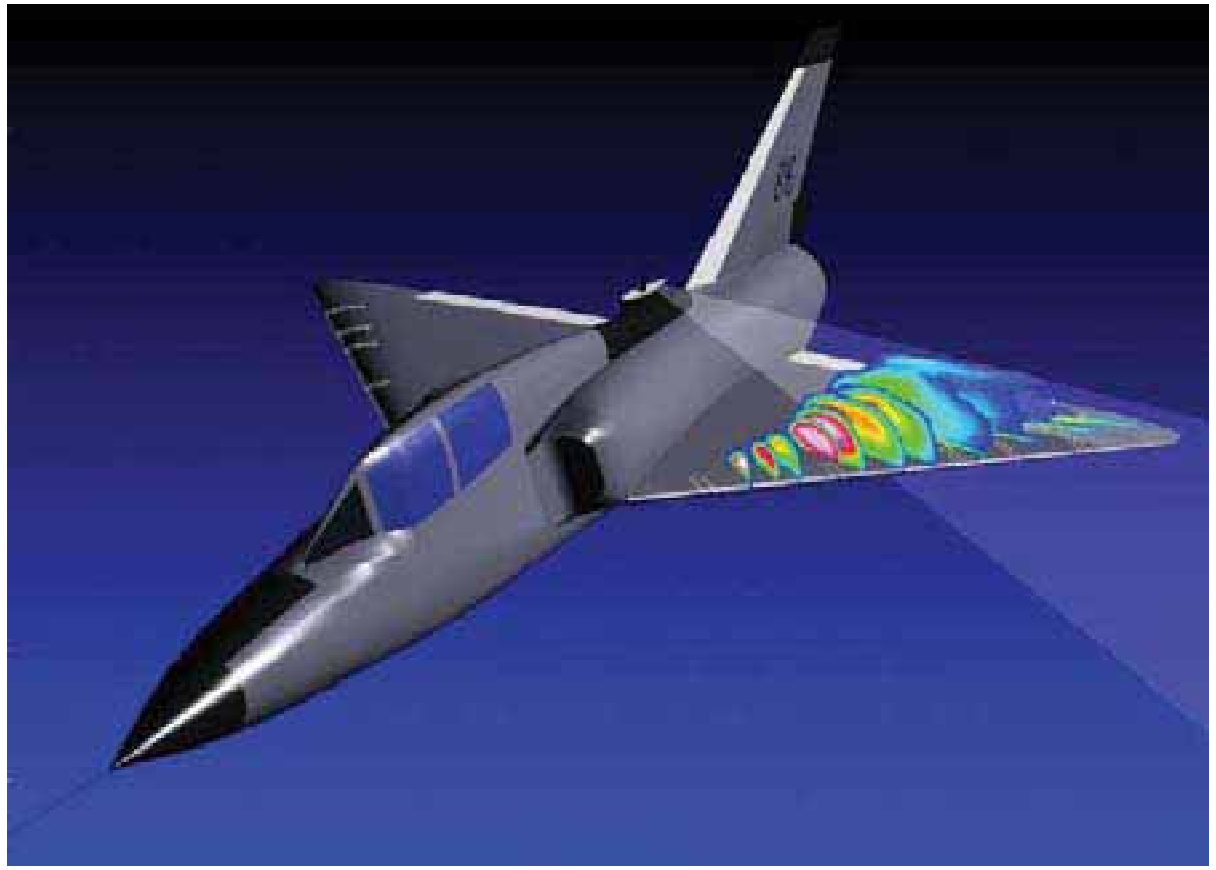
The NASA F-106B in flight with the vortex-flap modification.

The vortex flap's aerodynamic performance benefits as determined in the F-106B flight tests were extremely impressive. Improvements in the aircraft L/D resulted in very significant increases in sustained turn capability during maneuvers through the highest Mach number flown (0.9). For example, the airplane's achievable sustained g was increased by about 28 percent at a Mach number of 0.7. The quantitative performance results obtained in the flight program provided invaluable documentation and demonstration of the vortex-flap's potential benefits for highly swept military fighter aircraft. The calibration of analytical design methods and flow visualization data with flight data revealed complex flow fields that continued to challenge the capabilities of wind tunnels and computational fluid dynamics.

As previously discussed, initial F-106B in-flight flow-visualization results had indicated unexpected flow phenomena and multiple vortices. Therefore, the Langley researchers conducted a second series of flow visualization experiments beginning in 1990 to provide further information on the structure of multiple vortical flows for baseline and vortex-flap aircraft configurations. John Lamar and the engineering support staff conceived a refined flow-visualization system for these follow-up tests, providing much more research flexibility and integrated data over a larger viewing area by using a scanning light sheet source that was mounted in a streamline fairing atop the fuselage spine. Jay Brandon led the efforts for implementing the new visualization system on the aircraft. The flow visualization system included two video cameras (one located on the engine intake and one near the aircraft centerline aft of the canopy). Using this approach, researchers obtained flow information over a broad sector on and over the left wing during flight. In addition to the vapor screen information, they obtained on-surface results using oil flows and tufts on the wing upper surface. Brandon and Lamar served as co-investigators of the flight data.

The team obtained flow visualization results for vortex-flap settings of 30 and 40 degrees over a Mach number range of 0.3 to 0.9 in 1990. Once again, the researchers observed unexpected results for vortical flows. As had occurred previously for the basic wing, the vortex flap exhibited multiple vortices (on the flap surface), although this difference of the flow physics from that expected did not seem to result in degradation in predicted performance improvements.

The multiple vortices appeared to originate on the vortex flap and then migrate off the flap to run nearly streamwise over the wing as another vortex originated on the flap. This pattern was repeated many times down the wing depending on angle of attack. Oil-flow results confirmed existence of a highly complex flow pattern with multiple vortex systems as observed during the vapor-screen tests. Examinations of the research team's flight results showed that the multiple streamwise vortices observed above the wing originated at the flap leading edge where individual flap segments were joined. The team also conducted oil-flow studies with the joints sealed with fabric-backed tape to



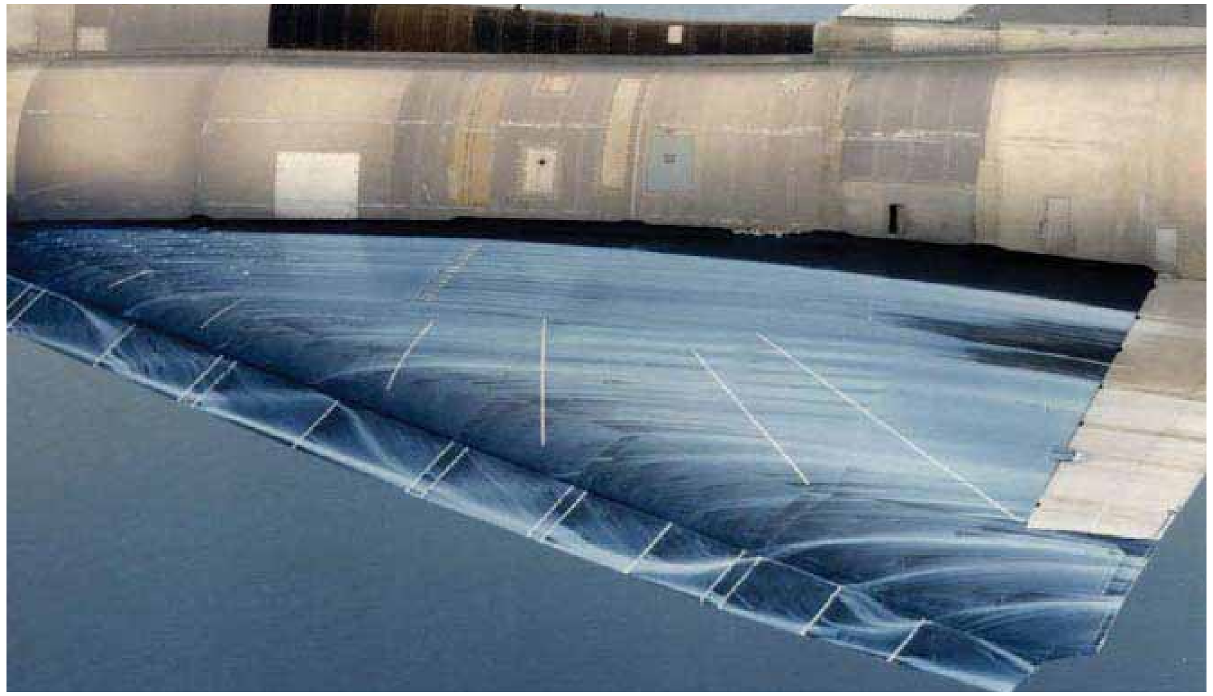
The scanning vapor screen technique.

F-106B researchers prepare for a night mission.

prevent air leakage and observed essentially the same results. The oil-flow studies indicated that the small geometric perturbations along the leading edge were sufficient to generate a leading-edge flow that was very complex and significantly different in details than that observed previously in wind-tunnel model tests and in CFD calculations.

After observing the unpredicted vortex topologies in flight, Jim Hallissy, Elliot Schoonover, and Tom Johnson tested the F-106 wind-tunnel model in the Langley 7- by 10-Foot High-Speed Tunnel. All previous wind-tunnel tests had shown a single leading-edge vortex system along the flap, as predicted by the design methodology. During storage of the model, some minor damage in the form of small dents and nicks had occurred to the flaps. Because leading-edge discontinuities were believed to be at least partially responsible for the multiple vortices seen in flight, these dents were not repaired prior to the tests. During the test the dents, or the subsequent application of tape flow trips, provided sufficient perturbations for shedding of vortices and formation of the multiple vortex system seen in flight. The extremely small perturbation size indicated that with normal manufacturing tolerances, it might be impossible to avoid the multiple vortex patterns seen in flight on a full-scale airplane with leading-edge devices similar to vortex flaps.

In summary, the major purpose for developing the vortex flap was to improve L/D ratio at high maneuvering lift coefficients. Despite the strikingly different flow field details developed on the airplane compared with computational theory and wind-tunnel predictions, the flaps' overall effectiveness was very close to predictions, resulting in significant improvements in maneuver capability, such as sustained-turn characteristics.



Surface-oil studies illustrate multiple vortex flows seen on the leading edge.

Langley researchers pose with the F-106B Vortex-Flap Research Aircraft in 1988.

Following the completion of vortex-flap flights, the NASA F-106B airplane was retired on May 17, 1991, in a formal ceremony at Langley. Later that year, the airplane was transferred to the Virginia Air and Space Center in Hampton, where it has been displayed to the public with the vortex-flap modification.

F-16XL Plans

Leadership of the High-Speed Research Program's integrated, NASA-wide high lift element was assigned to NASA Langley with Joseph R. Chambers, Chief of the Flight Applications Division, selected to lead the effort. A challenging problem facing a future supersonic transport is unacceptable takeoff noise caused by the high levels of thrust required to overcome inherently low lift and high drag of highly swept supersonic wings and poor subsonic cruise performance caused by the high induced drag of such wing shapes. Accordingly, wind-tunnel and computational efforts were undertaken to improve the subsonic L/D aerodynamic characteristics of candidate HSR configurations. The scope of research at Langley and the Ames Research Center included studies of various types of leading-edge designs, including fixed cambered configurations and deflectable cambered flaps and vortex flaps.

In 1993, Chambers advocated for flight testing of an appropriate airplane to obtain more detailed information on the impact of leading-edge devices, such as the vortex flap, for subsonic and high-lift conditions. NASA transferred one of its two F-16XL research aircraft from the NASA Dryden Flight Research Center to Langley for the proposed program. As previously discussed, Langley had conducted F-16XL low-speed and transonic vortex-flap tunnel tests during the early 1980s in concert with the aircraft's development. As the HSR Program interests in low-speed high-lift devices intensified, researcher David E. Hahne led wind-tunnel tests of an F-16XL model with several leading-edge flap configurations to begin the process of selecting candidate flaps to be flown on the airplane. In addition to aerodynamic studies, the research program was to include unconventional thrust management strategies to reduce power at certain takeoff conditions to further reduce noise. Noise level measurements would be made for the airplane with the flap modifications and throttle strategies. A piloted simulation of the F-16XL was implemented by Langley researchers in the Langley DMS in preparation for flight testing.

F-16XL aircraft painted by Langley for flow visualization tests.

The F-16XL's upper surfaces were painted black to enhance the flow visualization studies planned for the flight tests. Unfortunately, changes in program priorities terminated the F-16XL flight effort within HSR before modifications for vortex-flap flight activities could begin. NASA did, however, support a series of basic aerodynamic vortex-flow studies on the F-16XL airplane led by John E. Lamar in a project known as the Cranked-Arrow Wing Aerodynamics Project (CAWAP). Lamar's team included Langley's Clifford J. Obara, Susan J. Rickard, and Bruce D. Fisher, as well as Dryden's David F. Fisher. The team focused on detailed measurements and analysis of the aircraft's exhibited vortical-flow characteristics, including wing pressures, boundary-layer measurements, and flow visualization on the upper wing surface using tufts. The results were correlated with computational results, providing a database for additional analyses and adding to Langley's contributions in vortical-flow technology.

Status and Outlook

To date, NASA, industry, and academia have accomplished much in the development of aerodynamic theories and exploratory aerodynamic applications of vortex-flap concepts. Enhanced aerodynamic performance has been measured for a wide range of slender-wing configurations, including full-scale flight tests. However, the technology maturation level for potential production applications has remained below the level required for low-risk implementation by industry.

Many barriers and challenges cited in the earlier discussion of this topic will need solving before applications can be expected. The ultimate demonstration of an "adaptive" vortex-flap design (deflections automatically controlled for maximum efficiency by flight computer) on a high-speed aircraft with production-type fabrication and tooling will be necessary before the concept can applied. Also, the systems-level impacts of the vortex flap (weight, maintenance, failure modes, etc.) must be assessed and compared with more conventional approaches currently used such as conical wing camber, or conventional leading-edge flaps.

Unfortunately, recent high-performance military configurations have used lower wing-sweep angles than those appropriate for the slender-wing vortex-flap applications. As a result, designers have chosen the use of conical camber, conventional leading-edge maneuver flaps and hybrid-wing (wing-body strake and relatively unswept outer wing) design options. Further, the dramatic reduction in new military aircraft programs has left few opportunities for injection of this technology. On the other hand, recent interest in uninhabited combat air vehicles that use delta and highly swept wing planforms might permit a renewed interest in the concept. Such concepts would be of even greater interest if the application of "smart" materials could permit the use of continuous outer mold lines, thereby resolving issues regarding the impact of vortex-flap physical discontinuities on stealth and radar observables.

From a civil aircraft perspective, the demise of the NASA HSR Program and a pessimistic international outlook for large supersonic transports in the future does not portend of opportunities for vortex-flap applications to that class of vehicle. However, growing interest in economically viable supersonic business jets could conceivably rekindle interest in vortex-flap technology, especially if the concept could help designers attack the known operational barriers of environmental noise issues.

Finally, it is appropriate to note that Langley's success in developing and demonstrating the benefits of vortex-flow control with the leading-edge vortex flap for performance inspired NASA and industry to focus on solutions to stability and control problems of contemporary fighter configurations caused by uncontrolled vortex flows at high angles of attack. Examples of follow-up research included the control of vortical flows shed by pointed slender forebodies, noncircular forebody cross sections, and nose strakes. In proof-of-concept experiments, most of these stability and control problems were demonstrated to be amenable to improvement by the use of innovative mechanical and pneumatic (blowing and suction) techniques for vortex management.

Innovative Control Effectors: Smart Muscles

Concept and Benefits

The challenge of providing satisfactory controllability and handling qualities for aircraft has been a crucial requirement throughout the history of aviation. Attempts to provide adequate levels of control have resulted in a wide variety of conventional control effectors, including empennage-mounted elevators and rudders; wing-mounted ailerons, elevons, rudders, and spoilers; fuselage-mounted canards; wing warping; mechanical engine thrust vectoring in pitch and yaw; and differential engine thrust for multiengine configurations. The overriding requirement that aircraft must exhibit satisfactory responses to control inputs for all phases of operational envelope, including off-design conditions, has driven the development of these various concepts.

Evolving requirements for flight mission capabilities and unconventional configurations have forced the technology "push" and the applications "pull" for advanced control effectors. For example, during the early days of heavier-than-air flight, designers attempted to meet the fundamental need to provide aircraft that could be successfully flown by a human pilot through relatively mundane maneuvers and very limited flight envelopes. As aircraft mission capabilities rapidly expanded to faster speeds and higher altitudes, new challenges—such as compressibility effects, structural flexibility, flutter, excessive hinge moments, pilot stick forces, pilot-induced oscillations, and control reversal—were encountered and researched. These efforts produced solutions that enabled the improved capabilities offered by unconventional configurations. Some unconventional configurations, such as flying wings, required innovative controls (e.g., wing tip-mounted split ailerons) that serve as ailerons and rudders.

Military aircraft, in particular, have been the recipients of extensive research on flight controls because of stringent maneuverability requirements and challenging off-design operations. During World War II, for example, NACA, the military services, and industry devoted continuous efforts to reducing stick forces and enhancing roll performance, thereby ensuring that the razor-thin combat advantage in close-in dogfights would belong to U.S. pilots. Following World War II, the advent of supersonic flight with its attendant compressibility effects resulted in the emergence of new control concepts: powered control systems, differentially deflectable stabilators for pitch and roll control at high speeds, and the use of spoilers for roll control.

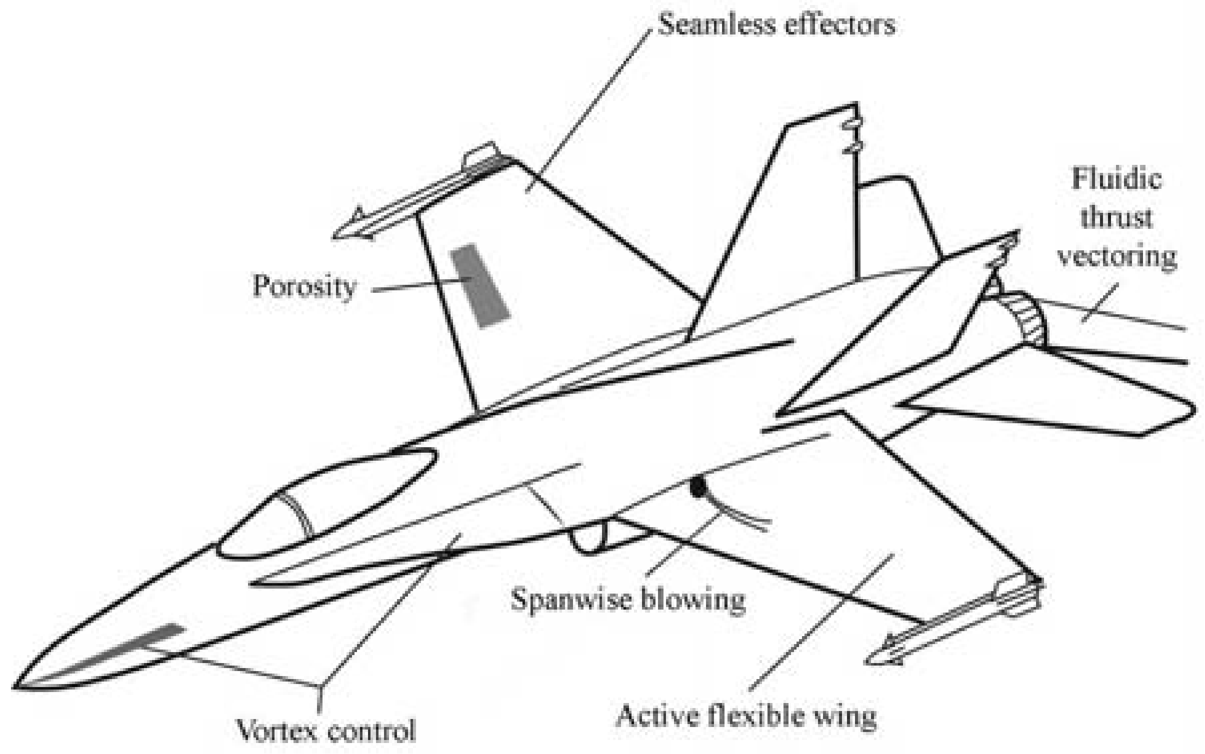
In recent years, the ongoing changes in aircraft mission capabilities have continued to invigorate studies of new control effectors. For civil aircraft, commercial transport designers have directed their attentions to ensuring adequate controllability during high-subsonic cruise conditions where shock-induced separation may cause steady or unsteady aerodynamic phenomena that degrade control effectiveness. In addition, designers strive for efficient outer-wing aileron configurations (or middle-wing spoilers) that "free up" valuable inner-wing trailing-edge locations for high-lift flap devices. More efficient flaps permit the designer to reduce the wing's size, thereby reducing weight and improving overall mission capability. Finally, propulsive control for multiengine civil transport configurations received recent attention after the heroic flight crew efforts of the 1989 DC-10 crash at Sioux City, Iowa, following hydraulic power loss caused by an engine structural failure. NASA's Dryden Flight Research Center has conducted extensive research on the propulsive control technique.

For military aircraft, an aircraft's full use for strenuous maneuvers and other requirements demands control effector research on barrier problems. For example, providing satisfactory levels of control effectiveness and coordination at high-angle-of-attack flight conditions in the presence of extensive flow separation has promoted interest in thrust vectoring, vortex-flow control, and using forebody strakes for lateral-directional control. Automatic departure and spin prevention have been developed and applied using advanced control system architectures. Another controls challenge has arisen from the application of stealth technology for low-observable configurations. Stealth configurations require special consideration, or elimination, of control surface geometries such as gaps, hinges, and other details that can degrade radar or infrared signature characteristics.

Recent disciplinary advances in structures and materials have led to a new family of "smart" materials that respond to stimuli with shape changes that could be integrated into innovative control effectors. "Morphing" configurations, which adjust external shape as a function of flight conditions, vehicle health considerations, or other factors, would use such an approach to provide control.

Innovative control effectors can be used with advanced adaptive control system architectures that sense the changes in flight environment and automatically schedule the control gains, feedback, and mixing to promote more optimal response characteristics as well as improved aerodynamic efficiency. The sketch illustrates some of the innovative control effector research topics conducted by NASA.

Vortex-flow control effectors modify and control the powerful vortical flows generated by highly swept wings, wing-fuselage strakes (also called leading-edge extensions), and fuselage forebodies to provide control at high angle-of-attack conditions. At relatively high angles of attack, such devices provide significantly larger control effectiveness than conventional wing or tail-mounted controls, which are usually ineffective for highly separated flow conditions.



Innovative control effector concepts studied by NASA-Langley.

Langley has led international research on the application of passive porosity—the use of perforated regions on aircraft surfaces to control aerodynamic pressures and flow characteristics—to modify aerodynamic phenomena such as shock locations, separation, and lift for enhanced performance, stability, and control. This approach permits relatively large variations in aerodynamic behavior without constraints, such as hinge moments, normally encountered with conventional aerodynamic control surfaces.

Spanwise blowing concepts use compressed air derived from engine bleed or other sources to modify airflow over lifting surfaces. By modifying and creating vortical-type flows as a result of steady or pulsed blowing in a spanwise direction, airflow over the upper surface may be significantly influenced, to the extent that vortex lift and reattachment of separated flows can be effected. Thus, aerodynamic performance as well as stability and control can be enhanced, particularly for high angle-of-attack conditions.

Due to extensive research by NASA, industry, and DoD, various types of mechanical thrust vectoring concepts have now been implemented in current military aircraft for enhanced maneuverability and control. A concept previously applied to rockets and missiles, known as fluidic thrust vectoring, uses fluidic rather than mechanical means to redirect engine thrust for vectoring, and offers several advantages over mechanical vectoring. Fluidic thrust vectoring concepts offer the advantages of reduced weight and maintenance associated with mechanical vectoring devices, as well as eliminating engine nozzle deflections and geometric changes that compromise aircraft signature characteristics and provide opposing pilots visual cues that can be used to anticipate evasive maneuvers during close-in air combat.

Challenges and Barriers

The foregoing innovative control effector concepts have received considerable research attention within the aerodynamic community, particularly for applications to highly maneuverable military aircraft. Revolutionary capabilities for maneuver enhancement and aircraft controllability are apparent; however, these concepts have not yet been applied to current aircraft due to risks associated with disciplinary and operational challenges. The following discussion identifies some issues that have arisen during NASA research on the concepts, most of which past Langley efforts have addressed and resolved.

Disciplinary Challenges

Many control concepts face significant challenges in the areas of aerodynamics and structural weight, as well as aeroelasticity and flutter. For example, the aerodynamic effectiveness of the control concepts must be maintained across the flight envelope. For high-performance aircraft, this requirement is especially daunting because of compressibility effects, shock-induced separation, and unsteady flow phenomena. Fundamental effector characteristics must be established through extensive wind-tunnel and flight aerodynamic research efforts. The rapid maturation of advanced CFD methods is now contributing to the assessment and solution of problems involving the effects of Mach number and other flight variables on control effectors.

These concepts must be designed to eliminate undesirable aeroelastic characteristics, such as flutter or aeroelastically induced control reversals, along with maintaining adequate control effectiveness. Evaluations of these phenomena are normally conducted in unique wind tunnels, including the Langley 16-Foot TDT, or in carefully controlled flight experiments.

The magnitude and character of control moments produced by innovative control effectors must also provide satisfactory control response characteristics. In particular, the aerodynamic moments produced by control actuation must vary in a linear fashion with the pilot's control inputs for satisfactory aircraft response, and unsatisfactory by-products known as "cross-axis" moments (for example, yawing moments produced by a roll control) must be minimized. Additional constraints, such as excessive control hinge moments, must be avoided and the weight of control mechanisms and actuation devices must be acceptable.

Operational Challenges

Significant challenges to the applications of innovative control effectors also exist relative to operational and environmental issues. Paramount to all operational issues is the cost of implementation, maintenance, and replacement of control systems. These cost considerations primarily involve associated control system software requirements and other requirements, such as certification time and cost.

Operational challenges to advanced controls include a myriad of issues dominated by maintenance requirements, health monitoring, and failure modes. In-depth analysis of each factor is mandatory before the ultimate feasibility of advanced concepts can be established. In addition, environmental effects (e.g., icing and corrosion) must be assessed and resolved.

Special constraints are placed on innovative control effectors that use auxiliary air for flow control mechanisms. Weight and engine performance issues severely restrict the potential benefits if, for example, excessive engine bleed requirements are necessary.

Arguably, the most important operational challenge to new control effectors is the opinion of evaluation pilots relative to the crispness, predictability, and effectiveness of advanced control effectors on aircraft response characteristics. If significant nonlinearities, cross-axis interactions, and degraded effectiveness occur during critical phases of flight, the control system will be rejected for application.

Langley Activities

Langley Research Center has historically led the research community in advanced flight control systems development. In addition to extensive in-house aerodynamic studies coupled with control system architecture and failure analysis methodology, the Center has partnered with other NASA Centers, industry, and DoD in advancing the state of the art in flight controls. Coupled with legendary contributions in developing conventional aileron, elevator/stabilator, and spoiler control effectors, Langley researchers have pursued many innovative concepts yet to be applied. The following discussions briefly describe some of these pioneering efforts.

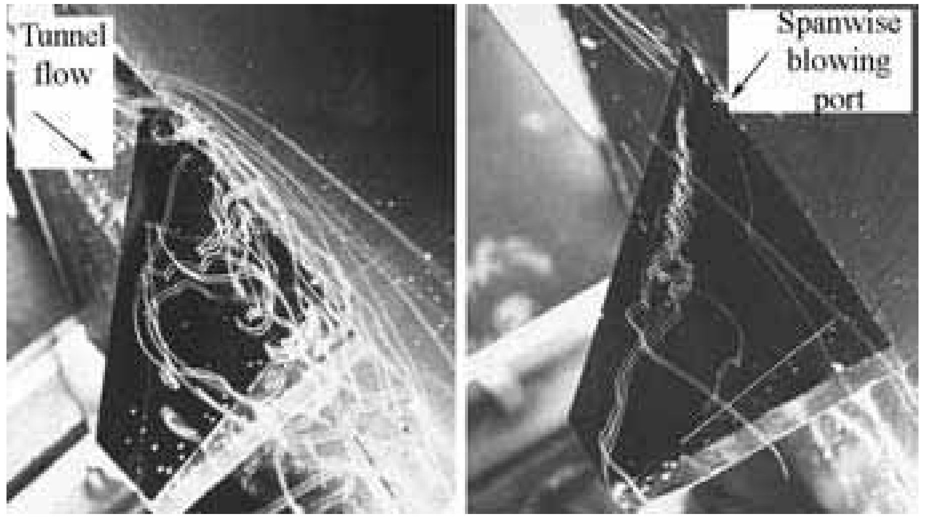
Spanwise Blowing

In the middle 1970s, an intense national interest arose in highly maneuverable military aircraft capable of flight at extreme angles of attack with controllable "care-free" characteristics. Associated with this activity was a mainstream of attention on vortical flows and the use of vortical flow control for enhanced lift and performance. As discussed in *Partners in Freedom*, Langley Research Center contributed directly to vortex technology in activities ranging from fundamental research to specific aircraft applications, including uses on the F-16 and F/A-18 aircraft. Edward C. Polhamus led a wide variety of vortex-control investigations conducted within the basic NASA research program, with industry and DoD partners, and with universities.

Within this environment of innovation and opportunity, Polhamus' group directed its efforts toward the potential use of several concepts to enhance the powerful aerodynamic effects of vortical flows for high-performance configurations. One concept was the use of a high-pressure jet blowing spanwise over a wing upper surface in a direction parallel to the leading edge to augment vortex lift and enhance favorable flow phenomena over the wing. Preliminary experiments indicated that spanwise blowing would aid in the formation and control of the leading-edge vortex shed by moderately swept wings. Polhamus assigned the lead role for spanwise blowing research in his group to James F. Campbell, who was assisted by researchers Gary E. Erickson, Jarrett K. Huffman, and Thomas D. Johnson, Jr.

Campbell and his associates accomplished exploratory spanwise blowing studies in 1974 during tests of simple wings with leading-edge sweep angles of 30 and 45 degrees in the Langley High Speed 7- by 10-Foot Tunnel. These early tests indicated that spanwise blowing significantly improved the aerodynamic characteristics of both wing models at high angles of attack. These tests also revealed that spanwise blowing generated large increases in lift at high angles of attack, improved the drag polars, and extended linear pitching moments to high lift conditions. The study also unveiled an important aspect of the spanwise blowing mechanism: full vortex suction lift was achieved at the inboard span station with a relatively small blowing rate, but higher blowing rates would be necessary to attain the full vortex-lift level at increased span distances.

Campbell and Erickson followed this exploratory study with additional wind-tunnel studies of increased sophistication and scope. They teamed for a study in 1977 involving tests of a 44-degree swept trapezoidal wing model for a range of angle of attack, jet momentum coefficients, and leading and trailing-edge flap deflection angles. They found blowing to be more effective at higher Mach numbers (0.5). The researchers found that spanwise blowing in conjunction with a deflected trailing-edge flap resulted in lift and drag benefits that exceeded the summation of the effects of each high-lift device acting alone. Of relevance to the current discussion, they found asymmetric blowing to be an effective lateral control device at the higher angles of attack.



Blowing off; vortex breakdown. *Blowing on; vortex breakdown delayed.*

Flow visualization of spanwise blowing on a swept trapezoidal wing for an angle of attack of 30 degrees.

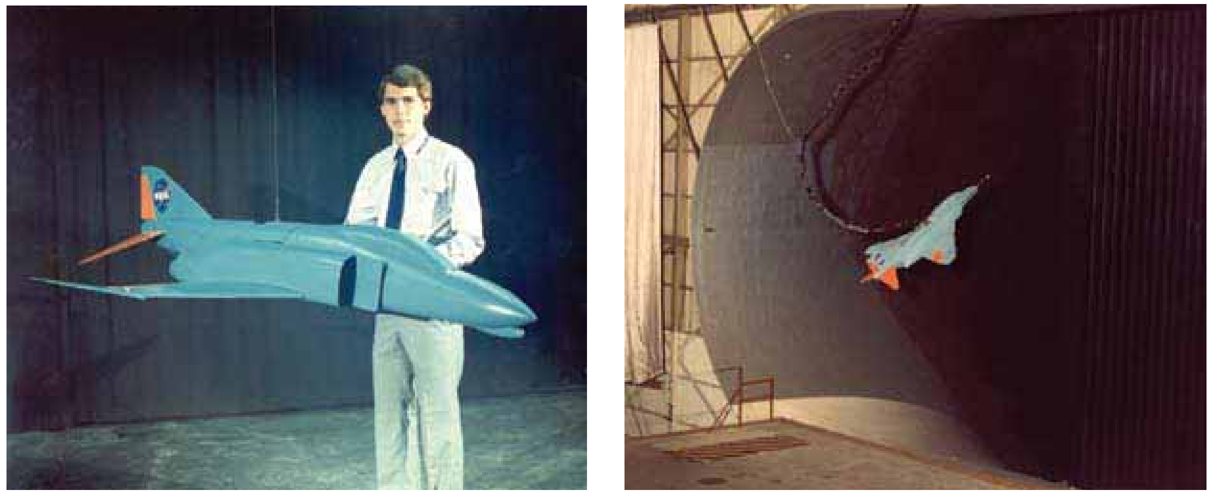
While Campbell and Erickson were pursuing their fundamental aerodynamic studies of the impact of geometric and pneumatic variables on the effectiveness of spanwise blowing, a group under Joseph R. Chambers and Joseph L. Johnson, Jr., at the Langley 30- by 60-Foot (Full Scale) Tunnel began research on the effects of spanwise blowing on the dynamic flight behavior of dynamically scaled free-flight models. Using the remotely controlled free-flight test technique described in other sections of this document, this group assessed the impact of spanwise blowing on longitudinal and lateral-directional behavior for generic and specific aircraft configurations.

In 1978, Dale R. Satran and Ernie L. Anglin led free-flight tests of a general research fighter configuration (based on a modified F-5 configuration) to evaluate spanwise blowing effects of two different wing planforms. One configuration incorporated the wing of the baseline F-5 design (34-degree leading-edge sweep) and the second configuration used a 60-degree delta wing. Three blowing ports were located on each side of the fuselage, oriented parallel to each wing panel's leading edge. Emphasis was on determining dynamic lateral-directional characteristics, particularly in the stall and departure angle-of-attack range; however, effects of spanwise blowing on longitudinal aerodynamics were also determined. The tunnel tests included measurement of conventional static force and moment data, dynamic (forced-oscillation) aerodynamic data, visualization of airflow changes created by spanwise blowing, and free-flight model tests. The effects of blowing rate, chordwise location of the blowing ports, and asymmetric blowing on the conventional aerodynamic control characteristics were investigated.

In the angle-of-attack regions wherein spanwise blowing substantially improved the wing upper surface flow field (i.e., provided reattachment of the flow aft of the leading-edge vortex), improvements in both static and dynamic lateral-directional stability and control were observed. Rolling moment substantially increased at high angles of attack when asymmetric blowing was used for roll control. In fact, the magnitude of rolling moment was as large as that provided by the ailerons at low angles of attack. However, the results also showed that unacceptable large adverse yawing moments were associated with asymmetric blowing, to the extent that full deflection of the rudder would be required to trim out the undesirable yawing moments and coordinate the roll maneuver.

National interest in spanwise blowing continued to expand in the late 1980s. Industry and DoD efforts began to focus on flight testing of specific full-scale aircraft to extend the limited aerodynamic database available in wind tunnels to full-scale hardware. These efforts also provided detailed engineering information on blowing requirements, engine bleed and ducting characteristics, and other system-level features required to design and determine the concept's feasibility. In a 1984 study, McDonnell Douglas modified an F-4C Phantom II airplane under Air Force sponsorship to investigate spanwise blowing. The goal was to validate wind-tunnel data indicating that the F-4C's existing chordwise BLC system could be replaced with a more maintenance-free spanwise blowing system without degrading performance. The designers piped high-pressure bleed air from the F-4C's J-79 engine compressors forward along the inside of the fuselage and expelled the flow through a nozzle in the fuselage near the wing's leading edge and just above the surface. The flight-test results showed that the approach speed could be reduced by about 7 kts and maneuverability was noticeably improved. Because the configuration's leading-edge jet did not penetrate to the outer wing panel, it was suggested that further improvements would occur if some of the blowing were distributed over the outer wing panel of the F-4C.

Langley's Jim Campbell and Dryden's Theodore (Ted) Ayers advocated for a follow-up NASA flight test of the F-4C at Dryden, which was supported by the Air Force. At Langley, Jarrett K. Huffman, David E. Hahne, and Thomas D. Johnson, Jr., led tests in the Langley 7- by 10-Foot High-Speed Tunnel and the Langley 30- by 60-Foot (Full-Scale) Tunnel to determine the optimum location and orientation of the outer panel blowing ports and the effect of blowing on lateral-directional characteristics. Huffman used a 0.10-scale F-4C model for his studies in the 7- by 10-foot tunnel,



Langley researcher David E. Hahne poses with F-4 free-flight model, shown in flight at high angles of attack in the Langley Full-Scale Tunnel.

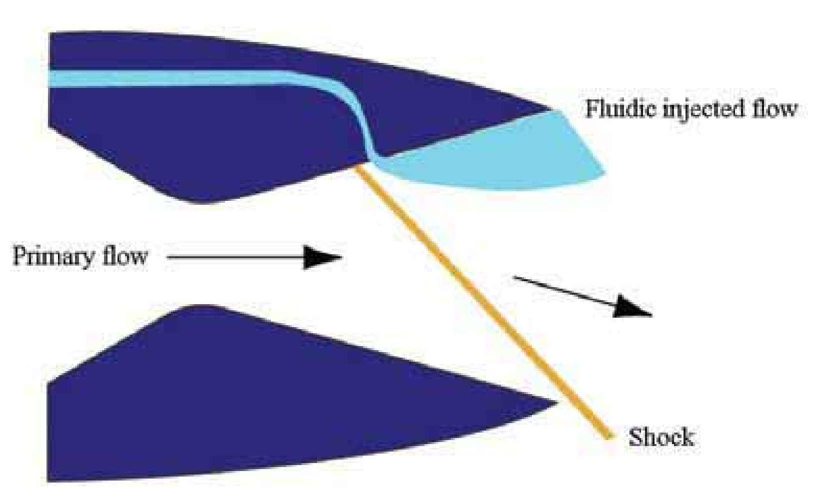
and Hahne used a 0.13-scale dynamically scaled free-flight model for flight and force tests in the 30- by 60-Foot Tunnel. Limitations in NASA resources prevented the planned flight tests at Dryden even though the static and free-flight test results were promising.

Langley and national interest in spanwise blowing waned following these 1980s studies and research on the concept's use in an asymmetric manner for roll control was terminated. Currently, it appears that the use of spanwise blowing for roll control still faces many fundamental issues, especially the level of engine bleed air required and the large adverse yawing moments produced by spanwise blowing for roll control.

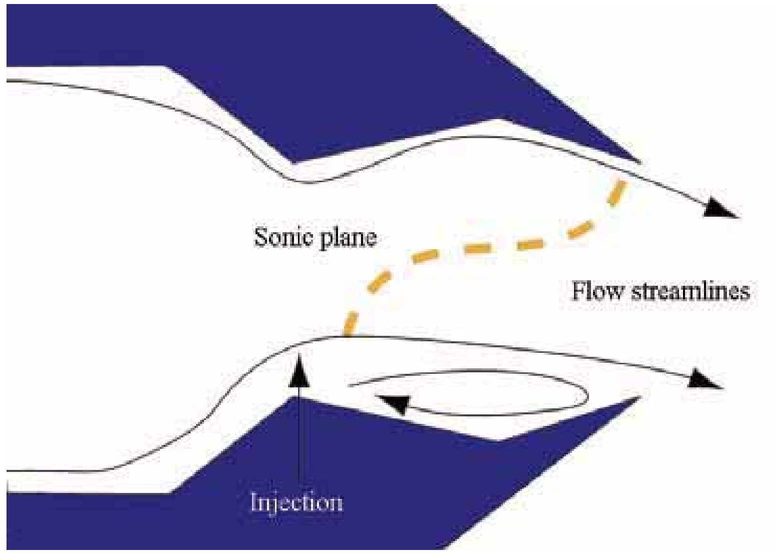
Fluidic Thrust Vectoring

Maintaining air supremacy for the United States requires stealthy, supermaneuverable aircraft. Decades of national research on mechanical engine thrust vectoring techniques initiated in the 1970s were designed to meet the demand for fighter aircraft with increased agility. This research and development culminated in the application of thrust vectoring to the Air Force's F-22 design. In the 1990s, additional requirements for low-observable aircraft and for lower exhaust system weights were the catalysts for research on the use of fluidic concepts for thrust vectoring. Langley has been a leader in the evolving technology for fluidic vectoring due to extensive in-house and cooperative research with industry, DoD, and academia. Researcher Karen A. Deere has contributed an excellent summary of Langley contributions in this area, and the reader is referred to her publication for detailed information (see bibliography).

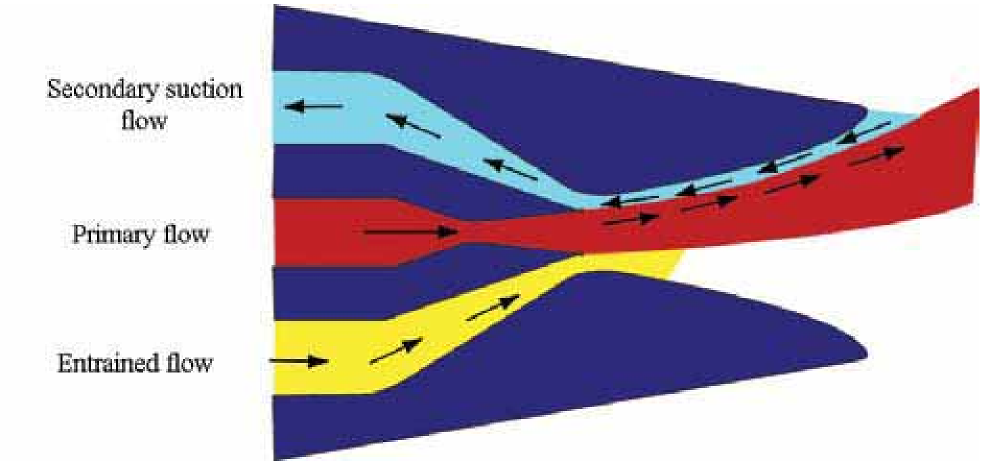
The concept of fluidic vectoring uses fluid control mechanisms to redirect the engine exhaust with no mechanical nozzle parts such as those used for mechanical nozzle vectoring concepts. Typically, the fluidic vectoring concepts use secondary air sources to create an off-axis deflection of the jet thrust. In the early 1990s, the staff of the Langley 16-Foot Transonic Tunnel, under the direction of Bobby Berrier, initiated a cooperative fluidic thrust vectoring program with the Air Force called Fluidic Injection Nozzle Technology (FLINT). David J. Wing led the NASA effort for the program. The results of the FLINT Program predicted that the potential benefits of fluidic thrust vectoring nozzles would be a 28- to 40-percent weight reduction by implementing fluidic throat area control, a 43- to 80-percent weight reduction by implementing fluidic throat area and exit area control, a 7- to 12-percent improvement in engine thrust-to-weight ratio, and a 37- to 53-percent reduction in nozzle procurement and life cycle costs. In addition to these considerations, fixed aperture nozzles would enhance low-observable characteristics by eliminating moving flaps, discontinuities, and gaps. Fluidic systems without moving external nozzle parts would also eliminate visual cues of vectoring control inputs that might be used by enemy pilots to anticipate an impending maneuver during close-in air combat.



The shock-vector-control concept for fluidic thrust vectoring.



The throat-shifting concept for fluidic thrust vectoring.



The counterflow concept for fluidic thrust vectoring.

Langley fluidic thrust vectoring concept studies are divided into three categories according to the method used for fluidic thrust vectoring: the shock-vector-control method, the throat-shifting method, and the counterflow method.

In the shock-vector-control method, an asymmetric injection of secondary air into the engine nozzle's supersonic primary flow of the divergent section is used to redirect the thrust angle. When the secondary air is injected into the primary flow, an oblique shock is created because the primary supersonic flow in the nozzle senses the secondary airflow as an obstruction. The primary flow is then directed through the oblique shock, producing large thrust vector angles. Unfortunately, thrust performance losses are typically high for this concept.

In the throat-shifting method of fluidic vectoring, the engine nozzle's effective throat is asymmetrically shifted by asymmetric injection of secondary flow. In the nonvectoring condition, the throat of the nozzle occurs at the nozzle's geometric minimum area. For thrust vectoring, the injection of secondary air creates a new skewed minimum area, which shifts the effective minimum area and creates an asymmetric pressure loading on the nozzle surfaces, resulting in a thrust deflection of the primary exhaust flow.

The counterflow method of fluidic thrust vectoring uses the approach of counterflowing the primary and secondary airstreams with the application of suction at a slot between the primary nozzle and collar. Mixing occurs in the shear layers between the aft-directed primary flow and the forward-directed suction flow, contributing to the establishment of asymmetric pressures that result in thrust vectoring. This concept is extremely promising for thrust vectoring but faces many technical challenges, including requirements for the suction supply source, aerodynamic hysteresis effects, and impact on airframe integration.

David J. Wing, Karen A. Deere, Bobby L. Berrier, Jeffery D. Flamm, and Stuart K. Johnson led fluidic thrust vectoring research conducted at Langley. They investigated promising concepts with computational and experimental tools, and supporting system studies were conducted when appropriate. Langley's development of a Navier-Stokes CFD code known as PAB3D played a key role in the analysis and design of fluidic vectoring methods. The research efforts have been characterized by intense interactions and collaborative studies with industry, DoD, and academia. The cooperative teams have collaborated on the design and testing of hardware, and Langley researchers have typically led experimental testing in the Langley Jet Exit Test Facility (JETF), a unique facility devoted to simulating propulsion systems at static (wind-off) conditions. The industry partners have generally led the nozzle's design, but Langley researchers originated and developed the most recent and promising dual throat nozzle designs.

The scope of fluidic vectoring concepts studied at Langley within the three primary types previously mentioned is extremely broad. Researchers conceptualized and evaluated variants of the types, adding to the basic knowledge and advances in the state of the art for thrust vectoring. Teaming has been extensive, including studies of the shock-vector-control concept with Rockwell, Rohr, Pratt & Whitney, General Electric, and Boeing. The throat-shifting concept has been explored with Pratt & Whitney and Lockheed Martin, and Langley joined Florida State University and the University of Minnesota to study the counterflow method.

Deere's summary publication provides results and details of the foregoing activities beyond the present publication's intended scope, and it is highly recommended for the interested reader. Briefly, results from Langley investigations of fluidic thrust vectoring concepts indicate that the most thrust efficient fluidic thrust vectoring concept is the throat-shifting method, but larger thrust-vector angles are obtained with the shock-vector-control method. However, the most recent throat-shifting nozzle designs developed by NASA and Lockheed researchers are now providing thrust vector angles equivalent to the shock-vector-control method with lower engine bleed requirements. The counterflow fluidic vectoring concept offers promise, but faces several significant technical issues. Langley's pioneering contributions and fluidic thrust vectoring technology are widely recognized and the Center is actively participating in and consulting on the continuous research on this topic.

Vortical Flow Control

As discussed in a previous section on the vortex-flap and spanwise-blowing concepts, as well as in *Partners in Freedom*, Langley has played a key role in fundamental research on vortical flow and its application to aircraft for enhanced performance, stability, and control. With the advent of long, pointed fuselage shapes and wing-body strakes, researchers identified vortical-flow mechanisms that generated large potential control moments, especially at high angles of attack. Beginning in the 1970s, Langley embarked on studies to control the powerful vortices shed by fuselage forebody shapes and wing-body strakes. Researchers discovered that they could produce large rolling and yawing moments for enhanced maneuverability by differentially deflecting these devices.

Dhanvada M. Rao and Langley's Daniel G. Murri were among the first to explore the feasibility of deflecting the wing-body strakes of configurations similar to the F-16 and F/A-18 in a differential manner to produce asymmetric vortex flow fields resulting in rolling moments. Their exploratory wind-tunnel results of this concept indicated very large rolling moments could be produced; however, research efforts on the concept were terminated because large adverse yawing moments, similar to those encountered for asymmetric spanwise blowing, were also produced.

Strong vortical flow emanating from the wing-body strake of the F/A-18 is clearly defined by natural condensation in air.

More productive Langley research on using vortical flow for vehicle control resulted from applications to high-performance aircraft for improved yaw control at high angles of attack. A primary control deficiency that limits the maneuverability of fighter aircraft is loss of rudder effectiveness when the vertical tails are submerged in the low-energy wake of the stalled wing at high angles of attack. Loss of yaw control at such conditions is especially critical for maneuverability because the primary source of rolling motions at extreme angles of attack is yaw control rather than conventional roll control. This phenomenon is a result of inertial distribution of the airplane's mass and the vehicle's relative responses to roll and yaw control inputs.

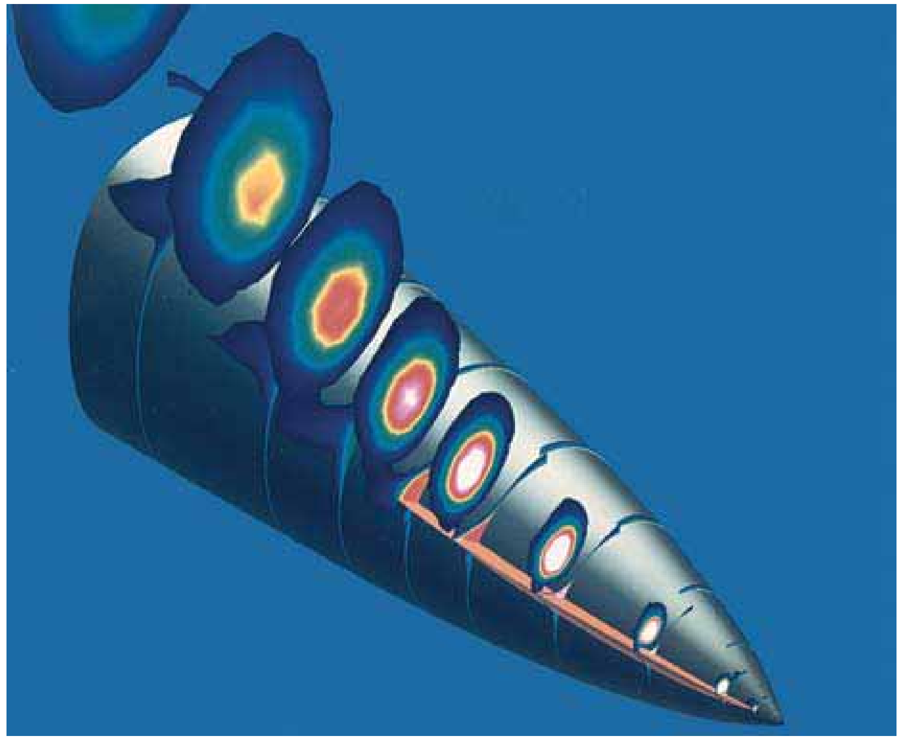
Researchers noted that naturally occurring, large asymmetric yawing moments developed on slender bodies at high angles of attack. They were therefore inspired to develop concepts that could precisely produce and control these potentially revolutionary levels of yaw control power. Initially, Langley staff demonstrated the use of jet blowing from a thin slot near the nose tip and proceeding along the typical fighter radar radome to be an effective controller for forebodies having geometric features known to promote strong vortex asymmetry effects. However, for forebody shapes not naturally prone to pronounced vortex asymmetry, a different vortex manipulation concept is required to generate an effective yaw control. In addition, the classic concerns over providing adequate levels of pneumatic blowing inhibited potential applications of the blowing concept.

Langley researchers developed a highly successful yaw control concept based on the use of deployable, differentially deflectable fuselage forebody strakes in the early 1980s. In cooperative research with the Air Force, Murri and Rao led the development of a pioneering wind-tunnel database that documented the fundamental flow physics associated with forebody strake controls for a variety of aircraft configurations. This early research indicated that differentially deflected forebody strakes could provide revolutionary levels of precision control for close-in air combat. Continuing evolution and refinement of the studies addressed potential effects of Reynolds number and providing a linear controller for the pilot.

In the middle 1980s, NASA launched its High-Angle-of-Attack Technology Program (HATP), which focused on the advancement of the state of the art for predicting and controlling aerodynamic phenomena for enhanced maneuverability at high angles of attack (see *Partners in Freedom*). Using the F/A-18 configuration as a baseline for wind-tunnel experiments, CFD predictions, and simulator and flight assessments, the HATP included an element to develop and evaluate the promising forebody-strake concept that the previous investigations had matured. Accordingly, a research project referred to as the Actuated Nose Strake for Enhanced Rolling (ANSER) flight experiment was planned. Dan Murri, Gautam H. Shah, and Daniel J. DiCarlo led the activities at Langley. The scope of activities at Langley required to define, assess, and optimize the strake configuration for the F/A-18 included conventional static wind tunnel force and moment tests across a range of Reynolds and Mach numbers, flow-visualization tests, free-flight model assessments of strake effectiveness, CFD studies, and piloted simulator studies of maneuverability and handling qualities on the Langley DMS. In addition to Murri, Shah, and DiCarlo, many other Langley researchers contributed to these efforts: Robert T. Biedron, Gary E. Erickson, Frank L. Jordan, Sue B. Grafton, and Keith D. Hoffler.

In conjunction with the ground tests of the HATP, NASA modified an F/A-18 fighter aircraft as its High Angle-of-Attack (Alpha) Research Vehicle (HARV) for a three-phased flight research program lasting from April 1987 until September 1996. The aircraft completed 385 research flights and demonstrated stabilized flight at angles of attack between 65 and 70 degrees using thrust vectoring vanes, a research flight control system, and the ANSER forebody strakes. The hardware's implementation on the HARV was a remarkable display of intercenter coordination and cooperation between Langley and the NASA Dryden Flight Research Center. Langley engineering and shop organizations designed and fabricated the ANSER forebody-strake hardware, and Dryden's staff completed the tasks of aircraft installation, verification, software control final design and development, and flight test evaluations. Flight assessment results were outstanding, demonstrating the effectiveness of this revolutionary control effector for advanced military aircraft.

Supporting tests for the Actuated Nose Strake for Enhanced Rolling experiment included free-flight model studies (top) and tests on a full-scale F/A-18 in the Ames 80-by 120-Foot Tunnel (above).



Computational results of the effect of forebody strake deflection on the F/A-18 forebody.

Close-up view of the forebody strakes on the F/A-18 High Angle-of-Attack Research Vehicle research airplane.

In-flight pictures of the High Angle-of-Attack Research Vehicle showing the right strake deployed (left) and smoke-flow visualization of the vortex path shed by the strake (right)

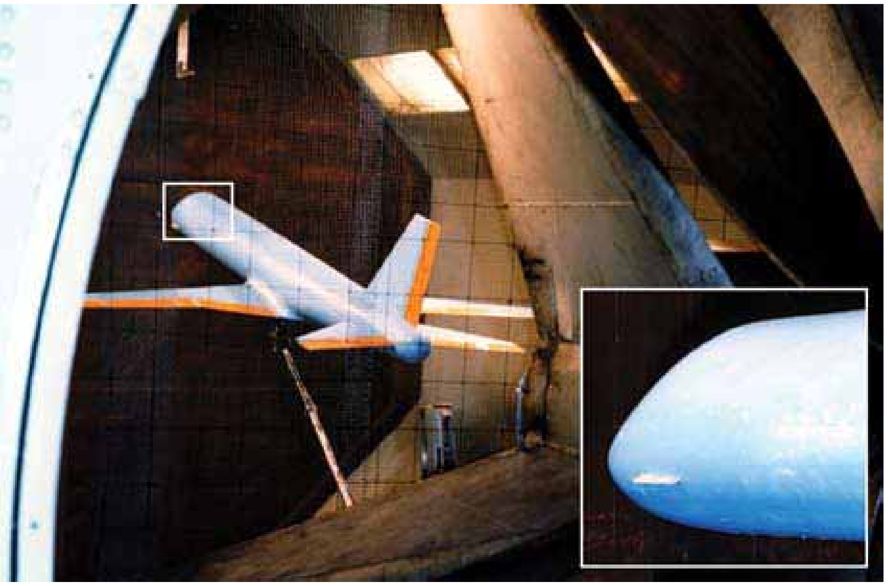
With the extremely favorable results of the HARV flight tests in the HATP, Langley initiated a cooperative program known as Strake Technology Research Application to Transport Aircraft (STRATA) with Boeing in 1997, the objective being to evaluate forebody-strake technology applied to transport aircraft configurations for enhanced directional stability and control. Because the sizing requirement for vertical tail geometry of conventional transport aircraft is usually based on critical asymmetric flight conditions, such as engine-thrust loss during takeoff or high-crosswind landings, alternate concepts that can reduce the size requirements for vertical fin and rudder areas (and thereby reduced weight) are of interest.

Unlike fighter aircraft, the typical operational angle-of-attack range for transport aircraft is relatively low, with landing approach angles of attack typically around 8 degrees. Thus, substantially less shed vortex strength exists on the fuselage at those conditions in contrast to the extreme angles of attack used by fighters. The McDonnell Douglas DC-9 and its subsequent derivatives have used fuselage forebody strakes for years to enhance directional stability at angles of attack within the transport operational environment. However, the STRATA Program was formulated to provide more fundamental information on the detailed aerodynamic effects of fuselage strakes for transport aircraft, including differential deflection for yaw control.

Langley's Gautam H. Shah led STRATA tests of a generic commercial transport model using a low-mounted swept wing and a conventional tail arrangement. Shah's tests, which were conducted in the Langley 12-Foot Low-Speed Tunnel, covered a range of geometric strake variables, including span and chord, strake incidence angle, and the effectiveness of deploying a single strake as a directional control device. The angle-of-attack range covered in the investigation was up to 25 degrees. Unfortunately, study results indicated that the magnitude of yawing moments produced by a single strake was extremely low relative to those that can be generated by conventional rudder.

Although some applications, such as stability augmentation in yaw, might use low levels of control effectiveness, a larger issue surfaced when it was discovered that the yaw control provided by the single strake was extremely nonlinear, making any application as a control device more difficult and complex than a conventional control effector, such as a rudder.

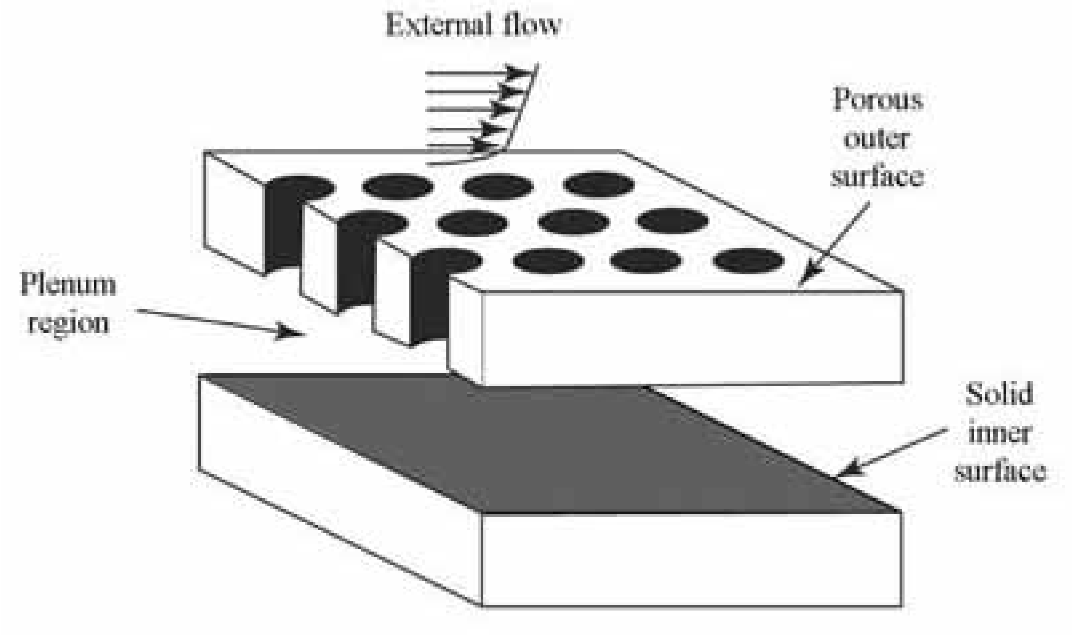
Even though the results of the STRATA tests were generally negative regarding using fuselage strakes for yaw control with representative transport aircraft in normal flight conditions, additional research might provide valuable information if such devices could improve emergency out-of-control recovery capability for extreme attitude conditions at high angles of attack.



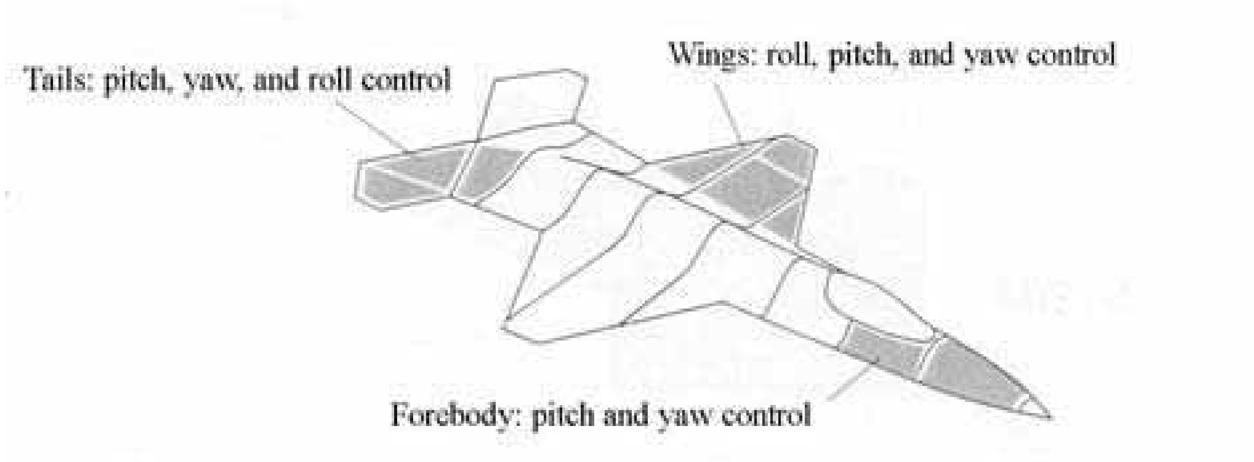
Model configuration tested in Strake Technology Research Application to Transport Aircraft project.

Passive Porosity

The passive porosity concept consists of a porous outer surface, a plenum, and a solid inner surface as shown in the illustration. Pressure differences between high-and low-pressure regions on the outer surface communicate through the plenum, thereby modifying the pressure loading on the outer surface. In addition, a small amount of mass transfer into and out of the plenum occurs that changes the effective aerodynamic shape of the outer surface. Using passive porosity began in the early 1980s as a means of shock-boundary layer interaction control. In the late 1980s and early 1990s, however, Langley researchers began a series of exploratory investigations to apply regions of porosity for aircraft stability and control enhancement. Richard M. Wood and Steven X. S. Bauer of Langley pioneered the initial control effector research that has since developed into a well-proven aerodynamic technology with a wide range of potential applications.



Passive porosity concept.



Potential passive porosity control effector arrangements.

Wood and Bauer's early research on the use of porosity to control aerodynamic moments included an effort with Michael J. Hemsch and Daniel W. Banks to evaluate the potential of porosity to alleviate large, uncommanded yawing moments generated by asymmetric vortex shedding on long pointed forebodies at high angles of attack. In the early 1990s, Bauer and Hemsch conducted an experimental wind-tunnel test in the Langley High-Speed 7- by 10-Foot Tunnel using porous and solid forebody models that demonstrated the ability of porosity to virtually eliminate such asymmetries. Wood and Banks immediately followed this test with a study in the 14- by 22-Foot Tunnel to couple forebody strakes with passive porosity to enhance the control authority of the both technologies.

In the early 1990s Wood led several teams involving Industry and DoD investigating advanced aerodynamic control effectors for military aircraft. Maturation of passive porosity technology was a major focus in both efforts. These programs resulted in the development of two fully porous wing models that underwent extensive testing in the 14- by 22-Foot Subsonic Tunnel and have served as the basis for most industry investigations.

Perhaps the best-known application of Langley passive porosity technology was to the U.S. Navy F/A-18E/F aircraft to help solve an unacceptable lateral "wing drop" characteristic that had been unexpectedly encountered during the early developmental flight testing of the preproduction aircraft. As discussed in *Partners in Freedom*, the availability of Langley's database and experience with passive porosity proved to be a critical contribution to the resolution of the problem and was incorporated in subsequent production aircraft. In this application, porosity was used by Navy and NASA engineers to stabilize flow separation phenomenon encountered during transonic maneuvers, ensuring symmetric stall behavior.

Langley researchers have also pursued the application of passive porosity for aircraft control effector systems. Applied to different areas of an aircraft, the use of porosity can permit the generation of a variety of control forces and moments. In applications, the porous cavities and interconnected plenums would be controlled and actuated by valves or other pneumatic control devices. Passive porosity has no external moving parts, preserves the vehicle outer mold lines, and provides a control force that varies linearly with vehicle lift in a predictable manner.

Langley's staff has also developed CFD methods to augment experimental studies by assisting in the analysis and design of passive porosity concepts. The CFD breakthrough was by Daryl L. Bonhaus in 1999, when he successfully reformulated the passive porosity boundary conditions. His efforts greatly improved the accuracy of passive porosity analysis and allowed for the design of passive porosity control effectors. The aerodynamic integration of passive porosity control effectors into revolutionary new configurations involves a departure from current aircraft design methods. Currently, aircraft airfoils are designed to maximize cruise performance, and then trailing-edge flaps (elevons, ailerons, etc.) are sized to provide sufficient moments to provide adequate control of the aircraft. With passive porosity concepts, the airfoils will be designed to generate a specified pressure distribution that can be modified by the actuation of the porosity device. Thus, the design of control effectors benefits greatly from the use of CFD. Modification, development, and validation of the highly successful Langley TetrUSS by Neal T. Frink, Daryl Bonhaus, Steve Bauer, and Craig A. Hunter has provided a powerful design tool for applications of the passive porosity technology.

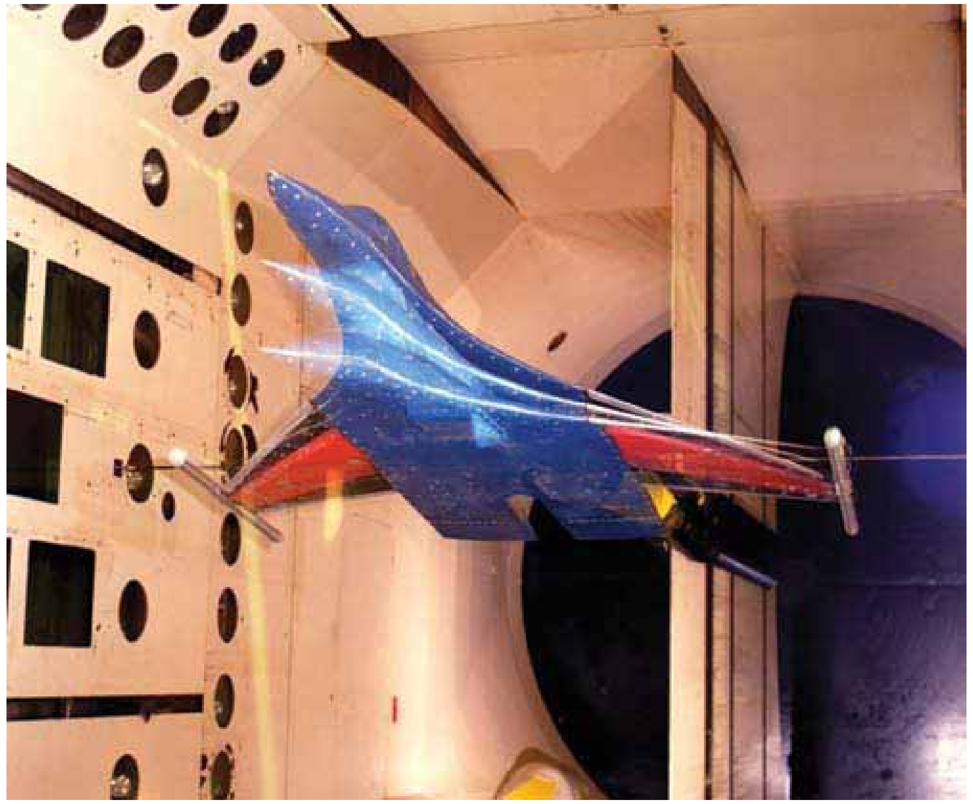
As might be expected, the numerous potential applications of passive porosity have resulted in extensive, ongoing cooperative research between Langley, industry, and DoD. In one such activity, Craig Hunter, Sally A. Viken, Richard Wood, and Steve Bauer led a design and analysis study of the application of passive porosity control effectors to an advanced multimission tailless fighter configuration developed under the Air Force Aero Configuration/Weapons Fighter Technology Program. Focusing on the low-speed, high angle-of-attack flight regime, the team used TetrUSS to develop a series of longitudinal and lateral-directional controllers. Study results indicated that passive porosity effectors could produce large nose-down control at high angle of attack, equaling or exceeding the control authority provided by conventional elevons. As discussed in the previous section on forebody control concepts, yawing moment is especially critical for low-speed maneuvers, and the study identified several yaw control concepts that generated large yawing moments, with low levels of adverse rolling moments.

Demonstrated success of passive porosity application to the F/A-18E/F prototype wing-drop problem, and the rapidly maturing aerodynamic analyses of advanced control effectors, resulted in a significant level of interest currently existing in future applications of the technology. Cooperative studies with industry and DoD are continuing, and all indications point toward extremely effective, versatile flow control devices based on passive porosity for aircraft control. Yet to be demonstrated, however, is the application and assessment of the concept to full-scale hardware and risk-reduction flight testing.

Active Flexible Wing

The rapid emergence of advanced composite technology for wing design and fabrication stimulated significant national interest in the late 1980s and early 1990s in the potential integration of active control and flexible wings for weight savings. By reducing wing stiffness requirements and instead employing advanced control technologies to avoid aeroelastic problems, the innovative use of aeroelastic characteristics and control systems has promised a potential breakthrough in wing design. Designers of conventional civil and military aircraft are now constrained by aeroelastic and structural phenomena such as flutter and aeroelastic-induced aileron control reversal. With revolutionary composite and control design procedures, researchers are exploring the benefits of using, rather than avoiding, wing flexibility effects. Langley researchers have been working in this research area since the middle-1980s, with participation by Center experts in aeroelasticity, flutter, active controls, and advanced instrumentation.

In the 1980s, two researchers at Rockwell International Corporation (now Boeing), Gerald Miller and Jan Tulinius, conceived an active flexible wing concept for advanced fighter aircraft. The Rockwell concept exploited wing flexibility and active leading- and trailing-edge control surfaces to provide high-performance roll rates without the use of all-movable horizontal tails. Discussed in a previous section on control of aeroelastic response, a cooperative program among Langley, the U.S. Air Force, and Rockwell was formalized to research and demonstrate this active flexible wing



Multiple exposure photograph of the active flexible wing model mounted in the Langley 16-Foot Transonic Tunnel.

(AFW) concept. Active control concepts considered during the research effort included active flutter suppression and rolling-load maneuver alleviation. The active flutter suppression system's goal was to use multiple surfaces and sensors to prevent two flutter modes occurring simultaneously. For the rolling-maneuver load alleviation design, the goal was to reduce wing loads at multiple points on the wing while executing roll maneuvers representative of fighter aircraft. As the research efforts intensified, Langley researchers successfully completed additional tests in 1989 and 1991 involving more than 20 researchers. Contributors to the program included Boyd Perry, Stan Cole, Carey S. Buttrill, William M. Adams, Jr., Jacob A. Houck, Anthony S. Pototzky, Jennifer Heeg, Martin R. Waszak, Vivek Mukhopadhyay, and Sherwood H. Tiffany. Key accomplishments of this second AFW Program included single- and multiple-mode flutter suppression, load alleviation and load control during rapid roll maneuvers, and multi-input/multi-output multiple function active controls tests above the open-loop flutter boundary. A highlight of the effort was a special issue of the highly respected AIAA Journal of Aircraft for January-February 1995 that summarized the research details, findings, and conclusions of the project.

After decades of NASA, DoD, and industry research on actively controlled flexible wings in wind tunnels, the next major challenge, piloted full-scale aircraft flight demonstrations, was ready to be addressed. To meet the challenge, NASA, the Air Force, Boeing, and Lockheed Martin initiated and are now participating in an Active Aeroelastic Wing (AAW) Flight Program at NASA's Dryden Flight Research Center using a modified Boeing F/A-18 aircraft. The program goal is to demonstrate improved aircraft roll control through aerodynamically induced wing twist on a full-scale high performance aircraft at transonic and supersonic speeds. Data will be obtained to develop design information for blending flexible wing structures with control law techniques to obtain the performance of current day aircraft with much lighter wing structures. The flight data will include aerodynamic, structural, and flight control characteristics that demonstrate and measure the AAW concept in a comparatively low cost, effective manner.

Begun in 1996, the AAW Program completed the wing modifications required for the research program. In preproduction versions of the F/A-18, the wing panels were relatively light and flexible. During preproduction flight tests (particularly at high-speed, low altitude conditions), the wings were too flexible for the ailerons to provide the required roll rates. This unacceptable result occurred because the high aerodynamic forces against a deflected aileron and resulting wing torsion would cause the wing to deflect in the opposite direction, causing severe degradation of roll control in the intended direction. The F/A-18 production aircraft were subsequently fitted with stiffer wings to minimize the undesirable loss of roll control.

NASA's active aeroelastic wing F/A-18A research aircraft maneuvers during a test mission.

The wing panels on a Dryden F/A-18 research aircraft were modified for the AAW research program. Several of the existing wing skin panels along the wing's rear section just ahead of the trailing-edge flaps and ailerons have been replaced with thinner, more flexible skin panels and structure, similar to the preproduction F/A-18 wings. In addition, the research airplane's leading-edge flap has been divided into separate inboard and outboard segments, and additional actuators have been added to operate the outboard leading-edge flaps separately from the inboard leading-edge surfaces. By using the outboard leading-edge flap and the aileron to twist the wing, the aerodynamic force on the twisted wing will provide the rolling moments desired. As a result, the flexible wing will have a positive control benefit rather than a negative one. In addition to the wing modifications, a new research flight control computer has been developed for the AAW test aircraft, and extensive research instrumentation, including more than 350 strain gauges, has been installed on each wing.

Langley's Jennifer Heeg leads a team of dedicated and skilled professionals currently conducting research within the AAW Program on the development and validation of scaling methodology for reliable wind-tunnel projections to flight. The team is applying a Langley method called wind tunnel to atmospheric mapping (WAM) for scaling and testing a static aeroelastic wind-tunnel model of the AAW aircraft. The WAM procedure employs scaling laws to define a wind-tunnel model and wind-tunnel test points such that the static aeroelastic flight-test data and wind-tunnel data will be correlated throughout the test envelopes. The specific scaling is enabled by capabilities of the Langley TDT and by relaxation of scaling requirements present in the dynamic problem that are not critical to the static aeroelastic problem.

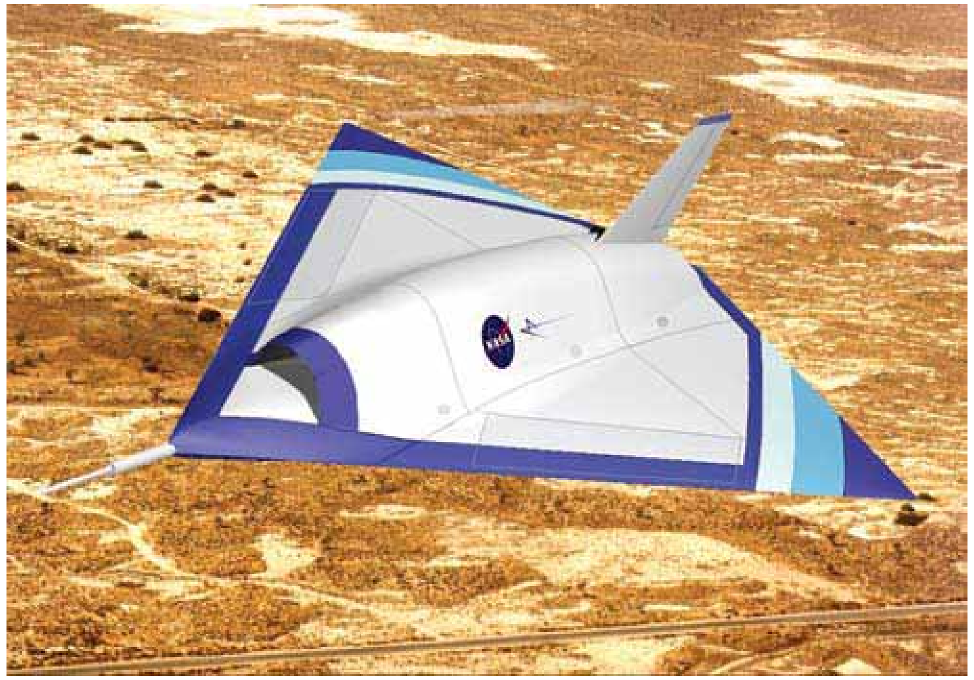
AAW flight tests began in November 2002 with checkout and parameter identification flights. New flight control software was then developed based on data obtained during 50 research flights over a 5-month period in 2003. The Langley-Dryden team evaluated the controls' effectiveness in twisting the wing at various speeds and altitudes. A second series of research flights planned to last into 2005 is scheduled to evaluate the AAW concept in a real-world environment. Obvious issues regarding flutter suppression, failure modes, and cost-benefit trades remain to be addressed before AAW concepts can be applied to production aircraft.

The NASA Smart Vehicle Program

Langley's researchers had aggressively pursued advanced control effector studies with industry and DoD in the 1990s. In one of the most important cooperative projects, Richard M. Wood served as team lead for a NASA-industry-Air Force military team (1990 to 1993) that included members from Langley, NASA Ames, McDonnell Douglas, and the DoD. The focused activity resulted in the conception and development of four advanced control effector technologies that were subsequently adopted by industry. The four patented technologies were passive porosity, advanced planforms, micro drag bumps, and advanced forebodies. Almost a decade later, an opportunity arose to carry some of the concepts to flight tests.

As discussed in other sections of this document, NASA initiated a program known as RevCon in 2000 to accelerate the exploration of high-risk, revolutionary technologies. The nine projects initially selected included a study known as the Smart Vehicle (SV) Program. The Smart Vehicle was envisioned by NASA and its partners to be an unmanned advanced technology demonstrator that would demonstrate the application of a set of novel aerodynamic effectors and an advanced adaptive vehicle management system to enhance the operational effectiveness of revolutionary air vehicles. Specifically, the demonstrator would use novel aeroeffectors as primary control devices in the research envelope, demonstrate the effectiveness of an adaptive closed loop vehicle control system that accommodates anomalies in the research envelope, and define the benefits of integrating an adaptive control system and novel actuators. The flight envelope was to include a design Mach number of about 0.8 at an altitude of 25,000 ft. The project would be conducted by a team led by Langley, with team members including Lockheed Martin Tactical Aircraft Systems (LMTAS), Physical Sciences, Inc., Tel Aviv University, Naval Air Systems Command, and NASA Dryden Flight Research Center.

Initially, the team considered several advanced control effector concepts, including passive porosity, spanwise blowing, seamless control effectors, inflatable flaps, pulsed jet vortex generators, oscillatory blowing, wing decamber "bumps," drooped leading-edge flaps, and reaction control systems. The team judged each of the foregoing effector concepts (and others) on research merit in terms of technology readiness level and disciplinary research and development required. The initial control effector concepts chosen were passive porosity, seamless control effectors, spanwise blowing, and decamber bumps. Fluidic thrust vectoring was identified as a desirable yaw control effector but was eliminated to reduce program cost.

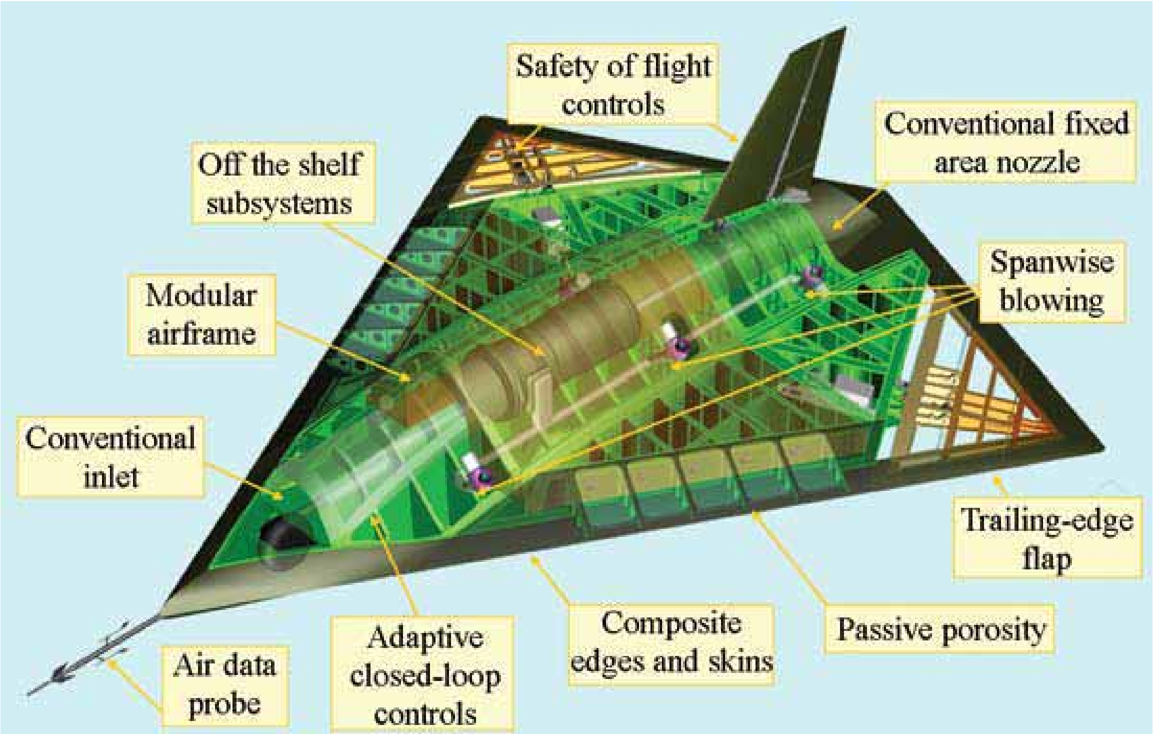


Artist's sketch of the RevCon Smart Vehicle Demonstrator.

Under the teaming agreement of the RevCon SV project, Langley would be responsible for project lead; risk reduction studies in low- and high-speed wind tunnels including the TDT and 16-Foot Transonic Tunnel facilities; design and development assistance of the advanced control laws to be used by the vehicle; development of design criteria for the passive porosity and spanwise blowing concepts; and vehicle fabrication, assembly, integration, and selected ground testing. Following the SV demonstrator's fabrication and initial checkout at Langley, it would be shipped to Dryden for final assembly, preflight completion and checkout, and research flight tests.

Langley's Manager for the SV Program was Jean-Francois M. Barthelemy, assisted by Scott G. Anders and Henry S. Wright. Major Langley contributions to the program were provided by Bobby Berrier (lead for aerodynamic data base development), Steven X. S. Bauer (porosity), Thomas M. Moul (aerodynamics), Richard F. Catalano (system studies), Stuart Johnson (system studies), John V. Foster (wind-tunnel testing), Richard J. Re (wind-tunnel testing), and Richard DeLoach (wind-tunnel techniques).

By spring of 2001, the NASA-industry team had conducted a phase I study and developed an attractive project within 8 months. At that time, NASA had developed an interest and vision in "morphing aircraft" that would employ many of the concepts involved in the SV demonstrator, and the SV concept was viewed by many as a stepping-stone to future revolutionary aircraft activities. However, it was also recognized that many of the technologies required additional research and development, and that the anticipated costs of the demonstrator program would be large. During the phase I studies, the demonstrator vehicle design had accelerated: conceptual design, initial structural and flutter analyses, CFD calculations for performance, and 6-degree-of-freedom flight simulations had been accomplished; systems-level analyses of various proposed technologies had been completed; and two wind-tunnel entries had been accomplished (low-speed configuration screening and transonic performance and control effector evaluations).



Elements of the Smart Vehicle.

Anticipated milestone events included a NASA RevCon go-ahead for phase II activities in the fall of 2001, shipping the vehicle to Dryden in the fall of 2004 and conducting the first flight tests during the summer of 2005. Unfortunately, NASA's funding for RevCon was redirected to providing a return-to-flight capability for the NASA X-43A (Hyper X) Program following the X-43A accident on June 2, 2001. NASA subsequently terminated its RevCon Program on September 30, 2001.

Following the cancellation of the RevCon Program, Langley provided advocacy and funding for a follow-up project within its Revolutionary Airframe Concepts Research (RACR) project. Known as the Aeronautical Flight Vehicle Technologies Demonstrator (AVTD) project, a similar SV vehicle configuration was retained based on a version of the LMTAS Innovative Control Effector Vehicle that had been used for several studies on advanced fighters, including an uninhabited air combat system. In addition, the new project's goal was changed to provide a robust, reusable, unmanned, modular high-performance flight demonstrator to serve as a test bed for maturation of advanced technologies, and the scope of applications was changed to emphasize potential civil as well as military applications.

By 2003, the research within AVTD had proceeded to include systems-level assessments of control effectors, vehicle conceptual design and cost estimates, wind-tunnel entries in the Langley 16-Foot Transonic Tunnel and the Langley 16-Foot TDT, supporting CFD studies for flow diagnostics and analysis, and simulation of flying qualities. Bobby L. Berrier, John Foster, Jerome H. Cawthorn, Richard J. Re, Craig A. Hunter, and Steve Bauer had conducted aerodynamic studies, and several options for vehicle configurations (wing planforms and configuration layouts) had been assessed.

A 7-week test program in the 16-Foot Transonic Tunnel at Mach numbers from 0.3 to 0.9 and angles of attack from –5 to 15 degrees significantly advanced the state of the art in advanced control effectors. The team conducted parametric studies and data were obtained on the effectiveness of passive porosity control effectors, seamless trailing-edge flaps, porosity and trailing-edge interactions, deployable bumps, and a rudder. The staff used CFD also to predict the effectiveness of deployable bumps and passive porosity, providing good qualitative trends.

Unfortunately, NASA cancelled the project in fiscal year 2004 because of resource constraints in the face of relatively large costs projected for SV flight tests.

Status and Outlook

The remarkable progress made by Langley researchers on advanced innovative control effectors continues to generate significant interest for applications, particularly within the military community. With the advent of highly lethal, signature-sensitive combat environments, designers are striving for unconventional approaches to maximize performance and handling qualities while maximizing stealth and reducing costs, maintenance, and vehicle weight. New technology fields are being pursued to maximize the effectiveness of advanced controls. For example, the introduction of controls allocation technology has reduced the concern about unwanted cross-axis moments from each effector. This technology was motivated by configurations that had several control effectors and could benefit from blending of the effector inputs to minimize control deflections, yet provide the desired control moments. Control law software has been developed that can provide the commanded control moment by combinations of control positions to optimize control strategy. One application is to provide proverse yawing moments with roll control while minimizing additional yaw control. At this time, however, the major barrier to implementation of many of the concepts is the lack of full-scale aircraft flight experience to resolve numerous application issues that cannot be resolved at model scale.

With the introduction of high-performance Uninhabited Air Combat Vehicles, many technology concepts conceived and developed at Langley are now appropriate for future applications. Langley's staff is continuing its quest to provide designers with valuable technology information for use in design and trade studies for future air vehicles. Undoubtedly, extensive demonstrations of the technologies discussed herein by manned or unmanned vehicles will occur in the near future.

Personal Air Transportation Concepts: On-Demand Revolution in Air Travel

Concept and Benefits

By the 1990s, demand for public air transportation in the United States had intensified to the point that widespread frustration over system shortcomings existed. Commercial flight delays due to the cascading effects of bad weather, inconvenient and indirect flight schedules, lack of physical comfort and overcrowding within airports and airplanes, and excessive "lost time" getting to and from remote airports had become more frequent. These frustrations stimulated the technical, regulatory, and political communities to consider and evaluate proposals for innovative modifications to the current air transportation system. Following the world changing events of September 11, 2001, the resulting adjustments to commercial aviation operations to ensure security, and the delays caused by security breaches, further aggravated the lost time and personal inconvenience of air travel.

Assessments of the current system's shortcomings have focused on the problems created since airline deregulation resulted in the centralized "hub and spoke" system now used by most major air carriers. Over 75 percent of aviation passenger traffic within the United States is conducted through only 30 major airports. Although the hub and spoke system will continue as a vital asset for long distance travel, it does not serve rural, regional, and intraurban travel very effectively. For travel distances of 100 to 500 miles, the public chooses to use automobiles 20 times more often than aircraft. Considering that the average home-to-destination auto speed for these trips is only 35 mph, and that projected highway congestion over the next 25 years will reduce this speed even further, a critical need exists for a revolutionary form of faster travel that can avoid the gridlock of either highways or hub and spoke airports. More frequently, analysis of the problem reveals that expanded use of over 5,000 public general aviation airports within the existing U.S. infrastructure might provide a solution to the anticipated future decline in public mobility.

Innovative concepts for personal air travel that have been periodically revisited over the past 80 years include personal-owner general aviation aircraft; personal air travel through distributed, on-demand air taxi operations; and even futuristic, self-operated personal air vehicles (PAV) capable of both roadable and airborne operations, as well as short-field operations from neighborhood roads and "at home" storage. Such concepts use the distributed air operational scenarios discussed previously and are compatible with an innovative and revolutionary vision of potential future air transportation. The unfulfilled perspectives within these visions would permit an unprecedented level of mobility for average citizens, resulting in significant improvement in productivity and quality of life.

Within its charter and mission to define and develop concepts to improve the quality of life for the U.S. public, and to conceive and mature technologies required for new systems and vehicles, NASA is conducting research designed to advance and accelerate the state of air mobility.

The Nation's underused public airports might provide significant public mobility.

To permit greater mobility and freedom in air travel, near-term NASA goals have been to develop and demonstrate technologies enabling the safe and cost-effective operations of today's small aircraft from the vast number of public airports. Additional efforts are underway to provide designers with methods of transforming today's personal-owner aircraft to eliminate extensive current public perceptions of unacceptable operational cost, lack of comfort, lack of safety (especially in adverse weather conditions), objectionable noise, and unacceptable training time and costs. Vehicle-oriented research goals are to develop technology for a small airplane that can fly out of small airports, to keep the cost less than $100,000 while being equipped for all weather operation, and to be unobjectionably quiet to the surrounding community. NASA is also conducting research on pilot-vehicle automation to make flying nearly as simple as driving a car.

Langley has also conducted research to enable the design of small (two passenger) personal-owner aircraft that have door-to-door travel capability, including the ability to travel in a limited roadable fashion on side streets, while taking off and landing at very small airfields. While the desire to have a true flying car is widespread and understandable, NASA researchers believe that the dream of the flying car will continue to be unfulfilled even 25 years from now. The problems that result when full highway roadability is coupled with flight capability will continue: vehicles that aren't very good cars, aren't very good aircraft, and are much more expensive than both.

Challenges and Barriers

An on-demand aviation system, with convenience, low costs, and proven safety, has been a dream of aviation innovators and futurists since the earliest days of flight. The proposed distributed air operational system's capacity to provide this capability has been firmly blocked in the past by a multitude of technical, regulatory, economic, and operational issues. The following discussion of challenges and barriers provides background on that which must be overcome to permit the successful implementation of a distributed, on-demand air system. The issues are addressed for two different vehicles: a near-term advanced general aviation-type aircraft designed for intercity and rural travel from nonradar-equipped small airports, and a futuristic roadable aircraft with ultra–short-field takeoff and landing capability designed for intraurban short trips. Both vehicles might be flown by either air-taxi pilots or by private owners. NASA and its partners are engaged in pioneering efforts to accelerate solutions to existing and anticipated challenges and barriers for both types of aircraft. Through its programs on general aviation technologies, small aircraft transportation systems, and personal air vehicles, the Agency is contributing significant stimuli toward this objective.

Disciplinary Challenges

The development of economically feasible air vehicles with satisfactory performance, flying qualities, and safety is a traditional NASA mission. Within the disciplines of aerodynamics, propulsion, stability and control, structures, and flight deck technology, NASA supplies advanced concepts and data for use by designers to ensure that the mission requirements of new vehicles can be met.

An advanced general aviation aircraft envisioned for intercity travel from rural airports creates technology requirements that are driven by cost, safety, security, environmental compatibility, and ease of use. Within the disciplines, these requirements translate into technical simplicity and innovative approaches to lower acquisition and operational costs. For example, reliable propulsion systems comparable with automotive systems will be mandatory. Structures and materials must be low cost, easily replaced, damage tolerant, and provide a high level of crashworthiness. For applications envisioned, aerodynamic characteristics of a vehicle are probably within the state of the art; however, the pilot-vehicle interface for flight planning, guidance, stability, and control will have to be exceptionally good to permit safe operations in marginal weather conditions by novice pilots.

The disciplinary requirements for a futuristic intracity aircraft are tremendously more demanding than an intercity vehicle. Envisioned as the ultimate personal-owner aircraft with ultra–short-field takeoff and landing capability and all-weather operations, the vehicle requires extensive advances in disciplinary technologies far beyond levels available today. Sophisticated powered-lift concepts, including morphing technologies like circulation control, will be required, as well as high power-to-weight engines, sophisticated control systems with extensive artificial stabilization, advanced navigation and guidance, and lightweight structures.

Operational Challenges

Arguably, the challenges and barriers to future personal air transportation are more dominant in the area of operations than those within the technical disciplines. For near-term aircraft, operating from small, nonradar equipped airports will pose stringent requirements on situational awareness and collision avoidance (both airborne and ground operations), guidance displays, and weather awareness. The far-term personal air vehicle faces even more issues. The complexity of flying an airplane in all-weather conditions (compared with driving a car), and the difficulty and costs involved in gaining a pilots license, create immediate barriers unpalatable to most of the public. The issues of regulatory requirements, certification, liability, and operational flexibility will require years of study, debate, and resolution before the dream can be realized.

Economic Challenges

No single factor affects the public's interest and willingness to use new technology more than cost. Acquisition cost of an excessively sophisticated vehicle (compared with automobiles) will immediately undermine advantages of new transportation capability and deter the application of advanced technology, no matter how impressive the benefits may be. Solutions regarding additional costs associated with pilot training and currency, maintenance, insurance, medical certificates, and other factors will require innovative approaches and perspectives.

In summary, the challenge of providing increased mobility and productivity to the public via advanced personal air transportation involves an extensive and complicated series of issues that ignite classical confrontations between technological, regulatory, and economic factors. Many argue that these same factors have faced every step of advancement in transportation, from sailing ships to locomotives to automobiles, yet when the barriers were ultimately addressed, new forms of transportation were adopted, and naysayers were proved wrong. In its role as an advanced research and development organization, NASA is addressing these issues.

Langley Activities

Although NASA has not conceived, developed, and demonstrated a vehicle appropriate for the futuristic personal air vehicle vision, early contributions include concepts, technology, and data in the areas of aerodynamics, flight dynamics, structures and materials, flight deck technology, propulsion, and controls, all key to the potential success and airworthiness of the vehicles. Past Langley research on relatively inexpensive concepts for individual airborne transportation are worthy of note.

During the 1950s and 1960s Langley conducted research on personal "flying platforms."

In the middle 1950s, considerable interest was expressed by the U.S. Army and associated industries over development of a general-purpose vertical takeoff and landing (VTOL) aircraft that could be operated by a single person and serve as a reconnaissance aerial vehicle. As envisioned, the vehicle would be able to hover or fly forward at speeds up to about 50 kts. Military versions would carry a payload of about 1,000 lb, and it was expected that the proposed vehicle would be simpler in construction and easier to operate and maintain than a small helicopter. Potential civil applications for the concept were quickly recognized, and studies of "flying platform" vehicles began to emerge.

With an extensive ongoing research program in rotorcraft and VTOL technology in the 1950s and 1960s, researchers at Langley conducted several investigations of the performance, stability, and control of such concepts. The necessity of minimizing the rotor diameter and slipstream velocity, and for providing protection for surrounding personnel and equipment, prompted the use of ducted fans—rather than rotors—which became a focal point of the Langley studies.

Under the direction of Marion O. McKinney, a team of Langley researchers conducted conventional static force and moment wind-tunnel tests as well as free-flight tests of several configurations incorporating either two- or four-duct arrangements. As early as 1954, McKinney's team started a series of free-flying model tests of ducted-fan flying platform configurations. Robert H. Kirby, Lysle P. Parlett and Charles C. Smith, Jr., led the research efforts, and early results revealed two serious problems inherent in any fixed-geometry ducted-fan configuration in forward flight. These problems are an undesirably large forward tilt angle of the platform required for trim at high speeds and nose-up pitching moment that increases rapidly with forward speed. Solutions to these two problems are imperative for practical operation of ducted-fan vehicles.

Parlett's test results indicated that a tandem two-fan arrangement exhibited less severe tilt angle and pitching moments than a side-by-side fan arrangement, but the tandem configuration required appreciably more power for forward flight. Analysis of these early results indicated that deficiencies might be alleviated by departing from the concept of ducted fans fixed with respect to the airframe and tilting the ducts for the forward flight condition. Subsequent tests by Smith with the tilting-duct arrangement showed that the problems have been minimized, providing pioneering research data that contributed to a rising interest in compact tilt-duct aircraft configurations, such as the Bell X-22 research aircraft in the 1960s. During the height of VTOL research at Langley in the 1960s, ducted-fan vehicles were studied in detail in the Langley 30- by 60-Foot (Full-Scale) Tunnel and the Langley 14- by 22-Foot (V/STOL) Tunnel. Current knowledge of the aerodynamic performance, stability, and control characteristics of this class of vehicle was contributed by research studies at Langley and at NASA Ames Research Center.

Langley has led the Agency's efforts in advancing the personal air transportation system capabilities for the past decade. The program's conception, planning and success to date can be attributed to the personal expertise, dedication, and leadership of Langley's Bruce J. Holmes, who is internationally recognized for his leadership and personal technical research for general aviation. Rising through the technical ranks, Holmes progressed from extensive technical contributions as a researcher for advanced general aviation aircraft configurations to a visionary program manager responsible for integrating and coordinating NASA, industry, FAA, and academic researchers on national-level programs to improve the national air transportation system. Most project activities discussed in this section (especially the near-term objectives and goals) were conceived or strongly influenced by his direction. Another NASA leader in visionary and futuristic perspectives on technology and personal air travel is Dennis M. Bushnell, Chief Scientist of Langley Research Center. His persistence in achieving the unthinkable, and his challenges to researchers to think beyond the envelope, has inspired numerous advances in innovation and revolutionary concepts at Langley. Bushnell's personal interest and managerial support for far-term PAVs of the future has provided the opportunities for Langley's researchers to pursue creativity and pioneering efforts in what is recognized as an exceedingly difficult research area.

The following discussion provides an overview of some of the most critical Langley research programs and contributions to the personal air transportation arena. Three research activities have been especially noteworthy in this topic. They are the NASA Advanced General Aviation Transport Experiments (AGATE) Program, which provided advanced technology to permit the domestic general aviation industry to remain a vibrant component of aviation; the NASA Small Aircraft Transportation System (SATS) Program, which is in the process of demonstrating the ability of advanced technology to permit routine operations of small aircraft from rural airports; and PAV studies, which explore the ability of technology in the near- and far-term years to provide revolutionary personal air transportation vehicles.

The NASA Advanced General Aviation Transport Experiments Program

Following the almost total collapse of the U.S. general aviation industry in the 1980s, the Nation searched for mechanisms to provide the resurgence required to reestablish this vital segment of the air transportation system. This decline included significant decreases in small aircraft deliveries, general aviation fleet size, flight hours, public use airports, pilot population, and new student pilots. At its peak in 1978, the general aviation industry delivered 14,398 aircraft. In 1994, the number of aircraft deliveries had fallen to an all-time low of 444. The average age of general aviation aircraft flying at that time was about 30 years. Flight deck technologies in use dated back as late as the 1950s, and piston propulsion technologies had remained unchanged for the past 40 years. Along with modifications of product liability issues, the potential impact of advanced technology to improve safety, reduce operating and training costs, and stimulate interest in general aviation was pursued.

Building on his long established relationship with the general aviation industry, Langley's Bruce Holmes took the lead in the formulation of cooperative planning with industry to create a new future for general aviation. Following Holmes' highly successful advocacy efforts within NASA and industry, in 1994 NASA created an AGATE Consortium under the general aviation element of the Advanced Subsonic Technology Program Office to revitalize national general aviation through the rapid development and fielding of new technologies, with a view toward providing an impetus for a new small aircraft transportation system.

Under the direction of Holmes and his Deputy Michael H. Durham, the AGATE team focused on goals that included the development of affordable new technologies, as well as new approaches to meeting industry standards and certification methods for airframe, cockpit, flight training systems, and airspace infrastructure for next generation single pilot, four to six seat, all-weather light airplanes. The AGATE alliance eventually grew to more than 50 members from industry, universities, the FAA, and other government agencies. Starting with NASA seed funding of $63 million in 1994, NASA, the FAA, the Small Business Innovation Research Program (SBIR), industry, and universities pooled nearly $200 million in combined resources among 39 cost sharing partners. About 30 other partners also joined the effort as noncost sharing, supporting members of the AGATE Consortium, totalling nearly 70 members.

The cumulative result of the AGATE alliance produced a revolution in the research and technology deployment capacity for all sectors of the general aviation industry. AGATE provided a voice for industry to provide national clarity and action on key technology development, certification, and standard-setting activities. During the AGATE Program, which ended in 2001, the general aviation industry research and technology capacity advanced from virtually nonexistent to world-class in avionics, engines, airframes, and flight training. Integrated with these advances was the rising advocacy for deployment of small aircraft at the Nation's distributed public airports for unprecedented advances in personal mobility and productivity for the public. Extensively cited as a classic example of NASA aeronautics at its best, the AGATE Program is viewed as the catalyst responsible for current interest in expanded use of small aircraft transportation systems.

The NASA Small Aircraft Transportation System Project

Following the highly successful AGATE Program, Bruce Holmes and his team of NASA-industry-academia-FAA partners turned attention to the next step in demonstrating potential benefits of a small aircraft transportation system for the U.S. public. Holmes began a difficult advocacy effort, which entailed a major step up in challenges from the technically focused AGATE Program. The new transportation system-focused program would entail numerous nontechnical factors not in the immediate control of NASA, such as local politics, community planning, and regulatory responsibilities. Despite outspoken critics and skeptics, Holmes and his team secured NASA funding in 2001 to begin a new program, called SATS, which would "put wings on America" and minimize the transportation woes and gridlock associated with clogged interstates and hub-and-spoke airports.

The NASA SATS Program envisions the on-demand use of small aircraft from distributed public airports.

SATS highlighted the fact that, away from the congested hub-and-spoke airports, underused capacity at over 5,000 public use airports is abundant. Unfortunately, fewer than 10 percent of public airports have precision instrument guidance, communications, and radar coverage for safe and accessible near-all-weather operations. To move to the new paradigm of small aircraft operating as a key component of the proposed transportation system, flight deck and flight path technologies and operating procedures would have to be developed to provide the missing components.

Many enabling technologies from the AGATE Program and a related program, the General Aviation Propulsion (GAP) Program managed by the NASA Glenn Research Center were poised to contribute to this futuristic vision. These technology advances included:

- New turbine engines with revolutionary thrust-to-weight and cost metrics
- Commercial off the shelf (COTS)-based avionics with vast improvements in cost, reliability, and capabilities
- Highway-in-the-sky graphical pilot guidance systems
- New approaches to crashworthiness
- Streamlined composite airframe manufacturing techniques
- Ice protection technology
- Digital engine controls (for single-lever power control)
- Graphical weather information in the cockpit
- Advanced flight training and pilot certification processes

With such technology now available, the SATS vision is to provide the Nation with an alternative to existing road and airline choices for travel. Goals include hub-and-spoke-like airport accessibility to the smallest of neighborhood airports, without needing radar and control towers, and without needing more land for protection zones around small airports. Obviously, this travel alternative must be cost-competitive with existing choices and meet public expectations for safety and accessibility.

Early consumers of SATS would have access to air-taxi-like systems with hired pilot operations. The SATS project goal is to develop technologies and operating capabilities to enable affordable, on-demand, near all-weather access to even the smallest of markets. Scheduled services may also appear in more dense transportation markets as entrepreneurs discover effective ways to meet market demands.

The congressional budget appropriation for the SATS Program included a mandate to prove that the SATS concept works. This mandate includes demonstration of four operational capabilities enabled by the integration of emerging technologies from the AGATE and GAP Programs. These four capabilities are:

- Higher-volume operations at airports without control towers or terminal radar facilities
- Lower adverse weather landing minimums at minimally equipped landing facilities
- Integration of SATS aircraft into a higher en route capacity air traffic management system with complex flows and slower aircraft; and
- Improved single-pilot ability to function competently in complex airspace

Representative cockpit display for Small Aircraft Transportation System applications.

Initial Langley planning for the SATS effort was led by Holmes and Durham within the General Aviation Program Office. Key NASA researchers included James R. Burley, David E. Hahne, Stuart Cooke, and Allen C. Royal. Later, a team of implementers was assigned to focus the SATS efforts, conduct the research, and ensure the success of the project objectives. Jerry N. Hefner was assigned as Project Manager for SATS, assisted by Langley researchers Guy Kemmerly, Sally C. Johnson, Mitchel E. Thomas, and Stuart A. Cooke, Jr., to conduct the SATS project in a public-private partnership with the FAA and the National Consortium for Aviation Mobility.

In view of the highly successful consortium-based approach used in AGATE, NASA facilitated the formation of a public-private alliance to encompass state-based partnerships for the execution of the SATS Program. These partnerships participate in continued technology development, system analysis and assessment, technology integration, and flight demonstrations of SATS operating capabilities.

In May 2002, NASA announced it had selected a partner for a joint venture to develop and demonstrate air mobility technologies for transportation using small aircraft and small airports. Known as the National Consortium for Aviation Mobility (NCAM), of Hampton, Virginia, NCAM leads a public-private consortium of more than 130 members. NCAM SATSLab members are: Maryland and Mid-Atlantic SATSLab (University of Maryland Research Foundation), North

Carolina and Upper Great Plains SATSLab (Research Triangle Institute), Southeast SATSLab (Embry Riddle Aeronautical University), Virginia SATSLab (Virginia Department of Aviation), Michigan SATSLab (Munro and Associates), and Indiana SATSLab.

The Langley Small Aircraft Transportation System Project Office, the FAA, and the NCAM SATSLabs became the driving forces behind SATS. The U.S. Congress approved $69 million for the 5-year proof-of-concept period.

Under Hefner's leadership, Langley, NCAM, and the FAA immediately worked toward a middle 2005 proof-of-concept demonstration of new operational capabilities geared toward technologically advanced small aircraft and small airports. The 2005 demonstration location was chosen to be Danville Regional Airport, Danville, Virginia. During the 3-day event, organizers planned to offer participants a look at the potential impacts that additional small aircraft traffic could have on the Nation's skies and the business prospects that could be available for air taxis and other services interested in capitalizing on a new air transportation system that would complement existing major airports.

Several technical concepts played a key role in the 2005 demonstration. The now well-known Global Positioning System (GPS) is an absolute necessity for SATS, providing critical data on aircraft position and track. Langley researchers worked to make GPS-based systems cheaper, smaller, and easier to install, particularly for retrofits to older aircraft. A system known as Automatic Dependent Surveillance-Broadcast was developed to emit a transmission every few seconds listing information such as location, speed, and destination of the aircraft. These data can be tracked by nearby pilots, air traffic controllers or others, providing airborne traffic awareness to others. A multifunction Cockpit Display of Traffic Information (CDTI) system compiles information transmitted by other aircraft emitters and give the pilot a visual representation of airborne activity and potential collision events. SATS also explored the use of enhanced vision concepts for improved visibility at airports without landing light systems. The highway in the sky display concept (discussed in another section of this document regarding synthetic vision) would use GPS and other sensors, such as Forward Looking InfraRed (FLIR), to create an animated flight path, displayed on a computer screen or even projected onto the inside of the windshield, for maneuver guidance and flight path information. Finally, NASA explored the use of single-pilot performance-enhancing systems that increase safety while reducing the need for two-person aircrews. In such systems, onboard computers monitor aircraft systems, warn of a malfunction, and even diagnose the problem and possibly offer a fix. Another computer-based aid is a concept for a virtual copilot that could handle tasks such as calling out altitudes or watching the flight path during the eventful final approach phase of a flight. If implemented on a laptop computer or even a personal data assistant, some of these concepts could conceivably be plugged into an older aircraft for low-cost retrofit. These technologies were developed and matured by researchers at Langley, industry, and at SATSLabs across the country.

The SATS 2005: A Transformation of Air Travel event was an impressive success at Danville on June 5-7, 2005. The three-day event attracted more than 3,000 aviation enthusiasts and was considered a great success in showcasing new aviation technologies. FAA Administrator Marion Blakey and NASA Administrator Michael Griffin presented keynote addresses stressing the value of the SATS vision. SATS personnel explained technologies and operating capabilities to a standing-room-only crowd with the help of live video feeds and pre-taped segment shows on a giant screen. During the live technical demonstration, six airplanes equipped with advanced cockpit displays were able to land safely and efficiently in a small airport that normally has no radar or air traffic control support.

Now that the 5-year proof-of-concept SATS project is complete, it is hoped that the SATS concept will continue with the development of federal regulations, airspace procedures, and industry products to accommodate SATS traffic.

Personal Air Vehicle Research

In addition to the relatively near-term objectives of the SATS Program and its focus on productive, on-demand use of existing small airports, NASA has taken a fresh look at innovative and revolutionary vehicle concepts that address the futuristic vision of PAVs. In accordance with NASA's mission to conduct long-term, high-payoff revolutionary research, Langley researchers assessed the potential of current-day and emerging technologies to enable the design of technically and economically feasible consumer-piloted vehicles. Langley researchers were extremely informed in and sensitive to the shortcomings of the many failed previous attempts to exploit the owner-operated light aircraft market and planned a relevant, phased program to develop technologies required for the concept. The scope of current Langley studies began with advanced vehicles that incorporated technologies developed within the AGATE and SATS Programs and extended the vision into the future with leapfrog vehicle capabilities, including limited roadability, super short field capabilities, and semiautonomous control and navigation.

Long a dream of frustrated motorists caught up in traffic jams and gridlock, the "flying car" is an extremely controversial topic that has been the target of innovators since the early 1920s. Over 70 individual designs for flying cars have been proposed during past years, with only two achieving FAA certification and none meeting DoT automotive regulations. In addition to the basic challenges of adequate consumer demand (necessary to lower production costs), the cost of pilot training and capability, massive liability issues, the issues of air traffic control, and an extensive number of skeptics, the PAV faces significant technical challenges. Integrating classical automobile and airplane configurations has so far resulted in unacceptable deficiencies and operational capabilities from both perspectives. The resulting vehicle is typically very heavy, slow, oversized, and much more expensive than automobiles and aircraft. However, in their efforts to alleviate the current and projected limitations of the Nation's transportation systems, researchers at NASA and industry explored new concepts that might be more appropriate for the envisioned missions.

At Langley, support for PAV studies initially came from seed money provided by NASA Headquarters and locally by the previously discussed creativity initiative stimulated by Dennis Bushnell. In 2003, NASA revamped its aeronautics program and created the NASA Vehicle Systems Program. Langley's Aerospace Vehicle Systems Technology Office (AVSTO) was an essential part of the Vehicle Systems Program. After extensive workshops with the aerospace community and NASA stakeholders were conducted to establish opportunities, goals, and approaches, NASA adopted an approach focused on vehicle sectors, including six different vehicle thrusts for the future. One such thrust was a Personal Air Vehicle Sector, led by Langley's Mark D. Moore. Moore's team included Andrew S. Hahn (PAV systems analyst), Russell H. Thomas (low-noise concepts), and Kenneth H. Goodrich (guidance and control concepts).

The overriding perspective of PAV research was that the market for small, single-engine general aviation airplanes has reached a plateau for many years and that "disruptive," revolutionary technologies are required to move into an era of aggressive new growth. The introduction of disruptive technologies and regulations into the existing market will change the customers, their requirements, and thus the components and vehicles. NASA projected the potential for a substantial market for a futuristic PAV that addresses customer preferences with regard to value of time, comfort, flexibility, and travel freedom.

Examples of the benefits of disruptive technology for PAV applications are indicated by comparisons with today's single-engine piston (SEP) airplane. Langley projected 15-year goals that were ambitious: the ease of piloting a small aircraft would change from the relative difficulty of today's SEP in IFR conditions to more relaxed semiautonomous operations; community and interior cabin noise would dramatically decrease to that of the typical automobile; acquisition cost (in 2004 dollars) would reduce from $300,000 to $100,000; fuel efficiency would increase from 13 mpg to 24 mpg; accidents would be reduced from today's 6.5 per 100,000 hr to 0.5 per 100,000 hr; and field length requirements would drop from 2,500 ft to about 250 to 500 ft.

As part of its PAV sector studies, Langley assessed the benefits of advanced technology for near-term missions involving rural and regional travel. Typical missions for this class of vehicle include a design range of 500 miles with a cruising speed of about 200 mph, a gross weight of about 3,400 lbs, and with IFR flight capability. With these missions in mind, goals of the research studies were to identify concepts to reduce training time and cost, community noise, and purchase price.

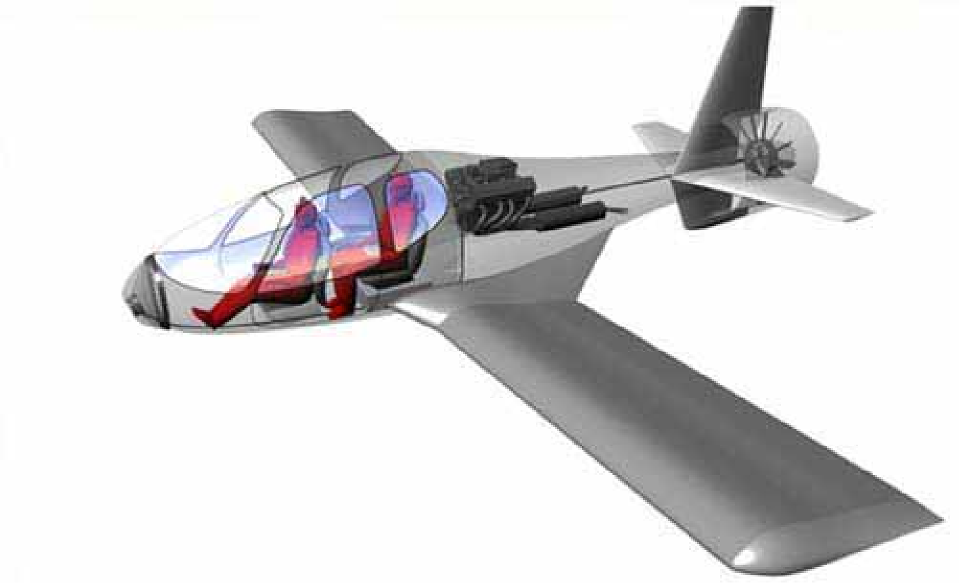
One of the most ambitious, and potentially high-impact, program goals was to identify approaches that reduce training time and cost by 90 percent from today's typical 45-day $10,000 experience to only 5 days at a cost of about $1,000. The technical breakthroughs to obtain this goal are rooted in the development, integration, and robustness of flight control systems and architectures that are both failsafe and reliable. Technical approaches pursued within the NASA program included development of a "naturalistic" flight control deck with control, guidance, sensing, avoidance, and an airborne internet.

Within Mark Moore's team, Ken Goodrich addressed the challenges of providing feasible approaches for automation to make flying small planes easier. The ultimate research goal was to develop vehicle concepts that are inherently "smart" and reduce demands for expertise and capability of the human pilot. Goodrich's efforts were part of a larger Langley project, known as the Autonomous Robust Avionics (Aura) project. Led by James R. Burley of the AVSTO, Aura invested in the areas of UAVs, PAV, and rotorcraft to enable smart vehicles that reduce the demands on human pilots.

Goodrich pursued a novel, futuristic approach to autonomous operations known as "H-mode" control. While H-mode is short for the technical term haptic, it can also be thought of as "horse mode." The concept involved is based on the fact that a horse, unlike a car, is more likely to be cognizant of obstacles, try to avoid collisions or other threats, and may even know how to find its way home without inputs from its rider. Likewise, within H-mode, the human pilot and the automation system physically "feel" one another's near-term intent, with intuitive monitoring and redirection. The concept's development and validation obviously entail detailed studies of sensors, system architecture and design, conflict detection and resolution, maneuver implementation, and failure modes. However, the benefits promised by such an approach would be remarkable, yielding a radical reduction in special piloting skills and training, loss of situational awareness, and pilot error.

Another ambitious PAV goal was to identify approaches that reduce community noise generated by small aircraft from today's levels of about 84 dBA at takeoff and landing conditions to only 60 dBA. Technical challenges to obtaining this goal include reducing the community (and cabin) noise generated by propulsion systems (propellers, exhausts, etc.) while meeting requirements for vehicle performance, reliability, and cost. Langley studies included the development of integrated and shielded ducted propeller systems with active wake control and acoustic suppression. Research in this area was led by Russell H. Thomas.

Progress toward a definition of the near-term PAV progressed to the point where a notional vehicle, known as the TailFan concept, served as a focus for assessing the benefits of advanced technology. The TailFan used an advanced ducted fan for low noise and safety, as well as an automotive engine and a dramatically simplified skin-stiffened structure to reduce manufacturing costs. The TailFan resembled current general aviation configurations in shape; however, it was specifically designed to address the minimum qualifications of ease, safety, noise, and comfort for PAV applications. In addition, it would be economically viable and environmentally friendly, enabling it to compete with alternative mobility choices of autos or airlines.



Notional "TailFan" personal aircraft.

The TailFan concept centered about an automotive V-8 engine (nominally the Corvette LS-1 engine) directly driving a reduced tip-speed ducted fan. The shorter fan blades generate higher frequency noise with the duct shielding absorbing the propulsor noise through embedded acoustical liners. Using an automobile engine with extensive muffling involves additional weight compared with aircraft engines, as does using a ducted fan compared with using a propeller. However, combining the two methods permits a total propulsion system cost reduction of over 60 percent while maintaining a reasonable time between overhaul and an extremely quiet integration.

The structure was radically simplified and designed for automated manufacturing, yielding a twelvefold reduction in labor. Use of a highly formed, skin stiffened structure reduces total part count (labor and inventory costs), while an unusually high degree of symmetry reduces unique part count (tooling costs). The all-aluminum structure uses automotive manufacturing methods with an untapered, skin-stiffened wing. The same parts are used for both sides of the wing simply by flipping the three spars and using the same four ribs and three skin panels. Rivets or laser welds are used in recessed troughs to attach the wing components under a strong polyester film wing covering for smoothness and weather protection. Identical vertical and horizontal tails use the same pressing molds for the same skin-stiffened construction. An axisymmetric tailcone is made with complex curvature, integral frames, and integral stringers pressed into each quarter panel. As the external skin is assembled, the internal structure is also assembled. The fan duct is made similarly of four identical sections. The combination of reduced tooling, assembly labor, and propulsion system costs are responsible for the much lower overall cost.

This $100,000 concept solution was based on a 2,000 unit per year production rate to permit affordability in the transition market between the current low production general aviation market and the high volume production of a future PAV market. Once a substantial market existed, and large production volumes are present, many performance compromises could be eliminated through investment in a higher tooling-based design and an optimum engine designed specifically for aircraft use.

Efforts included the demonstration of an LS-1 engine on the 150-hour FAA endurance test. Success has shown that it is possible for an automotive engine to perform the aircraft duty cycle. Also, NASA worked with the FAA to adapt rules for certifying quality assurance (QA) based products, instead of the current FAA certification standard of quality control (QC). The intent of QA-based certification was not to bypass the FAA's important role to ensure safety, but to permit certified processes (instead of parts) that enable safer small aircraft products. As long as small aircraft have to use specialty, small production volume, QC-based parts, there is little chance of small aircraft being affordable to the majority of mobility consumers.

Future Gridlock Commuter

While roadable aircraft have been attempted for over 50 years, a more practical dual-mode approach might be to require only side-street travel for limited distances in the equivalent of a safe taxi mode. This capability does not require full compliance with DoT regulations and safety standards. Instead, these dual-mode vehicles may meet a minimum set of standards that permit the vehicle to achieve a compact taxi mode with very few penalties. By meeting section 500 vehicle standards, these aircraft could travel at 25 mph on side streets, as long as the footprint can be limited to a 8.5-ft width and meet some additional relatively simple ground travel requirements. This mode of travel would require the addition of a wheel-drive concept, and although limited roadability does not overly penalize the air vehicle, it does involve some additional weight and complexity.

In Mark Moore's program, a notional Langley PAV concept known as the Spiral-Duct was conceived to combine highly integrated propulsion and aerodynamic lift in a lifting duct arrangement. The inner duct provided lift and thrust, while the outer panels provided control, even at very low takeoff and landing speeds. This vehicle would be capable of takeoff and landing in less than 250 ft. With folded wings, it could travel on the ground at speeds of 25 mph. Able to carry up to two passengers, this very compact and quiet vehicle would use an electric propulsion system as efficient as current compact cars.

Notional Spiral Duct Personal Air Vehicle.

The highly integrated propulsion-aerodynamic coupling would enable a 250-ft extreme short takeoff capability with no external high-lift system moving parts, such as wing flaps on conventional aircraft, and roll control would be achieved using moving outer wing panels. For the ducted propeller arrangement, yaw and pitch control would be enhanced through embedding the control surfaces into the propeller flow, and computerized active controls would be used to achieve outstanding stability and ease of control.

In 2004 and 2005 NASA redirected funding within its Vehicle Systems Program and the PAV activities at Langley were therefore terminated in 2005.

National Planning for Next-Generation Air Transportation System

Inspired to address the shortcomings of the present air system, and the challenges and opportunities of the future, the 108th Congress mandated the development of a national plan for the Next-Generation Air Transportation System. Legislation directed that this planning effort include experts in commercial aviation, general aviation, aviation labor groups, aviation research and development entities, aircraft and air traffic control suppliers, and the space industry. The parent organization for the study was known as the Joint Planning and Development Office (JPDO). Within the JPDO effort, a Futures Working Group (FWG) of over 150 stakeholders, U.S. Government employees, and contractors was formed under the Chairmanship of Langley's Bruce J. Holmes.

In May 2004, the FWG presented a set of 11 strategies derived from interviews and scenario-based planning. Due to the wide range of changes in the world situation, economy, and operating environment for air transportation envisioned between today and the study target year of 2025, the combination of strategies was aimed at transforming air transportation while addressing the Nation's needs in plausible futures that include a tripling (or shrinking) of the demand for air travel, fossil fuels becoming less available and more costly, a public that is increasingly concerned with the environment, an accelerating pace of production and distribution of goods, radically growing importance of international travel and commerce as the world becomes more interdependent, space travel becoming a reality, and conventional aircraft sharing the skies with uninhabited air vehicles that support safety, security, and national defense. Among the 11 strategies submitted to the JPDO, recommendations were made for a national transportation system that streamlines doorstep-to-destination travel to provide users with a wide range of options for managing efficiencies, costs, and uncertainties. In addition, priority was given to design, build, and deploy a network-centric, distributed air traffic management system to increase safety, scalability, capacity, efficiency, and opportunities for free-flight operations.

Status and Outlook

The highly successful demonstration of SATS technology in June 2005 was a critical milestone in NASA's vision of the future for small aircraft in air transportation. If, as hoped, the potential of advanced technology to open up the Nation's underused public airports is appreciated by the appropriate industrial, regulatory, and technical communities, there is no doubt that entrepreneurial interests will lead to a new generation of air-taxi capabilities.

The termination of NASA research on advanced PAV concepts in 2005 virtually eliminated Langley interest in this class of vehicle. Skeptics of the vision remain steadfast, and further maturation of the technical innovations that would enable such a revolutionary change in public transportation will require extensive, dedicated research efforts capped by convincing demonstrations of the technology's benefits.

The Future of Innovation: Primping the Pump

The remarkable changes in culture and resources that have occurred at Langley as it approaches its ninetieth year in 2007 have shaped, encouraged, and influenced the Center's ability to identify and assess revolutionary concepts. In its earlier history as an NACA laboratory, the staff enjoyed a technical atmosphere characterized by immaturity in aeronautical science and technology, limited expertise and availability of facilities in industry, and took a major role in the shaping of aeronautics, the aviation industry, and national defense. Freedom to conduct research on new concepts was widespread, a rich environment of technical challenges stimulated the researcher, and the technical state of the art in aeronautics accelerated at a breath-taking rate. The legendary contributions of NACA and Langley stand as evidence of the innovation and dedication that pervaded the Center in that era.

With the coming of the Space Age and the evolution of NASA Centers, the role of Langley greatly expanded, and its focus broadened to include support activities for NASA's space program and new areas of concern to the Nation, such as atmospheric science. Budgetary issues rose to new levels as the Apollo Program and ensuing space exploration activities began to have an impact on the ability of researchers to conduct studies on revolutionary concepts that strayed markedly from the evolutionary. Aeronautics programs within NASA also became more focused on near-term goals, in part to pacify NASA's stakeholders and Congress, who wanted near-term payoff and highly focused activities. In more recent years, the aviation industry has put its own unique wind tunnels, laboratories, and computational centers into operation, with capabilities as good as, or exceeding, NASA's aging facilities. Foreign technology, facilities, and advanced aircraft are now keeping pace with, or surpassing, the aeronautical leadership of the United States. Finally, aeronautics itself has become a self-professed/self-fulfilling prophecy. That is, the world of aeronautics has become–– according to Dennis Bushnell—"An asymptotic, barely evolutionary, mature science with only capacity, safety, and environmental issues." The reality of this perspective has led many to refer to aeronautics as a "sunset" technical area without excitement or fresh ideas.

Management at the NASA aeronautical centers (Langley, Ames, Glenn, and Dryden) recognized the constraints being placed on innovation and proceeded to implement new funding sources, known as the Center Director's Discretionary Fund (CDDF), as incubator mechanisms for fresh ideas. By providing resource and management support for selected efforts, the Centers protected and encouraged the potential for revolutionary studies. Specific advanced studies were judged and funded on a competitive basis with the participation of top management.

In 2001, Langley management reacted to a scenario wherein the Center's programs had become increasingly tightly controlled and out-of-the-box thinking and opportunities were becoming alarming constrained. Center Director Jeremiah F. Creedon and Associate Director for Research and Technology Competencies Douglas L. Dwoyer inaugurated a new program, known as the Creativity and Innovation (C&I) Initiative, to augment the existing CDDF resources and provide a competed opportunity for researchers to acquire a maximum amount of $300,000 per year for advanced ideas. The funding provides for research equipment, salaries, and travel, and an opportunity to impact the future of aeronautics and space technology. The program evolved from the mutual interests and advocacy of several senior managers, including Dennis M. Bushnell and Joseph Heyman. Heyman was the first manager of the C&I activity, later followed by Bushnell.

The C&I Initiative covers all technical elements of Langley's mission: aeronautics, atmospheric science, access to space, planetary and space exploration, and systems studies. The program stimulates and nurtures advanced ideas with minimal management and oversight. Proposals from Langley staffers are evaluated by a group of technical peers on the basis of technical content, inventive/creative content, and researcher capability.

Results of the C&I activity have been remarkably positive. Within the area of aeronautics, some topics receiving support have been: neural network flight controller, runway topography characterization, unconventional aircraft configurations, breakthrough noise suppression concepts, distributed propulsion, and circulation control/channel wing concepts.

Current Langley Director Roy D. Bridges, Jr., has embraced the spirit of the C&I Initiative, and the program has continued to thrive as a visible sign of the value placed on innovative ideas by management. The research community has taken notice and responded in excitement and interest, sparking continued growth of the legacy of Langley's contributions in advanced research.

In September 2004 Bridges announced a new Langley organizational structure which included a new element known as the Incubator Institute. Led by Richard R. Antcliff, the institute's mission is to stimulate new business and leading-edge research efforts for the Center. Antcliff's staff includes Dennis Bushnell (Chief Scientist), Mark J. Shuart (Associate Director for Transformation Projects). The name of the organization was subsequently changed to Innovation Institute to reflect its mission as a catalyst for fresh concepts and ideas. Antcliff and his staff face a daunting challenge in promoting and nurturing innovation during a chaotic atmosphere of change within the Agency's aeronautics program. Sweeping cultural and operational transitions are now occurring at Langley resulting in closure of many wind tunnels, severe reductions in funding for aeronautical research, and reductions in workforce. In addition, the fundamental method of securing resources for research is changing to a business mode of operation featuring competitive proposals and peer-reviewed awards for studies.

As Langley strives to align itself with the major thrusts and missions of the Agency, the benefactors of its leading-edge expertise and unique capabilities look forward to a continuation of this critical national asset and to the future U.S. leadership in aviation and aerospace technology.

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* *Shuttle-Mir: the United States and Russia Share History's Highest Stage* (SP-2001-4603, 2002). This CD-ROM is available from NASA CORE for $5 per copy plus shipping and handling (within the U.S., $6 for up to $25 order). To order the CD-ROM, please mail a check, money order or school purchase order to: NASA CORE, Lorain County JVS, 15181 Route 58 South, Oberlin, OH 44074, 440-775-1400, toll free 1-866-776-CORE, FAX 440-775-1460, nasaco@leeca.org, or http://core.nasa.gov on the Web. CORE also accepts orders by credit card (VISA or MasterCard).
* *U.S. Centennial of Flight Commission presents Born of Dreams ~ Inspired by Freedom* (SP-2004-4604, 2004). This DVD data disk is available by sending a self-addressed envelope for each DVD with appropriate postage (typically $1.90 within the U.S., $2.30 for Canada, and $5.60 for overseas - international customers are asked to purchase U.S. postage through an outlet such as www.stampsonline.com) to the NASA Headquarters Information Center, Mail Code CI-4, 300 E Street SW, Room 1H23, Washington, D.C. 20546-0001.
* *Of Ashes and Atoms: A Documentary on the NASA Plum Brook Reactor Facility* (NASA SP-2005-4605). Of Ashes and Atoms was produced and directed by James Polaczynski and written by him with Robert Arrighi. Narrated by Kate Mulgrew (Captain Janeway of the Star Trek Voyager series), this documentary illustrates the history behind Plum Brook Reactor Facility, operating from 1962-1973 as one of the first nuclear test reactors built in the United States and the only one built by NASA. While the reactor never reached its full potential, the personnel who have worked there made great achievements in terms of scientific discovery, as well as building, operating, and safely deconstructing a nuclear reactor. Plum Brook's rich history has significant lessons in terms of management, environmental stewardship, painstaking engineering, and scientific investigation. This DVD is available by sending a self-addressed envelope for each CD with appropriate postage (typically $1.90 within the U.S., $2.30 for Canada, and $5.60 for overseas - international customers are asked to purchase U.S. postage through an outlet such as www.stampsonline.com) to the NASA Headquarters Information Center, 300 E Street SW, Room 1H23, Washington, D.C. 20546-0001, 202-358-0000.
* Taming Liquid Hydrogen : The Centaur Upper Stage Rocket Interactive CD-ROM. (SP-2004-4606, 2004).

This CD-ROM is available by sending a self-addressed envelope for each CD-ROM set with appropriate postage (typically $1.90 within the U.S., $2.30 for Canada, and $5.60 for overseas - international customers are asked to purchase U.S. postage through an outlet such as www.stampsonline.com) to the NASA Headquarters Information Center, Mail Code CI-4, 300 E Street SW, Room 1H23, Washington, D.C. 20546-0001.

* *Fueling Space Exploration: The History of NASA's Rocket Engine Test Facility DVD* (NASA SP-2005-4607). This DVD contains a 25-minute and a condensed 7-minute documentary video on the RETF, which used to be a part of the NASA Glenn Research Center. RETF employees performed pioneering research from 1957 to 1995 on liquid hydrogen propulsion on the Centaur and Saturn rockets, as well as the Space Shuttle. Declared a National Historic Landmark in 1984, the RETF officially closed in 1995 and was torn down in 2003 to make way for the Cleveland airport's expansion. This DVD is available by sending a self-addressed envelope for each CD with appropriate postage (typically $1.90 within the U.S., $2.30 for Canada, and $5.60 for overseas - international customers are asked to purchase U.S. postage through an outlet such as www.stampsonline.com) to the NASA Headquarters Information Center, 300 E Street SW, Room 1H23, Washington, D.C. 20546-0001, 202-358-0000.

Historical Reports (NASA HHR)

* NASA Office of Defense Affairs: The First Five Years (HHR-32, 1970) by W. Fred Boone. Admiral Boone led the Office of Defense Affairs from December 1, 1962 through January 1, 1968, a formative early period in space history when cooperation between NASA, a civilian agency, and the military was especially important. This significant narrative charts these early efforts in coordination. Special thanks to volunteer Chris Gamble for scanning and formatting this book for the Web. . Online version available.
* *Research in NASA History: A Guide to the NASA History Program.* NASA HHR-64, revised June 1997. This monograph-sized publication is available by sending a stamped (for 8 ounces), self-addressed 9x12 inch envelope to the NASA History Division, Code IQ, Washington, DC 20546. . Online version available.

NASA Special Reports (NASA SP-4900)

* *Unmanned Space Project Management: Surveyor and Lunar Orbiter.* Washington,D.C.:NASA SP-4901, 1972. By Erasmus H. Kloman. NASA commissioned the National Academy of Public Administration to undertake this study to look at its innovative management techniques on these complex technological projects. **Out of print**. Online version available.

Other NASA Special Publications
(not in the formal NASA History Series)

* *Results of the Second Manned Suborbital Space Flight, July 21, 1961.* NASA, 1961. **Out of print**. Online version available.
* *The Impact of Science on Society.* NASA SP-482 by James Burke, Jules Bergman, and Isaac Asimov, 1985. Online version available.
* *Space Station Requirements and Transportation Options for Lunar Outpost.* NASA, 1990. Online version available.
* *Space Station Freedom Accommodation of the Human Exploration Initiative.* NASA, 1990. Online version available.

* *Why Man Explores.* NASA EP-125, 1976.
* *Results of the Second Manned Suborbital Space Flight, July 21, 1961.* NASA, 1961. **Out of print**. Online version available.
* *Apollo 13 "Houston, we've got a problem."* NASA EP-76, 1970. **Out of print**. Online version available.
* *Results of the Second U.S. Manned Orbital Space Flight.* NASA SP-6, 1962. **Out of print**. Online version available.
* *Results of the Third U.S. Manned Orbital Space Flight.* NASA SP-12, 1962. **Out of print**. Online version available.
* *MercuryProject Summary including Results of the Fourth Manned Orbital Flight.* NASA SP-45, 1963. **Out of print**. Online version available.
* *X-15 Research Results With a Selected Bibliography.* NASA SP-60, 1965. **Out of print**. Online version available.
* Exploring Space with a Camera. NASA SP-168, 1968. Online version available.
* Aerospace Food Technology. NASA SP-202, 1969. Online version available.
* What Made Apollo a Success? NASA SP-287, 1971. Online version available.
* Evolution of the Solar System NASA SP-345, 1976. Online version available.
* *Pioneer Odyssey* (NASA SP-349/396, revised edition, 1977) by Richard Fimmel, William Swindell, and Eric Burgess. Online version available.
* *Apollo Expeditions to the Moon.* NASA SP-350, 1975. **Out of print**. Online version available.
* *Apollo Over the Moon: A View From Orbit* (NASA SP-362, 1978) edited by Harold Masursky, G.W. Colton, and Farouk El-Baz. Online version available.
* *Introduction to the Aerodynamics of Flight* (NASA SP-367, 1975) by Theodore A. Talay. Online version available.
* Biomedical Results of Apollo (NASA SP-368, 1975) , edited by Richard S. Johnston, Lawrence F. Dietlein, M.D., and Charles A. Berry, M.D. Online version available.
* *Skylab: Our First Space Station* (NASA SP-400, 1977), edited by Leland F. Belew. Online version available.
* *Skylab, Classroom in Space* (NASA SP-401, 1977), edited by Lee Summerlin. Online version available.
* *A New Sun: Solar Results from Skylab* (SP-402, 1979) by John A. Eddy and edited by Rein Ise. Online version available.
* *Skylab's Astronomy and Space Sciences* (NASA SP-404, 1979), edited by Charles A. Lundquist. Online version available.
* *The Space Shuttle* (SP-407, 1976) . Online version available.
* *The Search For Extraterrestrial Intelligence* (NASA SP-419, 1977) , edited by Philip Morrison, John Billingham, and John Wolfe. Online version available.
* Atlas of Mercury (SP-423, 1978) by Merton E. Davies, Stephen E. Dwornik, et. al. Online version available.
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* *The Martian Landscape* (NASA SP-425, 1978)
* *The Space Shuttle at Work* (NASA SP-432/EP-156 1979) by Howard Allaway. Online version available.
* *Project Orion: A Design Study of a System for Detecting Extrasolar Planets* (NASA SP-436, 1980), edited by

David C. Black. Online version available.
- *Wind Tunnels of NASA.* NASA SP-440, 1981. **Out of print**. Online version available.
- Viking Orbiter Views of Mars (NASA SP-441, 1980) . Online version available.
- *The High Speed Frontier: Case Histories of Four NACA Programs, 1920-1950.* (NASA SP-445, 1980.) . Online version available.
- The Star Splitters: The High Energy Astronomy Observatories (SP-466, 1984) by Wallace H. Tucker. Online version available.
- Planetary Geology in the 1980s (SP-467, 1985) by Joseph Veverka.
- *Quest for Performance: The Evolution of Modern Aircraft.* (NASA SP-468,1985.) **Out of print**. Online version available.
- *The Long Duration Exposure Facility (LDEF): Mission 1 Experiments* (SP-473, 1984) ed. by Lenwood G. Clark, William H. Kinar, et. al. . Online version available.
- *Voyager 1 and 2, Atlas of Saturnian Satellites* (NASA SP-474, (NASA SP-474, 1984) edited by Raymond Batson. Online version available.
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- *Living Aloft: Human Requirements for Extended Spaceflight.* (NASA SP-483, 1985.) **Out of print**. Online version available.
- Space Shuttle Avionics System (SP-504, 1989) by John F. Hanaway and Robert W. Moorehead. Online version available.
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- Flight Research at Ames, 1940-1997 (SP-3300, 1998). Online version available.
- The Planetary Quarantine Program (SP-4902, 1974). Online version available.
- *Spaceborne Digital Computer Systems* (NASA SP-8070, 1971). Online version available.
- *Magellan: The Unveiling of Venus* (JPL-400-345, 1989) . Online version available.
- *Guide to Magellan Image Interpretation* (JPL-93-24) by John Ford, Jeffrey Plaut, et. al. Online version available.
- *The Apollo Program Summary Report* (Document # JSC-09423, April 1975) . Online version available.
- *Saturn Illustrated Chronology* (MHR-5, Marshall Space Flight Center, fifth edition, 1971) prepared by David S. Akens. Online version available.
- *Celebrating a Century of Flight* (NASA SP-2002-09-511-HQ). Edited by Tony Springer. Online version available.
- *Present and Future State of the Art in Guidance Computer Memories* (NASA TN D-4224, 1967) by Robert C. Ricci. Online version available.

NASA Educational Publications

Skylab: A Guidebook (NASA EP-107, 1973), by Leland F. Belew and Ernst Stuhlinger. Special thanks to Chris Gamble for formatting this book for the Web.

Spacelab: An International Short-Stay Orbiting Laboratory (NASA EP-165) by Walter Froehlich. The full text and rich images from this informative book about Europe's first major undertaking in human spaceflight are now available on-line thanks to volunteer Chris Gamble's expert help.

A Meeting with the Universe: Science Discoveries from the Space Program (NASA EP-177,1981). Written by a group of NASA scientists for a popular audience, this attractive photo book is not a formal NASA history, but a "history of space exploration--by NASA, by universities, by other government agencies, and by industries--all of whom have played major roles." Warm thanks to Hans-Peter Engel, who scanned and formatted this special book for the Web.

NASA Publications (NPs)

Science in Orbit: The Shuttle & Spacelab Experience: 1981-1986 (NASA NP-119, Marshall Space Flight Center, 1988). Provided by the European Space Agency, the Spacelab entails both an enclosed laboratory and an exposed platform for scientific experiments in space. Thanks to volunteer Chris Gamble for scanning and formatting this informative guide to this unique facility.

NASA Conference Proceedings

Life in the Universe : Proceedings of a conference held at NASA Ames Research Center Moffet Field, California, June 19-20, 1979 (NASA CP-2156, 1981), edited by John Billingham. Special thanks to Chris Gamble for formatting this volume for the Web.

Proceedings of the X-15 First Flight 30th Anniversary Celebration of June 8, 1989 These proceedings include comments by historians, pilots, and others with keen insights on the truly historic X-15 program that bridged aeronautics with astronautics during NASA's first decade.

NASA Technical Memoranda

- *Destination Moon: A History of the Lunar Orbiter Program* . Washington, D.C.: NASA TM-3487,1977. Written by Bruce Byers, this technical memorandum is a book-length scholarly work detailing the history of the robotic Lunar Orbiter Program, which provided very useful mission planning data for the Apollo program. Without the Lunar Orbiters' mapping of the lunar surface, it would have been extremely difficult, if not impossible, for Apollo planners to decide where to land the Apollo spacecraft on the Moon. A special thanks to Chris Gamble for formatting this document's complete text and illustrative diagrams for the Web. **Out of print**.

Contractor Reports

- *Computers in Spaceflight: The NASA Experience.* James E. Tomayko wrote this contractor report in 1988. A relatively unique document, this report covers computers in the Gemini, Apollo, Skylab, and Shuttle programs, as well as for robotic spacecraft and ground systems. Chris Gamble deserves kudos for his excellent work formatting the text of this prime reference document for the Web. This document should be available in hard copy, with photographs, in late February 1998 from NASA's Center for Aerospace Information (CASI). Contact CASI at 800 Elkridge Landing Road, Linthicum Heights, MD 21090, 301-621-0100 or email at help@sti.nasa.gov

Other Government Publications Related to Aerospace History

History of Research in Space Biology and Biodynamics at the Air Force Missile Development Center, Holloman Air Force

Base, New Mexico, 1946-1958. This early Air Force report contains information that NASA built upon in developing Project Mercury. It may be of special interest to some historians and buffs because of John Glenn's flight on STS-95 and because of the fortieth anniversary of the Mercury Seven selection in 1999. A very special thanks to Chris Gamble for formatting the complete text of this report for the Web.

Report of the Apollo 13 Review Board (a.k.a. the Cortright Commission): This is the report issued after the Apollo 13 accident which prevented the mission from landing on the moon and nearly cost the lives of the astronauts involved. Special thanks to Colin Fries and Sivram Prasad of the History Division for scanning and formatting this report for the Web.

Report of the Presidential Commission on the Space Shuttle Challenger Accident (commonly called the Rogers Commission Report), June 1986 and Implementations of the Recommendations, June 1987.
Online version available.

Transiting from Air to Space: The North American X-15 This case study by Robert S. Houston, Richard P. Hallion, and Ronald G. Boston is a long chapter in *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology* (AirForce History and Museums Program: 1998). A key contribution to the literature on the X-15, one of NASA's most successful research aircraft programs, this case study was previously published as a stand-alone volume. Special thanks to Hans-Peter Engel, who formatted this work for the Web.

Space Handbook: Astronautics and its Applications. This 1959 publication was a staff report of the Congressional Select Committe on Astronauticsand Space Exploration. An interesting historical document, this Handbook includes much information about astronomy and astronautics that we now know to be incorrect. Nevertheless, this document provides a snapshot of the beginning of the space era. Special thanks to John Henry, who scanned and formatted this document.

The First Century of Flight: NACA/NASA Contributions to Aeronautics. This is an informative and attractive Web exhibit set up in a timeline format. Special thanks to Tony Springer, who supplied the content; Ray Brown, who created the hard copy version; and Douglas Ortiz, who created the Web version.

New Series in NASA History Published by the Johns Hopkins University Press:
These books are available by calling 410-516-6956 or see http://www.press.jhu.edu/books/

* Cooper, Henry S. F., Jr. *Before Lift-off: The Making of a Space Shuttle Crew.* Baltimore: Johns Hopkins University Press, 1987.
* McCurdy, Howard E. *The Space Station Decision: Incremental Politics andTechnological Choice.* Baltimore: Johns Hopkins University Press, 1990.
* Hufbauer, Karl. *Exploring the Sun: Solar Science Since Galileo.* Baltimore: JohnsHopkins University Press, 1991.
* McCurdy, Howard E. *Inside NASA: High Technology and Organizational Change in the U.S. Space Program.* Baltimore: Johns Hopkins UniversityPress,1993.
* Lambright, W. Henry. *Powering Apollo: James E. Webb of NASA.* Baltimore: Johns Hopkins University Press,

1995.
* Bromberg, Joan Lisa. *NASA and the Space Industry.* Baltimore: Johns Hopkins University Press, 1999.
* Beattie, Donald A. *Taking Science to the Moon: Lunar Experiments and the Apollo Program* . Baltimore: Johns Hopkins University Press, 2001.
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* Johnson, Stephen B. *The Secret of Apollo: Systems Management in American and European Space Programs.* Baltimore: Johns Hopkins University Press, 2002.
* Lambright, W. Henry, editor. *Space Policy in the 21st Century* . Baltimore: Johns Hopkins University Press, 2002.
* Bilstein, Roger E. *Testing Aircraft, Exploring Space: An Illustrated History of NACA and NASA.* Baltimore: Johns Hopkins University Press, 2003.
* Butrica, Anderw J. *Single Stage to Orbit: Politics, Space Technology, and the Quest for Reusable Rocketry.* Baltimore: Johns Hopkins University Press, 2005.
* Conway, Erik M. *High-Speed Dreams: NASA and the Technopolitics of Supersonic Transportation, 1945-1999.* Baltimore: Johns Hopkins University Press, 2005.

New Series in NASA History Published by Texas A&M University Press
* Schorn, Ronald A. *Planetary Astronomy: From Ancient Times to the Third Millennium.* College Station: Texas A&M University Press, 1998. To order, see http://www.tamu.edu/upress/BOOKS/1998/schorn.htm

New Series in NASA History Published by The University Press of Kentucky
* Gorn, Michael H. *Expanding the Envelope: Flight Research at NACA and NASA.* Lexington: The University Press of Kentucky, 2001. To order see http://www.kentuckypress.com/index.cfm.
* Reed, R. Dale. *Wingless Flight: The Lifting Body Story* . Lexington: The University Press of Kentucky, 2002. To order see http://www.kentuckypress.com/index.cfm
* Ed. by Launius, Roger D. and Dennis R. Jenkins. *To Reach the High Frontier: A History of U.S. Launch Vehicles* . Lexington: The University Press of Kentucky, 2002. To order see http://www.kentuckypress.com/index.cfm.

New Series in NASA History Published by the University Press of Florida
* Ed. by Swanson, Glen W. *"Before This Decade is Out...": Personal Relections on the Apollo Program.* Gainesville: The University Press of Florida, 2002. To order see http://www.upf.com/index.shtml
* Benson, Charles D. and William B. Faherty. *Moon Launch!: A History of the Saturn-Apollo Launch Operations.* Gainesville: The University Press of Florida, 2001. To order see http://www.upf.com/index.shtml
* Benson, Charles D. and William B. Faherty. *Gateway to the Moon: Building the Kennedy Space Center Launch Complex*. Gainesville: The University Press of Florida, 2001. To order see http://www.upf.com/index.shtml.
* Bilstein, Roger E. *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles.* NASA SP-4206, 1980, 1996, and 2003. Gainesville: The University Press of Florida, 2003. To order see http://www.upf.com/index.shtml.
* Siddiqi, Asif A. *The Soviet Space Race with Apollo*. Gainesville: The University Press of Florida, 2003. To order see http://www.upf.com/index.shtml.
* Siddiqi, Asif A. *Sputnik and the Soviet Space Challenge* . Gainesville: The University Press of Florida, 2003.

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New Series in NASA History Published by Harwood Academic Press

- Ed. by Roger D. Lanius, John M. Logsdon and Robert W. Smith. *Reconsidering Sputnik: Forty Years Since the Soviet Satellite.* London: Harwood Academic Press, 2000. To order, see http://www.taylorandfrancisgroup.com/

New Series in NASA History Published by the University of Illinois Press

- Ed. by Roger D. Launius and Howard McCurdy. *Spaceflight and the Myth of Presidential Leadership.* Urbana, IL: University of Illinois Press, 1997. To order, see http://www.press.uillinois.edu/f97/launius.html

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- Hallion, Richard P. and Michael H. Gorn. *On the Frontier: Experimental Flight at NASA Dryden*. Washington, DC: Smithsonian Institution Press, 2003. To order, see http://www.si.edu/.

New Series in NASA History Published by CG Publishing, Inc.

- *The Mission Transcript Collection: U.S. Human Spaceflight Missions From Mercury Redstone 3 to Apollo 17* (NASA SP-2000-4602). To order send an International Money Order for $8.00 to CG Publishing Inc, Box 62034, Burlington, Ontario, L7R 4K2, Canada or call 905-637-5737.

Miscellaneous Publications of NASA History

- Dawson, Virginia. *Ideas Into Hardware: A History of the Rocket Engine Test Facility at the NASA Glenn Research Center* Cleveland, 2004. Online version available.

ABOUT THE AUTHOR

Joseph R. Chambers is an aviation consultant who lives in Yorktown, Virginia. He retired from the NASA Langley Research Center in 1998 after a 36-year career as a researcher and manager of military and civil aeronautics research activities. He began his career as a specialist in flight dynamics as a member of the staff of the Langley 30- by 60-Foot (Full-Scale) Tunnel, where he conducted research on a variety of aerospace vehicles including V/STOL configurations, re-entry vehicles, and fighter aircraft configurations. He later became a manager of research projects in the Full-Scale Tunnel, the 20-Foot Vertical Spin Tunnel, flight research at Langley, and piloted simulators. When he retired from NASA, he was manager of a group responsible for conducting systems analysis of the potential payoffs of advanced aircraft concepts and NASA research investments.

Mr. Chambers is the author of over 60 technical reports and publications, including NASA Special Publications: SP-514 Patterns in the Sky on the subject of airflow condensation patterns over aircraft; SP-2000-4519 Partners in Freedom on contributions of the Langley Research Center to U.S. military aircraft of the 1990s; and SP-2003-4529 Concept to Reality on contributions of the Langley Research Center to U.S. civil aircraft of the 1990s. He has made presentations on research and development programs to audiences as diverse as the Von Karman Institute in Belgium and the annual Experimental Aircraft Association (EAA) AirVenture Convention at Oshkosh, WI. He has served as a representative of the United States on international committees in aeronautics and has given lectures in Japan, China, Australia, the United Kingdom, Canada, Italy, France, Germany, and Sweden.

Mr. Chambers received several of NASA's highest awards, including the Exceptional Service Medal and the Outstanding Leadership Medal. He also received the Arthur Flemming Award in 1975 as one of the 10 Most Outstanding Civil Servants for his management of NASA stall/spin research for military and civil aircraft. He has a bachelor of science degree from the Georgia Institute of Technology and a master of science degree from the Virginia Polytechnic Institute and State University (Virginia Tech).

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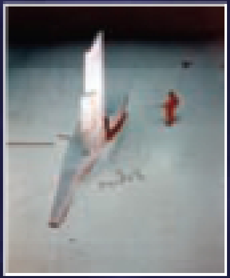

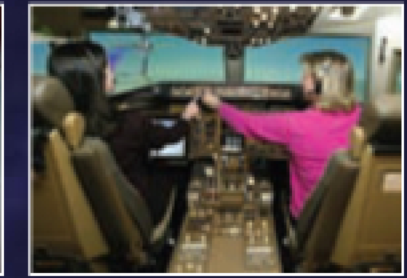

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