http://www.scribd.com/doc/991245/
NASA-70897main-PiF?autodown=pdf

Langley Contributions to the F/A-18

Vortex Lift and Maneuvering Flaps

In the early 1960's, the Northrop Company noticed an improvement in the maximum lift of the F-5 aircraft because of a small flap actuator fairing that extended the wing root leading edge. This phenomenon spurred interest in the effects of inboard vortex flows and led to a cooperative NASA and Northrop study, which was conducted in the Langley 7- by 10-Foot High-Speed Tunnel with a group led by Edward C. Polhamus. The cooperative study of hybrid wings centered on the use of relatively large, highly swept wing extensions at the wing-fuselage intersection, which promoted strong beneficial vortex-flow effects. The scope of the study included parametric studies to maximize the lift- and stability-enhancing effects of the wing extension concept, which became known at Northrop as the leading-edge extension (LEX). Studies were also directed at cambering the leading edge of the LEX to suppress the vortex at low angles of attack, and thereby minimize drag at cruise conditions. Northrop applied a large highly swept LEX to the YF-17 prototype aircraft to enhance lift and stabilize the flow over the YF-17 main wing at high angles of attack.

From these initial cooperative studies with Northrop, Polhamus and his associates put together a world-class vortex-lift research program that became internationally recognized for its experimental database, analytical procedures, and aircraft applications. In addition to Polhamus, key members of this team included Linwood W. McKinney, Edward J. Ray, William P. Henderson, John E. Lamar, and James M. Luckring. Their extraordinary research into the fundamentals and applications of vortex flows placed the Langley Research Center in an excellent position to aid the U.S. industry in the design of highly maneuverable advanced fighters. This experienced pool of experts would subsequently provide invaluable guidance and analysis to industry design teams in the development of the F-16 for the Air Force and the F/A-18 for the Navy.

F/A-18 with wing leading-edge flaps deflected and LEX vortices made visible by condensation.

In Vietnam, the lack of maneuverability of U.S. fighters at transonic speeds provided key advantages to nimble enemy fighters. Industry, the Department of Defense (DOD), and NASA were all stimulated to sponsor research to achieve unprecedented transonic maneuverability while maintaining excellent handling qualities. Langley researchers, under the leadership of Polhamus, conducted studies in the 7- by 10-Foot High-Speed Tunnel to obtain near optimum aerodynamic maneuver performance for wings, including the use of fixed and variable camber concepts. Some of the earliest systematic wind-tunnel tests were conducted by the group to determine the most effective geometries for wing leading- and trailing-edge flaps. In addition to tests of aerodynamic performance and stability and control, buffet studies were conducted to understand and develop methodologies for the prediction and minimization of undesirable buffet characteristics. The program was closely coordinated with flight tests of actual high-performance fighters at the NASA Dryden Flight Research Center. Flight evaluations of the effects of maneuver flaps on a YF-17 were also later conducted in the Dryden program.

Numerous discussions with Polhamus and his staff provided valuable guidance to the Northrop design team and the McDonnell Douglas team for the subsequent F/A-18 design. The insight and understanding provided by the broad database from Langley tests permitted development of the extremely effective leading- and trailing-edge flaps used by the YF-17 and the F/A-18. The F/A-18 and similar high-performance fighters use specific, computer-controlled schedules of flap deflection with Mach number and angle of attack for superior maneuverability throughout the flight envelope.

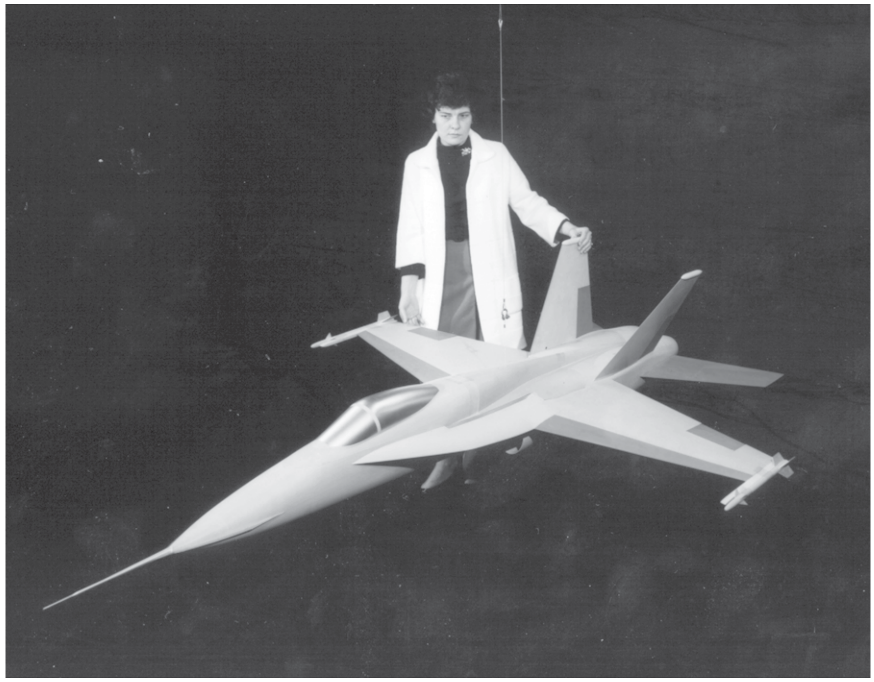
Development of the YF-17

On January 6, 1972, the Air Force issued a request for proposals (RFP) for a Lightweight Fighter (LWF) Program. In March 1972, the Langley Research Center was requested by DOD to participate in assessments and supporting tests of the competing YF-16 and YF-17 designs for the LWF. Langley researchers became members of DOD source evaluation teams to assess and check technical claims by each of the contractors. The sponsoring LWF Program Office requested that certain services of Langley be made available on an equal basis to the two competing teams. This remarkable arrangement provided each team with analysis and support if they desired.

Northrop placed a high priority on superior high-angle-of-attack characteristics and a high degree of inherent spin resistance for the YF-17. The company had also placed priorities in these areas during the development of the F-5 and T-38 aircraft, which had become known for outstanding resistance to inadvertent spins. Langley support was therefore requested for tests in the 30- by 60-Foot (Full-Scale) Tunnel and the 20-Foot Vertical Spin Tunnel.

To provide superior handling qualities at high angles of attack for fighter aircraft, Northrop provided the airframe with the required levels of aerodynamic stability and control characteristics without artificially limiting the flight envelope with the flight control system. This approach proved to be highly successful for the YF-17 and has been adopted by McDonnell Douglas (now Boeing) and used in all variants of the F/A-18 aircraft.

Researcher Sue B. Grafton conducted exhaustive tests in the Full-Scale Tunnel of the YF-17 configuration at high angles of attack in 1973. The results of the Langley tests revealed that Northrop had done an outstanding job in configuring the YF-17 design. The integration of the large LEX surfaces and the placement of the twin vertical tails provided exceptional tail effectiveness at high angles of attack. The small strakes added to the forward fuselage nose by Northrop resulted in extremely high directional stability at high angles of attack. Free-flight tests of the YF-17 model in the Full-Scale Tunnel



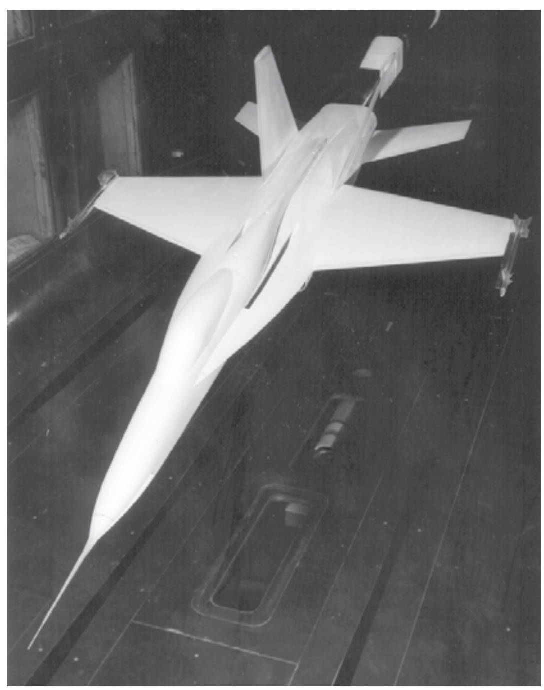
Project engineer Sue Grafton with the free-flight model of the YF-17 in 1973.

confirmed the excellent flying characteristics predicted by the wind-tunnel data and provided Northrop with highly positive predictions for upcoming flight tests of the two YF-17 prototypes at Edwards Air Force Base. The wind-tunnel data also formed the basis for piloted simulator studies at Langley and Northrop that helped Northrop design the flight control system for critical high-angle-of-attack conditions.

Spin and recovery tests in the Spin Tunnel also provided positive results for the YF-17. The scope of the tests in the Spin Tunnel was relatively broad for the fast-paced LWF Program and included the determination of the size of the emergency spin recovery parachute that would be required for flight tests. The results of the Spin Tunnel tests showed that the YF-17 would have remarkably good spin and recovery characteristics. In fact, the YF-17's characteristics were the best noted for any fighter configuration to that time.

Although not specifically requested by the Air Force, Langley had already conducted Air Force approved studies of the high-angle-of-attack characteristics of the YF-16 in the Langley Differential Maneuvering Simulator (DMS) and approval was given to conduct similar studies of the YF-17. Under the leadership of Langley researchers Luat T. Nguyen and William P. Gilbert, extensive studies were conducted in the DMS to verify the impressive behavior predicted by the wind-tunnel and free-flight model tests for more realistic air combat conditions. In addition, the simulation was used to refine certain elements of the flight control system for high-angle-of-attack conditions. The results of the simulator investigation showed the YF-17 to be highly maneuverable and departure resistant throughout the operational angle-of-attack range and beyond maximum lift.

A YF-17 prototype in flight with the open slots in the LEX adjacent to the fuselage.



YF-17 model in the Langley 8-Foot Transonic Pressure Tunnel for drag assessment studies.

The Langley predictions for the YF-17 behavior were subsequently confirmed in 1974 when two YF-17 prototypes began flight evaluations at Edwards Air Force Base. Handling characteristics at high angles of attack were excellent. The YF-17 could achieve angles of attack of up to 34 deg in level flight and 63 deg could be reached in a zoom climb. The aircraft remained controllable at indicated airspeeds down to 20 knots. Northrop consequently claimed that their lightweight fighter contender had no angle-of-attack limitations, no control limitations, and no departure tendencies within the flight envelope used for the evaluation.

Langley researchers conducted a cruise-drag test of the YF-17 in the Langley 8-Foot Transonic Pressure Tunnel in 1973. The test was initiated when Northrop questioned the high transonic drag levels predicted by the Air Force, which were based on results from other wind tunnels. The Air Force agreed that an independent NASA analysis would be appropriate and requested the test.

Langley researchers found that their results agreed with the Air Force predictions. Researchers then identified the major contributors to drag and provided recommendations to reduce it. Dr. Richard T. Whitcomb reviewed the YF-17 drag results and concluded that the wing design was the major factor in the unexpected drag levels. Whitcomb's suggestion for a wing redesign to solve the problem was unacceptable to Northrop.

F/A-18A TO F/A-18D

Development of the F/A-18

In April 1974, the LWF Program changed from a technology demonstration program to a competition for an Air Force Air Combat Fighter (ACF), and the flight-test programs for the YF-16 and YF-17 were rushed through in a few months instead of the planned 2 years. On January 13, 1975, the Air Force announced that the General Dynamics YF-16 would be the new ACF. Congress decreed that the Navy adopt a derivative of one of the LWF designs as the new Naval Air Combat Fighter to complement the F-14. On May 2, 1975, the Navy announced that the YF-17 design would form the basis of their new F/A-18 fighter-attack aircraft. Northrop, inexperienced in the design of naval fighters, teamed with McDonnell Douglas, which had extensive experience with a highly successful line of naval aircraft, including the F-4 Phantom. McDonnell Douglas became the prime contractor for the F/A-18 with Northrop the prime subcontractor.

The formidable task of converting the land-based YF-17 lightweight day fighter into an all-weather fighter-attack aircraft capable of carrier operations with heavy ordnance loads required significant changes from the earlier configuration. Structural strengthening and a new landing gear design were required for catapult launches and arrested landings. The aircraft gross weight rapidly grew from 23,000 lb for the YF-17 to a projected weight over 33,000 lb.

The required approach speeds for carrier landings resulted in modifications to the wing and LEX surfaces of the YF-17 configuration to provide more lift. McDonnell Douglas consulted the Langley research staff, and several individuals participated in the analysis of wind-tunnel tests that had been conducted at NASA Ames Research Center and McDonnell Douglas facilities. As a result of the analysis, changes were made to the aircraft configuration. The geometric shape of the YF-17 LEX was extended farther forward on the fuselage and the plan view of the LEX was modified to produce additional lift while retaining the good high-angle-of-attack characteristics exhibited by the YF-17.

The deflections of the wing leading- and trailing-edge flaps were increased and the ailerons were programmed to droop in low-speed flight to augment lift. Finally, a “snag” or discontinuity was added to the leading edges of both the wing and horizontal tails to provide more lift.

Formal Navy requests for specific NASA studies in support of the evolving F/A-18 configuration were received and accepted by Langley. The excellent correlation of Langley predictions for high-angle-of-attack and spin characteristics of the YF-17 prompted the Navy to request the full suite of tests at Langley for these characteristics. A request for tests in the Spin Tunnel and the Full-Scale Tunnel and helicopter drop models was received in late 1976.

The first preproduction F/A-18 made its first flight on November 18, 1978, and entered the initial phases of flight tests at the Patuxent River Naval Air Station in Maryland. The preproduction flight-test program lasted from January 1979 to October 1982, and the Langley staff was called on to help solve several critical developmental problems.

Cruise Drag

Initial results from flight evaluations at Patuxent River in 1979 indicated that the cruise performance of the F/A-18 was significantly below expectations, with a shortfall of about 12 percent in cruise range. The performance deficiency became a weapon for those who sought the termination of the F/A-18 Program. A number of reasons for the poor performance were identified. Modifications to the engines, computer-controlled schedules for the deflection of leading- and trailing-edge flaps, and other changes reduced the cruise range deficit to about 8 percent, but aerodynamic drag remained a problem.

In response to this critical threat to the program, a Navy and NASA F/A-18 working group was formed in late 1979. The NASA members were all Langley personnel led by researchers Richard Whitcomb, Edward Polhamus, and William J. Alford, Jr. With the addition of members from the Navy, McDonnell Douglas, and Northrop, the group totaled about 20 participants. After consideration of several approaches to reduce the drag of the aircraft, the group recommended wind-tunnel and flight studies of modifications to several configuration features. Modifications included increasing the wing leading-edge radius, variations in the LEX camber, and filling in the slots in the LEX-fuselage juncture. The Langley members identified the slots as a particularly undesirable feature with potentially high drag characteristics. Tests with favorable results were conducted in the Langley 8-Foot Transonic Pressure Tunnel in early 1980. These changes were implemented on the F/A-18 test aircraft at Patuxent River where they were found to favorably increase the cruise range of the aircraft. The impact of filling in the LEX slot on high-angle-of-attack characteristics was found to be acceptable in additional tests at Langley and F/A-18 flight tests.

High-Angle-Of-Attack, Spin, and Spin Recovery Characteristics

Langley responded to the Navy’s request for stall-spin tests in support of the F/A-18 with spin tunnel tests (1978), free-flight model tests (1978), and drop-model tests (1979). The results of the Langley spin tunnel and drop-model tests were very favorable. The F/A-18 configuration was found to be extremely resistant to spins. (The pilot was required to maintain prospin controls for over 20 sec to promote a spin.) When spins were entered, recovery could be effected very quickly. In the spin tunnel tests, the F/A-18 model demonstrated the best spin recovery characteristics of any modern U. S. fighter (as had the YF-17 configuration). During the limited model tests for spins, the phenomenon known as “falling leaf” was not encountered, but it became a problem in operational usage as will be discussed in a later section.

The F/A-18 free-flight model tests that were conducted in the Full-Scale Tunnel were very controversial; however, the model tests subsequently proved to be a major contributor to the success of the F/A-18 development program.

As previously discussed, early high-angle-of-attack tests had been completed in other NASA and McDonnell Douglas wind tunnels to tailor the geometry of the F/A-18 for good flight characteristics. The removal of the stabilizing nose strakes that were on the YF-17, which would have interfered with the radar performance on the F/A-18, and the revision of LEX shape had been carefully analyzed and designed from these results. When the Langley free-flight model underwent tests, the LEX and leading-edge flap schedule had been defined for flight tests.

When the Langley model was tested, however, the results obtained with this particular model indicated that the F/A-18 would exhibit a moderate yaw departure near maximum lift. Although not a flight safety concern, this result would infringe on the precision maneuverability of the aircraft. These undesirable results had been obtained at low wind-tunnel test speeds with a relatively large model and were dismissed with skepticism by the engineering community as having been caused by erroneous scale effects.

In 1979, an F/A-18 test aircraft at Patuxent River suddenly and unexpectedly departed controlled flight during a wind-up turn maneuver at high subsonic speeds. None of the baseline wind-tunnel data predicted this characteristic, and the F/A-18 Program was shocked by the event. The fact that the free-flight model had also exhibited such a trend did not go unnoticed, and a joint NASA, Navy, and McDonnell Douglas team was formed to seek solutions with the free-flight model at Langley. Following exhaustive wind-tunnel tests in the Full-Scale Tunnel, the team recommended that the wing leading-edge flap deflection be increased from 25 deg to 34 deg at high angles of attack. Following the implementation of this recommendation on the test aircraft (via the flight

F/A-18 drop model prepared for flight in 1978.

The F/A-18A free-flight model during tests in the Langley 30- by 60-Foot Wind Tunnel in 1978.

control computers), no more departures were experienced, and the flap deflection schedule was adopted for production F/A-18's.

This was not the first time that results from large free-flight models in the Full-Scale Tunnel had proven to accurately predict the flight behavior of an aircraft at high angles of attack, despite the low speeds of the wind-tunnel tests. (See *Langley Contributions to the F-16*, for example.)

The NASA High-Angle-Of-Attack Technology Program

The emergence of a generation of highly maneuverable fighter aircraft such as the F-14, F-15, F-16, and F-18 in the late 1970's resulted in a new perspective on operating high-performance aircraft at high angles of attack. Previous U.S. military experience with aircraft such as the F-4 and A-7 during the Vietnam era had been tormented with unacceptably high accident losses of these aircraft from inadvertent departures and spins from maneuvers at high angles of attack. Operational procedures required very careful and precise pilot inputs at high angles of attack to avoid loss of control, and handbook restrictions were placed on the operational use of angle of attack. With the advent of the new generation of fighters, flight at high angles of attack became a common occurrence and was no longer feared or avoided by pilots. Exploitation of high angles of attack provided the potential for new maneuvers and options for air combat tactics. These interests resulted in several major programs within DOD, industry, and NASA to develop the analysis and design methodologies for superior performance over an unlimited range of angle of attack.

In the early 1980's, NASA initiated a High-Angle-of-Attack Technology Program (HATP) among the aeronautics research centers (Langley, Ames, Dryden, and Glenn). The program included all the critical elements of high-angle-of-attack technology: aerodynamics, flight controls, handling qualities, stability and control, and the rapidly evolving area of thrust vectoring. In recognition of its extensive accomplishments in this field, Langley was designated the technology lead center for the program, and Dryden was designated the lead for flight research and operations. The Langley leader in the initial phases of the program was William Gilbert, who was followed by Luat Nguyen in later years.

A critical element in the HATP plan was the correlation and validation of experimental and analytical results with results from flight tests of a high-performance aircraft. The NASA team considered several aircraft configurations for this important task, including the F-15, F-16, F/A-18, and the X-29 forward-swept wing technology demonstrator aircraft. The advantages and disadvantages of each aircraft for the NASA program were thoroughly considered, and the F/A-18 was unanimously chosen as the desired test vehicle for several reasons. In flight, the F/A-18 had shown aerodynamic and aeroelastic phenomena of interest (vortex flows and tail buffet), stall-free engine operation at high angles of attack, excellent spin recovery characteristics, an advanced digital flight control system, and a large angle-of-attack capability (up to 60-deg trim capability at low speeds). The Navy's response to a request from NASA for a preproduction F/A-18 vehicle for the program was very positive. The Navy initially offered NASA an early production F/A-18A aircraft; however, NASA targeted the specially equipped preproduction F/A-18 (ship no. 6) that had been used at Patuxent River for the spin evaluation phase of the development program. The aircraft had completed its spin tests and had been stored in a hangar and stripped of its major components as a spare-parts aircraft. However, this particular aircraft was equipped with a special emergency spin recovery parachute system worth several million dollars and a programmable digital flight control computer adaptable to the variations desired in the HATP. The Navy approved the transfer of the stripped aircraft to NASA, and it was trucked to Dryden and reassembled by experts at Dryden with the Navy's help into a world-class research aircraft to be known as the F/A-18 High Alpha Research Vehicle (HARV).

F-18 HARV during flow visualization studies using smoke ejected at apex of LEX and wool tufts on upper surfaces.

The HATP studies were conducted in three phases. In the first phase, emphasis was placed on static and dynamic aerodynamic phenomena. This phase included extensive correlations of wind-tunnel and computational results with data from flight instrumentation on the HARV. These data correlations were conducted with common data sensor locations on the wind-tunnel models and the HARV. As a result of these aerodynamic experiments, the capabilities of emerging computational fluid dynamics tools and the interpretation of wind-tunnel test techniques were aggressively accelerated. Detailed studies of vortical flow structures emanating from the F/A-18 LEX and interactions with the vertical tail surfaces resulted in rapid progress in the understanding, prediction, and minimization of vertical-tail buffet phenomena. Finally, in-depth analysis of the flow fields shed by the nose and forebody of the F/A-18 resulted in wind-tunnel test procedures and validation of computational codes for future fighters.

An excellent example of the impact of this fundamental research is the LEX upper-surface fences mounted on F/A-18C/D aircraft. These devices greatly alleviate the vertical tail buffeting associated with sudden bursting of the core of the strong vortical flow shed by the LEX at high angles of attack. McDonnell Douglas developed the fence during parametric wind-tunnel experiments in its own wind tunnel; however, they did not have the resources or time to identify the flow mechanisms created by the fence. Within the scope of the HATP, Langley developed a laser vapor screen flow visualization technique that permitted rapid, global assessments of interactive flow fields. Using this technique, Langley researcher Gary E. Erickson conducted diagnostic tests on an F/A-18C model in the Navy David Taylor Research Center (DTRC) 7- by 10-Foot Transonic Tunnel, and he precisely identified the vortex-flow mechanisms associated with the benefits of the fences. The success of the vapor screen system so impressed the Navy and industry that they requested the Langley vapor screen system on other tests to understand nonlinear flow behavior at subsonic and transonic speeds.

In the second phase of the HATP, the HARV incorporated a relatively simple and cheap thrust-vectoring system for studies of aerodynamics at extreme angles of attack, and engineering development and evaluations of the advantages of thrust vectoring for high-angle-of-attack maneuvers. Previous efforts with the Navy involving experiments with thrust-vectoring vanes on an F-14 inspired the NASA team to adopt this simple concept instead of a program to develop internal engine vectoring at a cost of many more millions of dollars. (See *Langley Contributions to the F-14*.) Dryden managed and directed a contract with McDonnell Douglas to outfit the HARV with deflectable external vanes mounted behind the engines. The engine exhaust nozzle divergent flaps were removed and replaced with a set of three vanes for each engine, which resulted in both pitch and yaw vectoring capability. The specific vane configuration was analyzed and defined by tests of a powered model in the Langley 16-Foot Transonic Tunnel and the Langley Jet Exit Test Facility. Meanwhile, the aircraft flight computer was modified to permit research evaluations within a broad spectrum of thrust-vectoring parameters. The modification of the HARV proved to be extremely challenging, and several members of the staffs from Langley and Dryden assisted in the final implementation of the hardware and software of the thrust-vectoring system.

Extensive piloted simulator evaluations of the HARV with thrust vectoring were conducted in the DMS, with results indicating that the implementation of both pitch and yaw vectoring provided powerful, unprecedented controllability and precision for maneuvers at high angles of attack.

The results of the F/A-18 HARV thrust-vectoring flights were remarkable. The HARV became the first high-performance aircraft to conduct multiaxis thrust-vectoring flights,