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HIGH ANGLE OF ATTACK RESEARCH

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NASA's F/A-18 high angle of attack research aircraft is shown during a flow visualization test flight. Smoke streamers coincide with vortices shed from the aircraft's right leading edge extension as the helical patterns progress aft and eventually burst. Short tufts of yarn taped to the vertical tail surfaces align with the airstream, providing additional information about airflow patterns in this region. The aircraft was at approximately 20 deg. angle of attack during an AOA "sweep" from 15 to 30 deg. NASA photo by Fliteline Photography.

NASA Adds to Understanding Of High Angle of Attack Regime

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A NASA research program that integrates F/A-18 flight test and wind tunnel data with computational fluid dynamics (CFD) predictions is providing new understanding about the behavior of modern fighters at high angles of attack.

Test results and refined CFD models are being compiled into a comprehensive, validated database that will be used by designers of highly maneuverable and stall/spin-resistant military aircraft in the future.

The F/A-18 high angle of attack research program (HARP) is NASA's top aeronautics priority, according to agency officials. They estimate that program funding for Fiscal 1990 will be significantly higher than the 1989 figure of $6 million. The effort is completely research oriented with no applications-focused Defense Dept. funding involved. Military needs provided much of the program's original impetus, however.

This is one of three parallel efforts that will be devoted to high angle of attack research over the next few years, although each has slightly different objectives. The No. 2 Air Force/NASA X-29 aircraft was scheduled to start flight tests last week to examine agility issues and the high AOA regime with a forward-swept wing design. The Rockwell/MBB X-31 flight demonstrator, expected to fly late this year, will focus on the tactical utility of an aircraft tailored for agility and flight at high AOA conditions.

BETTER MULTI-AXIS AGILITY

The NASA Ames-Dryden Flight Research Facility, which has been conducting flight tests here with a specially configured McDonnell Douglas F/A-18, has about 60 people devoted to the program. NASA/Langley is providing wind tunnel and computer modeling data, and NASA/Ames is developing high angle of attack CFD codes for the program. Most of this work is aimed at improving the multi-axis agility of fighters through better prediction of aircraft aerodynamics at angles of attack in excess of 50 deg.

Since flight evaluations began in April, 1987, a former early-model Navy F/A-18 has completed 83 flights and reached stabilized angles of attack up to 55 deg. NASA testing so far has concentrated on obtaining flow visualization data through "on-surface" and "off-surface" techniques, as well as developing high AOA instrumentation (AW&ST Mar. 30, 1987, p. 20).

Visual indications of airflow patterns were obtained by releasing a glycol-based liquid through tiny holes in the F/A-18 forebody (nose and radome area) and on the leading edge extensions (LEX). Red dye mixed with the liquid would dry on the aircraft's skin, tracing a pattern of streamlines that correlated with the path of air molecules over the surface for a given flight condition. These streamlines were documented in flight as they developed by on-board cameras and by more detailed postflight photographs taken on the ground.

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This "on-surface" technique required a pilot to stabilize the aircraft at a given AOA for about one minute while the dyed liquid was released, giving it time to flow aft and evaporate. While effective, this process could only be used once on a given flight and provided data at a single flight condition. The aircraft surfaces of interest were painted white for these studies (AW&ST May 4, 1987, p. 50).

"Off-surface" flow visualization studies provided data at several flight conditions on each test mission. Smoke generators mounted inside the aircraft nose produced a narrow streamer of white smoke that was selectively expelled from orifices around the nose and forward end of the right LEX. These smoke trails followed airflow patterns above the aircraft surface, revealing vortices shed from the forebody and LEX. Yarn tufts taped to the aircraft's aft fuselage, wings and tail sections provided additional airflow visual information.

Cameras on the F/A-18 wingtips, vertical tails and upper fuselage provided accurate, three-angle views of the vortex cores. Off-aircraft viewing angles, obtained from a Flightline Photography Learjet flying above and behind the fighter, enabled researchers to correlate smoke streamlines and tuft patterns at high AOA.

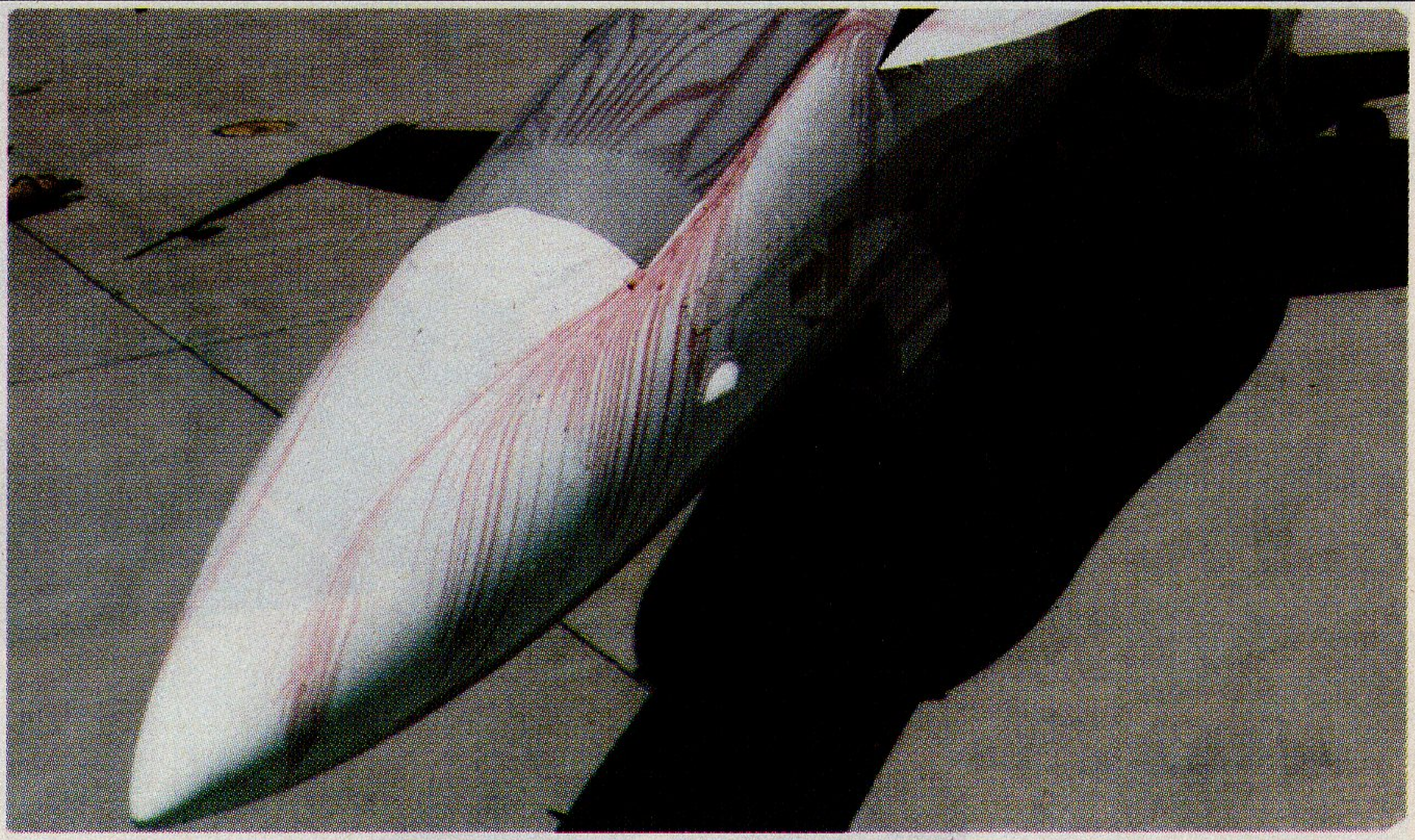
As of early May, NASA had "essentially completed" all planned flow visualization flight testing of the basic F/A-18 configuration, according to Donald H. Gatlin, high AOA project manager for Ames-Dryden. Although data analyses and correlation studies are still in progress, several high AOA phenomena have been identified, including:

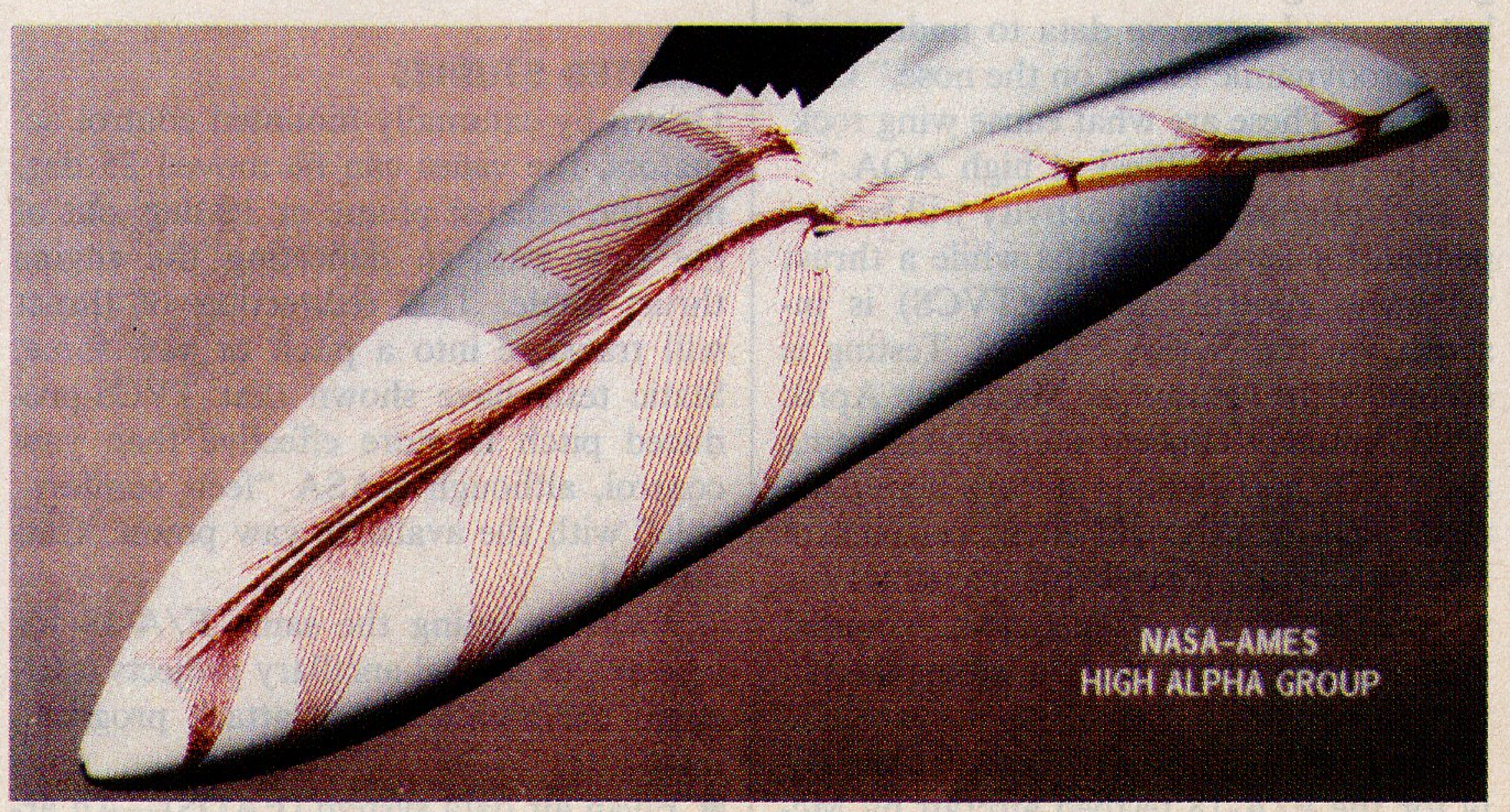
- The aircraft experiences a pronounced wing rock at about 47 deg. AOA. This motion decreases at 50 deg. AOA or at lower angles of attack. NASA researchers believe the wing rock may be caused by a forebody vortex that "moves around a lot" at about 45 deg., Gatlin said, causing pressures to vary on each side of the aircraft nose. This vortex is shed from near the forward tip of the radome, and appears as a "mini-tornado" that spirals back along the top of the canopy. NASA pilots have reported hearing a mild roaring sound above the canopy at high AOA, possibly caused by forebody vortices moving back and forth across the bubble-shaped transparency. Navy pilots also have reported this noise.
- Forebody vortices detected in flight are relatively weak below 25 deg. AOA and become more prevalent above 30 deg. Although computational fluid dynamics predictions show the forebody vortex progressing aft along the canopy rail area, flight tests indicate it lies higher, running across the top of the canopy itself. Gatlin said this may be tied to a limitation in the current CFD model, which stops near the wing leading edge. Wing flow field effects could account for observed differences, although CFD predictions have, in general, been quite good. Sideslip—which never can be completely eliminated during test maneuvers at high AOA—could affect the vortex location as well.
- Vortices shed from the forward edge of each leading edge extension are affected significantly by the presence or absence of a small, longitudinal LEX fence fixed to the skin of the LEX top surface. Photos show the vortex expanding in diameter but holding its helical shape as it pro-

The F/A-18 high angle of attack research program is NASA's top aeronautic priority

Photos Confirm CFD Predictions

Postflight photos of streamlines obtained by releasing a dyed, glycol-based liquid through tiny holes around the F/A-18 nose show airflow patterns at 30 deg. angle of attack (top and center). These flight test data compare well with computer-derived computational fluid dynamics (CFD) predictions of flow at the same AOA (bottom). In a nose-high attitude at 30 deg. AOA, the streamlines sweep from under the radome, back and across the side, then converge near the top surface as air flows rearward. Streamlines originating on the aircraft's left side, near the aft edge of the radome, sweep up sharply ahead of the leading edge extension (LEX), then curve over the top of the LEX. Just forward of the canopy, airflow splits slightly, curving down toward the LEX top surface, combining with flow from under the nose. □



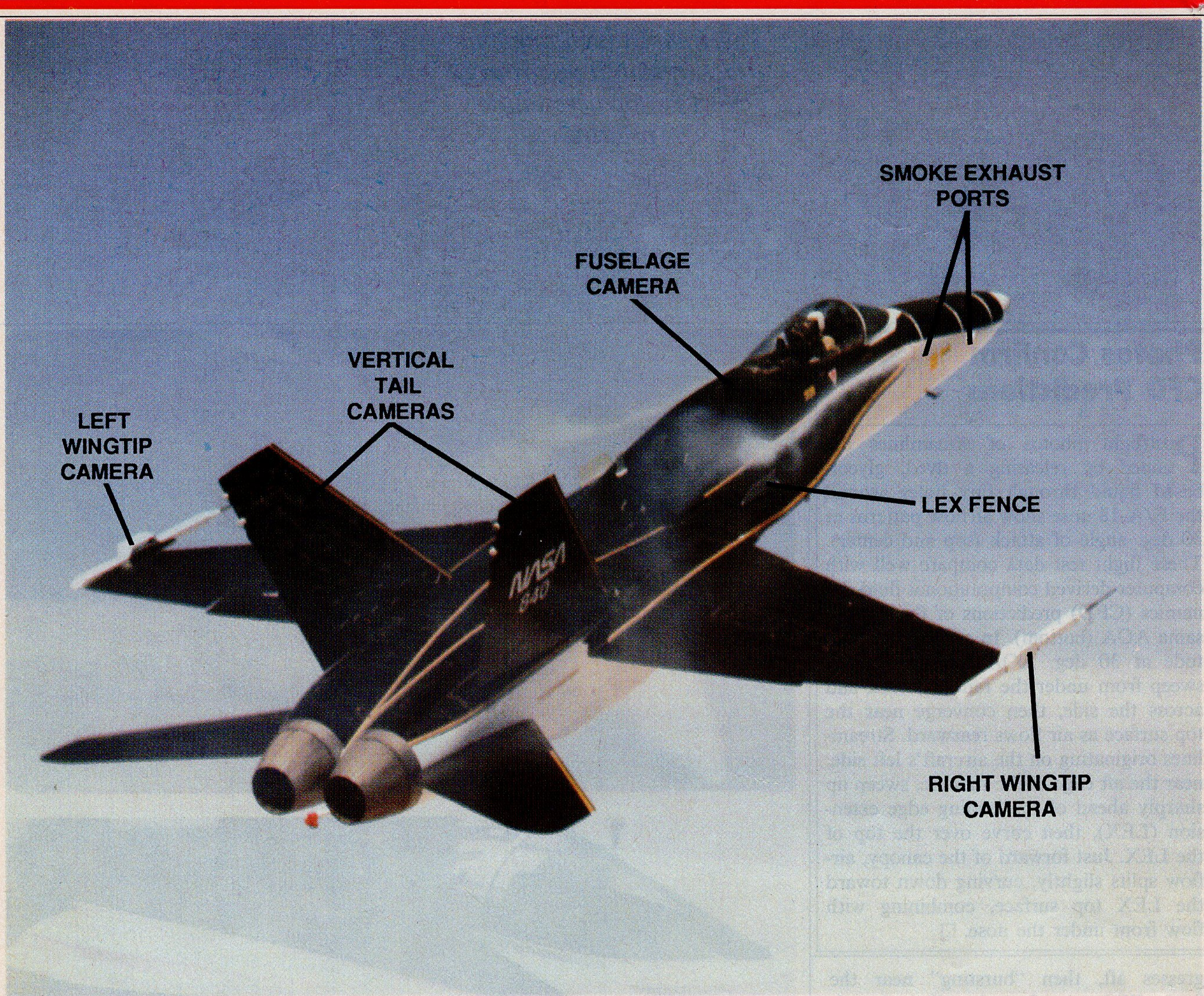


gresses aft, then "bursting" near the fence. Without a fence installed, though, this burst point occurs over the wing/fuselage region, implying the vortex affects aircraft aerodynamics farther downstream than with the added device. The fence was installed on operational F/A-18s to straighten airflow over the vertical tails and reduce buffet on these surfaces.

- At 35 deg. AOA, in stabilized flight, most of the lift appears to come from the aircraft fuselage and LEX. Most of the wing is stalled and the vertical tails appear to be largely blanked out, which minimizes lateral and directional control at these flight conditions.

The testbed aircraft is being modified now for the next phase of flights, which will obtain surface pressure measurements on the LEX and forebody areas at high angles of attack. Pressure survey flight tests are scheduled to begin in July.

The F/A-18 is instrumented with approximately 500 pressure "taps" or holes arranged in concentric rings around the fuselage from the nose to just forward of the cockpit, plus three additional rows on each leading edge extension. Blocks of these pressure taps are connected by small-diameter tubes to a scanivalve system that sequentially samples the pressure



NASA's high angle of attack research F/A-18 was modified with multiple cameras, a smoke generator and a glycol-based liquid system for flow visualization research between 25 and 55 deg. AOA. Off-aircraft viewing angles are obtained by a Flightline Photography Learjet.

at each location several times per second. When these samples are processed and correlated through computer data reduction routines, a detailed pressure map will be constructed, enabling researchers to characterize the vortex patterns.

"Being able to see pictures [obtained through visualization techniques] gives a good feeling for what the flow is doing, but we need pressure data to understand the aerodynamic forces on the nose," Gatlin said. "These are what cause wing rock and [other instabilities] at high AOA."

In September, flight activity will be suspended for several months while a thrust vectoring control system (TVCS) is installed on the NASA F/A-18. Testing is scheduled to resume in March or April, 1990, but will concentrate on evaluating the TVCS and refining it over about the next year. NASA will focus on control law and agility characteristics attainable with the thrust vectoring system. Minimal high angle of attack work is anticipated in this phase.

The TVCS is being designed specifically for the F/A-18 testbed aircraft by McDonnell Douglas Aircraft Corp. under a contract from NASA/Ames. The relatively simple, three-vane system is integrated with the flight control computer and is designed to improve pitch and yaw control at AOAs in the 50-60 deg. regime. The engines' standard outer nozzles will be removed, allowing three paddle-type vanes to be installed around each exhaust.

RELATED STUDIES

Driven by externally mounted control actuators, the vanes can be moved 25 deg. into the exhaust plume or 10 deg. out of the flow path in deflecting the engine thrust angle. This redirection of thrust will translate into a pitch or yaw force. Static tests have shown that TVCS-produced pitch is more effective than yaw control, although NASA "feels comfortable" with the available yaw power, Gatlin said.

NASA is using the same F/A-18 for research of several ancillary projects related to the high angle of attack program, including:

■ Flush air data system (FADS)—An array of pressure ports on the test aircraft's forebody was used to measure static and dynamic air pressures and flow angle at high AOA, then compared with similar data obtained with wingtip-mounted air data probes. Standard aircraft pitot probes mounted on the nose do not provide accurate airspeed, altitude, AOA and sideslip information at high AOA and create additional vortices that disturb airflow over the forebody and LEX. Wanting to eliminate these concerns, NASA developed an experimental, flush-mounted system similar to that used for air data sensing on the space shuttle for evaluation during the flow visualization tests. Correlation with pressure and flow angle information from the wingtip probes has been encouraging, according to Gatlin. NASA engineers are considering use of a real-time version of the system as a backup AOA source during vectored thrust testing.

■ Forebody controls—NASA/Langley wind tunnel tests indicate that a strake on each side of the F/A-18 nose/forebody area could improve stability at AOAs up

NASA F/A-18 testbed configured with a smoke generator and yarn tufts provides a visual indication of the vortices shed from the fighter's leading edge extension (LEX) at 30 deg. angle of attack. The testbed aircraft is being modified for the next phase of flights.

to about 70 or 80 deg. Extending from near the tip to the aft end of the nose radome, these 6-in.-wide strakes would be articulated to move together or differentially, providing a means of repositioning the forebody vortex and control air pressures around the nose. Above about 35 deg. AOA, these forebody strakes or vanes provide significant yaw power at flight conditions where tail-mounted rudder effectiveness is decreasing. Below 35 deg., the strakes have only a minor effect. Langley is studying the feasibility of adding strakes—controlled by the flight control system—to the F/A-18 testbed aircraft.

■ Vortex blowing and suction—Yaw control at high AOA might be enhanced by positioning the forebody vortex with small jets of air expelled from each side of the nose, providing a response similar to that of the strakes. Although the amount of air required is still being investigated by researchers at NASA/Ames and Stanford University, results so far appear promising, Gatlin said. This concept, despite the inherent complications of a sophisticated electro-pneumatic system, is an attractive alternative to strakes because it would not increase aircraft radar cross section as much and might be more compatible with on-board radar systems.

■ Full-scale wind tunnel testing—NASA will obtain an ex-Navy Blue Angels F/A-18 and move it to Ames this summer, installing it in the 80 × 120 ft. wind tunnel for tests at up to 60 deg. AOA. The tunnel can develop air velocities that closely approximate flight conditions at this angle of attack. The aircraft will be used to develop high AOA instrumentation and structural devices such as the forebody strakes and vortex blowing/suction system.

■ Agility/maneuverability testing—As part of the F/A-18 HARP, NASA is conducting a number of agility-related maneuvers to provide data to the Air Force and other NASA centers. Loaded rolls, pitch and heading captures, turn reversals and acceleration-deceleration tests were conducted during the first phase of the program. Some guidance information is being telemetered up to the test aircraft and presented on the head-up display as an aid to the pilot during these maneuvers. So far, the maneuvers are "not very repeatable and very difficult" to perform, Gatlin said. NASA is attempting to characterize the basic F/A-18 with these maneuvers for future agility comparisons with a thrust-vectored configuration.

■ An "iron bird" systems test unit—Built from a nonflying F/A-18 airframe, this testbed is hooked to a NASA/Dryden simulator. It will drive most aerodynamic surfaces, the flight control system and aircraft mission computer. A thrust vectoring system will be activated on the unit in August, enabling closed-loop testing to begin. Although complete structural tests cannot be conducted on the unit, it will have all aerodynamic models and system delays built in.

Gatlin noted that this would be the first time a high AOA program would have a full end-to-end set of research tools such as sub and full-scale wind tunnel models, a flight test vehicle, CFD models, and an "iron bird" systems test unit. □

Short-Range Air-to-Air Missile II gave the onboard computer flexibility to calculate and issue optimized commands for a greater variety of scenarios.

Autopilots have been developed that give bank-to-turn missiles response times similar to those that skid to turn without compromising stability margins or requiring software to filter from feedback signals the body's high frequency flexing.

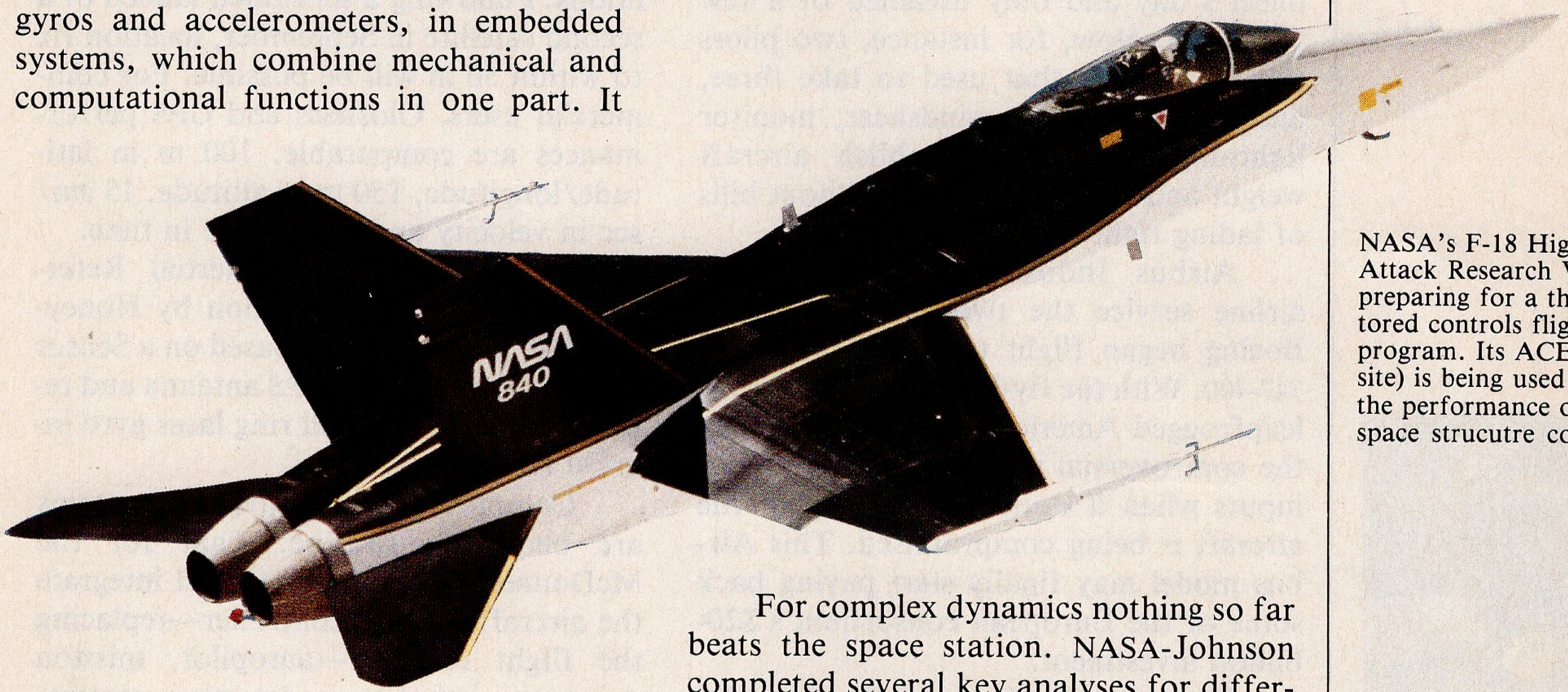
The Ada-Based Integrated Control System III program, sponsored by the Air Force Wright Aeronautical Labs, has successfully demonstrated the use of Ada high order language software in an integrated flight and fire control system. The system incorporated multifunction reference sensors, those that combine rate gyros and accelerometers, in embedded systems, which combine mechanical and computational functions in one part. It performed flight control, inertial navigation, and integrated flight fire control. F-15 test aircraft pilots found no difference in handling from F-15s with standard sensors and assembly language software.

NASA-Ames and the FAA have been working together to develop automation tools for assisting controllers in managing terminal air traffic. During 1988, a highly interactive set of tools for aiding the controller in merging traffic from adjoining routes was tested on a simulator manned by live controllers and airline crews.

Among the new crop of launch vehicles to appear this year was the Titan IV with Centaur upper stage. It is the first boost system to employ a strapped down inertial measurement unit platform using a ring laser gyro and guidance algorithms written in Ada.

Spacecraft having complex dynamics and control interactions and stringent pointing requirements commanded much attention. After extensive rework to correct anomalies in the Hubble Space Telescope control system components that hold the pointing stability to an accuracy of 0.007 arc-sec, final preparations were completed for shipping the telescope to NASA-Johnson. Launch is scheduled for next summer.

Following the launch in February of an SDI satellite, tests were carried out to determine the ability of sensors on board to detect and track simulated targets in space from a variety of angles. Sensors included laser radars, conventional radars, and optical devices working in the infrared and ultraviolet regions. Observations of targets were made in daylight and darkness, against deep space, and in Earth's shadows.



For complex dynamics nothing so far beats the space station. NASA-Johnson completed several key analyses for different space station configurations. Among them was an examination of computer models of flexible structures used to investigate control system interactions and the effects of the placement of sensors for determining shape, position, and movement of a structure and effectors for changing its shape and position.

NASA-Marshall's Advanced Control Evaluation for Structures (ACES-I) facility, which has a test configuration with 16 sensors and 9 effectors, was used to implement control design techniques on realistic large space structures and to evaluate performance of various controllers. ACES-I has many closely spaced, low frequency modes (43 modes under 8 Hz) with less than 2% damping.

The performance and mission requirements of these new aerospace systems now call for a total system's overview by guidance, navigation, and control specialists. This should make for an exciting challenge for anyone whose interests are in this field.

NASA's F-18 High Angle-of-Attack Research Vehicle is preparing for a thrust vectored controls flight research program. Its ACES-I (opposite) is being used to evaluate the performance of large space strucutre controllers.