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PREPARATIONS FOR FLIGHT RESEARCH TO EVALUATE ACTUATED FOREBODY STRAKES ON THE F-18 HIGH-ALPHA RESEARCH VEHICLE

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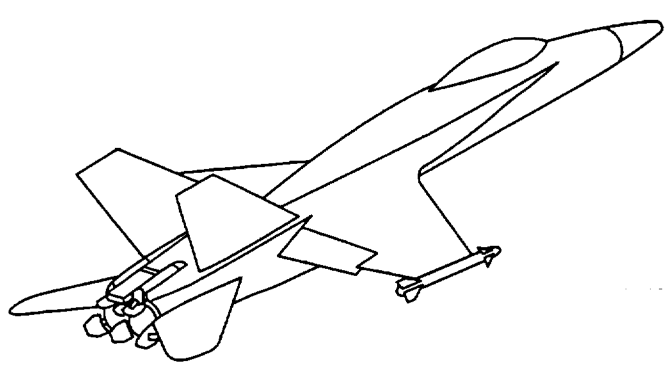

High-Angle-of-Attack Projects and Technology Conference

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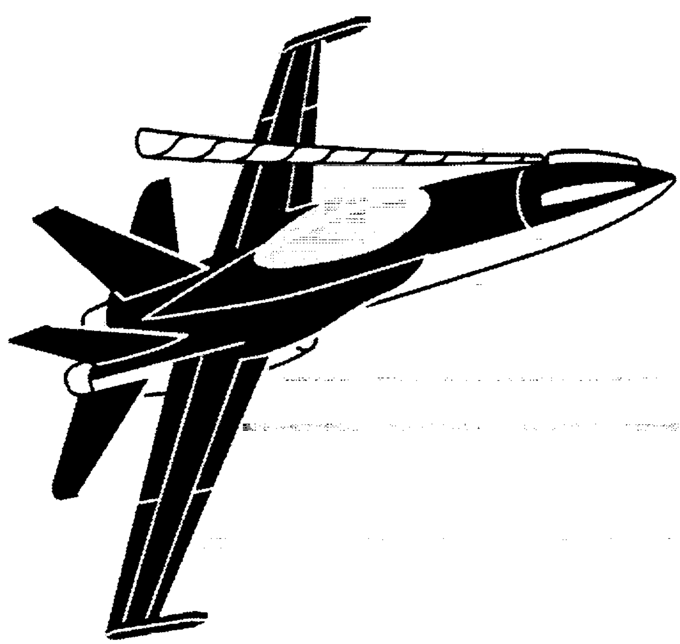
INTRODUCTION

A major goal of the NASA High-Angle-of-Attack Technology Program (HATP) has been to help develop technologies that can significantly improve the high-angle-of-attack controllability and maneuvering effectiveness of fighter aircraft. A wide range of advanced control concepts have been investigated under this program including propulsive control concepts as well as advanced aerodynamic control concepts. As part of the NASA HATP, flight tests are currently being conducted with a multi-axis thrust vectoring system applied to the NASA F-18 High-Alpha Research Vehicle (HARV). A follow-on series of flight tests with the NASA F-18 HARV will be focusing on the application of actuated forebody strake controls. These controls are designed to provide increased levels of yaw control at high angles of attack where conventional aerodynamic controls become ineffective. The series of flight tests are collectively referred to as the Actuated Nose Strakes for Enhanced Rolling (ANSER) Flight Experiment. (The ANSER acronym refers to "rolling" since the strakes provide the critical yaw control required to coordinate rolling maneuvers about the velocity vector at high-angle-of-attack conditions.)

The development of the actuated forebody strake controls for the F-18 HARV is discussed in reference 1, and a summary of the ground tests conducted in support of the flight experiment is provided in reference 2. This paper presents a summary of the preparations for the flight tests. Topics include the objectives of the ANSER Flight Experiment, a brief review of the strake development and the ground-test results, a description of the flight hardware, a discussion of aircraft integration considerations, and the flight test plans and schedule.



NOMENCLATURE

The moment reference for all of the wind-tunnel data presented is fuselage station 458.56 (25-percent mean aerodynamic chord) and water line 100.0.

b	reference wing span, 37.42 ft (full scale)
c_s	reference strake chord, .6775 ft (full scale)
C_h	strake hinge-moment coefficient (positive to close strake), hinge moment/$q_\infty S_s c_s$
C_n	body-axis yawing-moment coefficient, yawing moment/$q_\infty Sb$
C_p	static pressure coefficient, (local static pressure - free stream static pressure)/q_∞
FS	fuselage station, full scale, in
HARV	High-Alpha Research Vehicle
HATP	High-Angle-of-Attack Technology Program
M	Mach number
n_z	normal acceleration, g's
q_∞	free-stream dynamic pressure, lb/ft^2
S	reference wing area, 400 ft^2 (full scale)
S_s	reference strake area, 2.71 ft^2 (full scale)
TV	thrust vectoring
α	angle of attack, deg
β	angle of sideslip, deg
δ_s	strake deflection measured from the retracted position, deg

ANSER FLIGHT EXPERIMENT

The primary objectives of the ANSER Flight Experiment are to provide flight validation of a ground-test data base for a forebody control device and to evaluate the use of this type of control in enhancing fighter aircraft maneuverability.

In addition to the primary flight test objectives, many other important integration issues are being addressed that could aid in future application of forebody control concepts. Some of the issues that are being addressed include control law design implications, hydraulic/actuator requirements, structural loads, aircraft systems integration considerations, and pilot acceptance of the unique response characteristics of forebody controls.

ANSER FLIGHT EXPERIMENT

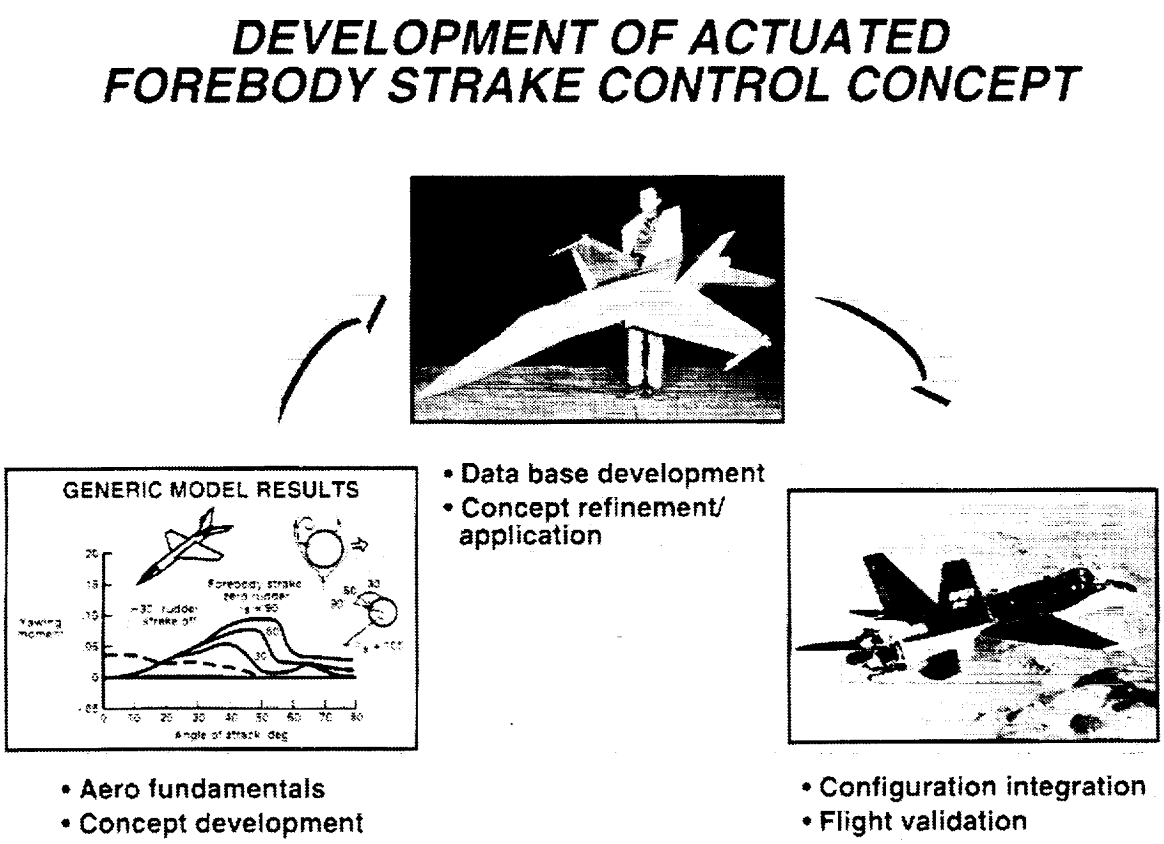
Objectives

- Obtain flight validation of ground-test data base for a forebody control device

- Evaluate the use of forebody controls in enhancing fighter aircraft maneuverability

DEVELOPMENT OF ACTUATED FOREBODY STRAKE CONCEPT

The overall development process of the actuated forebody strake concept has followed a successive series of studies from initial concept exploration to full-scale flight validation. The initial development tests of the actuated forebody strake concept were conducted using a generic fighter model and are described in references 3 and 4. These tests showed that the actuated forebody strake concept could provide high levels of yaw control over wide ranges of angle of attack and sideslip and that the yawing moment could be controlled by varying the strake deflections. The concept has been refined through a wide range of ground-based studies to develop the concept for application to the F-18 HARV and to support the planned flight tests[1, 2]. As mentioned previously, this paper presents a summary of the preparations for the upcoming flight research.



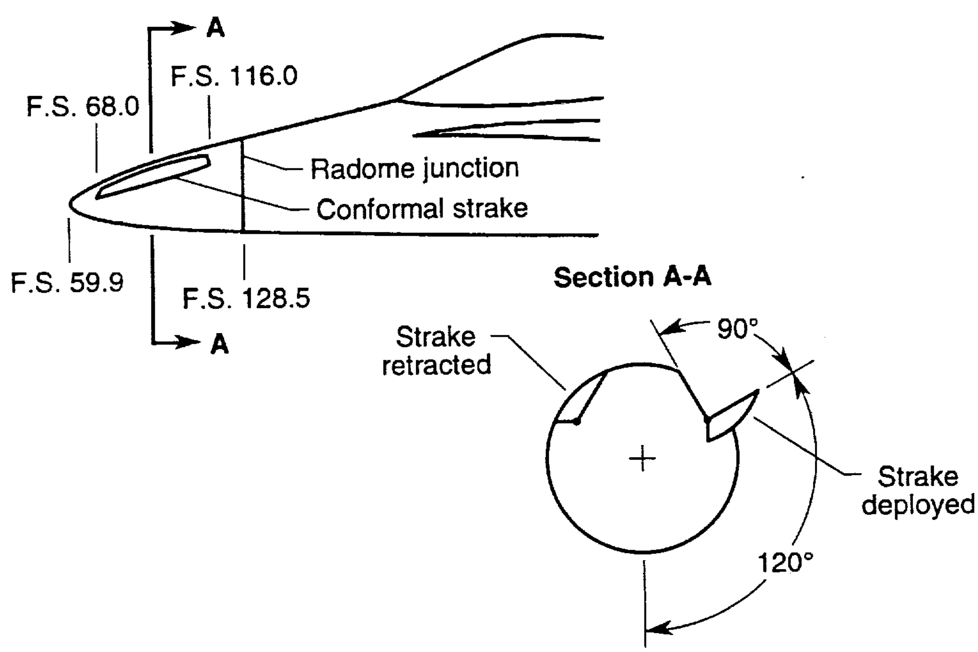
ANSER STRAKE DESIGN

A sketch of the conformal actuated forebody strakes designed for flight testing on the F-18 HARV is presented in the figure. This strake design includes a pair of conformal actuated strakes, each capable of a 90° deflection and positioned at a radial location of 120° from the bottom of the forebody. The term "conformal" indicates that when both strakes are retracted, the forebody retains the nominal F-18 HARV forebody contour.

It is recognized that implementation of actuated forebody strakes on the radome is probably not practical for current generation radar-equipped aircraft. However, actuated forebody strakes have been found to be very effective when located behind the radome, and many other forebody flow control devices (both mechanical and pneumatic) have been developed that minimize radar impact. In addition, the application of advanced (phased array) radars to future aircraft may relax the stringent radar-related requirements on the forebody.

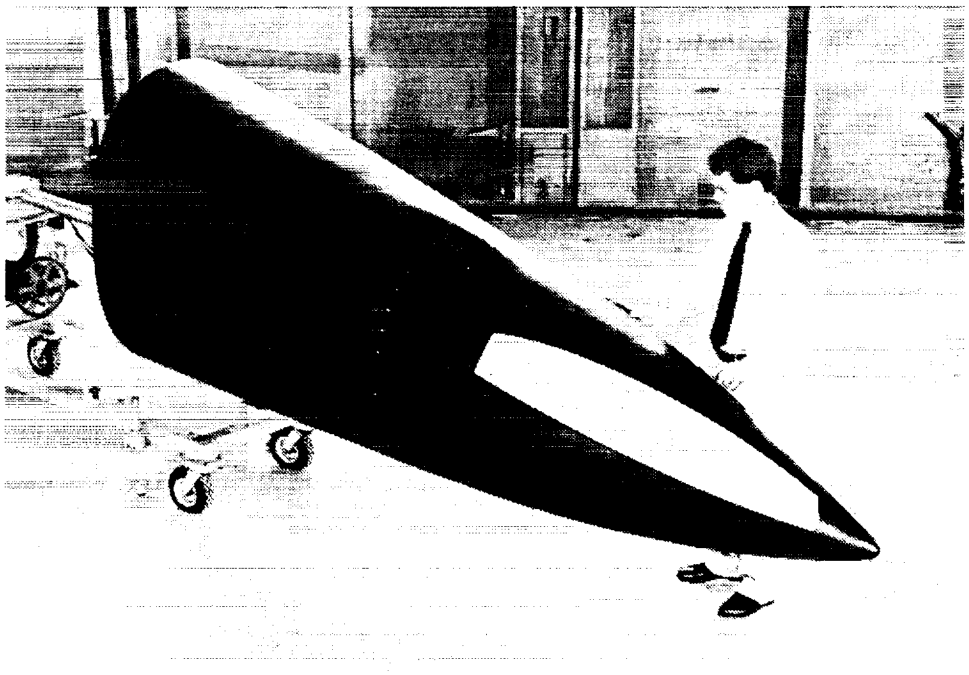
The ANSER configuration has been designed to allow the evaluation of a wide range of issues applicable to forebody controls, while minimizing the cost and complexity of the aircraft modifications. Therefore, the strakes are positioned to remain within the length of the radome of the full-scale F-18 HARV. The aircraft will be modified by attaching a newly fabricated radome incorporating the strakes and actuators and making the appropriate connections to the aircraft systems.

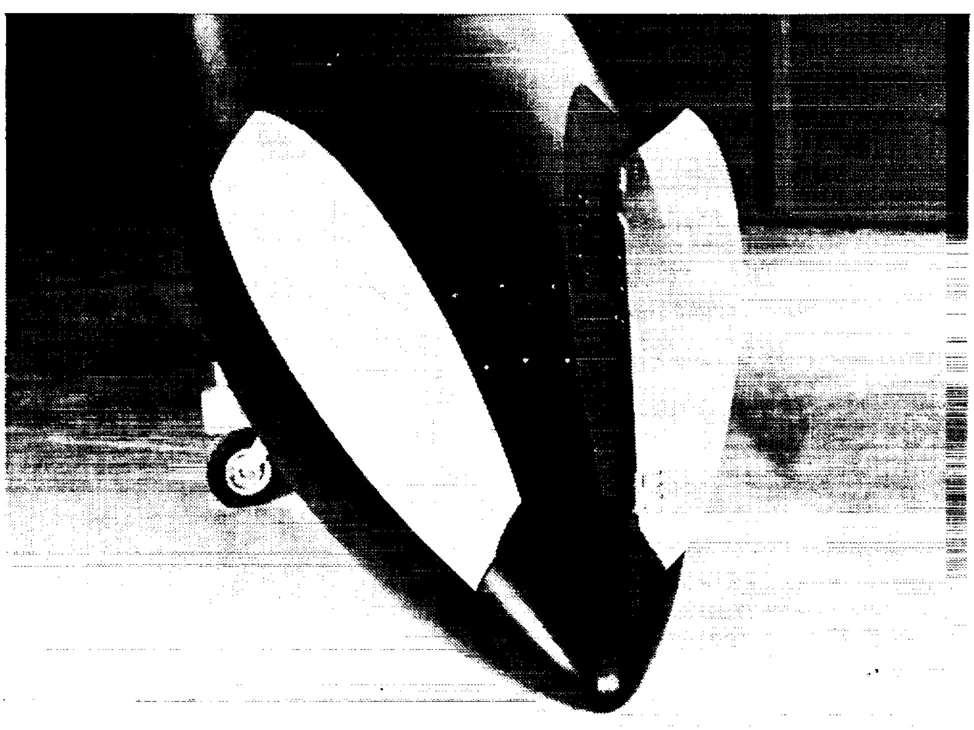
STRAKE DESIGN



ANSER STRAKE DESIGN

Some of the features the ANSER strake design are evident in the two photographs which show the strakes applied to a full-scale F-18 forebody wind-tunnel model.

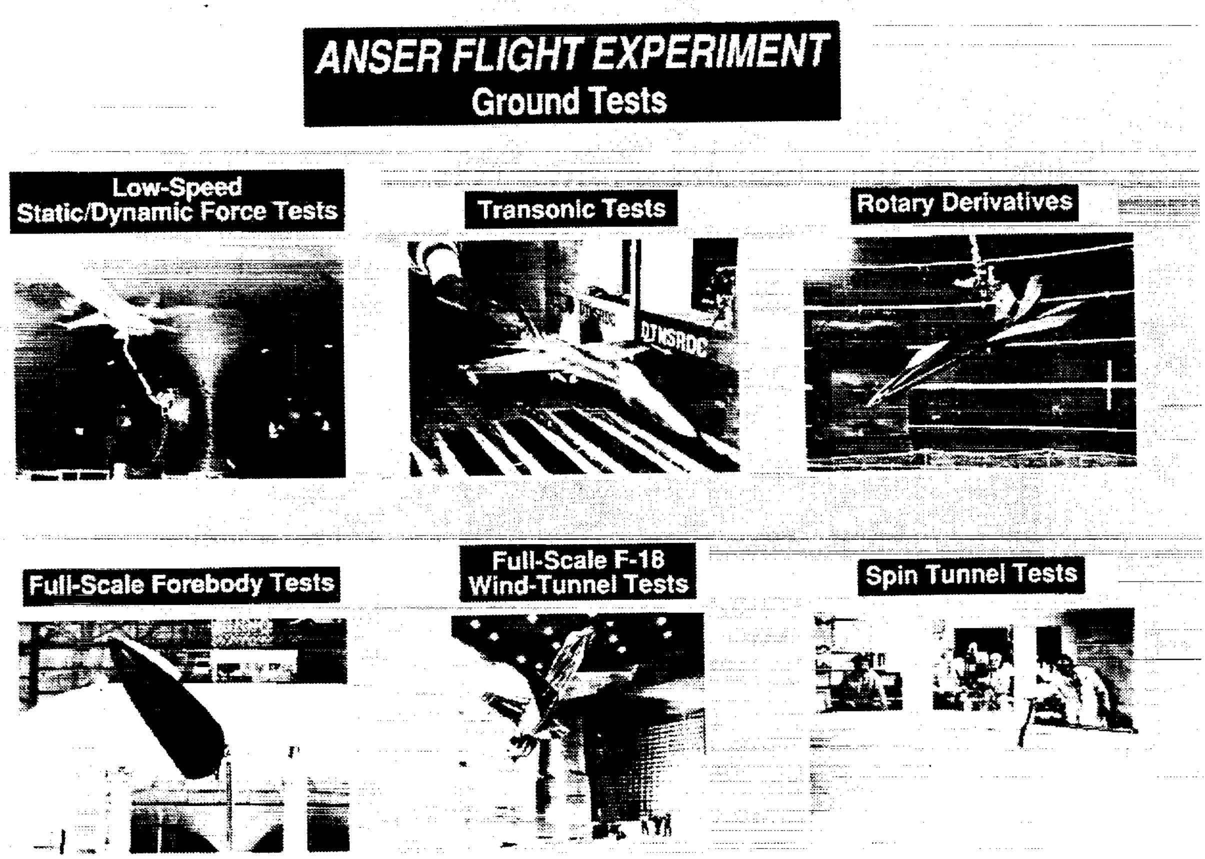




ANSER FLIGHT EXPERIMENT GROUND TESTS

The primary ground tests used in the analysis of the ANSER strake design are shown in the figure. The tests include low-speed static and dynamic force tests using a 16%-scale model in the Langley 30- by 60-Foot Tunnel, transonic tests using a 6%-scale model in the David Taylor 7- by 10-Foot Transonic Tunnel, rotary balance tests using a 10%-scale model in the Langley 20-Foot Vertical Spin Tunnel, full-scale F-18 forebody model tests in the Langley 30- by 60-Foot Tunnel, full-scale F-18 airframe tests in the Ames 80- by 120-Foot Tunnel, and free spinning tests using a 3.6%-scale model in the Langley 20-Foot Vertical Spin Tunnel.

During the strake development process, additional studies were conducted with a preliminary version of the ANSER strake design. These studies are described in reference 1 and included wind-tunnel free-flight tests and preliminary piloted simulation studies, both of which illustrated the enhancements in controllability and maneuverability provided by the strakes. Computational fluid dynamics studies have also been conducted for the same preliminary strake configuration (reference 5) and are continuing with the current ANSER strake design.



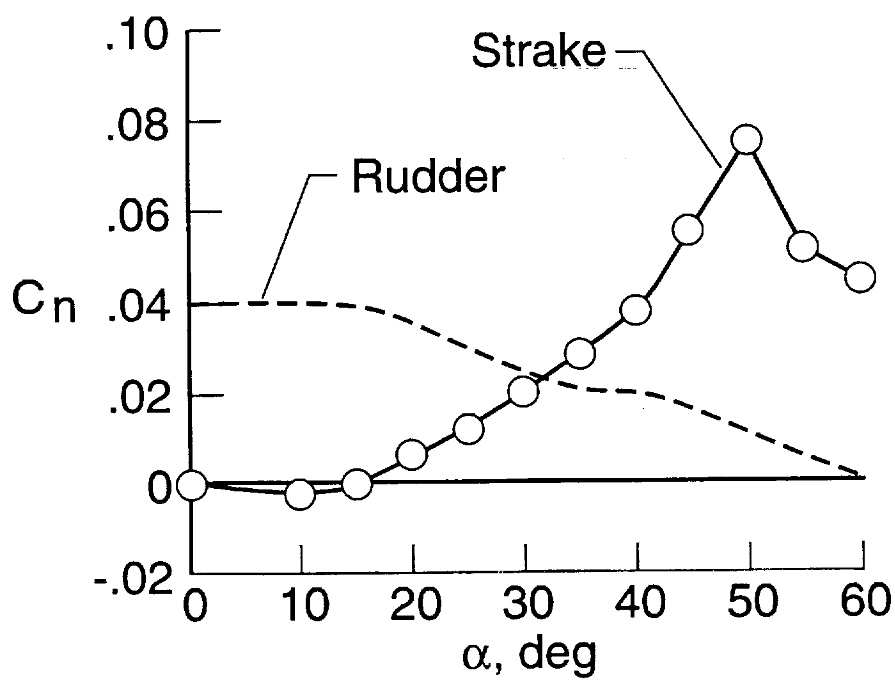
COMPARISON OF F-18 RUDDER AND
FOREBODY STRAKE YAW CONTROL POWER

The conventional rudders of the F-18 lose effectiveness as stall develops and the vertical tails become immersed in the low-energy stalled wake shed from the wings and fuselage. Although rudder effectiveness degrades rapidly above α=20°, the yaw control power provided by the strakes increases and produces very high levels of yawing moment at higher angles of attack. Although not shown here (see references 1, 2, 6, and 7), the results of all the ground-based studies indicate that the strakes also exhibit a number of other very desirable characteristics:

- The strakes remain effective over wide ranges of sideslip, Mach number, and aircraft rotation rate (about the velocity vector).
- They produce relatively small coupled rolling and pitching moments.
- They provide a well behaved variation of yawing moment with strake deflection.

COMPARISON OF F-18 RUDDER AND FOREBODY STRAKE YAW CONTROL POWER

16%-Scale F-18 Model

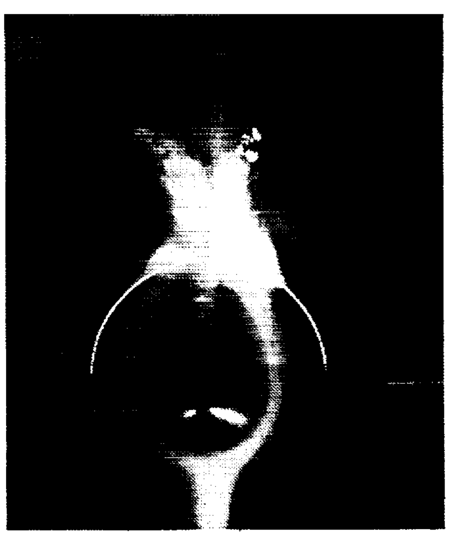


EFFECT OF STRAKE DEFLECTION ON
FOREBODY CROSSFLOW CHARACTERISTICS

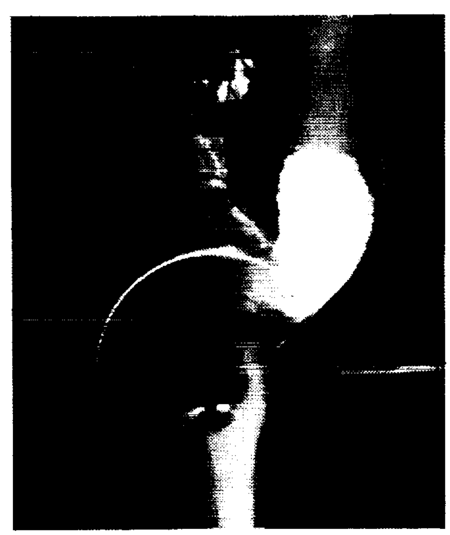
Flow visualization and pressure distribution results were obtained with the full-scale F-18 forebody model and are used to describe the basic aerodynamic mechanisms that are responsible for the yawing moments generated by the strakes. The photographs show head-on views of the forebody cross-flow characteristics at α=50° and FS 107.0 (about 80-percent down the length of the strake) that were obtained using a laser light sheet technique. With the strakes retracted, the photograph shows that the flow has separated symmetrically to produce a pair of small counter-rotating forebody vortices located above the forebody. However, with a maximum strake deployment, the photograph shows that the strake generates a much larger vortex, located above the strake and displaced away from the forebody.

FULL-SCALE F-18 FOREBODY LASER SHEET FLOW VISUALIZATION α = 50°

Strakes Retracted



Strake Deployed 90°

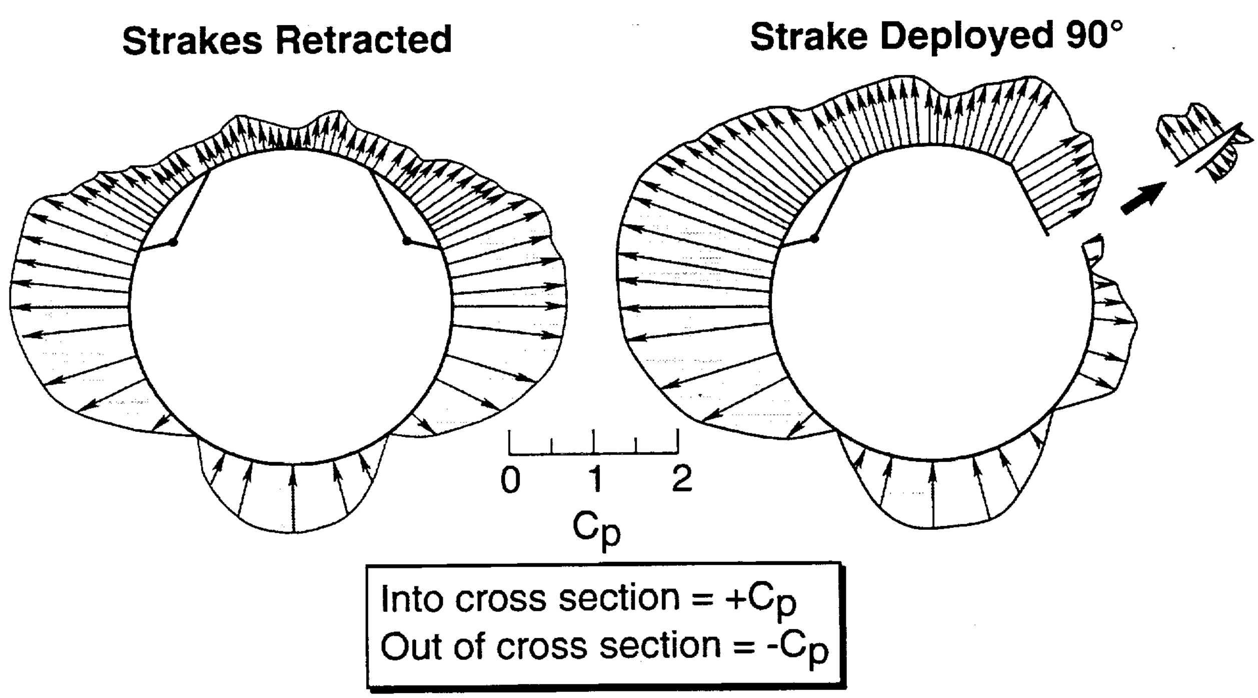


EFFECT OF STRAKE DEFLECTION ON
FOREBODY PRESSURE DISTRIBUTIONS

The sketches show pressure distributions measured around the forebody for the same conditions shown in the photographs. With the strakes retracted, large suction pressures develop as the flow accelerates around the sides of the forebody. The flow then separates and the "footprints" of the two small vortices are evident on the top of the forebody. When a strake is deployed, the suction pressures are reduced on the strake-deployed side of the forebody and the suction pressures are increased on the strake-retracted side. Although it is not shown here, the increased suction pressures on the strake-retracted side of the forebody are accompanied by a delay in the primary separation line (visualized using oil flow). Therefore, it appears that a strake deployment generates a dominant vortex that delays separation and accelerates the flow on the strake-retracted side and forces separation and decelerates the flow on the strake-deployed side. These changes in flow velocity generate differential suction pressures that produce side forces and yawing moments in the direction away from the strake deployment.

EFFECT OF STRAKE DEFLECTION ON FOREBODY PRESSURE DISTRIBUTION

Full-Scale Isolated ANSER Forebody Model
FS 107, α = 50°, q = 13 psf

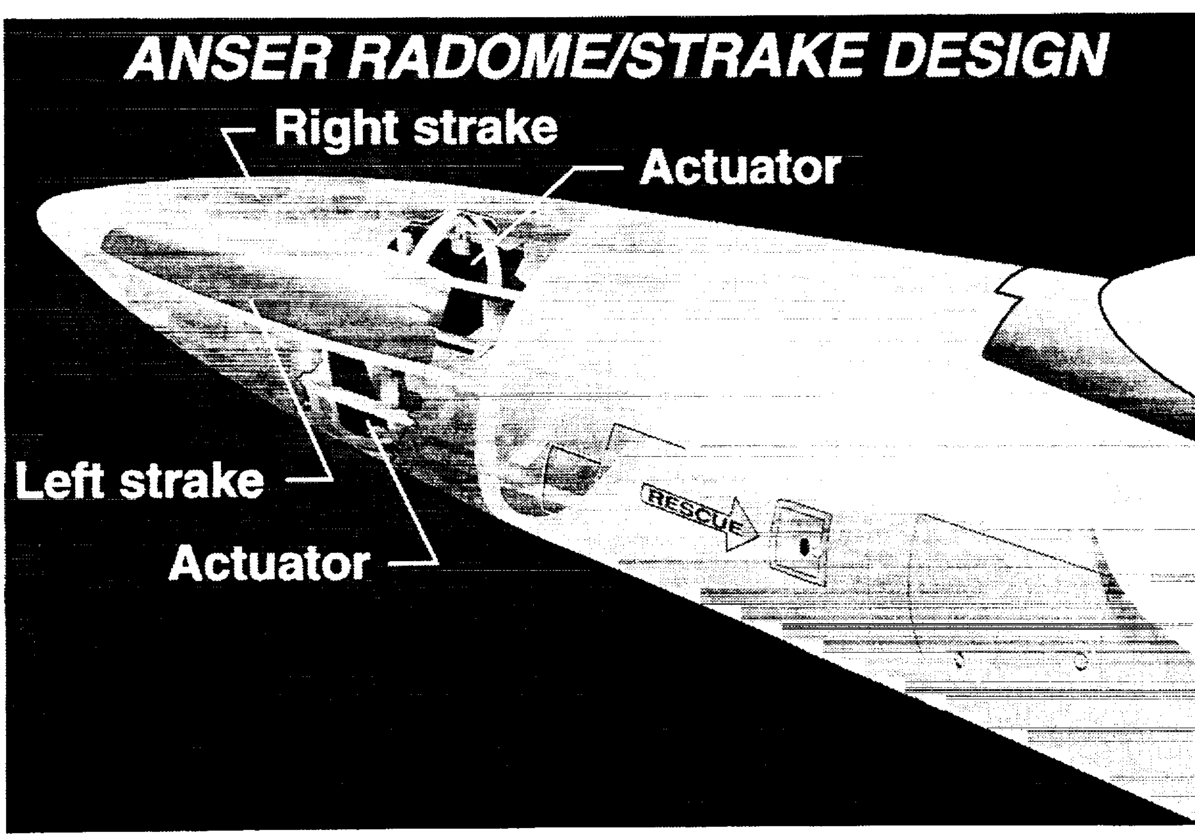


ANSER RADOME/STRAKE DESIGN

As shown in the figure, the approach being taken to modify the F-18 HARV for the ANSER Flight Experiment is to replace the basic radome with a newly fabricated radome that incorporates the strakes, actuators, and instrumentation. The flight radome and strake components have been designed and fabricated at NASA Langley and are shown on the following page. The radome and strake structures consist of aluminum skin panels that are riveted to aluminum stringers and bulkheads. Fiberglass fairings are used in several areas but are not used as load-bearing components. The hydraulic actuators used to drive the strakes consist of modified F-18 aileron actuators and are discussed in more detail in a subsequent figure.

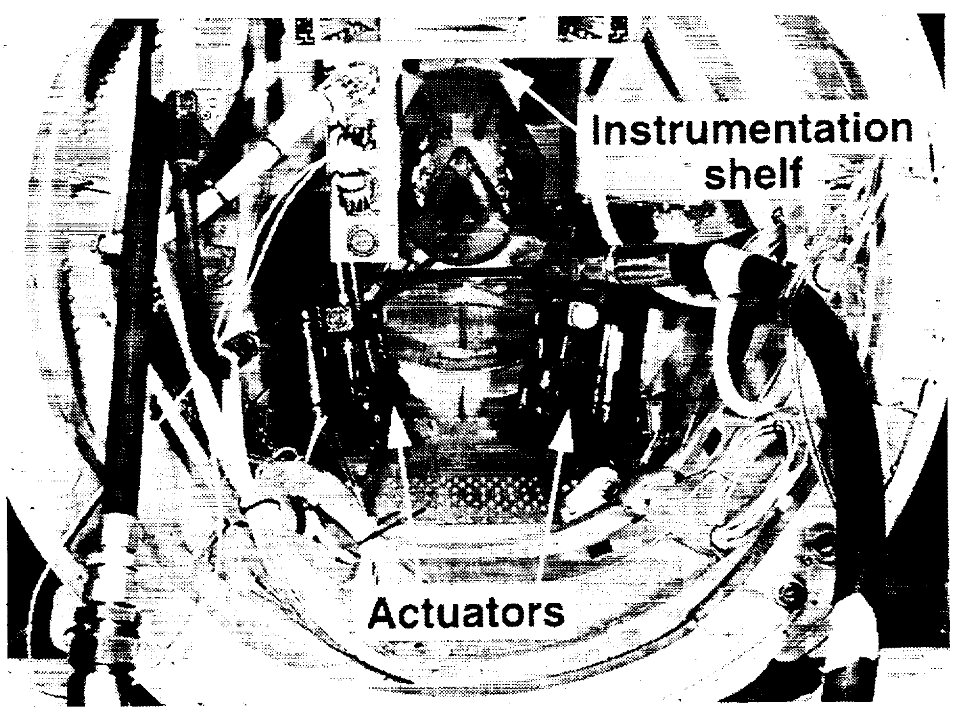
In addition to the existing instrumentation system on the HARV, the newly fabricated radome incorporates specific instrumentation required for the ANSER Flight Experiment. A total of 215 pressure orifices have been installed to provide surface pressure distributions around the radome, on the strakes, and on the nosecap. Assessment of radome structural loads and strake hinge moments will be provided by strain gauge measurements, and vibration information associated with the strakes will be obtained using accelerometers. In addition, a smoke port will be incorporated on each side of the radome and will be connected to the existing HARV smoke generating system to allow visualization of the forebody and strake vortex flowfields.

The total weight of the research radome, including all components and instrumentation, is approximately 263 lbs (radome structure and fairings at 134 lbs, two strakes at 19 lbs each, two actuators at 20 lbs each, and instrumentation at 51 lbs). It should be noted that no effort was made to minimize weight of the research hardware since, when integrated onto the HARV, the radome will be ballasted up to a total weight of about 615 lbs to maintain the desired aircraft center of gravity. For comparison, the weight of a standard F-18 composite radome is approximately 121 lbs. A more detailed description of the flight test hardware is presented in reference 8.



ANSER FLIGHT HARDWARE

The two photographs show various aspects of the ANSER flight hardware.

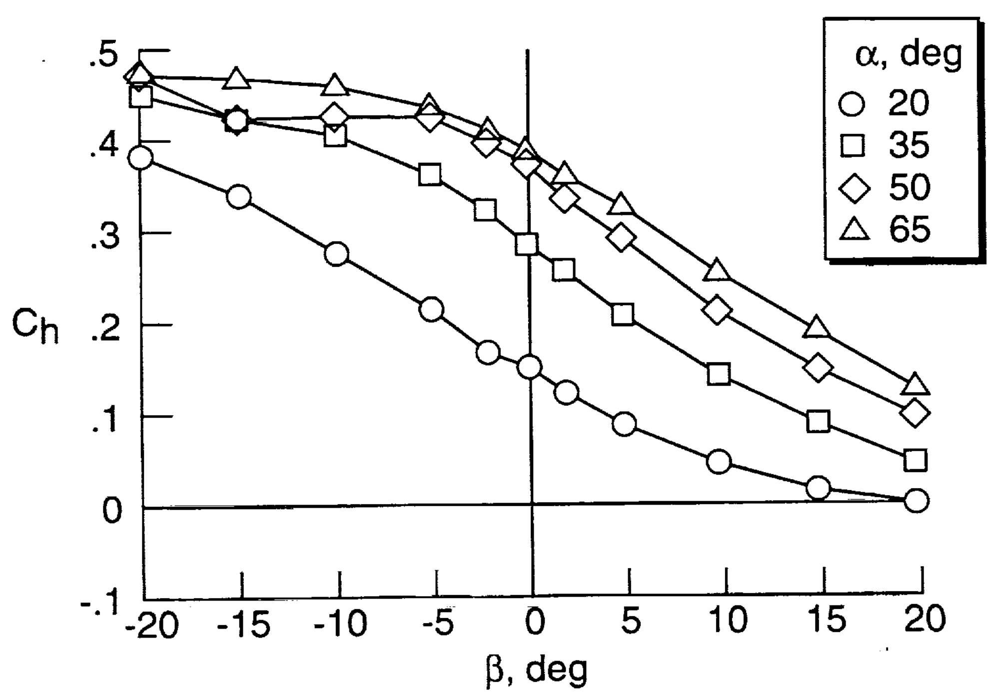


STRAKE HINGE MOMENT CHARACTERISTICS

Strake hinge moment measurements have been obtained during full scale F-18 forebody model tests in the Langley 30- by 60-Foot Tunnel and during full-scale F-18 airframe tests in the Ames 80- by 120-Foot Tunnel. All of the results have shown that the strakes produce maximum hinge moment coefficients at high angles of attack and sideslip with a full strake deflection on the windward side. An example of these results, shown in the figure, were obtained on a fully deployed left strake during full-scale F-18 forebody tests in the Langley 30- by 60-Foot Tunnel. Although the maximum hinge moment coefficient occurs at high angles of attack, the aircraft can only reach these conditions at relatively low dynamic pressures. When the dynamic pressure envelope of the aircraft is taken into account, the maximum hinge moment loads occur near an angle of attack of 20° and at relatively small sideslips. Under these conditions, the actuator force required to offset the hinge moment is approximately 1000 lbs.

With a projected area of 2.71 ft^2 (each), the strakes are much smaller than any other aerodynamic control surface on the F-18 HARV. For example, each F-18 aileron has an area of approximately 12.2 ft^2 and each rudder has an area of approximately 8.1 ft^2. The hydraulic actuators used to drive the strakes consist of F-18 aileron actuators that have been modified for longer stroke, higher rate, and less force capability. The strake actuators have a stroke of ±2.84 inches that provides each strake with a deflection of 0° to 90°. Based on the hinge moment measurements, the strake actuators have been designed to provide a rate capability of 180 deg/sec under the highest expected load (~1000 lb). This control surface rate allows a maximum strake deployment in 1/2 sec, which is the same time required for a maximum rudder deflection for this aircraft (30° deflection at 60 deg/sec).

STRAKE HINGE MOMENT
Full Left Strake Deflection
Full-Scale F-18 Forebody, LaRC 30 x 60



STRUCTURAL CONSIDERATIONS

A significant issue when integrating forebody controls on an aircraft involves the structural loads induced on the forebody. The strakes designed for the F-18 HARV, in general, produce much larger aerodynamic side forces on the forebody than would be obtained for the same flight condition without the strakes deployed. In addition, the anticipated higher maneuvering rates and accelerations provided by the strakes would be expected to induce larger inertial loads. In order to evaluate these structural considerations, a high-fidelity aerodynamic and inertial loads model for the forebody was incorporated into the existing HARV/ANSER simulation. The forward fuselage loads were then predicted through real-time piloted simulation where a wide matrix of maneuvers were flown that were expected to maximize the forebody loads.

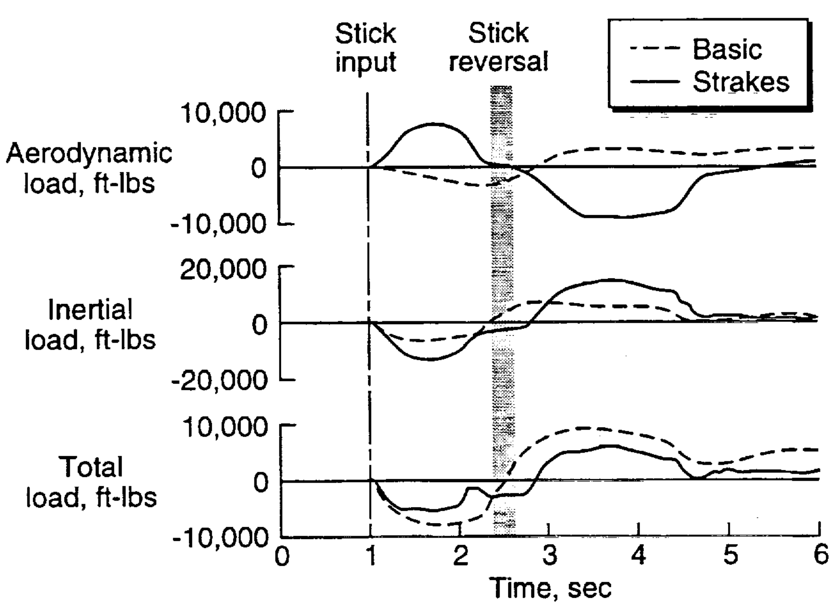
A typical example of the results from the loads simulation is shown in the figure for an initial condition of α=30°, M=0.5 and n_z=4.2. These results are presented as time histories of fuselage side bending loads for a maneuver consisting of a full right lateral stick input followed several seconds later by a full lateral stick reversal. The time histories show the aerodynamic, inertial, and total side bending load at fuselage station 190 (several inches in front of the canopy) during the maneuver, with and without the strakes operating. For the basic aircraft (with the strakes inactive), the aerodynamic load on the forebody opposes the direction of motion because of the sideslip generated by the maneuver. When the strakes are used for control, however, the result is a large aerodynamic load on the forebody in the direction of the maneuver. In both cases, the inertial loads act in the direction opposite the maneuver, but are higher with the higher accelerations provided by the strakes.

The net result, since the aerodynamic and inertial loads act in opposite directions, is that the total load on the forward fuselage is actually lower when using the strakes for control than with the basic radome. This result indicates that although the use of forebody controls can increase aerodynamic and inertial loads, the opposing nature of these loads can reduce or eliminate the need for a stronger aircraft structure and its inherent weight penalties.

FUSELAGE SIDE BENDING MOMENT

Full Lateral Stick Input and Reversal

α = 30°, M = 0.5, FS190



ANSER CONTROL LAWS

In addition to the actuated forebody strakes, the thrust vectoring control system that is currently being flown on the F-18 HARV will be retained during the ANSER Flight Experiment. Because of this, a versatile set of flight control laws have been developed that will allow several combinations of advanced control concepts to be compared directly with the basic F-18 capabilities. The control laws have been developed utilizing an advanced design methodology (ref 9) incorporating analytical synthesis techniques combined with nonlinear piloted simulation using the Langley Differential Maneuvering Simulator.

These flight control laws will be implemented using the existing Research Flight Control System on the F-18 HARV and will include 4 research modes: (1) control augmentation using strakes (including pitch thrust vectoring); (2) control augmentation using multi-axis thrust vectoring; (3) control augmentation using strakes and multi-axis thrust vectoring; and (4) a programmed strake mode. The first control law mode is designed to evaluate yaw-control augmentation using strakes only. Pitch thrust vectoring is used in this mode, however, to allow the aircraft to trim at higher angles of attack than possible with aerodynamic controls alone. The second control law mode (with strakes deactivated) is the same set of advanced thrust-vectoring control laws currently under evaluation on the F-18 HARV. This control law mode will be retained during the ANSER Flight Experiment to allow a direct comparison between strake augmentation and thrust vectoring augmentation. The third control law mode combines strakes and multi-axis thrust vectoring to provide the maximum potential agility. The fourth control mode is designed primarily to obtain aerodynamic data (control effectiveness, pressures, hinge moments, flow visualization) with varying strake deflections. This mode will allow pre-programmed deflections of the strakes and will use the thrust vectoring system to maintain a stabilized flight condition.

ANSER CONTROL LAWS

Mode	Flight Test Usage
• Strakes only (with pitch TV)	• Agility • Handling qualities
• Multi-axis TV	
• Strakes + Multi-axis TV	
• Programmed strakes	• Aerodynamic data

FLIGHT TEST PLANS

The primary objectives of the ANSER Flight Experiment are to provide flight validation of a ground-test data base for a forebody control device and to evaluate the use of this type of control in enhancing fighter aircraft maneuverability. One focus of the flight tests will be on obtaining aerodynamic measurements (strake control effectiveness, surface pressures, hinge moments, and flow visualization) for comparison with ground-test results. Another focus of the flight tests will be to evaluate the overall payoffs in agility and controllability obtainable with this type of control. A total of 60 to 70 flights are anticipated to accomplish the envelope expansion and research phases of the flight test program.

ANSER FLIGHT EXPERIMENT
Approach

- Obtain control effectiveness characteristics, pressures, hinge moments, and flow visualization

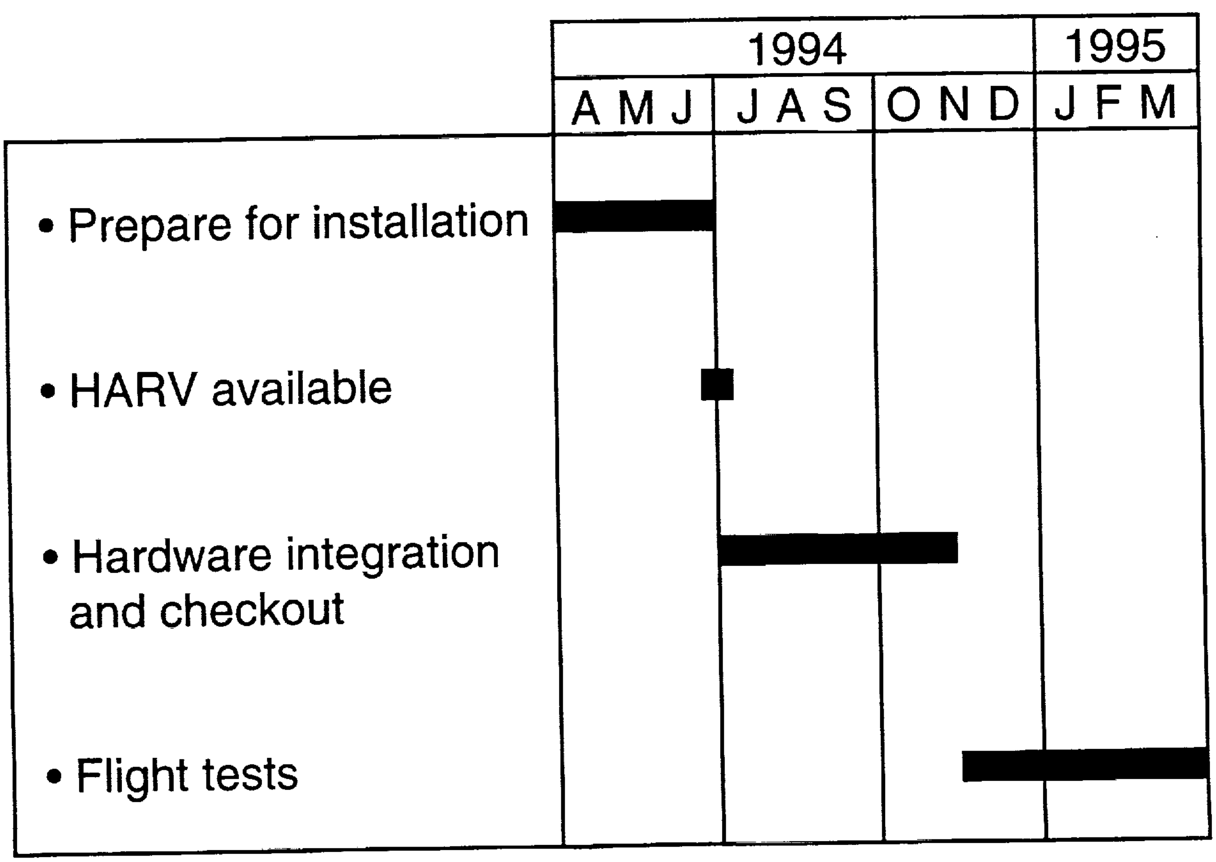
- Determine effects on aircraft response when using strakes for control and stability augmentation

PROJECT SCHEDULE

The flight hardware has been delivered to NASA Dryden where the preparations for integrating with the F-18 HARV are underway. Once the current flight test phase is completed, the aircraft will be available to begin the integration of the new research radome. This hardware integration is expected to begin by the latter part of June and continue through November 1994. Following this integration, several months of flight tests will be directed toward expanding the operational envelope of the F-18 HARV with the ANSER modification. The research flights will follow this period of envelope expansion and are expected to run through March 1995.

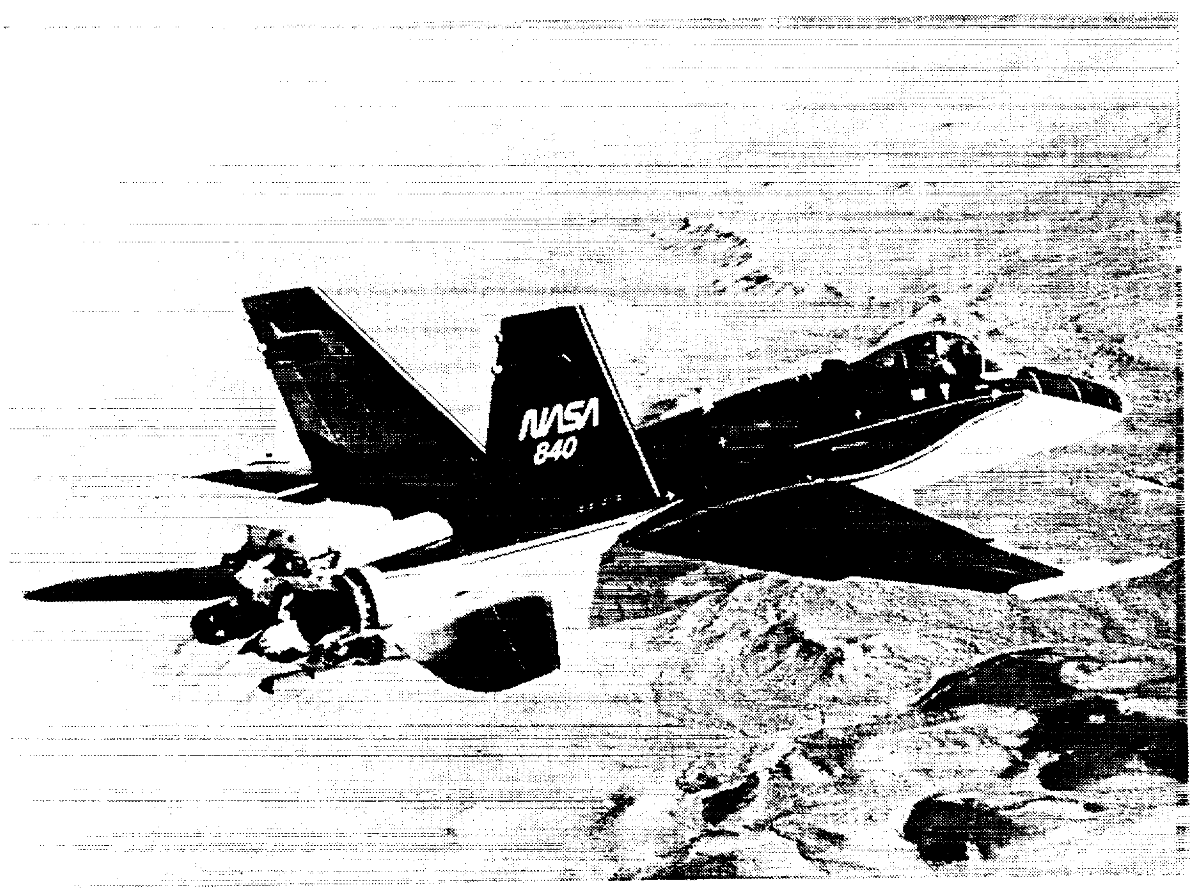
ANSER FLIGHT EXPERIMENT

Schedule



CONCLUDING REMARKS

A wide range of coordinated activities have been used to develop the actuated forebody strake control concept. Although directed toward a specific forebody control concept, these studies are providing an overall understanding of forebody controls characteristics and design implications. Favorable results from these efforts have provided confidence that the ANSER strake design will be a very effective yaw control device at high angles of attack, and can provide significant enhancements in maneuverability by providing the critical yaw control required to coordinate rolling maneuvers at these high-angle-of-attack conditions. The objectives of the flight tests using the F-18 HARV are to provide flight validation of the ground-based studies and to evaluate the use of forebody controls in enhancing fighter aircraft maneuverability. It is expected that the flight tests will begin during the latter part of 1994 and be completed in early 1995.



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