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ABSTRACT

This paper gives an overview of the NASA F-18 High Alpha Research Vehicle. The three flight phases of the program are introduced, along with the specific goals and data examples taken during each phase. The aircraft configuration and systems needed to perform the disciplinary and interdisciplinary research are discussed. The specific disciplines involved with the flight research are introduced, including aerodynamics, controls, propulsion, systems, and structures. Decisions that were made early in the planning of the aircraft project and the results of those decisions are briefly discussed. Each of the three flight phases corresponds to a particular aircraft configuration, and the research dictated the configuration to be flown. The first phase gathered data with the baseline F-18 configuration. The second phase was the thrust-vectoring phase. The third phase used a modified forebody with deployable nose strakes. Aircraft systems supporting these flights included extensive instrumentation systems, integrated research flight controls using flight control hardware and corresponding software, analog interface boxes to control forebody strakes, a thrust-vectoring system using external postexit vanes around axisymmetric nozzles, a forebody vortex control system with strakes, and backup systems using battery-powered emergency systems and a spin recovery parachute.

NOMENCLATURE

ANSER	actuated nose strakes for enhanced rolling
CRAFT	control power, robustness, agility, and flying qualities tradeoffs
DPRAM	dual-port random access memory
FCC	flight control computer
FS	fuselage station, in.
HAIRRY	High-Angle-of-Incidence Requirements for Roll and Yaw
HANG	High-Alpha Nosedown Guidelines
HARV	High Alpha Research Vehicle

HATP	High-Alpha Technology Program
KEAS	knots equivalent airspeed
LEX	leading-edge extension
MATV	Multi-Axis Thrust Vectoring
MDA	McDonnell Douglas Aerospace
NACA	National Advisory Committee on Aeronautics
NASA	National Aeronautics and Space Administration
OBES	on-board excitation system
PGME	propylene glycol monomethyl ether
RAV	remotely augmented vehicle
RFCS	research flight control system
SRC	spin recovery chute
STEMS	standard test evaluation maneuvers set
TVCS	thrust-vectoring control system
VISTA	Variable-Stability In-Flight Simulator Test Aircraft
α	angle of attack, deg
θ	radial nose angle, deg

INTRODUCTION

Interest in high-angle-of-attack flight has increased in recent years. High-angle-of-attack research has progressed from stall characteristics to spin resistance and is now in the area of poststall agility. To support this recent interest, NASA has developed the High-Alpha Technology Program (HATP). One of the objectives of this program is flight validation of ground-based design methodologies, and a modified F-18 aircraft was used to this end. This aircraft is called the NASA F-18 High Alpha Research Vehicle (HARV).

History: Missile Platforms to Departures to Air Combat Maneuvering and Agility

Research into high-angle-of-attack flight has waned and revived over the history of aviation (fig. 1).[1,2] High-angle-of-attack research has also changed over the years. Initially, high-angle-of-attack research was only concerned with stall characteristics. Research then evolved to departure and spin characteristics, and now concentrates on exploring the poststall region of the high-angle-of-attack envelope. Early jet aircraft emphasized high performance with classical metrics,

primarily speed and altitude. These aircraft were designed with little regard for flying qualities at high angle of attack, α, other than minimal attention to departure resistance. Aircraft that began as gun platforms moved towards missile platforms. The F-100 Super Sabre, the F-104 Starfighter, and the F-4 (née F-110) Phantom II aircraft are examples of this trend.

Figure 1. Interest level of high-angle-of-attack activity.

With a shift in emphasis back to air combat maneuvering from nonmaneuvering missile platforms during the Vietnam conflict,[3] initial emphasis shifted back to air combat training with existing aircraft. Development of aircraft to take advantage of high-α flight began later. Advances made in fly-by-wire and fully digital flight controls allowed some degree of confidence in using some of the high-α regime. The early examples of these aircraft were the F-16 and F/A-18 (née YF-17), and today are the JAS-39 Gripen, the Euro-Fighter 2000, and the F-22 Lightning aircraft.

NASA Formulation of the High-Alpha Technology Program

With this recent interest in high-α flying qualities in the aircraft community, NASA has emphasized high-α research as well, although NASA has always been interested in high-α flight.[4–7] Research conducted by NASA includes aileron rudder interconnects, thrust vectoring, and unconventional control surfaces to allow greater enhancements in high-α flight dynamics and solve classical problems such as wing rock, departure, nose slice, and high-α pitching-moment discrepancy.[8,9] Ground-based research on thrust vectoring has demonstrated the promise of being able to exert moments in corners of the envelope where aerodynamic forces and control

power are very low. Use of forebody flows for aircraft control at high α was also shown to have great potential.[10]

Three high-α flight programs started in the 1980's: the X-31A research aircraft,[11] the F-16 Variable-Stability In-Flight Simulator Test Aircraft (VISTA) Multi-Axis Thrust Vectoring (MATV) project,[12] and the NASA-sponsored HATP using the HARV.[4,5,7,13–17] Stated objectives of these programs were, respectively, demonstration of enhanced fighter maneuverability at poststall angles of attack with a controlled-configuration vehicle design; retrofit of thrust vectoring on an existing design to evaluate tactical usage of such a system; and a pure high-α research program to understand basic high-α aerodynamics, possible control law synthesis, innovative control effectors, inlet and engine integration research, and possible expansion of design guidelines.

All of the NASA aeronautics centers participated in the HATP, and the program was directed by a representative steering committee (fig. 2). NASA Ames Research Center contributed computational fluid dynamics and their 80- by 120-ft wind-tunnel facility.[18–21] NASA Langley Research Center worked with subscale wind-tunnel testing, advanced control law synthesis, and computational fluid dynamics.[10,22–26] NASA Lewis Research Center worked on inlet and engine integration.[27,28] NASA Dryden Flight Research Center conducted the flight research with the F-18 HARV.

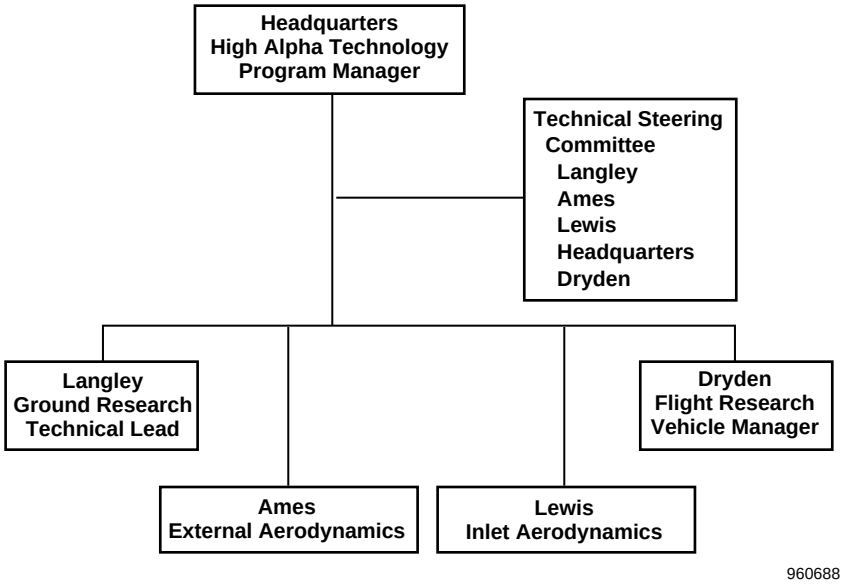

Figure 2. High-angle-of-attack technology program organization.

The aircraft selected was the full-scale development F-18 Ship 6, now called the NASA F-18 HARV.[7,17,29] Prior to use for NASA research, this F-18 airframe had been used for the high-α and spin testing of the F-18 configuration. To gain more redundancy than exists in fleet F/A-18 aircraft, a battery-powered emergency system had been installed in this particular airframe. This aircraft had also been previously fitted for a spin recovery chute (SRC). These special modifications for this particular airframe led to its selection. The aircraft was subsequently modified extensively to

include thrust vectoring, a unique instrumentation system, unique aircraft systems, additional emergency systems, a modified flight control computer,[29] and later, forebody strakes.

VEHICLE AND SYSTEM DESCRIPTION

The aircraft configuration is described below. The systems used on the HARV enabled the aircraft to perform different research missions. Many of these systems are introduced here, such as the SRC, the emergency power systems, the thrust-vectoring control system (TVCS), the research flight control system (RFCS), the forebody strake system, the simulation, and the remotely augmented vehicle (RAV) system.

High Alpha Research Vehicle

The HARV has had three configurations: the baseline F-18 configuration, the thrust-vectoring installation configuration, and the additional forebody vortex–flow control configuration (fig. 3). These three configurations correspond to the approximate phases of the flight tests and are discussed later in the paper. This large and ambitious flight test matrix was only possible with a phased approach to the program. The HARV is a full-scale development airframe of the F/A-18A aircraft and is a twin-engine, single-place, fighter/attack aircraft. The early aircraft used the F-18

EC89 62-1

(a) Phase one, no TVCS, no ANSER system.

Figure 3. HARV configuration for the three phases of the flight program.

EC91 0028-9

(b) Phase two, TVCS installed, no ANSER system.

EC95 43197-1

(c) Phase three, TVCS installed, ANSER system installed.

Figure 3. Concluded.

type designation, of which the HARV aircraft is one. Later, the U.S. Navy changed the type designation to F/A-18 to align the designation with the diverse roles of fighter and attack. The F-18 aircraft was built for the U.S. Navy by McDonnell Douglas Aerospace (MDA) (St. Louis,

Missouri) and the Northrop Corporation (Newbury Park, California). The HARV is powered by two modified General Electric (Lynn, Massachusetts) F404-GE-400 afterburning turbofan engines rated at approximately 16,000 lbf static thrust at sea level. The F-18 aircraft features a midwing configuration with a wing-root leading-edge extension (LEX) that extends from the forward portion of the fuselage and blends into the wing (fig. 4). Table 1 shows the HARV nominal

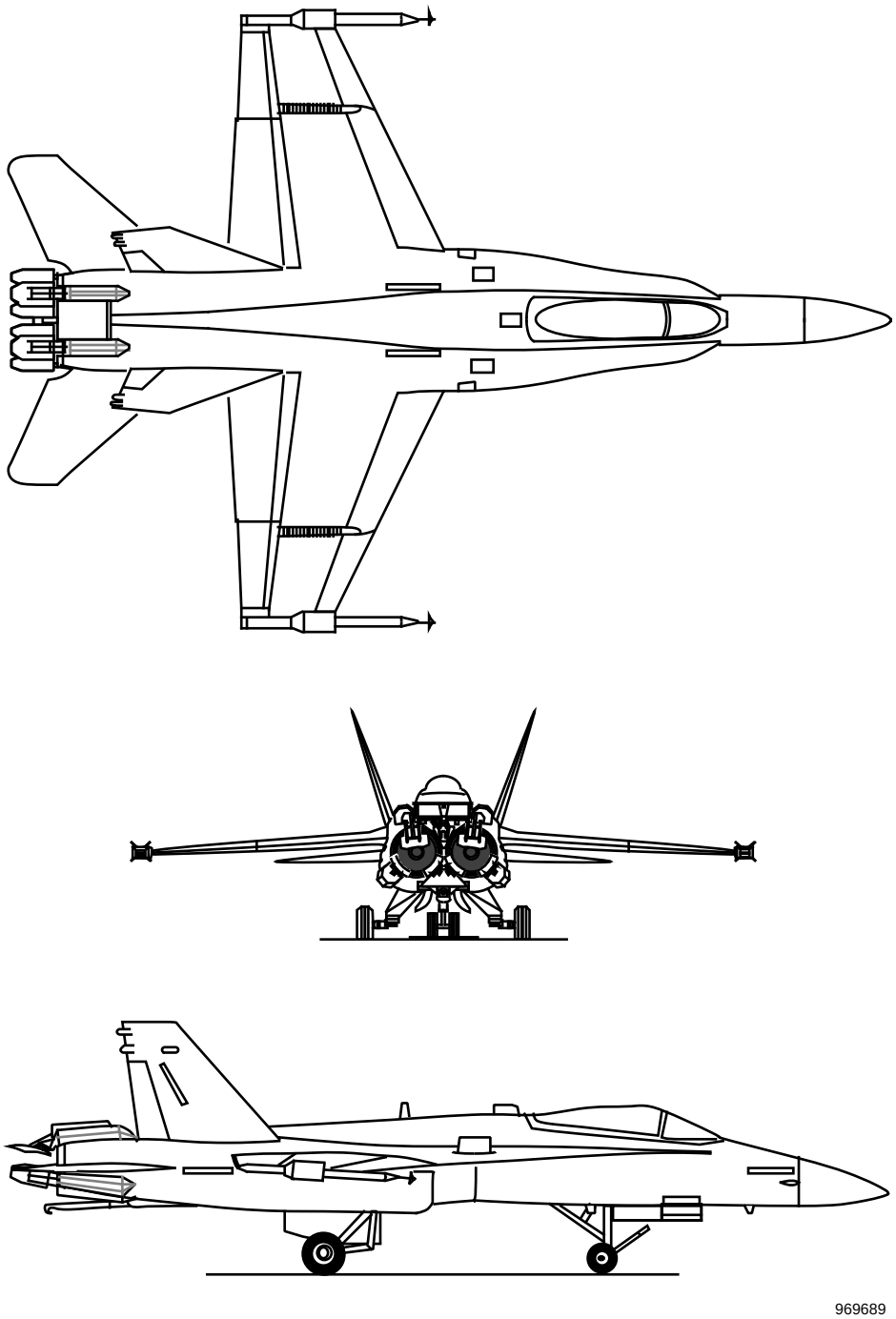

Figure 4. Three views of the HARV general layout (phase two TVCS configuration).

dimensions and weights. The flight envelope was also limited with the various systems on board the aircraft (fig. 5), although with the SRC installed and the center of gravity forward of 26.5 percent mean aerodynamic chord, the aircraft was not limited in α.

Table 1. Nominal dimensions of the NASA F-18 HARV. Internal fuel is 6480 lbm, which corresponds to approximately 60 percent fuel. The HARV is in the clean configuration, with landing gear retracted and pilot and support equipment included.

Parameter	Phase one	Phases two and three
Weight, lbm	31,980	36,099
Reference wing area, ft^2	400	400
Reference mean aerodynamic chord, ft	11.52	11.52
Reference span, ft	37.4	37.4
Overall length, ft	56	56
Center of gravity		
Percent mean aerodynamic chord	21.9	23.8
Fuselage station	454.33	456.88
Waterline	105.24	105.35
Roll inertia, slug-ft^2	22,040	22,789
Pitch inertia, slug-ft^2	124,554	176,809
Yaw inertia, slug-ft^2	139,382	191,744
Product inertia, slug-ft^2	–2,039	–2,305
Wing aspect ratio	3.5	3.5
Stabilator span, ft	21.6	21.6
Stabilator area, ft^2	88.26	86.48

The HARV carries no stores or missiles and is highly instrumented for research purposes. The wingtip launching rails and missiles were replaced with wingtip camera pods and airdata sensors. The in-flight refueling capability and tail arresting hook were retained; 24 flights were made with in-flight refueling, but the tailhook was never used.

For the first phase of the flight test program, the aircraft was flown in the baseline configuration as described above. In this configuration, the maximum attainable trim α was approximately 55°, limited by the maximum aerodynamic control. Most HARV modifications were internal for this phase of the program and consisted mostly of an extensive instrumentation system for recording research aircraft parameters of interest. Also incorporated in this phase were onboard systems to emit an evaporating dye, propylene glycol monomethyl ether (PGME), to mark on-surface

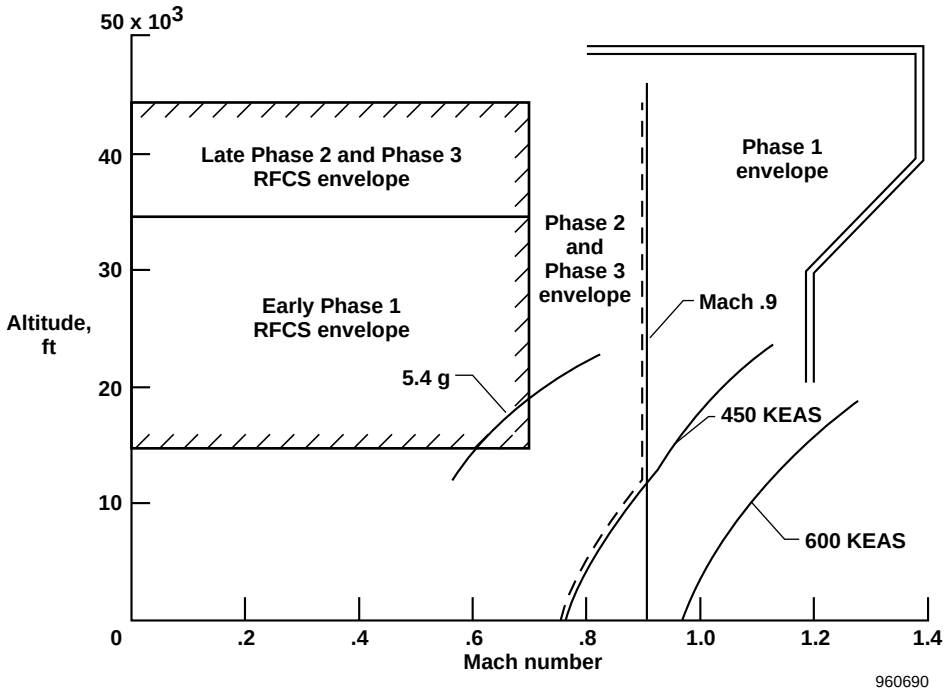

Figure 5. HARV envelope.

forebody streamlines,[30] and smoke to trace off-surface flows around the forebody and the LEX vortices.[31–35] Later, the ports used for the PGME were plumbed to pressure instrumentation so that extensive pressure surveys could be made of the aircraft forebody. Early in this phase a noseboom was installed and calibrated for airdata. The noseboom was known to interfere with forebody flows, so wingtip airdata probes mounted on wingtip pods were fabricated and calibrated so that the noseboom could subsequently be removed. A rotating rake was installed on the LEX to measure vortex characteristics for a few flights.[36] Late in the first flight phase, an SRC was installed on the aft fuselage of the aircraft to prepare for the upcoming thrust-vectoring flights.

Near the end of phase one, vertical longitudinal fences were installed on each LEX upper surface. These fences were developed as a modification to the U.S. Navy F/A-18 aircraft to reduce tail buffeting and increase structural life. Because of the desire to maintain a consistent external geometry for aerodynamic research with established ground and flight aerodynamic data bases, these fences were generally not used during aerodynamic characterization research on the HARV aircraft. An aerodynamic evaluation of these fences was conducted, and they were used for most of the TVCS and the actuated nose strakes for enhanced rolling (ANSER) research with controls, flying qualities, propulsion, and handling qualities.

Also incorporated near the end of the phase one flight test program, in preparation for phase two, was a set of battery-powered emergency backup systems. These battery-powered systems were to power the hydraulics, electronics, and electrical systems of the aircraft in the event of a dual-engine flameout. These systems were from the original U.S. Navy spin testing of the aircraft.

The second phase of the flight test program was centered on the TVCS. Six paddle-like vanes were positioned, three around each engine, so that they could impinge on the exhaust flow and create thrust vectoring. With these vanes functional, an additional 15° of trim α are available to a maximum 70° α.

The conventional F-18 flight control system was modified to include an RFCS and the capability to command the thrust-vectoring vane actuators. The RFCS was an embedded computer executing research flight control laws that could be engaged and disengaged by the pilot within a limited envelope. The RFCS control laws and F-18 701E computer (General Electric, Lynn, Massachusetts) control laws operate in parallel; both computed continuously throughout the flight. The conventional F-18 control laws were used for takeoff, for landing, and as a backup in case of RFCS failure. The second set of control laws was a research control law set.[37] The hardware to accommodate this dual set of flight control laws resulted in one of the single largest changes ever incorporated in F-18 flight control computers (FCCs). During this phase, the aircraft underwent a second major downtime to make an extensive modification to instrumentation, including an inlet rake in the right engine.[27]

The final flight phase of the HARV project emphasized forebody vortex–flow control. A modified forebody was fabricated at NASA Langley with mechanically actuated strakes. NASA Langley also designed the control laws to control the forebody control surfaces. The strakes are the aerodynamic surfaces of the ANSER system, but some extensive internal changes, both hardware and software, were made as well. An analog interface box was required to perform fault detection and control of the actuators for the strakes. When the RFCS was designed, the intent was to only control the six vanes of the TVCS, but the addition of the strakes for the ANSER system required two new command paths out of the FCCs, which required the analog interface box. The control law release was also called ANSER. NASA Ames had proposed an alternative concept using slot blowing.[38–40] The project could only take one concept to flight, and the NASA Langley actuated strake was selected as a more mature technology than the other concepts.

Data Acquisition and Research Instrumentation

The instrumentation system used for data acquisition changed greatly over the course of the life of the aircraft. The original instrumentation system provided aircraft attitudes, rates, center-of-gravity and cockpit accelerations, angular accelerations, α, angle of sideslip, multiple total and static pressures, aerodynamic surface pressures, total temperature, stick and rudder-pedal forces and positions, control surface positions, fuel quantities, strains, temperatures, and discretes such as switch positions. Wingtip probes that provided research airdata were updated from a National Advisory Committee on Aeronautics (NACA) probe configuration to a free-swiveling self-aligning probe configuration, although the tip retained a similar configuration to the NACA probe tip. A second instrumentation system was added to obtain 1553 bus data from the FCCs, mission computers, inertial navigation system and other remote terminals, aerodynamic surface pressures, aeroservoelastic accelerometers, nose and wing flush airdata sensing pressures, engine pressures, strains, temperatures, and discretes such as nose strake interface box status bits. Thrust-vectoring vane loads and critical temperatures were added for phase two, and additional forward fuselage

loads, interface box parameters, and nose strake instrumentation were added for the third phase of the flight program. Each of these systems was telemetered with no recording on board the aircraft. A research inlet rake was installed in the right inlet duct (fig. 6), and a third system was provided to obtain the inlet research data. In order to avoid a third telemetry stream, the third system was digitally recorded on board.

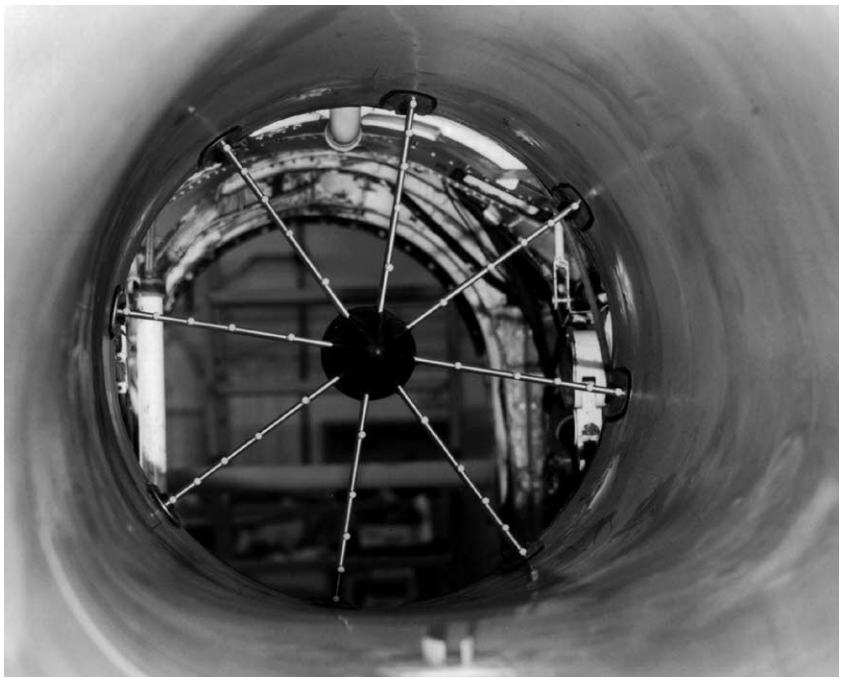

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Figure 6. Instrumented inlet rake installed in the right inlet (looking aft).

Maximum data rates were as high as 2142 samples/sec and as many as nearly 2000 parameters. Control room displays were planned in advance to optimize monitoring scans, for familiarization, and to maximize potential flight research time. Examples shown are of the spin page, as used by the mission controller during high-α and high-yaw-rate maneuvers (fig. 7), and the flightpath reconstructor used by flight mechanics researchers to monitor aircraft motions and state during parameter identification maneuvers (fig. 8).[41]

Spin Recovery Chute

An SRC was added to the aircraft late in the first phase. This system was a significant modification to the aerodynamics of the aircraft. The SRC system was previously used by MDA and the U.S. Navy for the spin testing done in the full-scale development testing of the F-18. This system was reinstalled to reduce the amount of validation required of the flight control software for high-α flight. High-α velocity-vector rolls with thrust vectoring, which were planned, were anticipated to appear exactly identical to spins in conventional aircraft.[42] The SRC installation was

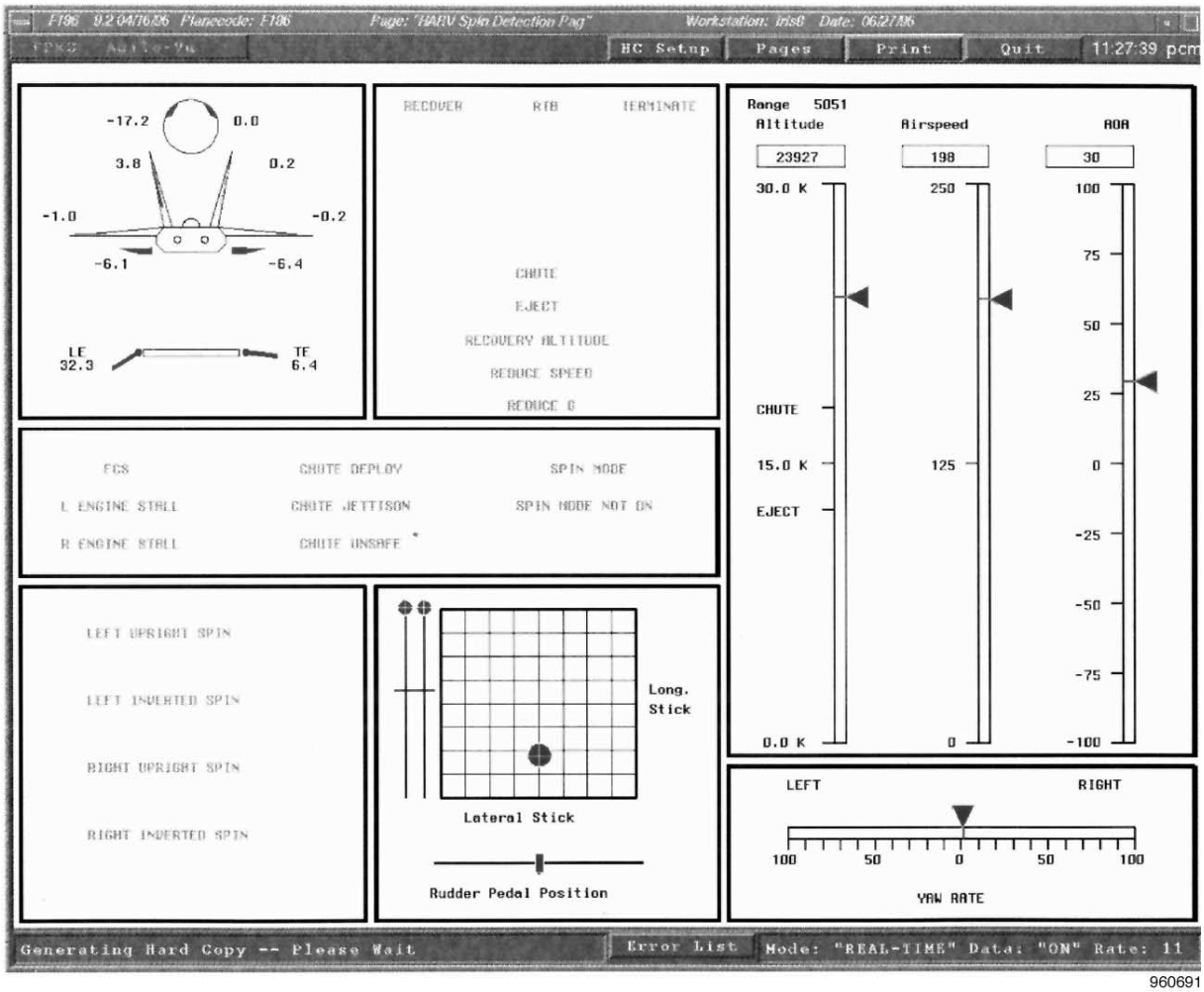

Figure 7. Mission controller spin page display for monitoring high-α and high-yaw-rate maneuvers.

done as further risk reduction in the event of a failure of the thrust-vectoring system and the subsequent failure of conventional control-recovery techniques. The aircraft limitations with the SRC installed were Mach 0.9 and 600 knots equivalent airspeed (*KEAS*). The system was never fired in flight, but was test-fired during a high-speed taxi test (fig. 9). Flight test during phase two proved the aircraft could recover using control surfaces during low and oscillatory spin modes, control law down modes (reversion from RFCS control laws to 701E computer control laws) at peak yaw rates of velocity-vector roll to simulate failures and recovery, and control law down modes with maximum aggravated control inputs during velocity-vector rolls.

During phase three, simulation studies revealed that asymmetric strake failures at high *g* and high α (40°–55° α) resulted in unacceptable recovery characteristics. A positive strake closure system was designed, and the SRC was retained for all of phase three. When envelope expansion of each phase was complete, however, the SRC system was found to be of lessening importance, but no method was found where its deletion could be made, even after envelope expansion. Operationally, the SRC consumed a great deal of time—time that could have been better spent on research tasks had the SRC been removed from the aircraft.

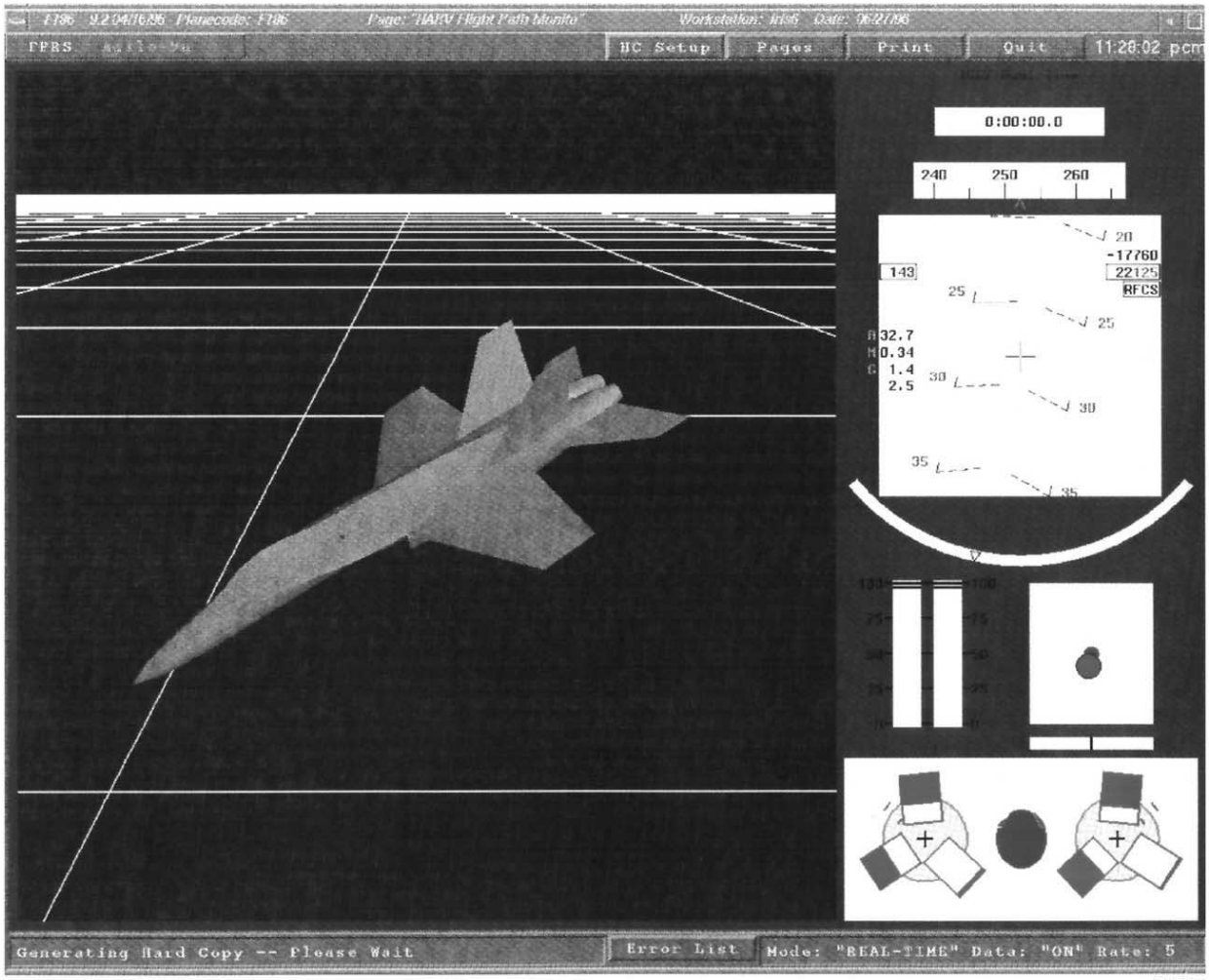

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Figure 8. Flightpath reconstructor as used by flight mechanics researchers during parameter identification maneuvers.

Emergency Power Backup Systems

Battery-operated emergency power systems were installed in the aircraft at the end of phase one in preparation for phase two. These systems were previously used in the full-scale development spin tests, reducing certification time for the HARV application. The intent of these systems was to continue aircraft systems operation in the event of a dual-engine flameout or unrecoverable dual-engine stalls. If called upon, the emergency power system provides power for FCCs, mission computers, inertial systems, and airdata computers. Additionally, the batteries power a hydraulic pump to provide hydraulic pressure to the aircraft control-surface actuators. The system was modified from the U.S. Navy spin flight configuration by increasing battery capacity, and power could be maintained for approximately 14 min using continuous maximum control-surface motions. At the end of phase two, the project team concluded the aircraft envelope had been sufficiently cleared out so that the emergency system could be removed without excessive risk, and

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Figure 9. Spin recovery chute as installed and demonstrated.

that the useful life of the system had been run. The emergency power system was removed. This decision was based on the excellent record of 0 unintentional engine stalls during 277 high-α flights. A total of 383 high-α flights was made with 0 unintentional engine stalls.

The TVCS was primarily a mechanical system of three high-temperature nickel steel vanes, or paddles, installed around each engine. As existing structure and the SRC of the aircraft had to be considered, the vanes were not equally spaced around the engines or equally sized (fig. 10). Extensive heat shielding was required to prevent excessive temperatures from impinging on the systems and aircraft in the aft fuselage area. These minor variations in spacing and sizing resulted in a slight asymmetry to the thrust-vectoring effectiveness control power.[43–46] This implementation

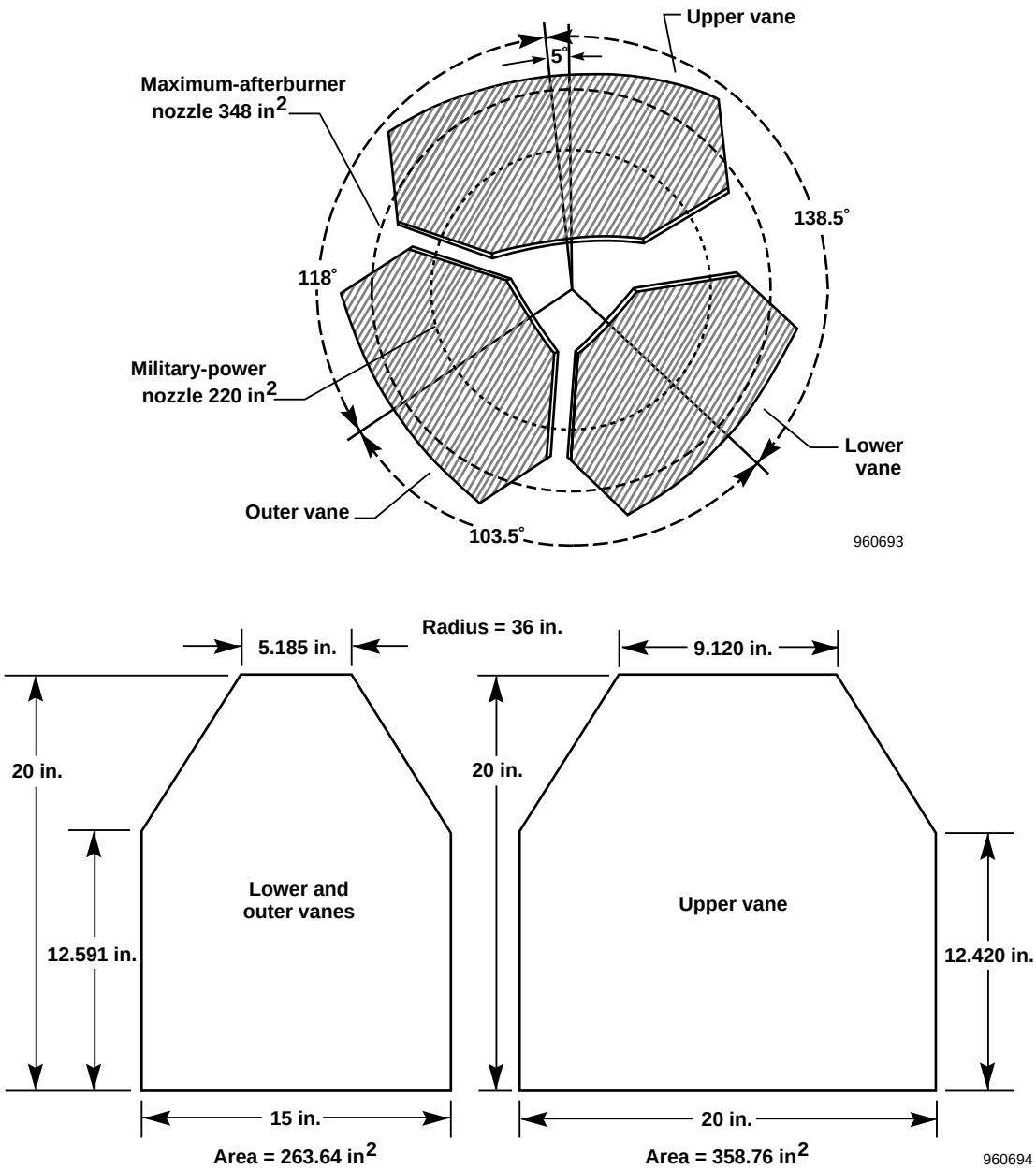

Figure 10. Thrust-vectoring vane geometry, end view (left engine looking forward) and vane platforms.

of a TVCS was intended only as a research system. No effort was expended on making the system more than a boilerplate operational system to allow research to be gathered, because maintenance is intensive on such a system and useful life of the system was expected to be short.

With the TVCS and SRC installed, the project had to contend with a large weight and balance problem. The installation of the TVCS increased the weight by 2200 lbm. The addition of the SRC, emergency systems, and ballast* increased the weight by an additional 1500 lbm, and 419 lbm was added by equipment and wiring not directly related to the TVCS.

With this additional weight, the inertia values were approximately 50 percent greater than the previous flight-tested maximum for the interdiction mission. As a result, the maximum symmetric *g* allowed was reduced to 5.4 and –2.0. During asymmetric maneuvering, the aircraft was limited to between 4.3 *g* and 0 *g*. In addition, the weight distribution acted as a pitch damper and was perceived as a time delay to the pilot when flying exceptionally high gain tasks.

Failure in these cases was anticipated in the aft cockpit canopy sill area near fuselage station (*FS)* 300, possibly hampering ejection, so instrumentation strain gages were installed and monitored for the remainder of the program. Installation of the TVCS limited maximum speed to 450 *KEAS* on the HARV aircraft. These *g* and airspeed limitations were the results of analysis only; no extensive flight envelope clearance was done in the program. The system might have been capable of a much greater performance envelope than was used had there been a such requirement.

Research Flight Control System

In order to control the six new control surfaces, a modification was made to the FCCs.[7,47] The Pace 1750A (Performance Semiconductor Corp., Sunnyvale, California) FCCs were modified to incorporate a dual-port random access memory (DPRAM) and RFCS (fig. 11). The purpose of the DPRAM was to pass parameters back and forth between the 701E computers and the RFCS. The purpose of the RFCS was to allow rapid changes and reduced development time for experimental control laws of the unique control effectors in the high-α envelope. For the most part, the RFCS flight control software was designed to be class B software and not flight critical. As such, the verification and validation of the RFCS flight control software was greatly streamlined, allowing rapid changes to be effected in the event of unexpected research results. This class B capability of the FCCs made the aircraft a very flexible and capable research tool, where different systems could be flown and compared back-to-back with other systems on an aircraft of a known configuration. Changes of this sort were done many times in the course of the program, and this innovative approach and execution greatly aided in gathering timely and effective research data. Having a dedicated research team in place that could rapidly handle changes provided a very flexible approach to problem solving. Parts of the control law executive and some limit functions were deemed flight critical, and thus were isolated in the software and tested according to class A standards.

*To maintain an acceptable center of gravity, a total ballast of 893 lbm was added to the forward fuselage.

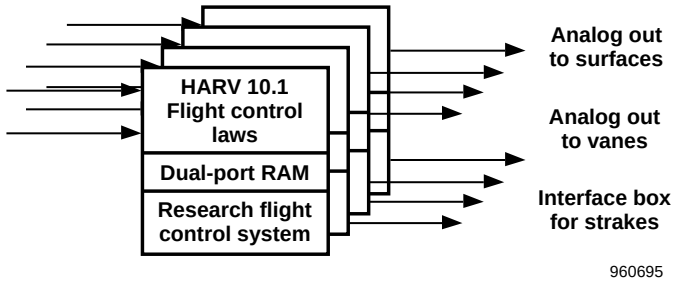

Figure 11. Flight control computers incorporating a research flight control system.

During phase one, the 701E computers had carried the then-current fleet production 8.3.3 flight control law release by MDA. With the RFCS upgrade, the 701E computers were updated to the new release of the fleet production MDA 10.1 F-18 release. The RFCS control laws would be engaged within certain envelope restrictions imposed by the flight control law software. The envelope for RFCS flight was restricted to less than Mach 0.7, a minimum altitude of 15,000 ft mean sea level, and an initial maximum altitude of 35,000 ft mean sea level that was later expanded to 45,000 ft mean sea level. Because of potential errors in the flight software within the RFCS control laws, the 701E computer control laws were always retained as a backup. Any RFCS anomalies that might threaten the aircraft would be mitigated by reverting to the 701E computer control laws. As figure 11 shows, the basic F-18 control system retained control over all input and output signal management functions, including commands to the thrust-vectoring vanes. When the RFCS was not engaged, the basic system commanded the vanes to a fixed, retracted position of –10 deg. A solenoid-latched switch was installed on the instrument panel to arm the system, and the nosewheel steering switch on the stick was selected to engage the RFCS. To disengage, the pilot activated the paddle switch to revert to 701E computer control laws. All control laws used a programmable fade to prevent instant gain changes. Later, the Pace 1750A processors were upgraded to the Pace 1750AE configuration.

Research functions were also implemented in the mission computers and selectable through the digital-display interfaces. These research functions included the synthesis of some control system feedbacks not available in the standard F/A-18 aircraft, as well as unique research displays used by the HARV pilot. These displays in the head-up display included fixed reticles for tracking tasks, vertical lines for target gross acquisitions during tracking, and displays to annunciate the aircraft control mode. Another part of the flight software was the on-board excitation system (OBES). Software in the OBES held preprogrammed research and envelope expansion maneuvers and could perform frequency sweeps, doublets, or even act to degrade control power for individual or multiple surfaces. The OBES was used for flutter envelope clearance,[48] control power research studies,[49] and aerodynamic[41,50–54] and control law parameter identification research.[25]

Forebody Strakes

For the third and final phase in the HARV flight test project, a set of ANSER was installed on the forebody of the HARV.[10] These strakes were designed with a longitudinal hinge line to actively

control the forebody vortices and separation lines (fig. 12), which allowed roll control at high α to be performed.[55] The strakes were designed and tested by NASA Langley and installed and flown at NASA Dryden. Control laws were also designed by NASA Langley to control the strakes. The ANSER required that two additional control-surface commands be brought from the FCCs. Initially, it was thought that the TVCS or two vanes would have to be deactivated because of the limited actuator analog input/output available from the FCCs. This deactivation would not allow back-to-back comparisons of the TVCS and ANSER or of an integrated ANSER–TVCS mode. Finally, the FCC motherboard cards were modified, which allowed commands to be tapped out of the DPRAM and into an analog interface box. The interface box is required to perform all the fault detection and actuator control that is normally done by the FCCs.

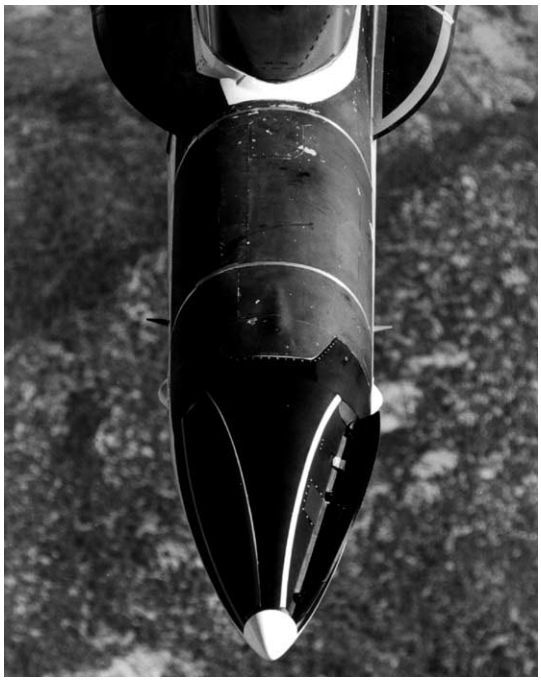

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Figure 12. Forebody vortex control strakes installed on the HARV.

Simulation

Simulations were an important component of the project support and research infrastructure. The batch version of the simulation was the most basic, followed by a fixed-base cockpit with software simulation, then a hardware-in-the-loop simulation with varying levels of hardware, and finally a full iron-bird F-18 with complete hydraulics and actuators for all surfaces except for leading- and trailing-edge flaps. The fixed-base cockpit could also use a large screen visual display mounted in front of the cockpit. Many of the components in the cockpit are flight-rated hardware, such as the up-front controller, the head-up display, and the digital-display interfaces. The hardware-in-the-loop simulation used FCCs, an interface box, and simulated actuator models. The mission computers were used in all fixed-base simulations.

The simulation aerodynamic model used was the MDA F-18 aerodynamic model. The aerodynamic model reflected results obtained from flight testing. To this model, NASA added the pitching-moment increments, drag increment, and directional-stability increment caused by the SRC installation; rudder control power increment caused by thrust vectoring in the pitch plane; and aerodynamic interaction caused by thrust vectoring.[16] Rotary balance data were investigated but were not used. The comparison of spins from flight data with simulation data indicated that the incorporation of rotary balance data with the MDA aerodynamic model would result in excessive damping in the simulation. This simulation facility was built at NASA Dryden and dedicated almost exclusively to the HARV project.

NASA Langley also made extensive use of their differential maneuvering simulator for control law evaluations and development. Project pilots made extensive use of the differential maneuvering simulator during the early development cycle of control laws that were eventually used in flight evaluation[10,56] and the maneuver development that subsequently improved the results and efficiency of the flight test. The Patuxent River Naval Air Test Center (Lexington Park, Maryland) dome simulation was used to evaluate power approach with various failures of the TVCS. This evaluation was not repeated for the forebody strake phase of flying because the strakes were ineffective at the low angles of attack (less than 15° α).[10]

Remotely Augmented Vehicle System

The RAV capability was also incorporated on the HARV.[57] This system allowed uplink control of the instrument landing system needles and other indicators used to guide the pilot to precise flight conditions. Otherwise, excessive pilot workload caused by the high-α environment might prevent accurate research maneuvers from being accomplished. A photographic still camera on the right wingtip of the aircraft could be triggered from a console on the ground using the RAV system as well. The RAV system and simulation facilities were closely aligned and exemplify the well-founded infrastructure that aided the ability of the project to gather data in the most efficient manner possible.

RESEARCH PHASES

Because of the large research program to be performed, a staged research and instrumentation approach was taken (fig. 13). Each flight phase was used to perform specific research. The three phases are described in the following subsections.

Phase One

Phase one consisted mostly of aerodynamic research. Some preliminary work for the TVCS was performed by controls and propulsion.

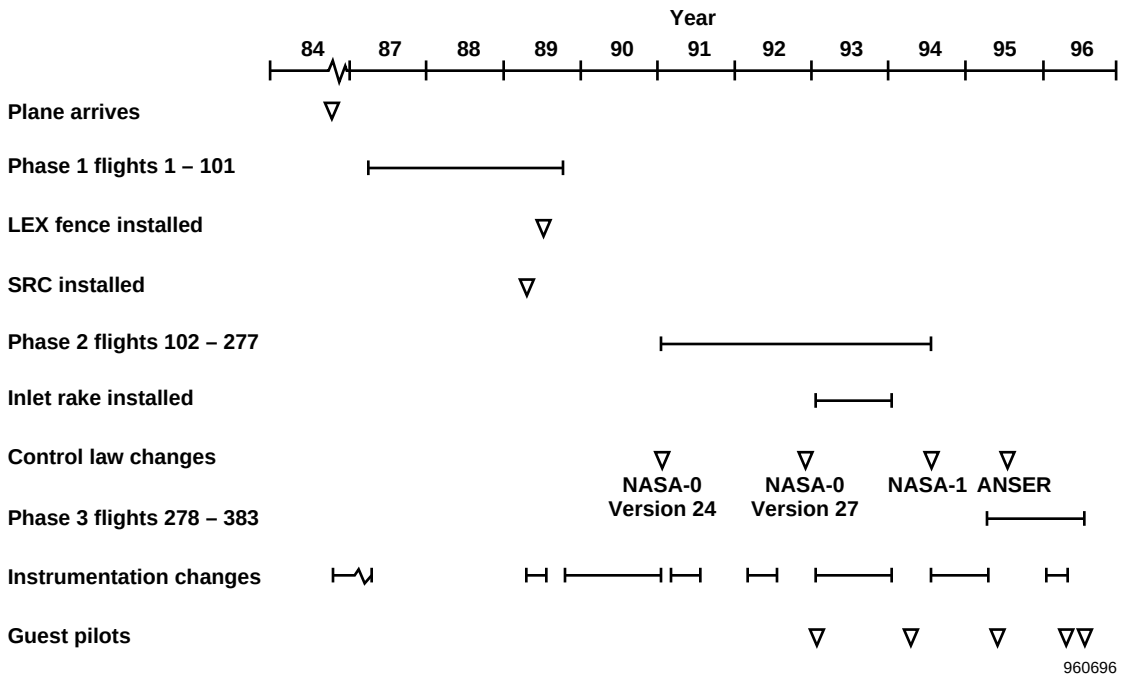

Figure 13. HARV research phase chronology.

Aerodynamics

Aerodynamic research dominated in phase one (fig. 14). Specific aerodynamic experiments performed included extensive flush-port pressure surveys over the forebody and the LEX of the aircraft, on- and off-surface flow visualization, LEX vortex surveys, and wing rock surveys. The forebody pressure data allowed characterization of forebody vortex footprints over the HARV aircraft.[58–61] Research using these data included flush airdata sensing[62–66] and wing rock at high α, and provided baseline data for comparison to wind-tunnel and computational fluid dynamics results.[39] Photographs of PGME traces (on-surface flow visualization) were also used for comparison with computational fluid dynamics and wind-tunnel results.[67] One result was the discovery of a laminar separation bubble on the forebody that allowed fine-tuning of some computational fluid dynamics codes and an interpretation of wind-tunnel results; results comparisons are excellent (fig. 15). The LEX survey rake data allowed characterization of the LEX vortex for comparison to light-sheet wind-tunnel and computational fluid dynamics data (fig. 16). The smoke system allowed off-surface flow visualization of the LEX and forebody vortices. The system also allowed comparisons of vortex burst point and vortex interaction patterns with wind-tunnel and water-tunnel data. Wing rock was extensively documented in this phase of the program with the smoke systems, forebody pressures, and flight mechanics instrumentation.

Controls

Baseline data were gathered in the control discipline with the HARV control system. This work was performed in preparation for the thrust-vectoring work in phase two. Principle interest was in the FCCs and the 1553 bus, both of which required modification for the thrust-vectoring flight tests.

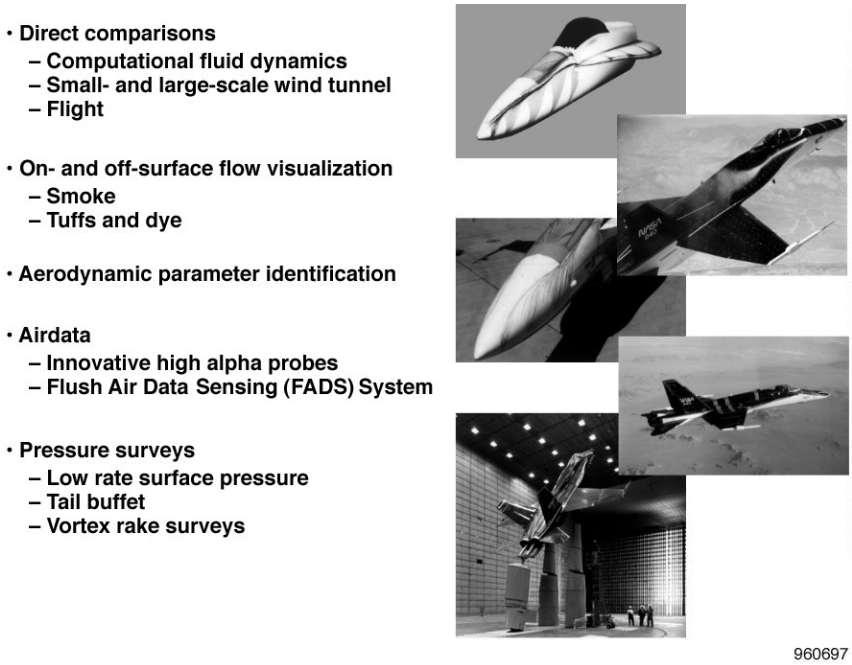

Figure 14. Aerodynamic research.

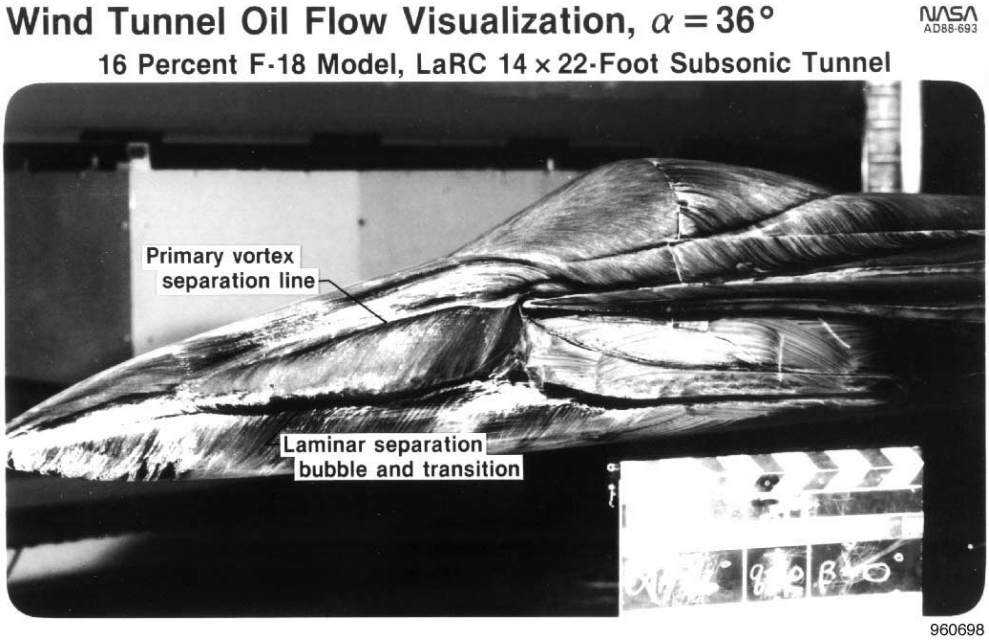

Figure 15. Forebody flow visualization in wind tunnels and flight with significant laminar flow and separation.

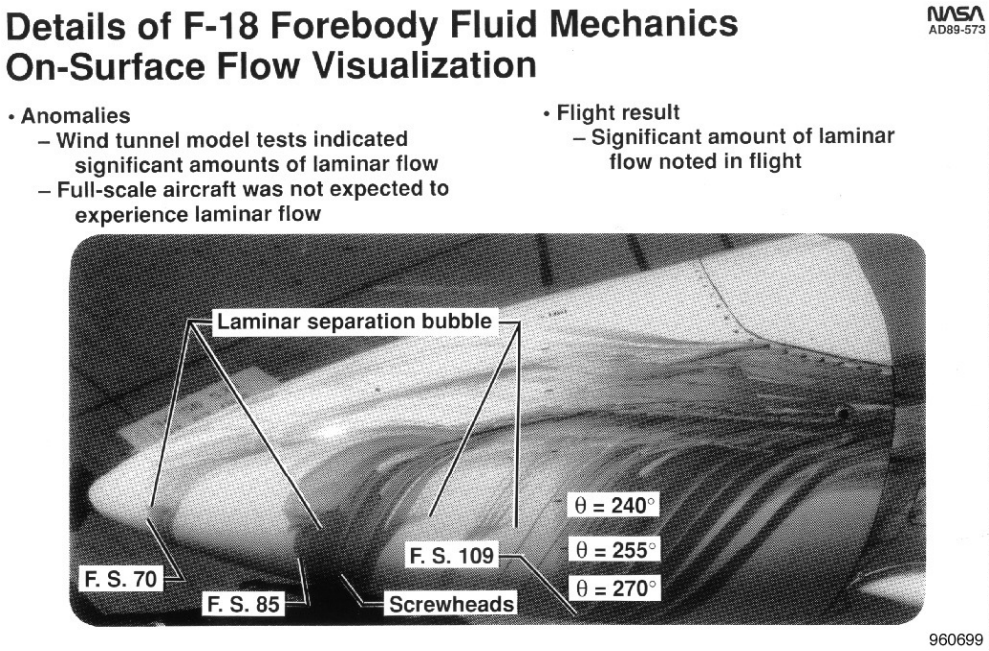

Figure 15. Concluded.

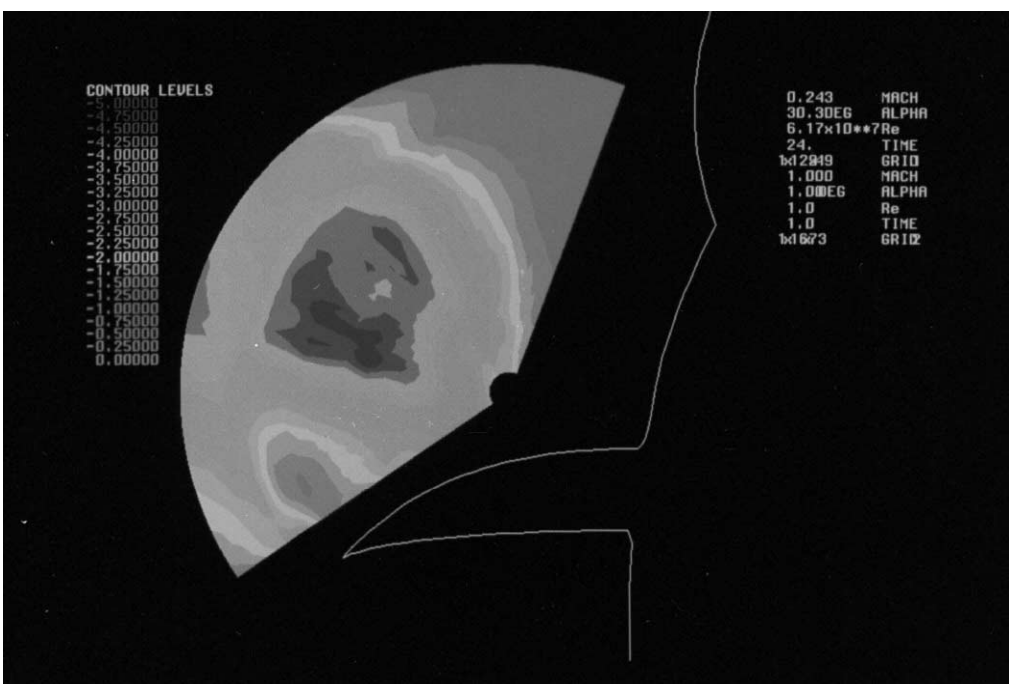

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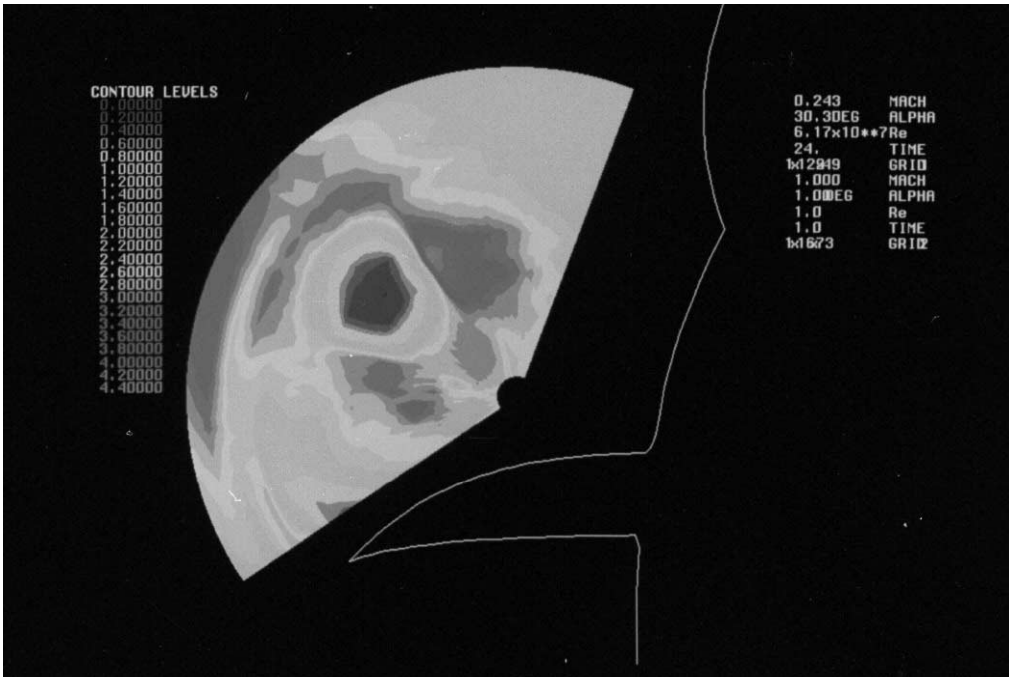
Figure 16. Leading-edge extension vortex survey rake results.



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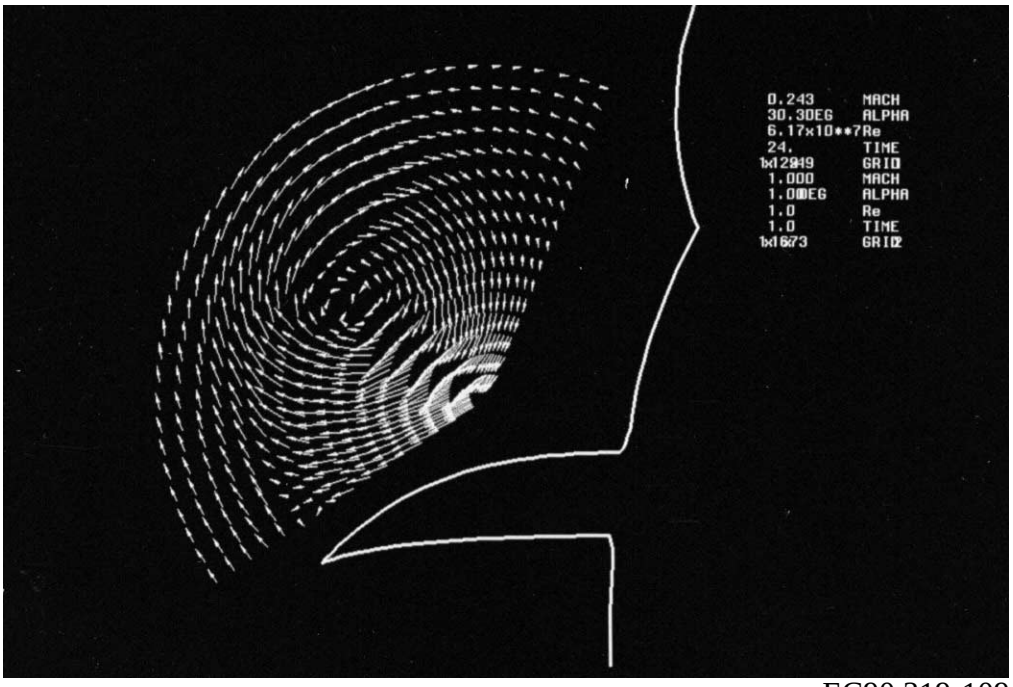

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Figure 16. Concluded.

Propulsion

Baseline data were gathered in the propulsion discipline with the HARV systems in preparation for the thrust-vectoring work in phase two. Principle interest was in the area of baseline data on engine characteristics used to create a thrust estimator for controls work with thrust vectoring.

Phase Two

Phase two of the flight program concentrated mostly on thrust-vectoring controls and propulsion, although some aerodynamic research was still conducted. Initially, 25 different experiments were vying for flight time in this phase. Many of these experiments were deleted after prioritization of experiments, and only those most applicable to the HATP were selected for flight.

Aerodynamics

Aerodynamic research in phase two obtained LEX and forebody data as before but at higher α conditions possible because of the TVCS capability. Wing, aft fuselage, and left vertical-tail pressure surveys were also obtained during this phase.[21] High sample-rate dynamic pressures were measured on the right vertical tail for tail buffet research (fig. 17). The tail buffet data were taken with the LEX fences both installed and removed for vortex-tail interaction studies and were compared with full-scale wind-tunnel and computational fluid dynamics data.[68,69] The OBES, installed with the RFCS for this phase of flying, allowed comparison and evaluation of three different techniques of aerodynamic parameter identification.[41,50–54] These techniques were an OBES-programmed sequential single-surface doublet series, an OBES-programmed input to a single surface, and a RAV-programmed optimal pilot-flown series.

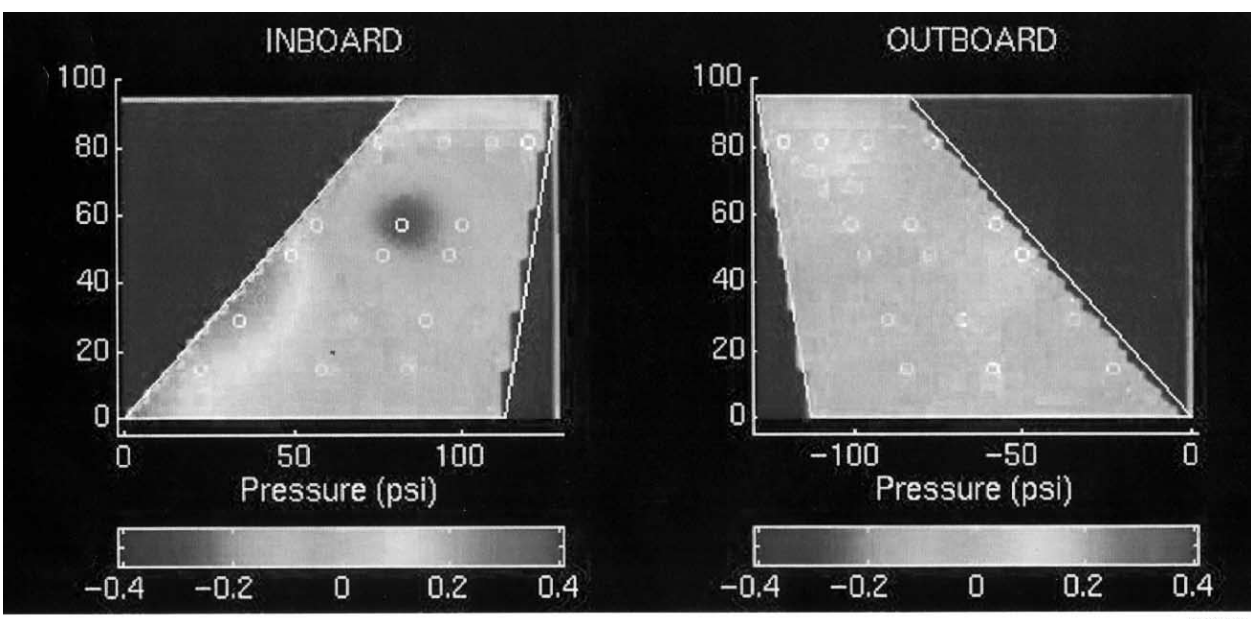

Figure 17. Tail buffet data from flight. Mach = 0.6; α = 30°.

Controls

Controls research came to the forefront during phase two (fig. 18).[70] The addition of the TVCS and the associated changes to the aircraft systems caused great changes to operation of the flight test. The added control power of the TVCS eliminated the transient wing rock in the 38°–45° α region (fig. 19). Seven different control design methodologies were used for TVCS operation.

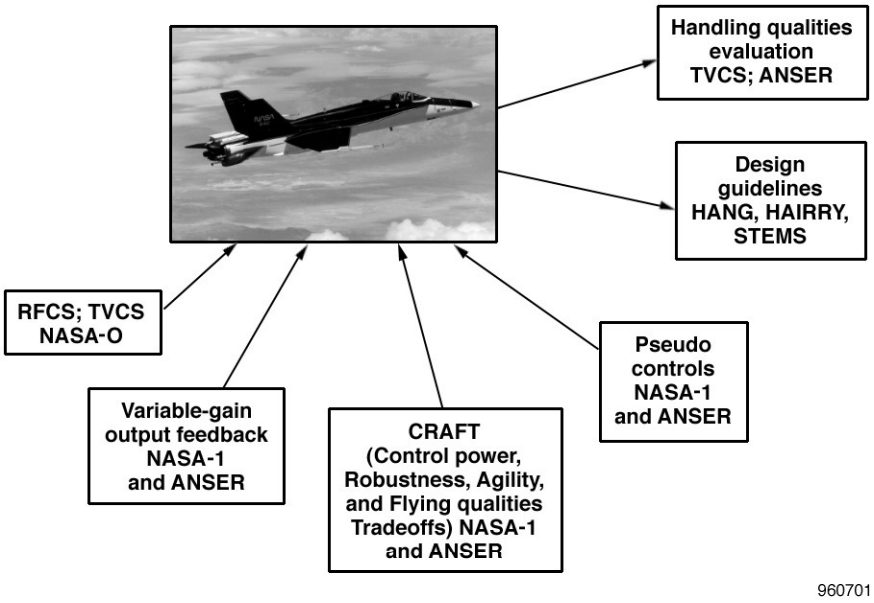

Figure 18. Controls research.

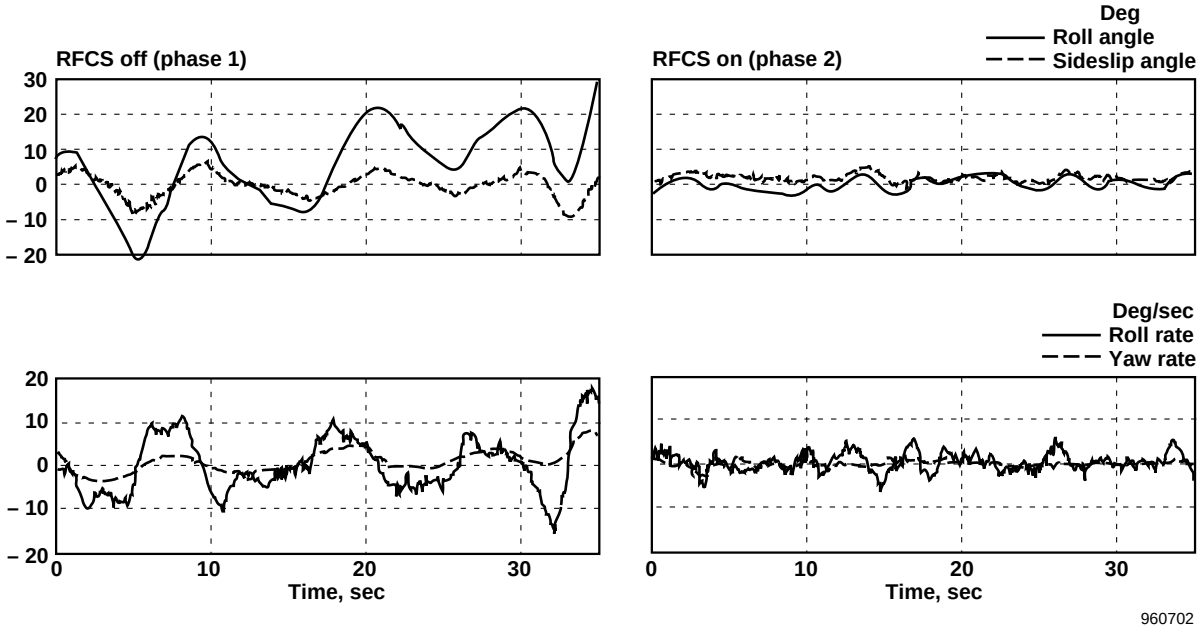

Figure 19. HARV dynamic motion at 40° α without the TVCS (phase one data) and with the TVCS (phase two data).

Regardless of design methodology, the longitudinal control laws used α command at high angles of attack. In all cases, the α command began to blend well before the maximum lift α was reached. Where the crossover occurred depended upon the individual control law. At low angles of attack, the longitudinal control laws are conventional blends of pitch-rate command and normal-force command. Because of program constraints, pitch-rate command control law architectures at high angles of attack were not investigated.

The lateral axis commanded wind-axis roll rate. Directional control commands varied between control laws from pure angle-of-sideslip command to stability-axis roll rate. In every case, the control laws were designed to be flown "feet on the floor." Many pilots, although not all, expressed dissatisfaction with this scheme for yaw control at high angles of attack.

The first control law was the initial control law set, referred to as NASA-0[71] and originally provided by MDA as a part of the TVCS modification. The initial set was later modified by the NASA Langley, MDA, and NASA Dryden team. The NASA-0 control law used a longitudinal model-following design and an eigenstructure assignment design in the lateral–directional axes. This control law also used a schedule for mixing pitch and yaw commands to the TVCS vanes, referred to as Mixer 1.[37] Because much of the high-α maneuvering proposed for the HARV looks like "controlled-spin" conditions, a down mode from the RFCS to the basic flight control system during these maneuvers would satisfy the built-in spin mode logic, and an immediate spin recovery would be initiated. As a result, yaw rate–expansion flights (spins) were flown as a part of the envelope expansion of the NASA-0 control law and the TVCS. Seventy-five spin attempts (at flight idle and military power settings) resulted in 70 fully developed spins. Low and oscillatory spin modes were investigated with yaw rates varying from 25 deg/sec to as high as 90 deg/sec (left and right). This yaw-rate expansion gained confidence that the SRC would not be required to recover the aircraft from a spin and resulted in the SRC never being fired in flight. During phase two, NASA Langley developed a control law, called NASA-1, as a precursor to the later TVCS and ANSER control law.[25,26] The NASA-1 control law, and later the ANSER control law, used a technique called variable-output feedback gain to design the longitudinal axis.[72,73] An eigenstructure-assignment design procedure known as control power, robustness, agility, and flying qualities tradeoffs (CRAFT)[26,74] was used in the lateral–directional axes in combination with a control power allocation technique called pseudo controls.[75] In addition, NASA-1 and ANSER control laws used Mixer 4.2[76] to control the TVCS vanes. The experience gained with the NASA-1 control law as risk reduction for the ANSER control law was extremely positive. The OBES allowed variation in surface rates and limits to vary control power for evaluation of various levels of pitch recovery in a NASA Langley–led research task called High-Alpha Nosedown Guidelines (HANG).[49] Later, a similar set of evaluations was made in lateral–directional variations called High-Angle-of-Incidence Requirements for Roll and Yaw (HAIRRY).[77]

Guest-pilot programs were occasionally flown during the course of the program. Some of these guest-pilot programs were limited in scope, such as demonstration of the aircraft capabilities; others were more extensive and produced significant findings in control power effectiveness[78] and flying qualities.[77] Guest pilots had a large role in the HARV project, especially near the end of the program. The HARV project also saw some turnover of pilots because of the length of the program. This turnover resulted in a large cross section of piloting technique in evaluation of the aircraft that was further augmented by the guest-pilot pool (table 2).

Table 2. Pilots of the NASA F-18 High Alpha Research Vehicle.

	Organization	Agency
Project Pilots		
Einar Enevoldson	Dryden	NASA
Ed Schneider	Dryden	NASA
Bill Dana	Dryden	NASA
Jim Smolka	Dryden	NASA
Mark Stucky	Dryden	NASA
Phil Brown	Langley	NASA
Guest Pilots		
Dave Prather	Patuxent River	U.S. Navy
Chuck Sternberg	Patuxent River	U.S. Navy
Ric Traven	Patuxent River	Canadian Air Force
Billie Flynn	F-16 MATV	Canadian Air Force
C. J. Loria	Patuxent River	U.S. Marine Corps
Dan Griffith	Defense Research Agency	United Kingdom
Larry Walker	McAir	McDonnell-Douglas
Jeff Peer	F-16 VISTA	CalSpan
Rogers Smith	Dryden	NASA
Greg Fenton	Patuxent River	U.S. Navy
Bob Roth	Patuxent River	U.S. Navy
Tom McMurtry	Dryden	NASA
Gordon Fullerton	Dryden	NASA
Dana Purifoy	Dryden	NASA

Validation flights of a proposed high-α MIL-STD-1797A guideline were also made by using basic fighter maneuvers and some limited air combat maneuvering. This maneuver series is called the standard test evaluation maneuvers set (STEMS).[79]

Propulsion

During expansion of the high-α envelope with the TVCS, a concern was raised regarding the possible stall margin of the General Electric F404 engines. During phase one, no problems had been encountered, but with the increased α in phase two, the precaution was taken of adding a bias in the "T56" feedback. The T56 parameter is a temperature feedback sensed between stations 5 and 6 in the engine, and adding a bias to this feedback results in greater stall margin than exists without it. The bias was three-position selectable: no bias, 40 R in the medium position, and 85 R in the high position. During the envelope expansion, no unintentional engine stalls were encountered, and the T56 bias was never required during any of the flight testing.

Part way through phase two, the right engine and inlet of the HARV aircraft were extensively instrumented.[27] Flush static ports and high-rate pressure sensors were installed in the inlet lip and down the duct. The highly instrumented inlet rake was installed just forward of the right engine compressor face at this time. The data from these instruments were recorded on board the HARV aircraft. A high rate of digital data recording was used in the hope of capturing an engine stall during high-α dynamic maneuvering flight. During steady-state flight, no engine anomalies had been recorded; to capture an engine compressor stall, military power setting spins were flown to 90 deg/sec yaw rate. In these maneuvers, several self-recovering pop-stalls did occur, and the data were successfully captured (fig. 20). During this phase, investigations were also made into planar waves (organ pipe effect), and research continued in engine diagnostics and real-time thrust measurement. At the end of phase two, the inlet rake and most of the inlet instrumentation was removed.

Phase Three

Phase three had primary emphasis on forebody vortex control,[38] called the ANSER system. The program lead for this phase was NASA Langley, with NASA Dryden providing support in implementation of the ANSER system in the flight program.

Actuated Nose Strakes for Enhanced Rolling

Controls research for the ANSER system helped to evaluate the benefits and tradeoffs with regard to thrust vectoring, strakes, and combinations of the two. By using the same control law design synthesis as NASA-1 and making mode and gain selection available to the pilot through the digital-display interfaces, direct back-to-back comparisons were performed to quantify these differences. The control law was a development and expansion of the previously flown NASA-1 control laws.[26] Three modes were available to the pilot with this system. These three modes were a thrust vectoring–only mode, a thrust-vectoring mode in longitudinal control with a thrust-vectored and strake-blended mode for lateral control, and a strake mode with thrust-vectoring control longitudinally and strakes controlling the lateral mode. Additional OBES-programmed maneuvers were flown to investigate internal closed-loop control law parameters for identification to help characterize the overall system performance of the ANSER controls and the aircraft.

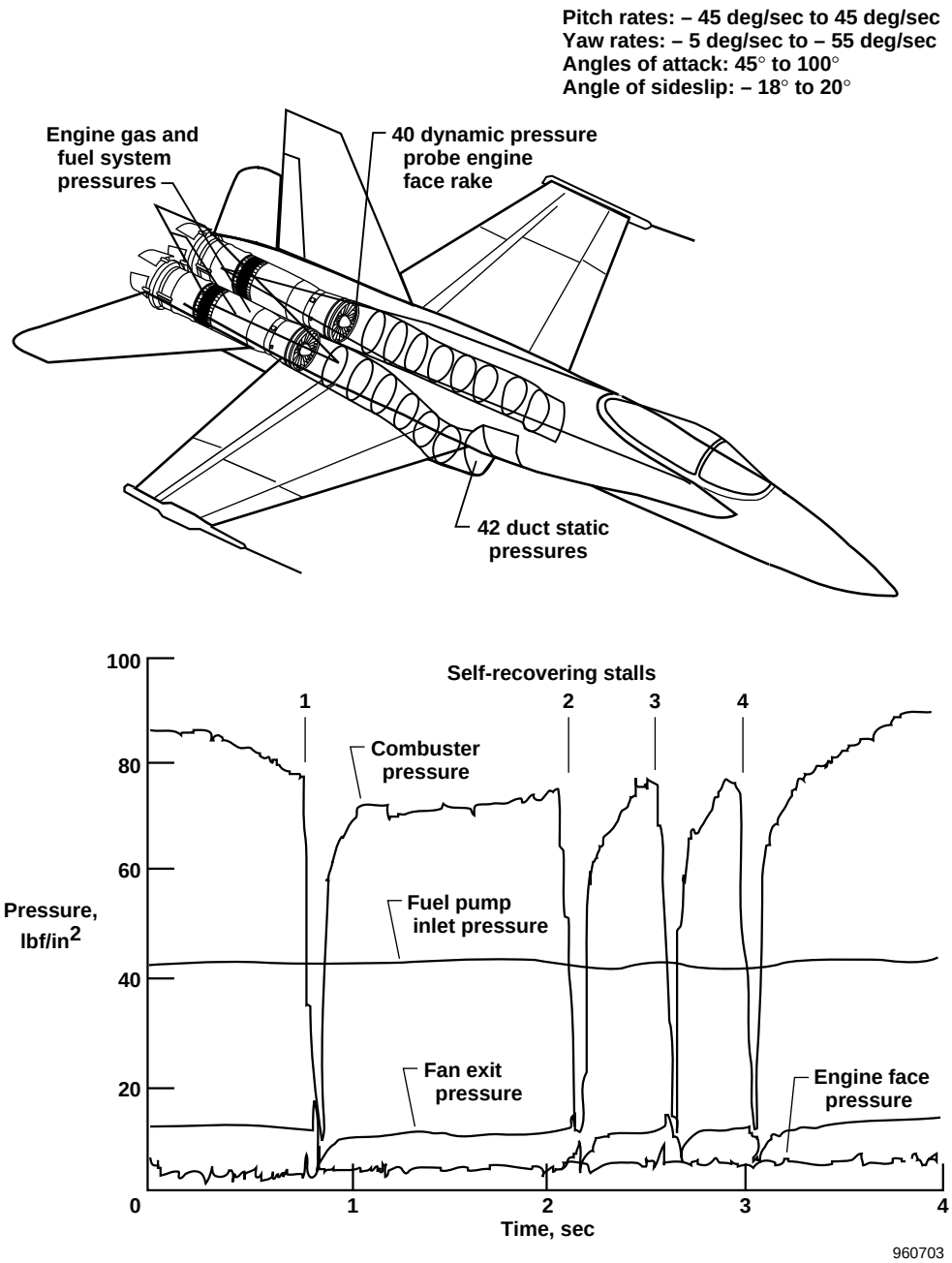

Figure 20. Rake and inlet on right side, in-flight compressor pop-stall time history.

Aerodynamics

Forebody pressures were used to characterize effects of forebody vortex control.[10,55] Additional pressure ports were installed on the strakes to measure integrated forces and moments and to examine areas of separation and the vortex footprints on the forebody. The smoke system was used again, and effects of forebody vortex rollup into the stronger LEX vortices were quantified. One result of the smoke visualization tests was the reduction of the vortex coherence to 4 or 5 body lengths of the aircraft behind the strake. Comparison of the strake vortex path with wind-tunnel and

water-tunnel results has shown the flight and wind-tunnel data agree well. The strake vortex is approximately one vertical-tail height above the tips of the vertical tails. The water-tunnel results indicate the strake vortex passes between the tips of the vertical tails (fig. 21). Some OBES-programmed aerodynamic parameter identification maneuvers were also flown to verify wind-tunnel and computational fluid dynamics predictions regarding the effectiveness of the strakes.

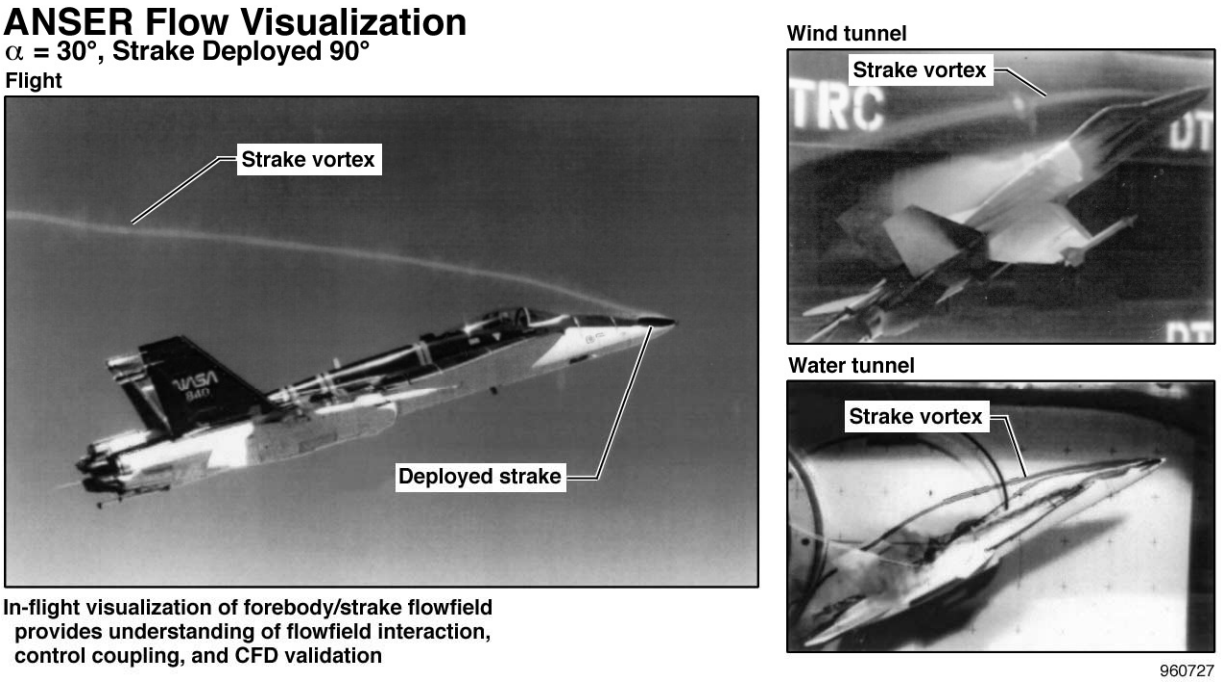

Figure 21. ANSER forebody vortex control comparisons.

Controls

Controls research in phase three concentrated on the ANSER control laws. An evaluation of the STEMS flying qualities was also made,[79,80] and a short study of falling-leaf characteristics of the HARV configuration was flown. These maneuvers may be used in a MIL-STD-1797A release to evaluate aircraft flying qualities. The HARV investigation is the most complete of the STEMS evaluations yet flown. The STEMS evaluations were performed with ANSER control laws flown back-to-back with the 701E computer control laws as a control. The ANSER control laws allowed the variation in control effectors and compared forebody strake vortex control with thrust-vectoring and basic F-18 aerodynamic control. The intent was to evaluate the ability of the maneuver to discriminate the high-α flying qualities differences between the augmented unconventional control and baseline aircraft.

CONCLUDING REMARKS

The NASA F-18 High Alpha Research Vehicle (HARV) project, as a part of the NASA High-Alpha Technology Program (HATP), has proven to be a flexible, capable research tool to investigate the high-angle-of-attack regime with particular emphasis in the areas of aerodynamics, propulsion, control law research, and handling qualities. Many of these capabilities were essential to the performance of the project and to the extensive body of research produced by the program.

The effectiveness and timeliness of the project were greatly aided by innovative thinking and execution. The aircraft was an excellent tool for research in many areas because of a well-founded infrastructure, significant research instrumentation, a flexible approach to problem solving, and a dedicated research team. The research base incorporated into the HARV project and the HATP spanned all major aeronautics centers within NASA.

Two major mechanical systems were developed. The first system was the thrust-vectoring control system. These vanes were intended as an add-on research system only, hence their boiler-plate and maintenance-intensive nature. Emergency backup systems, which were risk-reducing in envelope clearance, proved to have a limited useful life that was designed into the program schedule. The research instrumentation was kept separate from the aircraft systems so that parallel work could be performed on instrumentation and aircraft systems. The second system was the actuated nose strakes for enhanced rolling control laws. These control laws were also designed as a research system for forebody vortex control. The spin recovery chute was also found to have a limited useful life within the program, but no provision for its deletion was ever made.

The three flight phases of the project staged intensive research into different parts of the schedule, allowing for completion of a very ambitious research program. Aerodynamics dominated the first phase of the research flights, and controls and propulsion dominated phase two. The third and final phase of the flight research was primarily in forebody vortex control, although significant work was also done in various control law synthesis techniques and flying qualities evaluations.

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13. ABSTRACT (Maximum 200 words)
This paper gives an overview of the NASA F-18 High Alpha Research Vehicle. The three flight phases of the program are introduced, along with the specific goals and data examples taken during each phase. The aircraft configuration and systems needed to perform the disciplinary and interdisciplinary research are discussed. The specific disciplines involved with the flight research are introduced, including aerodynamics, controls, propulsion, systems, and structures. Decisions that were made early in the planning of the aircraft project and the results of those decisions are briefly discussed. Each of the three flight phases corresponds to a particular aircraft configuration, and the research dictated the configuration to be flown. The first phase gathered data with the baseline F-18 configuration. The second phase was the thrust-vectoring phase. The third phase used a modified forebody with deployable nose strakes. Aircraft systems supporting these flights included extensive instrumentation systems, integrated research flight controls using flight control hardware and corresponding software, analog interface boxes to control forebody strakes, a thrust-vectoring system using external postexit vanes around axisymmetric nozzles, a forebody vortex control system with strakes, and backup systems using battery-powered emergency systems and a spin recovery parachute.

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