AN OVERVIEW OF CONTROLS AND FLYING QUALITIES TECHNOLOGY ON THE F/A-18 HIGH ALPHA RESEARCH VEHICLE

Joseph W. Pahle and Keith D. Wichman
NASA Dryden Flight Research Center
Edwards, CA

John V. Foster and W. Thomas Bundick
NASA Langley Research Center
Hampton, VA

ABSTRACT

The NASA F/A-18 High Alpha Research Vehicle (HARV) has been the flight test bed of a focused technology effort to significantly increase maneuvering capability at high angles of attack. Development and flight test of control law design methodologies, handling qualities metrics, performance guidelines, and flight evaluation maneuvers are described. The HARV has been modified to include two research control effectors, thrust vectoring, and actuated forebody strakes in order to provide increased control power at high angles of attack. A research flight control system has been used to provide a flexible, easily modified capability for high-angle-of-attack research controls. Different control law design techniques have been implemented and flight-tested, including eigenstructure assignment, variable gain output feedback, pseudo controls, and model-following. Extensive piloted simulation has been used to develop nonlinear performance guidelines and handling qualities criteria for high angles of attack. This paper reviews the development and evaluation of technologies useful for high-angle-of-attack control. Design, development, and flight test of the research flight control system, control laws, flying qualities specifications, and flight test maneuvers are described. Flight test results are used to illustrate some of the lessons learned during flight test and handling qualities evaluations.

NOMENCLATURE

ANSER	actuated nose strakes for enhanced rolling
CRAFT	control power, robustness, agility, and flying qualities tradeoffs
HAIRRY	High-Alpha Investigation of Requirements for Roll and Yaw
HANG	High-Alpha Nosedown Guidelines
HARV	High Alpha Research Vehicle
HATP	High-Alpha Technology Program

KIAS	knots indicated airspeed
MDA	McDonnell Douglas Aerospace
N_z	normal acceleration, *g*
PIO	pilot-induced oscillation
$p_{stability}$	stability-axis roll rate, deg/sec
p_{wind}	wind-axis roll rate, deg/sec
q	body-axis pitch rate, deg/sec
$r_{stability}$	stability-axis yaw rate, deg/sec
RFCS	research flight control system
STEMS	standard evaluation maneuvers set
t	time, sec
α	angle of attack, deg
β	angle of sideslip, deg
θ	pitch angle, deg
ϕ_{wind}	wind-axis bank angle, deg

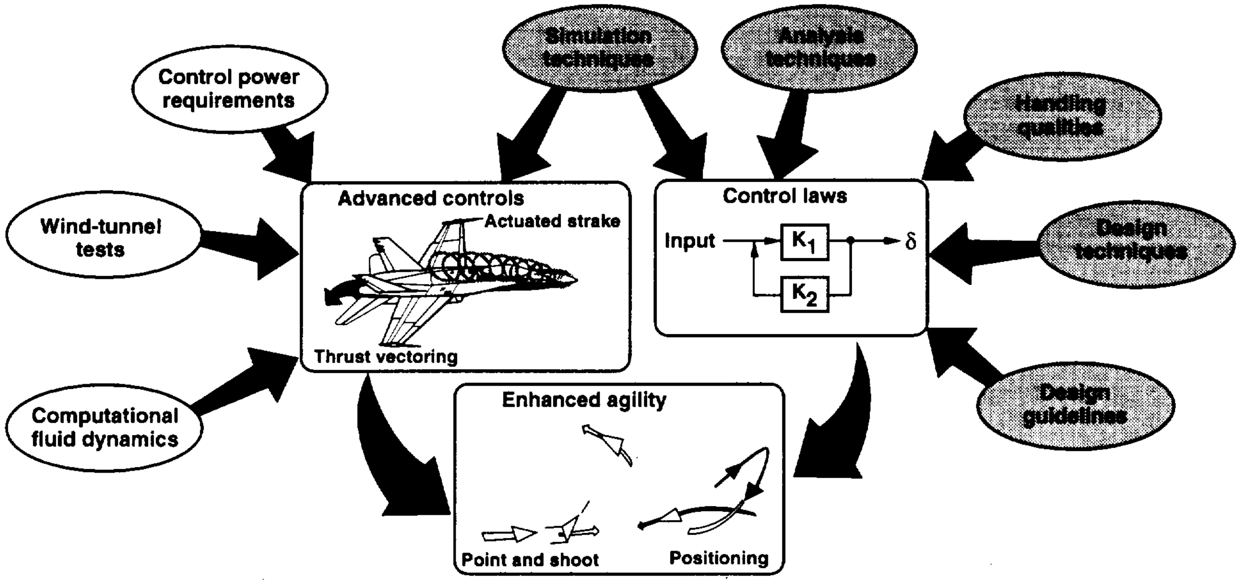
INTRODUCTION

Prior to the 1970's, U.S. fighter airplanes exhibited poor stability characteristics at high angles of attack. As a result, maneuvering was often limited by abrupt departure boundaries, and stall and spin accidents were a major cause of loss of aircraft and crew.[1] With the emergence of "all-aspect weapons," close-in combat scenarios of future fighter aircraft are predicted to be dominated by the aircraft that can most rapidly point the nose to obtain the first weapons firing opportunity. Thus, the demand for increased agility and carefree maneuvering throughout the envelope led to a significant change in philosophy toward high-angle-of-attack flight. This change in attitude from "avoidance" to one of "exploitation" spawned the development of research programs such as the X-31A Enhanced Fighter Maneuverability,[2,3] F-16 Multi-Axis Thrust Vectoring,[4] X-29A vortex flight control system,[5] and NASA High-Alpha Technology Program (HATP),[6] which were designed to explore and exploit various aspects of the high-angle-of-attack flight regime.

The HATP is a multicenter, multidisciplinary program designed to take advantage of the unique facilities and expertise at the NASA research centers and combine development of analytical tools, ground tests, and flight testing. The computational fluid dynamics research and wind-tunnel testing were supported by the NASA Ames Research Center and the NASA Langley Research Center. Inlet aerodynamics work was led by the NASA Lewis Research Center, and control law research and development was supported by NASA Dryden Flight Research Center and

NASA Langley Research Center. Flight testing was conducted at the NASA Dryden Flight Research Center.

As figure 1 shows, the HATP includes research in computational fluid dynamics techniques for computing the behavior of new control effectors and aircraft aerodynamics at high angles of attack, wind-tunnel tests for experimental investigation of these same phenomena, analytical and simulation studies of control power requirements, and a concurrent flight test activity to focus the evaluation of all the technology areas. The shaded bubbles (fig. 1) show those HATP technologies primarily contributing to control law and handling qualities development at high angles of attack.



960563

Figure 1. HATP research disciplines.

The approach to control system design for current- and previous-generation fighter configurations has been primarily driven by two key requirements: achieving angular accelerations and rates for maneuvering, and achieving closed-loop dynamics that provide the desired piloted flying qualities for precision tasks. Maneuvering requirements were addressed primarily by proper control sizing to provide the necessary control moment (often called control power) where needed. On configurations using conventional aerodynamic controls, well-defined control system requirements were typically specified for low-angle-of-attack conditions. Requirements for high angles of attack were not defined other than requiring sufficient margin from entering out-of-control flight. This lack of definition reflects the common characteristic of conventional aerodynamic controls where control effectiveness rapidly degrades at high angles of attack.

As the demand for high-angle-of-attack maneuverability has increased, the reliance on advanced control effectors and high-authority control augmentation has increased to compensate for the loss of airframe stability. In addition, nonlinear dynamic effects, such as inertial and kinematic coupling and yaw coordination, are greatly amplified at high angles of attack. As a result, high-angle-of-attack control power and flying qualities requirements have become inseparably linked and must be considered together with control system design methodologies and the maneuvers used to evaluate the overall result. The design of control systems for high angle of attack, α, presents new challenges and requires new and integrated approaches to ensure that the flying qualities and maneuvering performance are optimized.

The purpose of this paper is to provide an overview of the results used to develop and evaluate some of the technologies useful for high-α control. Design, development, and flight test of the research flight control systems, control laws, flying qualities specifications, and flight test maneuvers will be briefly described. Some aspects of the concurrent development of control laws, specifications, and evaluation maneuvers will be discussed. Flight test results will be used to illustrate some of the lessons learned during flight test and piloted evaluations.

CONTROLS AND FLYING QUALITIES RESEARCH SCOPE

One of the goals of the HATP has been to develop a flight-validated control system design process for high angles of attack. As figure 2 shows, flight control design can be represented as an iterative process beginning with airplane model development and an initial control law design and progressing through simulation and flight test stages. Results at each stage, requiring specific methods and criteria, are fed back to retune the design or perhaps even completely redesign the control law. Because high α was not a well-understood flight regime when the HATP began, many elements of the design process did not exist or were not yet flight tested. The approach in the HATP

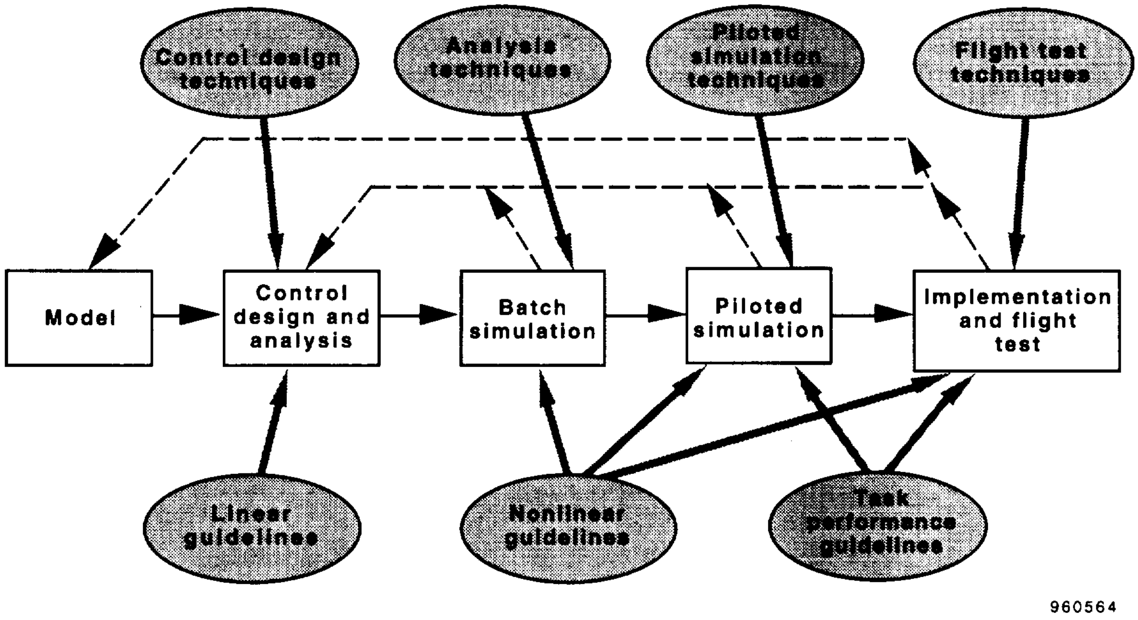


Figure 2. Flight control design process.

was to address the critical design guidelines and methods and to exercise each element in the design process using the NASA F/A-18 High Alpha Research Vehicle (HARV) as the flying test bed.

Although high-α flight was not a complete unknown, little information was available on how to effectively integrate innovative control effectors with advanced control laws to achieve a significant increase in high-α maneuvering capability. The HATP was structured to evaluate the technologies that could be used to answer some initial questions:

- Can thrust vectoring and forebody strakes be used to provide adequate, predictable control power at high angles of attack? What strategies can be used to effectively allocate the control power available?
- What flight control design techniques can be used or are well-suited for the high-α flight regime? Are existing linear control design techniques adequate, or will nonlinear techniques be required?
- What level of increased controllability and agility is required for a "usable" high-α flight envelope? What requirements or guidelines can be used to define a "usable" envelope?
- What flying qualities metrics should be used to design and evaluate the control laws? Can we extend the existing low-α criteria? What new or evolving approaches should be evaluated? What maneuvers should be used in the evaluation? What parameters should the pilot control with the stick and rudders at high angles of attack?

A number of issues regarding military utility were outside the scope of the HATP and will not be covered in this paper. These areas include specific tactics for successful air combat, weapon/airframe integration, and displays for increased tactical awareness at high α.

SIMULATION FACILITIES

A broad range of ground-test and simulation facilities were used concurrently during the HARV program. The primary piloted simulation used in the development of performance guidelines and handling qualities evaluations was the fixed-base, 40-ft dome differential maneuvering simulator at NASA Langley. The differential maneuvering simulator was also used in the control law design process and flight maneuver development.[7] The piloted simulation at NASA Dryden was limited to forward visuals only, but could be linked with an all-software, hardware-in-the-loop, or iron-bird capability. The NASA Dryden simulation was used for flight planning, engineering, and software development and was the primary site for software and hardware testing. A configuration-controlled batch simulation, common to both sites, was used as a benchmark with which to compare other dissimilar simulations.

During the HARV program, different flight control laws were planned to be designed and evaluated in flight to cover a broad scope of controls and handling qualities research. To facilitate design and implementation of control laws using various design techniques, the overall control law structure was separated into modules (fig. 3). This modularity allowed the longitudinal and the lateral–directional control laws to be designed using different methodologies. Additionally, the mixer and thrust estimator were designed and modified independent of the control laws, reducing the gain scheduling requirements within each control law by isolating those functions dependent on engine parameters.

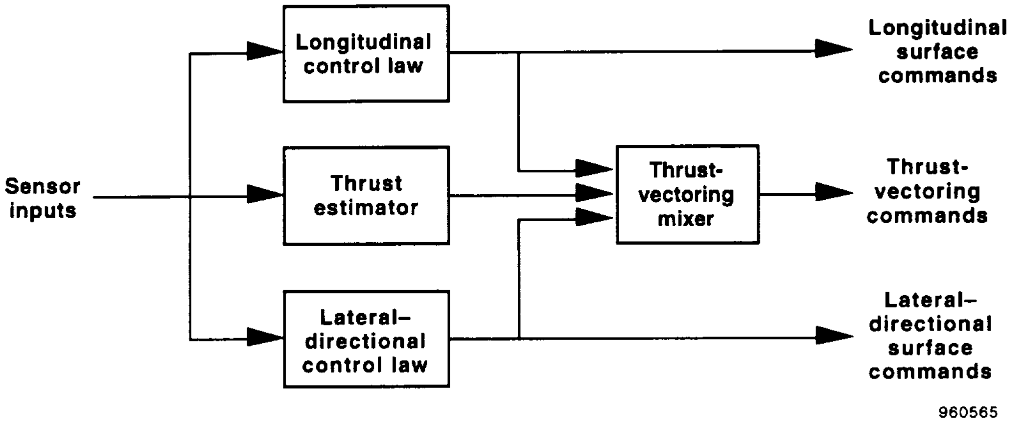


Figure 3. Modular control law structure.

Four research control laws were designed during the HARV program (table 1). The control laws are described very briefly in the following section. In addition to the major control law releases, modifications were required for some of these control laws during flight testing. Only up-and-away flight within a limited envelope (at less than Mach 0.7 and an altitude between 15,000 and 45,000 ft) was considered during the design and flight test because the emphasis in the HATP was on high-α research. The different methodologies used to accomplish these designs will be discussed briefly in a later section.

For all of the control laws, angle of attack was a critical parameter used for feedback and gain scheduling. Unfortunately, angle of attack is not available in the production F/A-18 system at greater than approximately 35°. Angle of attack, angle-of-attack rate, angle of sideslip, and sideslip rate were computed in the HARV mission computer using information from the inertial navigation system.[8,9] The signals were then passed to the flight control computer over a 1553 bus and transferred to the research flight control system (RFCS) through the dual-port random-access memory interface. Significant time delay was present in these signals (from approximately 40 to 80 msec), and various techniques were used to compensate for it.[10] Initially, using the computed sideslip angle as an inner-loop feedback was desired, but flight test showed poor comparison with the wingtip probes and none of the control law designs evaluated in flight used the signal as feedback.

Although several methods to obtain sideslip at high-α were proposed, no viable alternative to this computed sideslip was tested during the program.

Table 1. HARV control laws.

Control law	First flight	Axes	Design technique	Control parameter
NASA-0	July 1991	Longitudinal	Nonlinear model-following	Blend of pseudo N_z and α
		Lateral–directional	Eigenstructure assignment	$p_{stability}$; $p_{stability}$
NASA-1A	June 1994	Longitudinal	Variable-gain output feedback	Blend of N_z and α
		Lateral–directional	CRAFT and pseudo controls	$p_{stability}$; β
ANSER	July 1995	Longitudinal	Variable-gain output feedback	Blend of N_z and α
		Lateral–directional	CRAFT and pseudo controls	$p_{stability}$; $r_{stability}$
NASA-2	None	Longitudinal	Nonlinear dynamic inversion	Blend of q and α
		Lateral–directional	Nonlinear dynamic inversion	$p_{stability}$; β

The control laws actually used in flight were tested using a progression of maneuvers designed to evaluate performance, handling qualities, and agility. A wide spectrum of open-loop and closed-loop tasks were used. Examples of the open-loop maneuvers are α and g captures, pullup-pushovers, stability-axis rolls, and roll reversals, all at various angles of attack to a maximum 65°. Air-to-air tracking and gross-acquisition tasks in longitudinal and lateral–directional axes were incorporated early into the flight test plan to identify flying qualities problems. In addition, a limited number of basic fighter maneuvers and close-in combat engagements were flown. This relatively quick progression from open-loop to tracking was integrated into the more typical controls envelope expansion to give a “quick-look” evaluation. The tradeoff is that the closer the tasks got to actual air combat, the better the evaluation but the more difficult the engineering interpretation. To enable correlation of flight results with simulation results, most of these maneuvers were also flown in piloted simulation.

The U.S. Air Force–sponsored standard evaluation maneuvers set (STEMS) study conducted by McDonnell Douglas Aerospace (MDA) (St. Louis, Missouri) focused on developing critical evaluation maneuvers for control system design. Several of these maneuvers were developed specifically for high angles of attack. The purpose of these maneuvers was to definitively show variations in critical control system characteristics and expose problem areas. Obviously, one requirement was that the maneuvers be suitable for flight test by being repeatable and reasonably easy to perform. As an example, the lateral gross acquisition (fig. 4) has been shown to be an excellent maneuver for evaluating lateral–directional control system characteristics. This maneuver was originally developed for the MDA linear flying qualities guidelines study. The maneuver was then used for control law development and lateral control power evaluations[11] before becoming part of the STEMS. Another maneuver used extensively was a combined longitudinal and lateral–directional fine tracking. Figure 5 shows an overplot of two fine-tracking maneuvers performed on different flights by different pilots and control laws. The figure clearly shows that consistent results within a desired α region can be obtained for predominantly heads-up high-α maneuvers. The desired α during these maneuvers was 45°, and both maneuvers show significant fine-tracking evaluation time where angle of attack was within ±10° of the desired value.

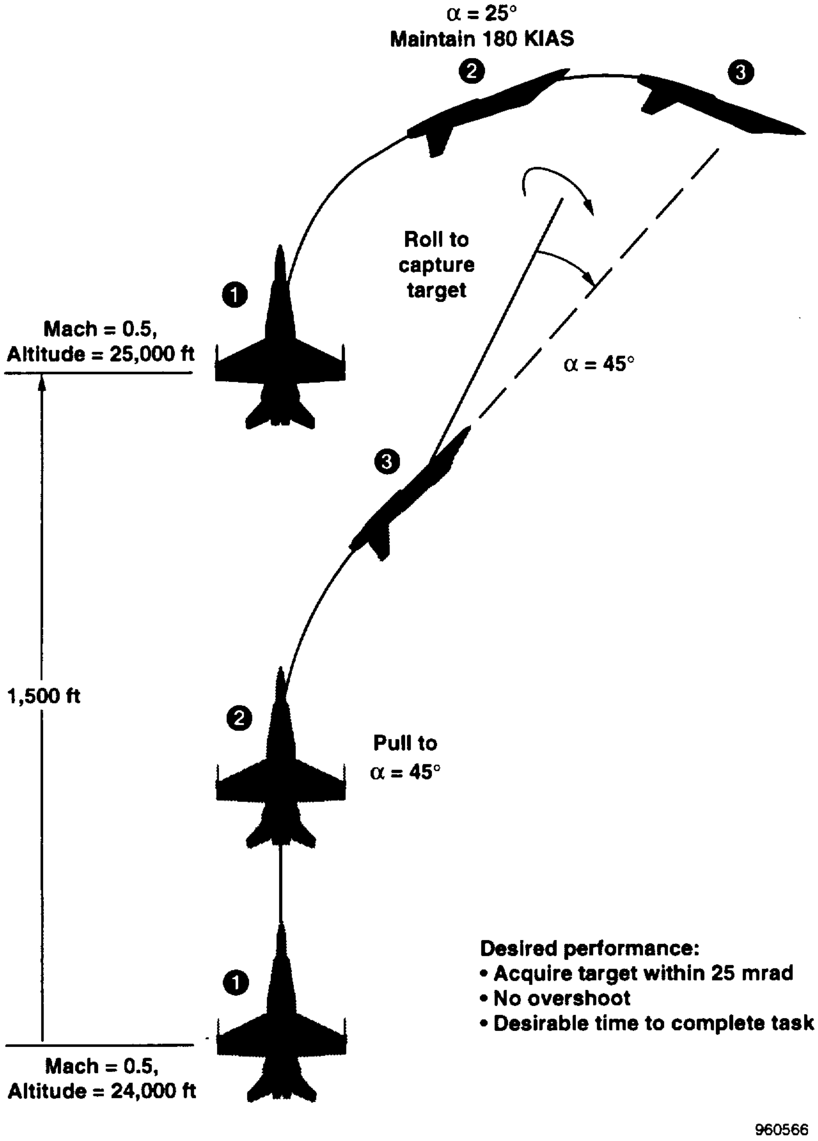


Figure 4. Illustration of a lateral gross-acquisition maneuver for 45° α.

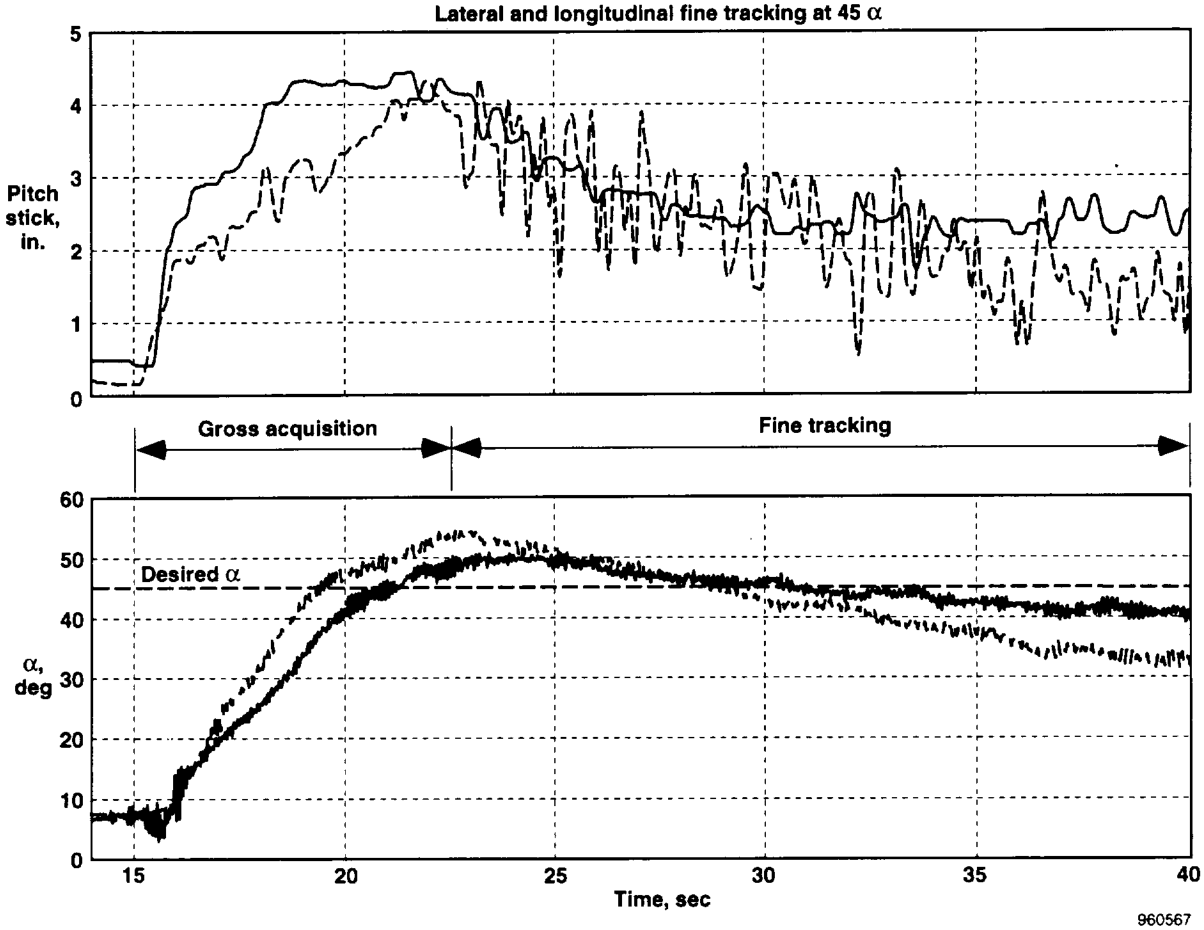


Figure 5. Time histories of two fine-tracking maneuvers flown by different pilots using different control laws.

NASA-0 Control Laws

The first set of RFCS control laws, known as NASA-0, were initially developed by MDA and NASA to demonstrate the research utility of the thrust-vectoring control system and to allow initial RFCS flight envelope expansion.[8,9] Integrating aerodynamic and propulsive controls, the control laws were designed for large-amplitude maneuvering as well as stabilized flight at high angles of attack for data acquisition. The pilot commanded α and stability-axis roll rate in the longitudinal and lateral–directional axes, respectively. In the low-α, high-dynamic pressure envelope where a blended pitch-rate and normal-acceleration response is desired, the commanded normal acceleration was converted to an α command from a simple model of the lift curve at a fixed, nominal gross weight. In this way, the NASA-0 control law was an α command system throughout the envelope.

This control law was used to conduct the first documented closed-loop, multiaxis thrust-vectoring flight. During envelope expansion, considerable high-α data were obtained in steady-state flight (to a maximum 70° α), and preliminary performance results were obtained in maneuvers similar to those described in the previous section. Control law modifications were required after initial envelope expansion to eliminate control law deficiencies that would have affected subsequent flying qualities evaluations, implement an on-board excitation system used initially for aeroservoelastic clearance, and add the capability to parametrically vary the nosedown pitch control power to support control power[12] research. The on-board excitation system capability was used extensively as a generic research tool and was retained for all subsequent control law designs.

As a result of some of the control law changes, gross-acquisition tasks in all axes seemed to improve, but tracking performance in the pitch axis had degraded. Postflight analysis using some of the low-α linear handling qualities tools (Smith-Geddes and Neal-Smith procedures) showed similar trends as those seen in flight.[13,14] The Smith-Geddes and Neal-Smith tools, developed primarily for analysis, were used in a redesign process to fine-tune control law modifications. Although only a limited number of comparisons were flown, results from flight test indicated improved tracking for this control law (Version 28) over the previous control law (Version 27) with no degradation in the gross-acquisition results. Figure 6 shows a summary of the limited handling qualities evaluations accomplished with all versions of the NASA-0 control law, generally resulting in a Level 1–2 result. The histogram shows Cooper-Harper ratings for both longitudinal and lateral–directional axes summarized across all pilots, flight conditions (including angle of attack), and evaluation maneuvers described previously.

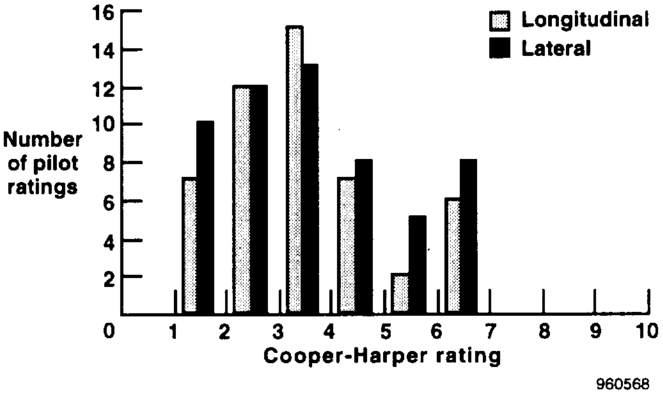


Figure 6. Summary of Cooper-Harper ratings for the NASA-0 control laws (all versions).

NASA-1A Control Laws

A prime objective in the NASA-1A control law design was to demonstrate that enhanced agility, poststall maneuvering, and good handling qualities could be achieved simultaneously. Steady-state flight at high α was still required to support flight research in other HATP disciplines. This requirement was a major determinant in the choice of an α command system at high α and normal acceleration at low α for the longitudinal axis. The pilot commanded stability-axis roll rate in the lateral axis and angle of sideslip (approximate) in the directional axis.

The NASA-1A control law was designed in-house by the NASA Langley/NASA Dryden control law design team. This intercenter approach was deemed an advantage in that it brought together expertise and experience in control theory, simulation, flight dynamics, control system implementation, and flight test techniques. The high-α linear design and open-loop performance guidelines (to be discussed in a later section) were used as they became available to guide the NASA-1A design. In particular, the linear guidelines for 30° and 45° α were directly applied to the design of the lateral–directional control law. Using engineering pilots and NASA research pilots, including the HARV project pilots, the NASA-1A control law was evaluated extensively in piloted simulation in the NASA Langley differential maneuvering simulator, and the results were incorporated into the design process.

Flight performance of the NASA-1A longitudinal control law was mixed. The pilot disengaged the RFCS on the first flight of this control law because of high-frequency vibration. After some analysis, it was determined that a units error had been made during the aeroservoelastic analysis, and some unmodelled vane dynamics were not adequately suppressed. Structural filters were designed, implemented, and tested within 2 weeks, highlighting one benefit of the RFCS. Envelope expansion resumed with no further structural interactions noted. Steady-state α control proved to be excellent, and pitch authority was rapid and crisp. For example, the maximum pitch rates achieved in flight were within the performance guidelines with the only significant deviation being at 55° α, where pitch-rate capability is limited by insufficient control power.[15] The most significant deficiency observed during the flight tests was the overall sensitivity of the control law, resulting in increased surface activity, rate and position saturation, and pilot-induced oscillations (PIOs) during tracking tasks. The pitch sensitivity in flight was much greater than that expected from the piloted simulation results. This flight test experience led to additional research in the areas of PIO analysis and prediction tools and improved piloted simulation maneuvers and techniques.[16,17]

Flight performance of the lateral–directional control law was generally good. For example, the maximum wind-axis roll rates achieved in flight were very close to the design guideline except at angles of attack of approximately 60°, and good lateral–directional tracking and predictability was obtained. However, some discrepancies were noted during the flight evaluation. The pilots did not like having the rudder pedals command sideslip and preferred a conventional pedal response. For angles of attack in the 60°–70° range, an asymmetry was observed in the airplane roll response. Stability-axis rolls to the right initiated at 60° α were completed, whereas rolls to the left could not be completed. In fact, rolls to the left reversed direction to the right, although left stick was maintained throughout. Grit strips were applied to the forebody in an attempt to alleviate this asymmetry, and rolls to the left at 60° α were successful. However, after the grit was applied, a 1-Hz limit-cycle oscillation in roll with a peak bank-angle amplitude of approximately 0.5° was observed on several occasions. Attempts to reproduce this oscillation in the simulation were unsuccessful.[15]

Actuated Nose Strakes for Enhanced Rolling Control Laws

The actuated nose strakes for enhanced rolling (ANSER) control law was the only control law flown on the HARV designed to command the actuated forebody strakes as well as the thrust-vectoring and conventional aerodynamic effectors. The ANSER control law was developed to accomplish the same broad scope of objectives as the NASA-1A control law with the additional requirement of expanding the ANSER flight envelope and acquiring aerodynamic and flow visualization data regarding the forebody strakes. The control law commanded the standard aerodynamic surfaces and had three modes of operation for the research effectors selectable by the pilot: TV mode uses pitch and yaw thrust vectoring; S mode uses actuated forebody strakes and pitch thrust vectoring; and STV mode uses actuated forebody strakes plus pitch and yaw thrust vectoring. The mode-switching feature performed well and allowed back-to-back comparison of agility and handling qualities for the TV, S, and STV modes during one flight. Flight results indicated thrust vectoring and actuated forebody strakes were both effective for controlling the aircraft in body-axis yaw at high angles of attack.[18]

To minimize design time and changes to the flight software, the initial plan was to use the NASA-1A design as the ANSER control law TV mode. Some changes to the NASA-1A lateral–directional control laws were required in addition to the strake modifications. These changes included reducing the feedback gain magnitudes at 55° and 60° α to eliminate the 1-Hz roll oscillation observed with the NASA-1A control law, limiting the trailing-edge-down aileron deflection as a function of α to reduce adverse yaw, and changing the rudder pedal path to provide a conventional pedal response. Because the effect of the strakes on airplane longitudinal dynamics was minimal, the plan had been to use the NASA-1A longitudinal control law in all three ANSER modes without change. However, the longitudinal sensitivity observed during NASA-1A flight testing forced some changes to the longitudinal controller prior to ANSER flight test. To aid in flight test evaluation, a dial-a-gain feature was implemented in the ANSER control law to provide the capability for the pilot to select one of three sets of gains (low, medium, and high) for the longitudinal controller. Additionally, the dial-a-gain feature allowed for a wider variation of comparison between flight and piloted simulation results and produced data for evaluation of PIO prediction and analysis tools.

Four releases of the ANSER control law were required to provide the necessary changes in the on-board excitation system to accommodate the many parameter identification, aerodynamic, flow visualization, and aeroservoelastic research maneuvers. One difference of significance in the four versions was a change in the α-scheduled symmetric deployment of the nose strakes in S mode and STV mode. This change was prompted by the occurrence of a small-amplitude oscillation in the strake deflections in the 15°–20° α region. The new symmetric schedule slightly changed the character of the oscillations but did not eliminate them. The inability to reproduce these oscillations in simulation is thought to be a result of modeling errors, perhaps in the aerodynamic models or in signal delays.

Target-tracking performance of the ANSER longitudinal control law was significantly improved over the NASA-1A control laws. Evaluation of the three gain sets early in the ANSER flight tests resulted in the medium gain set being selected as the default feedback gains for most of the flight testing. Overall longitudinal and lateral–directional performance of the controller was good as evidenced by the clustering of pilot ratings at 3 and 4 in the histogram of the Cooper-Harper ratings (fig. 7) received during ANSER flight testing. These ratings are summarized for all pilots, flight conditions, and rated tasks combined. Ratings were found to be strongly pilot-dependent, especially for the target-tracking task at 30° and 45° α. Ostroff, Murphy, Murri, and Hoffler provide details on the breakdown of ratings by task, angle of attack, and pilot and provide comparison of flight results with piloted simulation results.[16,18–20]

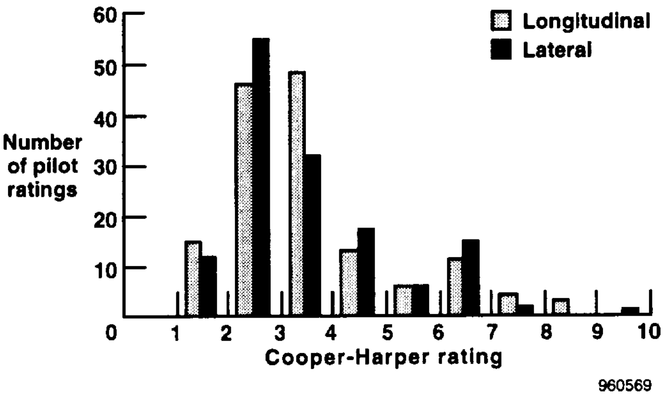


Figure 7. Summary of Cooper-Harper ratings for the ANSER control laws.

NASA-2 Control Law

Initially, it was thought that because the high-α aerodynamics are dominated by nonlinear effects, a completely nonlinear control law design technique would be required to take full advantage of the flight regime. For this reason, a nonlinear dynamic inversion control law was designed by Honeywell Systems and Research Center (Minneapolis, Minnesota) and NASA engineers.[21] Although preliminary all-software piloted simulation results were very positive, this particular nonlinear dynamic inversion control law showed unexpected design and implementation flaws when tested in the hardware-in-the-loop simulation. The control law was very sensitive to differences allowed among the four channels by the quad input signal management, a function resident in the basic F/A-18 flight control computers. Eventually the differences (multiplied by high surface-command gains) would grow large enough to cause failure enunciation at the actuator because of a force fight between the channels. These flaws could not be rectified in time to meet the schedule, and the flight test of this control law was abandoned.

HIGH-ANGLE-OF-ATTACK FLIGHT CONTROL DESIGN GUIDELINES

The approach used in the HATP to address flying qualities requirements was to categorize the requirements under three topics: linear closed-loop handling qualities guidelines, agility and open-loop control power guidelines, and nonlinear maneuvering performance guidelines. For the purposes of this research, addressing each category separately was necessary, but it was recognized that these areas are closely linked and must be considered together in the development of final guidelines.

Linear Flying Qualities Guidelines

Well-accepted flying qualities design guidelines for low angles of attack, such as MIL-STD-1797, have been available for many years, but little flying qualities design criteria were available for high angles of attack. Preliminary longitudinal and lateral–directional flying qualities requirements at high α were addressed by NASA-sponsored simulation studies conducted by MDA.[22] The MDA flying qualities studies focused on closed-loop flying qualities requirements from 30° to 60° α. These studies were conducted to identify critical flying qualities requirements, evaluation maneuvers, and piloted test techniques for high angles of attack. These guidelines and maneuvers were used as they became available in the development and testing of the HARV control law designs. Maneuvers developed in the simulation and used for handling qualities evaluation were further refined and used successfully in flight at high angles of attack.

One objective of the MDA studies was to identify key figures of merit that define the flying characteristics pilots desire for acceptable performance. Conventional parameters such as roll-mode time constant and short-period frequency and damping were evaluated to determine if low-α measures were suitable for high-α applications. In addition, agility and open-loop control power guidelines focused on measures of maximum maneuvering performance such as peak pitch and roll rates and time to roll to a bank angle. The importance of meaningful, definitive figures of merit was highlighted by Murphy,[23] where numerous candidate parameters were analyzed and correlated to pilot opinion.

In general, results of these studies indicated that typical figures of merit used for low angles of attack were suitable for high angles of attack, but significant differences in the requirements between the two regimes were clear. For example, lateral-axis dynamics criteria (fig. 8) indicated large variations in requirements with α. The implication of this large variation is that the control law design must adjust to provide the desired dynamic response.

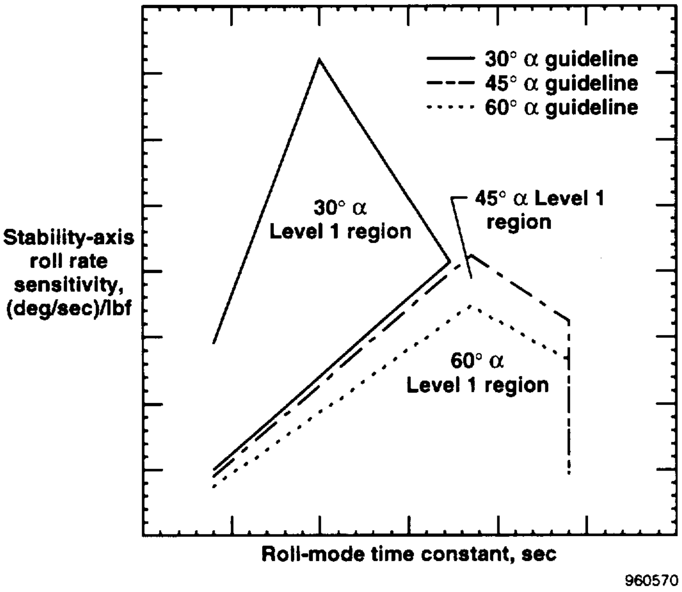


Figure 8. Example linear design guidelines for the lateral axis showing variations of the Level 1 regions with α.

Correlation of the flight data with this simulation database is still ongoing. Preliminary results, however, indicate similar trends but suggest different boundaries between the levels.[14] One problematic aspect of this particular set of criteria is that it is fundamentally based on linear lower-order equivalent systems. The F/A-18 HARV flight dynamics are not always represented well in this framework when evaluated with maneuvers that traverse a large α range and thus violate linear assumptions. Additionally, maneuvers at high α are often dominated by nonlinear effects such as control rate or position limits. For a typical high-α full-stick 360° roll in flight, the lateral–directional aerodynamic surfaces and yaw thrust vectoring are saturated throughout much of the maneuver. As a result of this control limiting, wind-axis roll-rate response can be fairly linear with time and is not easily represented as a unique first-order response.

Agility and Open-Loop Control Power Guidelines

The definition of agility has been under continuing debate for many years; however, general agreement exists that agility involves the ability to achieve angular rates or accelerations for maneuvering. Examples include peak pitch-acceleration, peak roll-rate, and time-to-bank criteria. Because these criteria are closely tied to maximum available control power, agility and open-loop control power guidelines are interrelated and were addressed together in this research. Preliminary agility and control power guidelines were developed in a variety of simulation studies, and flight validation was accomplished on many of these criteria. The importance of well-understood control power requirements was recognized because of its strong impact on airplane design. For example, nosedown control power can determine the horizontal tail size and center-of-gravity location. Similar to the linear flying qualities studies, a major objective in control power and agility research was to identify key figures of merit that define the maneuvering performance desired by pilots. Also, maneuvers that define maneuvering performance and are suitable for flight testing were highly desired.

Open-loop maneuvering goals were addressed early in the HATP by Hoffler in the development of maneuvering and agility goals for the HARV.[24] These guidelines were intended to provide preliminary guidance for design of the thrust-vectoring system. Although these guidelines were developed primarily for the HARV, they were generally suitable for preliminary assessment of configurations using advanced controls. Figure 9 shows flight results using the NASA-1A control law (at 1 *g* and an altitude of 25,000 ft) plotted against the 1-*g* maximum pitch-rate guideline.

Agility metrics were addressed through simulation and flight experiments to identify key figures of merit that the pilot uses to judge airplane response.[25] The approach involved piloted evaluation of definitive maneuvers for a range of performance levels. Figure 10 shows examples of maneuvers that were evaluated. One of the objectives of this study was to evaluate a broad range of agility and handling qualities levels to assess the tradeoff between these two areas. Analysis of the flight data and correlation with simulation is still in progress.

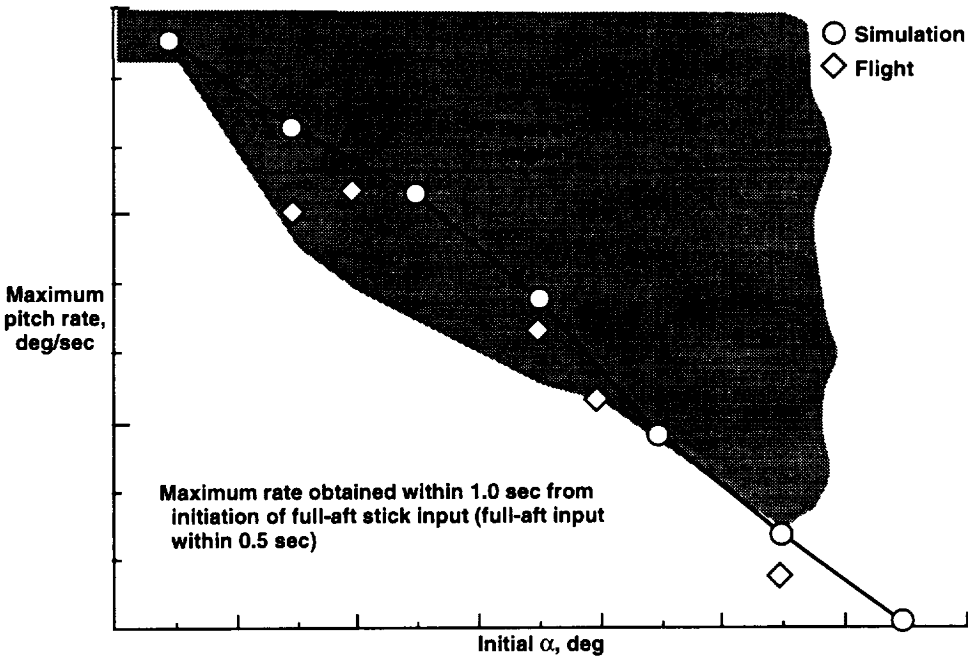


Figure 9. Comparison of NASA-1A simulation and flight results with pitch-rate guideline (maximum afterburner power at an altitude of 25,000 ft).

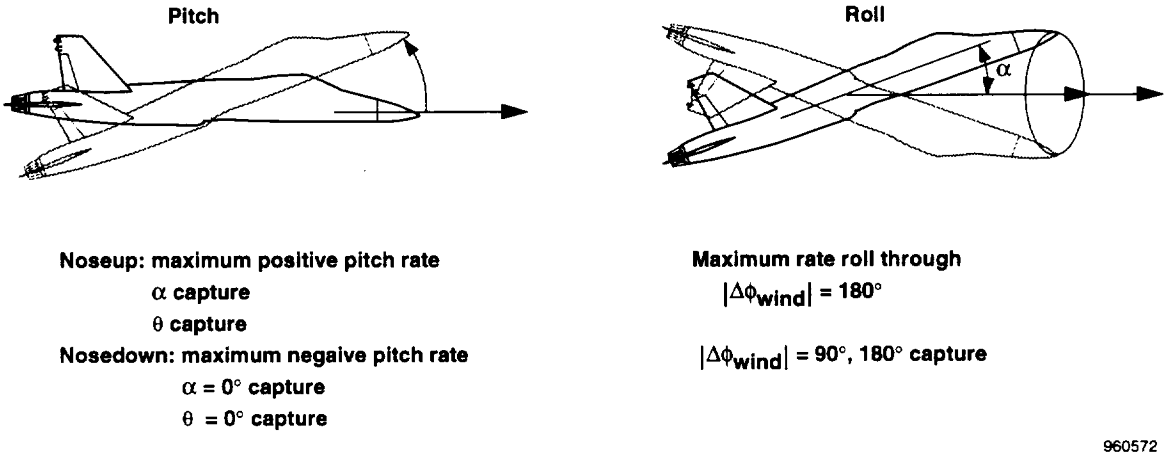


Figure 10. Example agility maneuvers used in simulation and flight test.

Beginning in 1990, broad-scope control power assessments were initiated as part of a joint NASA–U.S. Navy study addressing controls design requirements for next-generation fighter aircraft. The High-Alpha Nosedown Guidelines (HANG) program addressed the minimum nosedown control response required for safety of flight. This study used piloted simulation to develop a database focused on nosedown response requirements. Results showed that pilots judged minimum nosedown requirements on the short-term response such as pitch acceleration and pitch-rate buildup, and a single design value was identified.[25] The NASA-0 control laws included pilot-selectable variability in nosedown pitch authority and command shaping using variable-rate and position-limiting logic. The piloted simulation results using this capability were validated through a series of flight evaluations. Figure 11 shows pitch control power variations from three maneuvers flown sequentially on a single flight. The three identical maneuvers, full-stick pushovers from initial conditions of 1 *g*, an altitude of 25,000 ft, and 50° α, are overplotted to show the dramatically different aircraft responses that were evaluated by the pilot and compared to the design values selected from simulation. Results of this study are in use for next-generation designs, and tactical nosedown requirements are now being addressed in simulation studies.

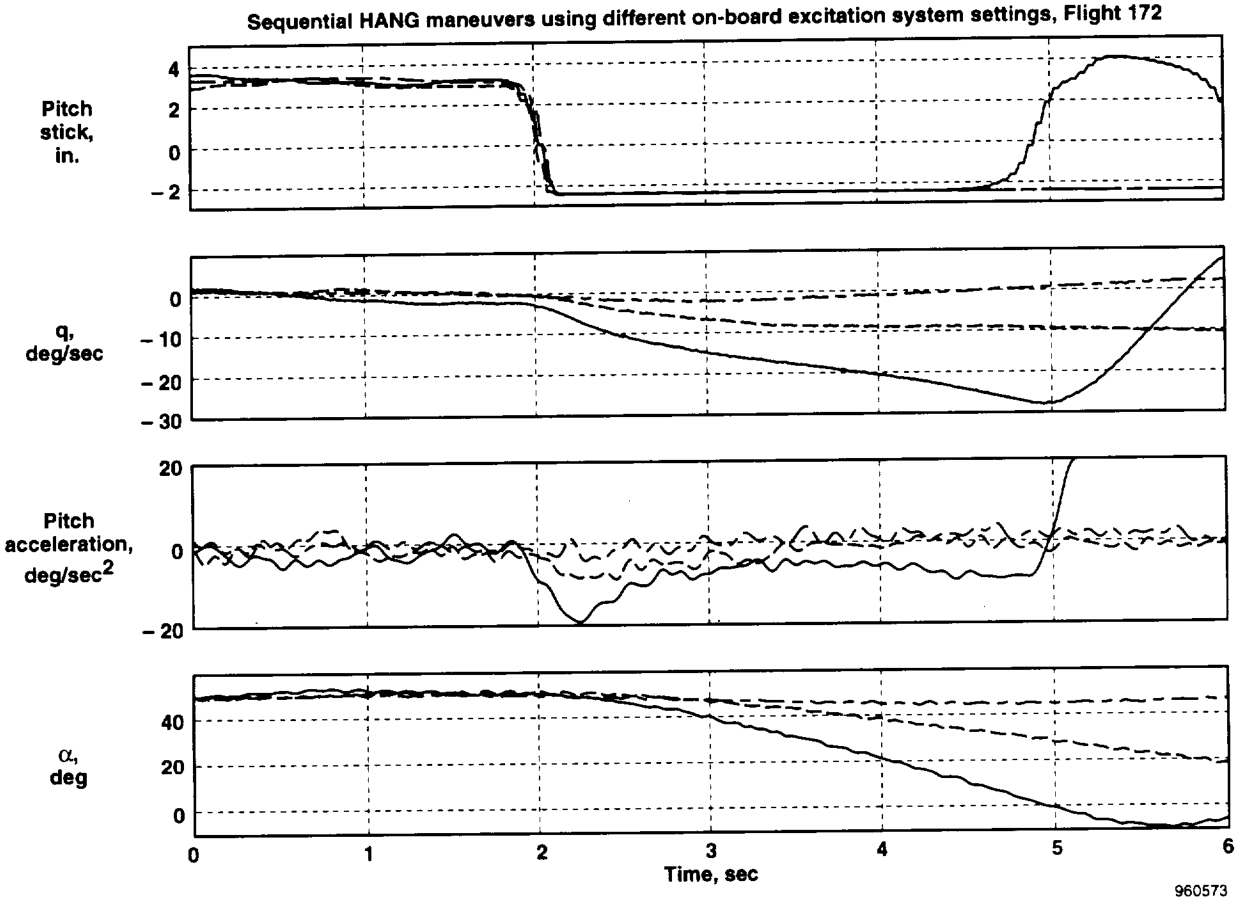


Figure 11. Three sequential HANG pushover maneuvers from 50° α showing aircraft response for different levels of pitch control power.

The High-Alpha Investigation of Requirements for Roll and Yaw (HAIRRY) program addressed high-α roll maneuvering requirements for various performance levels.[11] The HAIRRY study also used piloted simulation to develop an extensive database of roll maneuvering requirements from 15° to 60° α. Whereas the HANG study focused on safety-of-flight considerations, the HAIRRY study addressed the tradeoff of roll maneuverability with tactical effectiveness. Generally, a clear variation in roll maneuvering requirements with angle of attack was identified. Figure 12 shows a preliminary criterion, based on the simulation results, where time to roll is used as a figure of merit. Limited flight evaluations using the HARV were completed, providing preliminary validation of the simulation results.[26] In general, the flight results (fig. 12) indicate reasonable correlation with the simulation criteria, but a comprehensive flight program is needed to fully validate the simulation results.

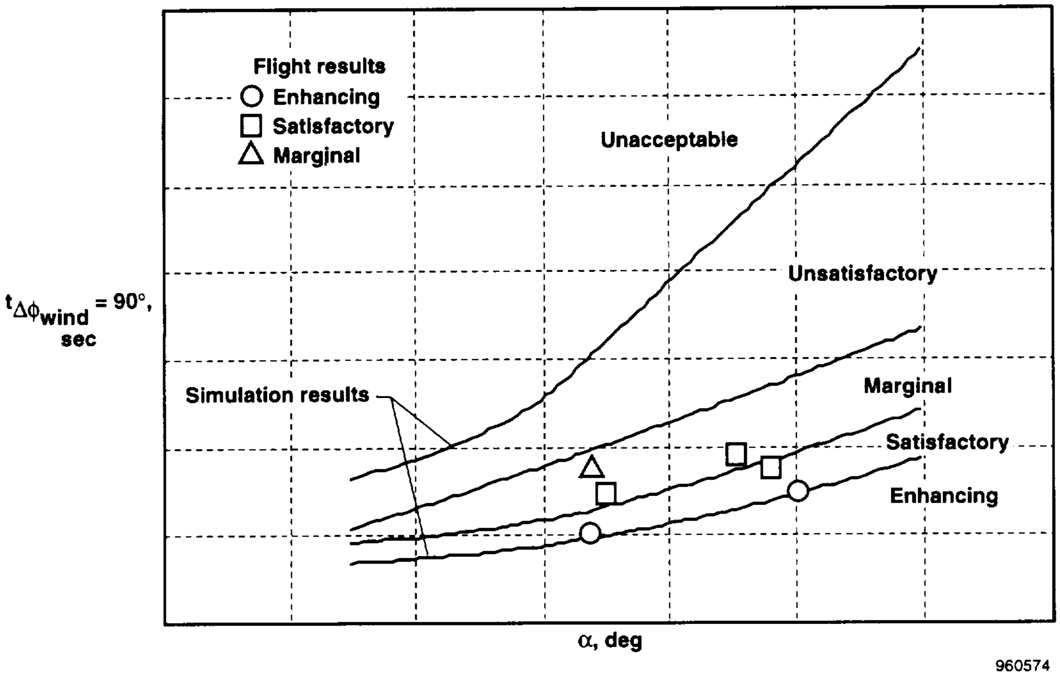


Figure 12. Preliminary roll-maneuvering criteria from the HAIRRY study.

Nonlinear Maneuvering Performance Guidelines

Nonlinear performance guidelines addressed handling qualities issues related to nonlinear characteristics of aircraft dynamics. Examples included roll overshoot during aggressive bank-angle captures and sideslip excursions during rolling maneuvers. In the HATP, numerous guidelines were developed, primarily from piloted simulation.[7] Use of these guidelines involved a "cut-and-try" approach because explicitly integrating the guidelines into control law design is difficult. However, these requirements have been shown to have a significant impact on flying qualities and highly influenced the HARV control law design throughout the program.[15,27] Figure 13 shows simulation and flight results from one control law configuration plotted with the combined 1-*g* roll performance and overshoot guidelines. Initially, the roll overshoot guideline was not included, and roll rate was maximized without consideration to roll overshoot. Pilot comments during simulation and flight evaluation of the NASA-0 (Version 27) control laws, however, indicated that the roll overshoot was a key factor in determining the tradeoff between performance and controllability. The NASA-1A and ANSER lateral control law designs significantly reduced the roll overshoot, and this reduction resulted in improved pilot comments.

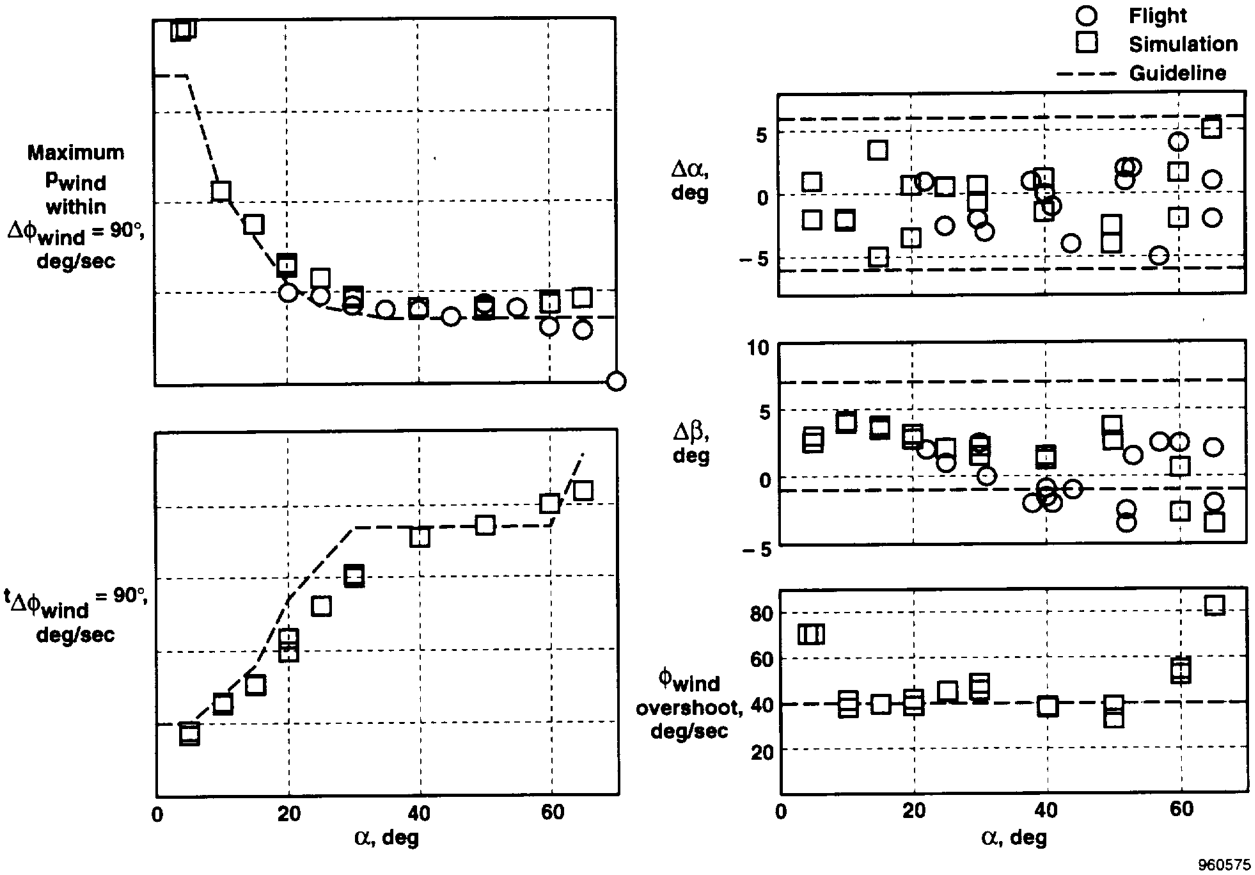


Figure 13. Comparison of simulation and flight results with nonlinear performance guideline: maximum p_{wind} and time to achieve ϕ_{wind} = 90° plotted with $\Delta\alpha$, $\Delta\beta$, and ϕ_{wind} overshoot criterion.

CONTROL LAW DESIGN METHODOLOGIES

A goal of the HARV program was to develop flight-validated control design methodologies for application to the very nonlinear high-α regime. A number of different control law design methodologies were used and implemented over the life of the HARV program in order to cover a broad spectrum of effective ideas and to increase the experience base at high α. The design methodologies were selected in order to evaluate technologies that were thought to be critical to next-generation aircraft control law development. These technologies include:

- the capability to integrate handling qualities specifications easily in the design phase.
- robust stability and maneuvering performance throughout the envelope, particularly at high α.
- efficient control power allocation.
- integrated aerodynamic, forebody vortex, and propulsive controls.

Longitudinal Control Laws

Two significantly different techniques were used to design the longitudinal axis in the NASA-0 and NASA-1A and ANSER control laws. For both control laws, symmetric leading and trailing flap were commanded as a function of α, identical to the standard F/A-18 control laws. Horizontal stabilator and pitch-vectoring commands were blended with a washout to eliminate steady-state vectoring commands caused by thermal limits on the vanes.

The NASA-0 technique was a continuous, nonlinear model-following scheme that tried to force the aircraft response to a desired second-order transfer function.[28] Desired eigenvalues were defined by the selection of the short-period parameters for the lower-order transfer function. Open-loop dynamics were computed from a nonlinear aerodynamic model contained in the control laws. Control system gains were computed from the algebraic difference between the desired and open-loop short-period approximations. Compensation was added to account for the high-frequency effects (actuator and sensor dynamics and structural filtering) neglected in the simplified nonlinear aerodynamic model. Pitch rate, estimated α rate, and α were used as the primary feedback. Nonlinear compensation included inertial coupling (roll rate times yaw rate) and gyroscopic coupling. At low dynamic pressures and high throttle settings typical of high-α thrust-vectored flight, gyroscopic coupling was a significant part of the cross-axis vehicle dynamics.

The NASA-1A and ANSER longitudinal control laws were a direct digital design accomplished using variable-gain output feedback, an approach initially developed for NASA Langley under contract. The technique is derived from a stochastic, optimal, discrete, output-feedback design approach developed by Halyo and Broussard[29] and is useful for extending the operating envelope of linear control laws. Traditional design methods involve performing constant-gain designs at several different operating points using linear techniques, then creating a gain schedule between points using some type of curve fit. With the variable-gain output feedback technique, all design points are handled simultaneously. Linear models at several aircraft operating points are integrated into a single design problem to obtain a variable-gain global controller with gains that are functionals of aircraft parameters (fig. 14). Gains are adjusted for varying operating conditions by evaluating these functionals, which may be linear, such as f(Mach), or nonlinear, such as $f(\alpha^3)$. This technique can be used with many different control structures, but for the HARV, a proportional-integral filter structure was used with the control equations implemented in incremental form.[30] For NASA-1A and ANSER, feedback gains were computed simultaneously for 39 design points, or flight conditions, and a gain-scheduling algorithm for computing feedback gains between design points was designed at the same time. Feedback parameters were pitch rate, α, and normal acceleration. A detailed discussion of the design, simulation, and flight results can be found in references.[30,31]

Variable-gain output feedback is an optimal control design technique that computes feedback gains by minimizing a quadratic cost function. A drawback to this technique is the difficulty in directly incorporating handling qualities criteria such as the MDA linear guidelines. Tuning the variable-gain output feedback design in the sense of adjusting a single feedback path is also difficult because the technique does not readily accommodate changing one gain at a time. This difficulty was encountered in the adjustment of the integrator gain, which reduced the longitudinal sensitivity in the NASA-1A redesign. By adjusting weighting matrices, however, the designer was able to adjust gains so the dominant change was in the integrator gain.

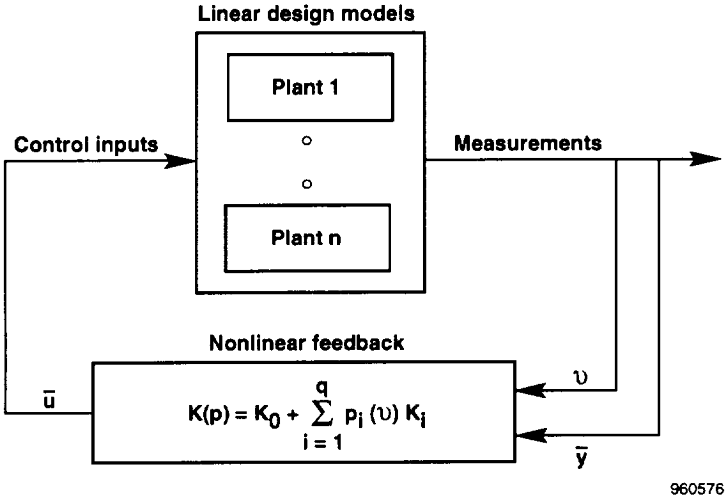


Figure 14. Variable-gain output feedback design method.

Lateral–Directional Control Laws

The NASA-0 and NASA-1A and ANSER control laws used eigenstructure assignment[32–35] for the basis of the lateral–directional control law design, although the control laws varied greatly in focus and actual implementation. Both control laws used a fairly conventional set of feedback parameters that included roll and yaw rates, lateral acceleration, and estimated sideslip rate.

The NASA-0 control law approach was a fairly standard eigenstructure-assignment design. Control power allocation was through a fixed ratio of surface deflection. At a dynamic pressure greater than approximately 150 lbf/ft^2, however, the control laws transitioned to the standard F/A-18 lateral–directional commands with some additional yaw thrust vectoring. This transition was required because of inadequate stability margins and excessive gains resulting from this eigenstructure-assignment design.

The NASA-1A and ANSER lateral–directional control laws were divided into two modules to try to separate the tasks of designing the feedback gains from allocation of the multiple control effectors. Feedback gains were designed at 12 flight conditions using a methodology called control power, robustness, agility, and flying qualities tradeoffs (CRAFT)[15] and then scheduled with flight condition.

The CRAFT technique addresses the design objectives of satisfying the control power constraints, providing adequate robustness, maximizing agility, and providing satisfactory flying qualities. The CRAFT technique provides a graphical method to allow the designer to perform the tradeoffs required during the linear design phase to achieve a design that is the best compromise among the four design objectives.[15] As figure 15 shows, these tradeoffs are accomplished by systematically evaluating the closed-loop system at specified design points over an appropriate design space. At each design point, closed-loop metrics, which quantify the design objectives, are evaluated and plotted over the design space. In a sense, the CRAFT technique is a "brute force" approach in that the designer attempts to find the best solution by designing and computing metrics for a large number of designs. The advantages of the CRAFT technique are that it automates the process of designing over the matrix of points and provides a composite graphical display of the results. These plots indicate the desirable regions in design space based on metric values. Graphically overlaying desirable regions gives the designer a clear view of the tradeoffs and sensitivities involved. Gain scheduling the resulting single-point designs, however, is still required.

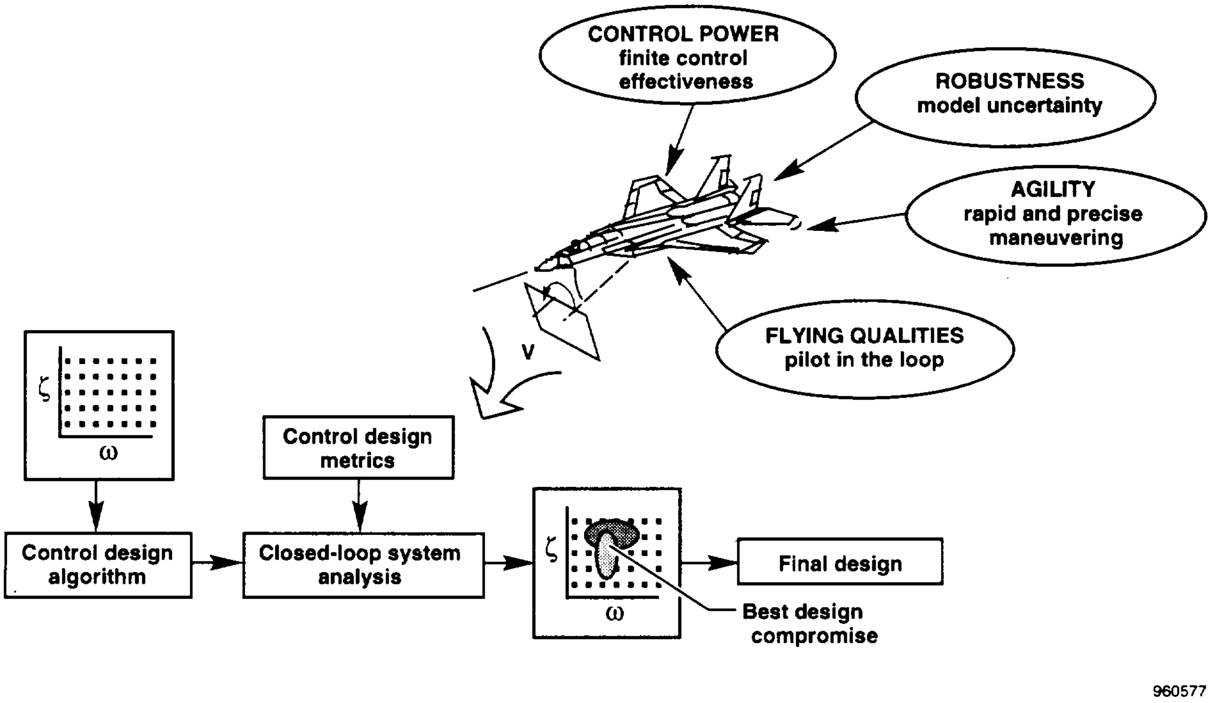


Figure 15. CRAFT design method.

The feed-forward path includes inertial compensation and a distributor to apportion the control law commands to the appropriate aerodynamic and thrust-vectoring control effectors. The distributor was designed using a technique known as pseudo controls.[36] For example, the rudder, yaw thrust-vectoring system, and actuated nose strakes effectively produce body-axis yawing moment. The relative control effectiveness of each effector, though, is not constant over the entire flight envelope. Using a model of the relative control effectiveness of each surface over the flight envelope, pseudo controls allow the designer to develop surface schedules that apportion the command to the control effectors in a manner that maximizes the moment in the desired axis while minimizing the moment produced in the other axes.

THRUST-VECTORING VANE MIXER

The HARV produces multiaxis thrust vectoring using an experimental thrust-vectoring system with six thrust-vectoring vanes.[9,37] These thrust-vectoring vanes are interfaced with the flight control laws through a separate function known as the mixer. The control effectiveness of each vane is highly nonlinear, dependent on engine parameters and flight condition, and—unlike conventional aerodynamic surfaces—very dependent on the position of the other vanes around the same engine. This latter behavior made conventional surface scheduling impractical. Isolating the thrust-vectoring control allocation within the mixer allows the control laws to be designed or modified separately, as mentioned previously, with three moment commands (pitch, roll, and yaw) rather than six vane commands. In addition, the mixer adjusts the thrust-vectoring commands to account for changes in thrust level and losses in thrust caused by thrust vectoring[38] and limits the commands as a function of flight condition to avoid excessive structural loads.

Because direct measurement of in-flight gross thrust was not available to the flight controls, in-flight gross thrust was calculated from a model of ideal gross thrust based on nozzle throat area, nozzle pressure ratio, and ambient pressure.[28] Comparison with in-flight real-time thrust measurement[39] values for each engine indicated that results of this estimated gross thrust were within approximately 7 percent of measured values.

Two mixer designs were used in the HARV program. The first was developed by the contractor[28] and delivered with the first release of the NASA-0 control laws. A second mixer (Mixer 4.2) was developed by the HARV controls team to improve the vectoring performance, add the capability of roll vectoring, and implement a priority scheme between the vectoring commands when the thrust-vectoring system was not capable of satisfying those commands simultaneously.[40] Mixer 4.2 was used in the NASA-1A and ANSER control laws, and a modified version was used in the NASA-2 design. Even though Mixer 4.2 was designed with roll thrust-vectoring capability, roll thrust vectoring was not used in the NASA-1A and ANSER control laws.

Both mixers were based on ground tests with a 14.25–percent model of the HARV thrust-vectoring system.[41] This high-pressure cold-jet test was conducted to measure the thrust-vectoring effectiveness of the vane system (that is, to measure the thrust vectoring as a function of the vane deflection angles). Recent flight results from parameter identification show excellent comparisons with the cold-jet results. For the Mixer 4.2 design, a numerical optimization procedure was used to invert the cold-jet data to obtain vane deflection angles as a function of desired pitch- and yaw-moment commands. To conserve memory in the flight computer, these inverted data were stored in variable-density, nonrectangular arrays such that data outside the irregularly shaped boundary of achievable thrust vectoring were not included.

ROLE OF PILOTED SIMULATION IN DESIGN PROCESS

A program goal had been to demonstrate that even in the relatively unknown high-α flight regime, the amount of flight test time required to develop a new control law and the number of design changes during flight testing could be minimized by extensively using piloted simulation in an iterative process with control design and tuning and with new high-α design guidelines. Obviously, this goal was not accomplished with unqualified success because the occurrence of PIO with the NASA-1A longitudinal control law was not predicted by simulation, although the control law was evaluated extensively in the NASA Langley differential maneuvering simulator with multiple pilots, including the project flight test pilots. The reasons for this are not clear, but possibilities include lack of motion cues, pilot adaptation because of familiarity with the tasks and the control laws, and generally low pilot gain in simulation compared to flight. Reliability of simulator results may be improved by carefully defining the task, giving careful consideration to all pilot comments, and fully investigating the reasons for isolated poor pilot ratings.[16]

CONCLUDING REMARKS

The High-Alpha Technology Program (HATP) was considered unique because of the broad scope of research that was conducted during the program. Significant progress was made in developing design guidelines that did not exist prior to the HATP, and these results should provide a foundation for future designs.

Conventional flying qualities metrics were successfully evaluated at high angles of attack. Correlation to flight for those metrics based on low-order linear systems was a complicated task because of nonlinear response characteristics. Good handling qualities were achieved, but numerous issues such as pilot command variables were left unresolved. Appropriate evaluation maneuvers were shown to be critical to expose control system problems.

Performance in the conventional and poststall flight regimes can be significantly improved with a thrust-vectoring and forebody-vortex control capability and advanced control laws. The large increase in controllability was critical in achieving the unprecedented levels of agility and carefree maneuverability demonstrated. Flight results indicated thrust vectoring and actuated forebody strakes were effective for controlling the aircraft in body-axis yaw at high angles of attack.

Linear control law design techniques can be used successfully in nonlinear flight regimes with some nonlinear compensation techniques to account for cross-axis coupling terms readily apparent at high angle of attack. Ease of modification is an important consideration in implementation and subsequent use of research flight control laws. Capabilities such as an on-board excitation system and dial-a-gain can be effectively used to reduce the flight test time required.

The importance of an accurate simulation model was clearly demonstrated. Every step of the design process relied heavily on a model that accounted for the nonlinear aerodynamics as well as flight computer and sensor characteristics. Piloted simulation was shown to be a key element in helping to mature a design prior to flight and addressing problem areas. However, pilot-induced oscillation prediction, using simulation and current analytical methods, was shown to be a significant problem area that will require focused study for future designs.

A primary goal of the controls research in the HATP was to accelerate and mature controls design technology for future fighter aircraft. This paper has summarized the approach to achieving this goal by discussing research activities on the various elements in the design process. Several control design methodologies were evaluated in flight, illustrating the strengths and weaknesses in the design process.

REFERENCES

[1] Chambers, Joseph R., "High-Angle-of-Attack Technology: Progress and Challenges," *High-Angle-of-Attack Technology*, NASA CP-3149, vol. 1, May 1992, pp. 1–22.

[2] Herbst, W. B., "X-31A at First Flight," *Flying Qualities*, AGARD CP-508, Feb. 1991, pp. 29-1–29-8.

[3] Canter, Dave E., "X-31 Post-Stall Envelope Expansion and Tactical Utility Testing," *Fourth High Alpha Conference*, NASA CP-10143, vol. 2, July 1994.

[4] Kidman, David S., Vickers, Jesse E., Olson, Brian P., and Gerzanics, Michael A., *Evaluation of the F-16 Multi-Axis Thrust Vectoring Aircraft*, AFFTC-TR-95-12, Sept. 1995.

[5] Smith, W., "X-29 High AOA Flight Test Results: An Overview," *SAE Aerospace Atlantic Conference and Exposition*, April 1993.

[6] Gilbert, William P., Nguyen, Luat T., and Gera, Joseph, "Control Research in the NASA High-Alpha Technology Program," *AGARD Fluid Dynamics Panel Symposium on Aerodynamics of Combat Aircraft Control and of Ground Effects*, Oct. 1989.

[7] Hoffler, Keith D., et al, "Evaluation Maneuver and Guideline Development for High Alpha Control Law Design Using Piloted Simulation," AIAA-94-3512, Aug. 1994.

[8] McDonnell Aircraft Company, *NASA High Alpha Research Vehicle Thrust Vectoring Control System (HARV/TVCS)*, Control Law Specification Document, Mar. 1989.

[9] Pahle, Joseph W., Powers, Bruce, Regenie, Victoria, Chacon, Vince, Degroote, Steve, and Murnyak, Steven, *Research Flight-Control System Development for the F-18 High Alpha Research Vehicle*, NASA TM-104232, April 1991.

[10] Carter, John F., "Inertially Derived Flow Angle Measurements," *High-Angle-of-Attack Projects and Technology Conference*, NASA CP-3207, April 1992, pp. 51–68.

[11] Foster, John V., Ross, Holly M., and Ashley, Patrick A., "Investigation of High-Alpha Lateral-Directional Control Power Requirements for High-Performance Aircraft," AIAA-93-3647, Aug. 1993.

[12] Ogburn, Marilyn, Ross, Holly M., et al, "Flight Validation of Ground-Based Assessment for Control Power Requirements at High Angles of Attack," *Fourth High Alpha Conference*, NASA CP-10143, July 1994.

[13] Wichman, Keith D., Pahle, Joseph W., Wilson, R. Joseph, Connelly, Patrick J., and Kelly, John W., "High Alpha Handling Qualities and Agility Flight Research on the F/A-18 High Alpha Research Vehicle," *Fourth High Alpha Conference*, NASA CP-10143, vol. 2, July 1994.

[14]Wichman, Keith D., Pahle, Joseph W., Bahm, Catherine M., Davidson, John B., Bacon, Barton B., Murphy, Patrick C., Ostroff, Aaron J., and Hoffler, Keith D., "High Alpha Handling Qualities Flight Research on the NASA F/A-18 High Alpha Research Vehicle," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[15]Murphy, Patrick C., et al, "Preliminary Evaluation of HARV NASA-1 Control Law Flight Test Results," *Fourth High Alpha Conference*, NASA CP-10143, vol. 2, July 1994.

[16]Hoffler, Keith D. and Messina, Michael D., "Flight Test and Piloted Simulation Assessment of Evaluation Maneuvers and Nonlinear Guidelines Developed for High-Alpha Control Law Design," *High Angle-of-Attack Technology Conference*, Sept. 1996.

[17]Bacon, Barton J., "PIO Susceptibility of the F-18 HARV: Analysis/Prediction vs. Flight," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[18]Murri, Daniel G., Fisher, David F., and Lanser, Wendy R., "Flight-Test Results of Actuated Forebody Strake Controls on the F-18 High-Alpha Research Vehicle," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[19]Ostroff, Aaron J. and Wichman, Keith D., "Flight Evaluation of a Variable-Gain Output Feedback Longitudinal Control Law for the NASA F/A-18 High Alpha Research Vehicle (HARV)," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[20]Murphy, Patrick C., Davidson, John B., Lallman, Fredrick J., Morelli, Eugene A., Messina, Michael D., Thomson, Michael P., and Connelly, Patrick J., "An Evaluation of Design Methodology and High-Alpha Design Criteria for the ANSER Lateral-Directional Control Law," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[21]Enns, Dale, Bugajski, Dan, Hendrick, Russ, and Stein, Gunter, *Dynamic Inversion: An Evolving Methodology for Flight Control Design*, Jan. 1995.

[22]Wilson, David J. and Citurs, Kevin D., *High Angle of Attack Flying Qualities Design Guidelines*, NASA CR-4681, vol. I and II, Feb. 1996.

[23]Murphy, Patrick C., Bailey, Melvin L., and Ostroff, Aaron J., *Candidate Control Design Metrics for an Agile Fighter*, NASA TM-4238, March 1991.

[24]Foster, John V., Bundick, W. Thomas, and Pahle, Joseph W., "Controls for Agility Research in the NASA High-Alpha Technology Program," SAE-912148, Sept. 1991.

[25]Ogburn, Marilyn, Batterson, James, et al, "High-α Agility/Handling Qualities," *High Alpha Technology Program Workshop*, Nov. 1989.

[26]Ross, Holly M., Foster, John V., and Lluch, Daniel C., "High-Angle-of-Attack Roll Performance Guidelines: Simulation and Flight Validation Results," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[27]Davidson, John B., Foster, John V., Ostroff, Aaron J., Lallman, Fredrick J., Murphy, Patrick C., Hoffler, Keith D., and Messina, Michael D., "Development of a Control Law Design Process Utilizing Advanced Synthesis Methods with Application to the NASA F-18 HARV," *High-Angle-of-Attack Projects and Technology Conference*, NASA CP-3137, vol. 4, April 1992, pp. 111–158.

[28] McDonnell Aircraft Company, *NASA High Alpha Research Vehicle Thrust Vectoring Control System (HARV/TVCS): Theory and Implementation of the HARV/TVCS Mixer Predictor*, HARV-MJH-12, Aug. 1989.

[29] Halyo, Nesim, Moerder, Daniel D., Broussard, John R., and Taylor, Deborah B., *A Variable-Gain Output Feedback Control Design Methodology*, NASA CR-4226, Mar. 1989.

[30] Ostroff, Aaron J. and Proffitt, Melissa S., *Longitudinal-Control Design Approach for High-Angle-of-Attack Aircraft*, NASA TP-3302, Feb. 1993.

[31] Ostroff, Aaron J., Hoffler, Keith D., and Proffitt, Melissa S., *High-Alpha Research Vehicle (HARV) Longitudinal Controller: Design, Analyses, and Simulation Results,* NASA TP-3446, July 1994.

[32] Moore, B. C., "On the Flexibility Offered by State Feedback in Multivariable Systems Beyond Closed Loop Eigenvalue Assignment," *IEEE Transactions on Automatic Control*, vol. 21, Oct. 1976, pp. 689–691.

[33] Andry, A. N., Jr., Shapiro, E. Y., and Chung, J. C., "Eigenstructure Assignment for Linear Systems," *IEEE Transactions on Aerospace and Electronic Systems*, Sept. 1983, pp. 711–729.

[34] Sobel, K. M. and Shapiro, E. Y., "Application of Eigensystem Assignment to Lateral Translation and Yaw Pointing Flight Control," *The 23rd IEEE Conference on Decision and Control,* Dec. 1984, pp. 1423–1428.

[35] Davidson, John B. and Schmidt, David K., *Flight Control Synthesis for Flexible Aircraft Using Eigenspace Assignment*, NASA CR-178164, June 1986.

[36] Lallman, Frederick J., *Relative Control Effectiveness Technique with Application to Airplane Control Coordination*, NASA TP-2416, April 1985.

[37] Bowers, Albion H., Pahle, Joseph W., Wilson, R. Joseph, Flick, Bradley C., and Rood, Richard L., "An Overview of the NASA F-18 High Alpha Research Vehicle," *High-Angle-of-Attack Technology Conference*, Sept. 1996.

[38] Johnson, Steven A., *Aircraft Ground Test and Subscale Model Results of Axial Thrust Loss Caused by Thrust Vectoring Using Turning Vanes*, NASA TM-4341, Jan. 1992.

[39] Alexander, R. I. and Ray, Ronald J., *Development and Flight Test of a Real-Time Thrust Measurement Technique on the X-29A/F404 Advanced Technology Demonstrator*, NASA TM-101707, Sept. 1989.

[40] Bundick, W. Thomas, Pahle, Joseph W., Yeager, Jessie C., and Beissner, Fred L., Jr., *Design of a Mixer for the Thrust-Vectoring System on the High-Alpha Research Vehicle*, NASA TM-110228, June 1996.

[41] Bowers, Albion H., Noffz, Gregory K., Grafton, Sue B., Mason, Mary L., and Peron, Lee R., *Multiaxis Thrust Vectoring Using Axisymetric Nozzles and Postexit Vanes on an F/A-18 Configuration Vehicle*, NASA TM-101741, April 1991.