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RESEARCH FLIGHT-CONTROL SYSTEM DEVELOPMENT FOR THE F-18 HIGH ALPHA RESEARCH VEHICLE

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ABSTRACT

The F-18 high alpha research vehicle was recently modified by adding a thrust vectoring control system. A key element in the modification was the development of a research flight-control system integrated with the basic F-18 flight-control system. This paper discusses design requirements, system development, and research utility of the resulting configuration as an embedded system for flight research in the high-angle-of-attack regime. Particular emphasis is given to control system modifications and control law features required for high-angle-of-attack flight. Simulation results are used to illustrate some of the thrust vectoring control system capabilities and predicted maneuvering improvements.

INTRODUCTION

The demand for increased agility to engage in future air combat scenarios successfully may result in a marked increase of intentional flight at high angles of attack. Unfortunately, the effectiveness of aerodynamic controls is often inadequate to achieve the maneuvering requirements imposed by high angle of attack and low dynamic pressure. Thrust vectoring concepts have been proposed as one way to increase control power at high angle of attack. Several flight research technology programs incorporating thrust vectoring concepts are being conducted by the U.S. Department of Defense and NASA. These programs include the Defense Advanced Research Project Agency (DARPA) X-31 (ref. 1), the U.S. Air Force short takeoff and landing (STOL) and maneuver demonstrator (ref. 2), and the NASA High-Angle-of-Attack Technology Program (HATP).

The NASA HATP was designed to develop and validate some of the technology required for high-angle-of-attack flight. Three key technology areas; aerodynamics, advanced controls, and maneuver management are being addressed by this program. A key element of the program is the flight validation of the various research technologies. To provide this flight validation, the NASA F-18 high alpha research vehicle (HARV) has been modified to use thrust vectoring to provide the high-angle-of-attack capability required to complete the research objectives of the program. The primary modifications include a thrust vectoring vane system (TVVS) to provide the required control power for high-angle-of-attack flight and a research flight control system (RFCS) to provide a flexible, easily modified capability for high-angle-of-attack research control laws. The combination of the RFCS and the TVVS is called the thrust vectoring control system (TVCS). Figure 1 is an artist's conception of the HARV/TVCS with the TVVS installed.

This paper reviews the design and development of the RFCS and describes the integration of the research control system with the basic F-18 flight-control system. The modifications to the aircraft systems that were required to operate at high-angle of attack will also be described. The control system modifications and control law features required for high-angle-of-attack flight are emphasized. Simulation results will be used to illustrate the capabilities and predicted performance of the thrust vectoring system.

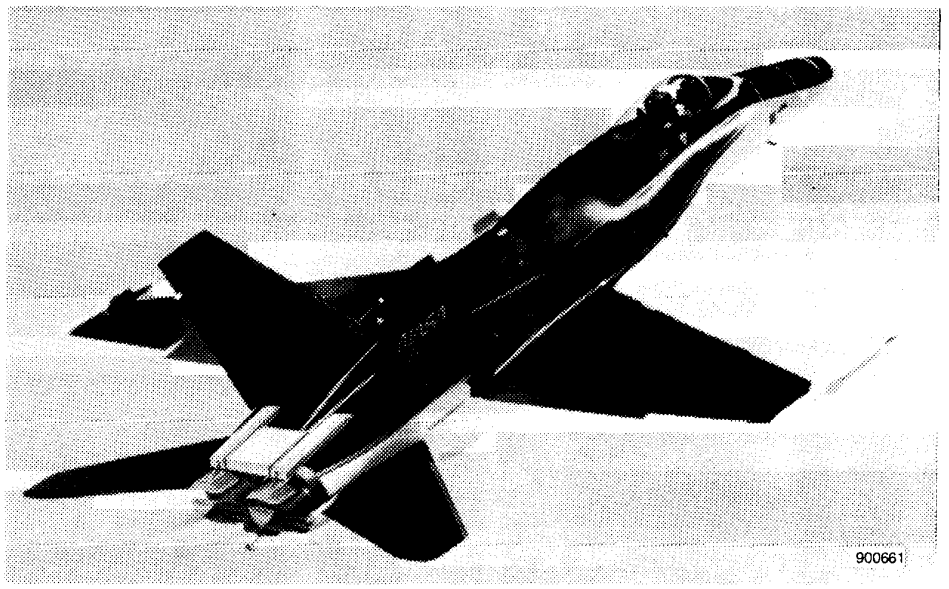

Figure 1. Artist rendering of F-18 HARV with thrust vectoring system installed.

NOMENCLATURE

A/D	analog-to-digital converter
g	gravity
HUD	heads-up display
HARV	high alpha research vehicle
HATP	High-Angle-of-Attack Technology Program
INS	inertial navigation system
I/O	input/output
M	Mach
MC	mission computer
N_z	normal acceleration, g
N_y	lateral acceleration, g
p	roll rate, deg/sec
q	pitch rate, deg/sec
r	yaw rate, deg/sec
q	dynamic pressure
C_{Lmax}	maximum lift coefficient
RAM	random access memory
RAV	remotely augmented vehicle

RFCS	research flight-control system
TVCS	thrust vectoring control system
α	angle of attack, deg
β	angle of sideslip, deg
θ	pitch angle, deg
ϕ	bank angle, deg

DESIGN REQUIREMENTS

The design philosophy for the RFCS was to develop a system capable of performing research tasks at high angle of attack at a reasonable cost with the main interest being the high-angle-of-attack, low-speed regime. As a result, the flight envelope was limited to altitudes from 15,000 to 35,000 ft and Mach number less than 0.7. The design point was Mach 0.25 at 25,000-ft altitude. At the design point, the performance requirements of the TVCS capability alone (no aerodynamic surfaces used) are given as

Parameter	Minimum	Desired
Pitch acceleration (q)	0.37 rad/s^2	0.50 rad/s^2
Yaw acceleration (r)	0.28 rad/s^2	0.35 rad/s^2

Additional maneuvering requirements were later specified for angular rates and accelerations in the pitch and roll axes, and maximum time to bank 90° both in 1-g flight and at elevated g (M = 0.6). Lateral—directional axis coordination and departure resistance guidelines were also specified. An example requirement for wind-axis roll rate as a function of angle of attack is shown in figure 2. These thrust vectoring design requirements were developed from piloted simulation studies using the differential maneuvering simulator (DMS) at Langley Research Center.

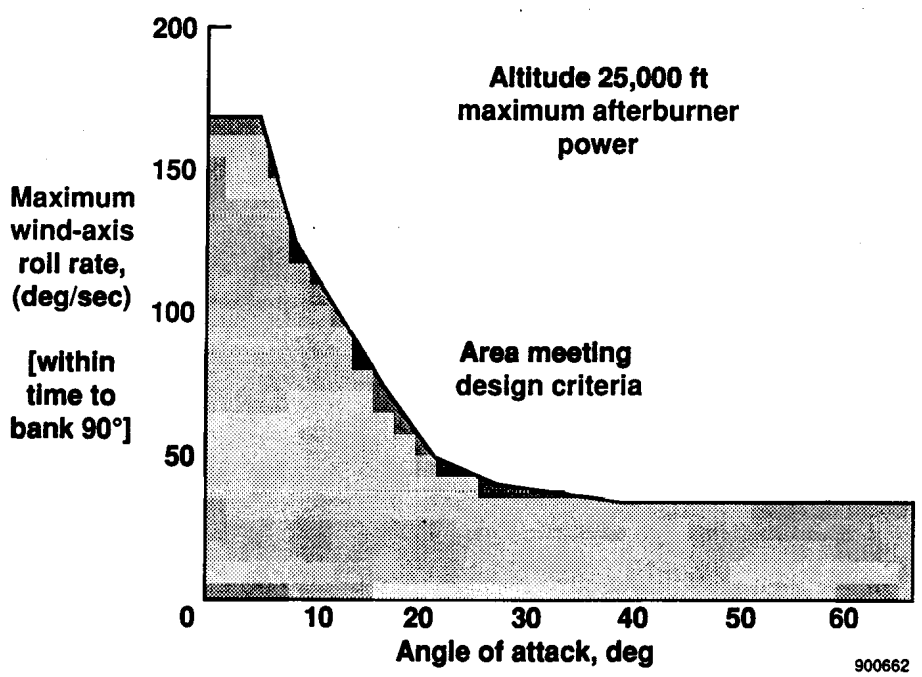

Figure 2. Example of RFCS maneuvering design requirement.

The TVCS/RFCS system was required to perform both highly maneuverable tasks representative of air combat maneuvers as well as steady flight at high-angle of attack to obtain aerodynamic data. Recovery from any flight condition was required to be performed with aerodynamic control alone. The RFCS was required to be fail-safe with positive reversion to the basic flight-control system in the case of failures. In addition, the system was required to maintain as much flexibility as possible to accommodate future research needs without having to make major system modifications.

DESIGN DESCRIPTION

The HARV is a pre-production, single-seat F/A-18 aircraft previously used for high-angle of attack and spin testing. The basic F-18 system has been extensively tested in these regimes and has been shown to be robust and controllable (refs. 3, 4). It is, therefore, an excellent platform for high-angle-of-attack research. Extensive instrumentation has been added to the HARV for high-angle-of-attack flow visualization, pressure measurement, and parameter identification (ref. 5).

The addition of the TVCS required that modifications be made to the aircraft avionics, flight controls, hydraulics, cockpit, and engines. A complete description of the modifications required can be found in references 6 and 7.

The TVCS modification included adding six thrust vectoring vanes (three located about the center line of each engine) and removing the divergent portion of the engine nozzles and external nozzle flaps (fig. 3). The location and geometry of the thrust vanes were a result of design trade-offs between thrust vectoring performance and possible interference with aerodynamic surfaces or the vanes themselves. The final TVCS design does not represent a production prototype, but is strictly an experimental installation for the evaluation of the thrust vectoring control.

The engine control system was modified to provide a selectable turbine discharge temperature bias for additional engine stall margin at high angles of attack. An emergency spin recovery parachute was mounted on the upper aft portion of the fuselage between the two engines. The HARV also has an emergency hydraulic and electrical system for protection against inadvertent loss of engine power during the flight tests.

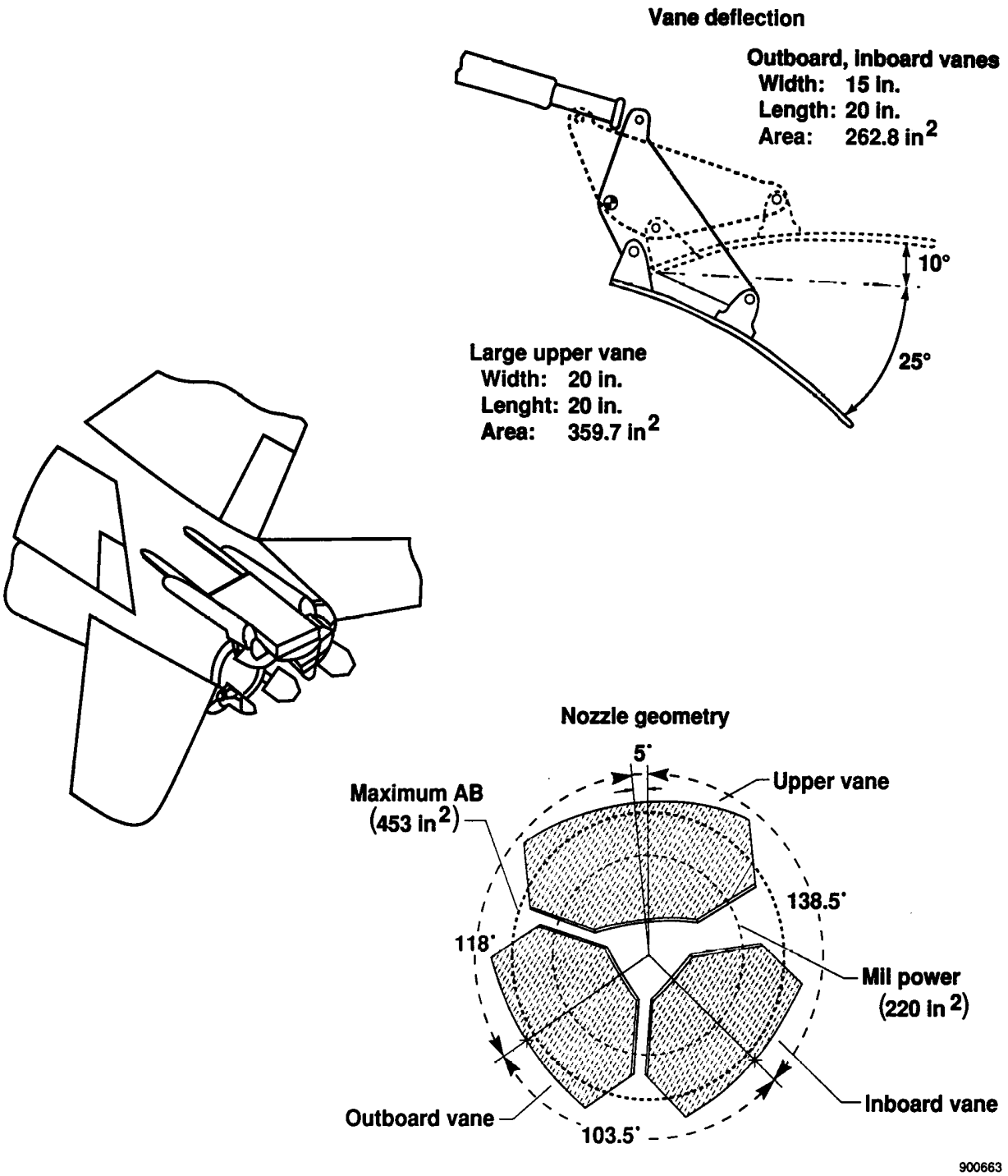

Figure 3. HARV thrust vectoring system.

The predicted performance of the thrust vectoring system compared with the desired performance is shown in figure 4. Simulation models indicate that the minimum required pitch accelerations can be achieved (if no yaw vectoring is required at the same time), while the predicted yaw accelerations are approximately 75 percent

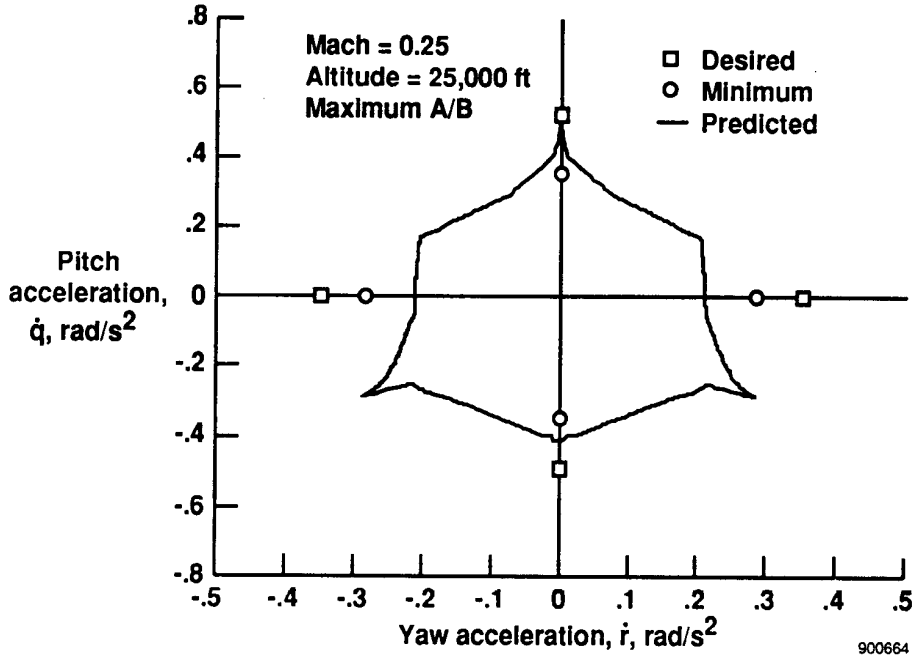

Figure 4. Predicted pitch and yaw acceleration using only thrust vectoring.

of the minimum required. Although the predicted results do not achieve the desired goals, the resulting pitch and yaw accelerations from the thrust vectoring system still represent a significant increase in control power over the basic F-18 in the high-angle-of-attack regime. Ground tests with the engines running and initial flight test will be used to determine the actual thrust vectoring capability.

Control System Integration

The flight-control system design uses an RFCS in addition to the basic F-18 control system. The RFCS provides an experimental embedded computer that can be engaged by the pilot to exercise full-authority control of the aircraft with the turning vane—research control laws. The basic F-18 control system is used for normal flight with the TVCS disengaged, including takeoff and landing, and it is also used in the event of an RFCS failure. The RFCS control laws and basic F-18 control laws operate in parallel, both computed continuously, throughout the flight envelope.

The integration of the basic F-18 flight-control system and the RFCS is shown in figure 5. The RFCS is an embedded system, where the RFCS processor resides within the same avionics box as the basic flight-control system. The RFCS control laws are programmed in Ada[1], and are completely independent of the basic control laws. This allows new research control laws to be added without affecting the basic flight-control system. The RFCS is synchronized with the basic system through a hardware pulse. All information to and from the RFCS is handled by the basic flight-control system through dual-port random access memory (RAM) to minimize communication delays and to isolate the basic system from RFCS failures. All I/O and failure monitoring is done within the basic system.

[1] Ada is a programming language based on PASCAL, originally developed on behalf of the U.S. Department of Defense for use in embedded computer systems.

Sensor inputs, pilot inputs, and airdata parameters are input to the basic flight-control system through analog-to-digital (A/D) converters. These signals are then compared in the input signal management, and a selected signal is sent to the basic control laws and the RFCS. Surface position commands are computed in both the RFCS and basic control laws. The output signal selection and fader logic determine which surface commands will be used by the actuator signal management and which commands will eventually be sent to the actuators. A MIL-F-1553 bus interface provides additional inputs to both flight-control systems (fig. 5). Data from other avionics systems are used by the basic flight-control system for outer-loop control functions only, while the RFCS requires data from the bus for inner-loop feedbacks (see the Avionics and Mission Computer Modifications section).

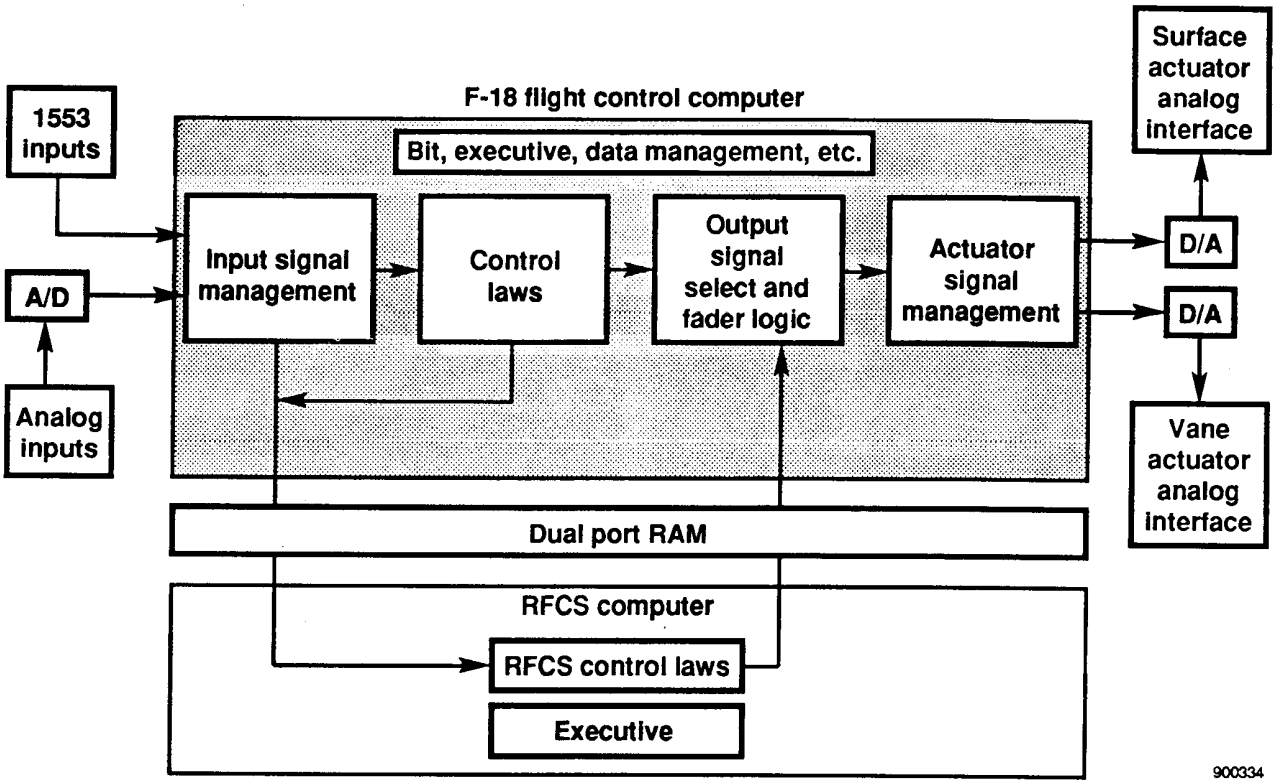

Figure 5. Integration of basic F-18 and research flight-control system.

To retain the integrity of the basic F-18 system, all failure monitoring, redundancy management, and I/O signal management functions are performed within the basic flight-control system as previously described. The functionality of the basic control laws was left unchanged except when it was required to incorporate RFCS I/O. Although the output signal management was modified to include the turning vane actuator commands, the basic F-18 control laws maintain the vanes in a fixed, retracted position (−10°). The basic system not only provides all of the pilot and sensor inputs to the RFCS, but also supplies internal basic F-18 control law results which can be used by the RFCS control laws if desired. Built-in-test functions are resident in both the basic system and RFCS computers. The basic flight-control system monitors its own health as well as that of the RFCS. The capability to monitor parameters within the basic and RFCS control law computers was added for flight-test information and evaluation. Sixty-four programmable words of data can be put on the aircraft MIL-F-1553 bus at 80 Hz and recorded for subsequent analysis.

Because both sets of control laws are being computed all the time, the basic F-18 control laws were modified to handle a forward-loop integral path in the longitudinal axis. The input and output of this integrator is set to zero

when the RFCS is engaged to prevent integrator windup (which can result in hard-over commands) when making the transition from the RFCS to the basic F-18 control laws. A similar design is used in the RFCS control laws to set integrators to zero when the RFCS is not engaged.

The basic flight-control system determines when the RFCS can be armed and then engaged. The RFCS performs additional checks to ensure that engagement occurs during stabilized flight to minimize transients. Batch nonlinear simulation runs were used to determine the arm and engage maneuvering limits. Currently, the programmable RFCS arm—engage limits are set at the following values

Parameter	Arm and engage limits
Roll rate (p)	± 30 deg/sec
Pitch rate (q)	± 15 deg/sec
Yaw rate (r)	± 15 deg/sec
Normal acceleration N_z	-1 to $2\ g$
Lateral acceleration N_y	$\pm\ 0.5\ g$
Angle-of-attack rate (α)	± 100 deg/sec
Angle of sideslip rate ($\dot{\beta}$)	$\pm\ 5$ deg/sec
Angle of sideslip acceleration ($\dot{\beta}$)	± 50 deg/sec^2

Avionics and Mission Computer Modifications

Angle of attack is not available above approximately 35° because of the position limits of the sensor vanes mounted on the forward fuselage. The initial RFCS control law design also required sideslip rate as an inner-loop feedback, a signal which is not available in the basic system. For this reason, The HARV mission computer (MC) now provides airdata parameters necessary for inner-loop feedbacks used in high-angle-of-attack control laws in the RFCS. Angle of attack, angle of attack rate, angle of sideslip, and sideslip rate are now computed in the MC using data from the inertial navigation system (INS), making the avionics system an integral part of the control system architecture. Figure 6 shows the interface between the avionics systems and the flight-control system. The MC is the bus controller and distributes information to and from the avionics. The RFCS required parameters calculated in the MC are first sent to the basic flight-control system and passed to the RFCS though dual-port RAM since the RFCS does not have a direct bus interface.

The algorithm for calculating the airdata parameters is shown in figure 7. Local wind velocities are determined from a comparison of the three components of inertial velocity with true airspeed components (transformed to the Earth axis). The calculated winds are essentially held constant when the aircraft is maneuvering, or when angle of attack is greater than 25° because of the time constant of the filters used for the winds. After the wind velocity components (the vertical component is assumed to be zero) are subtracted from the inertial velocity components, the inertially derived angle of attack and angle of sideslip are calculated. The angle of attack and angle of sideslip rates are calculated from approximations to the kinematic equations of motion.

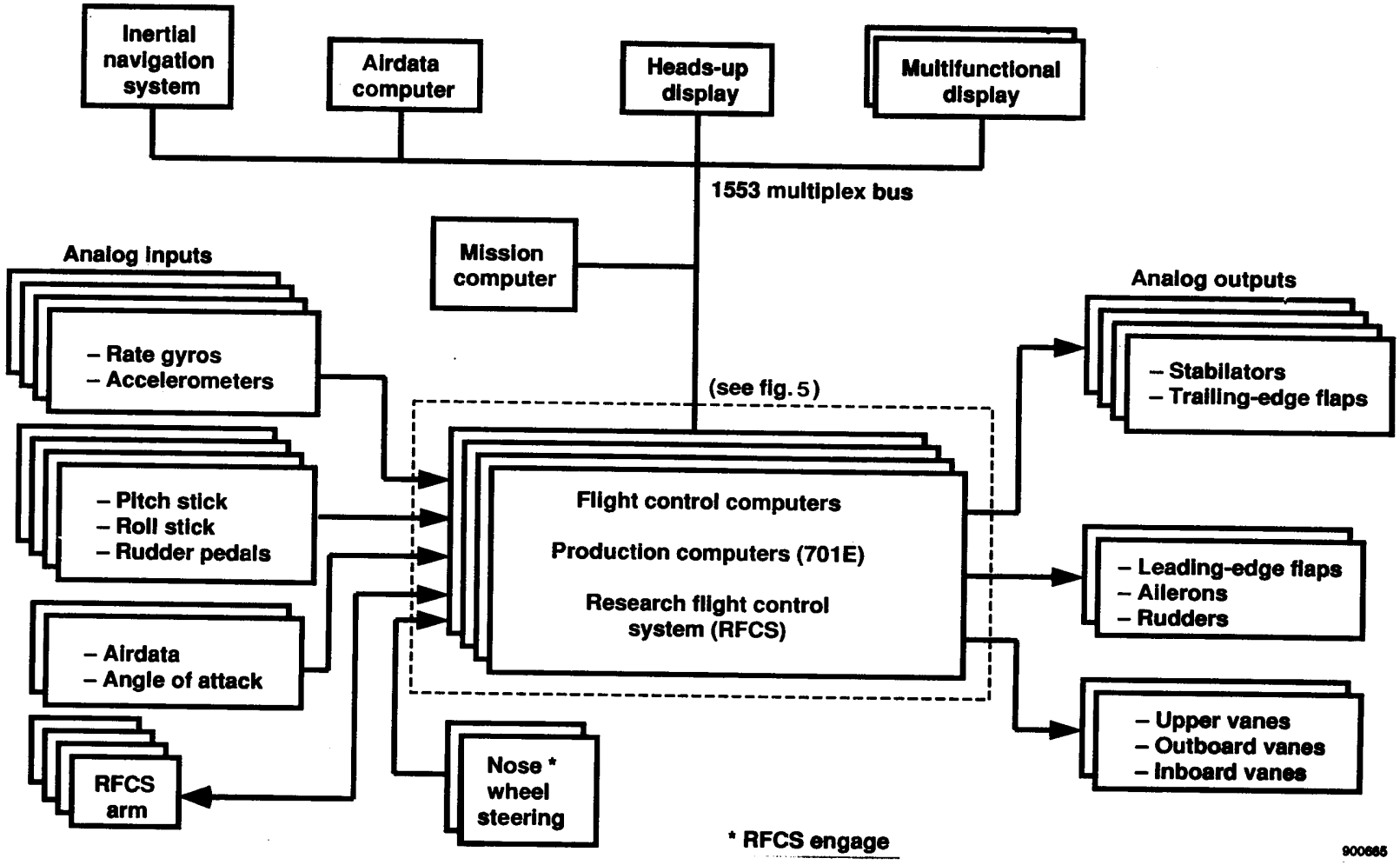

Figure 6. HARV control system components.

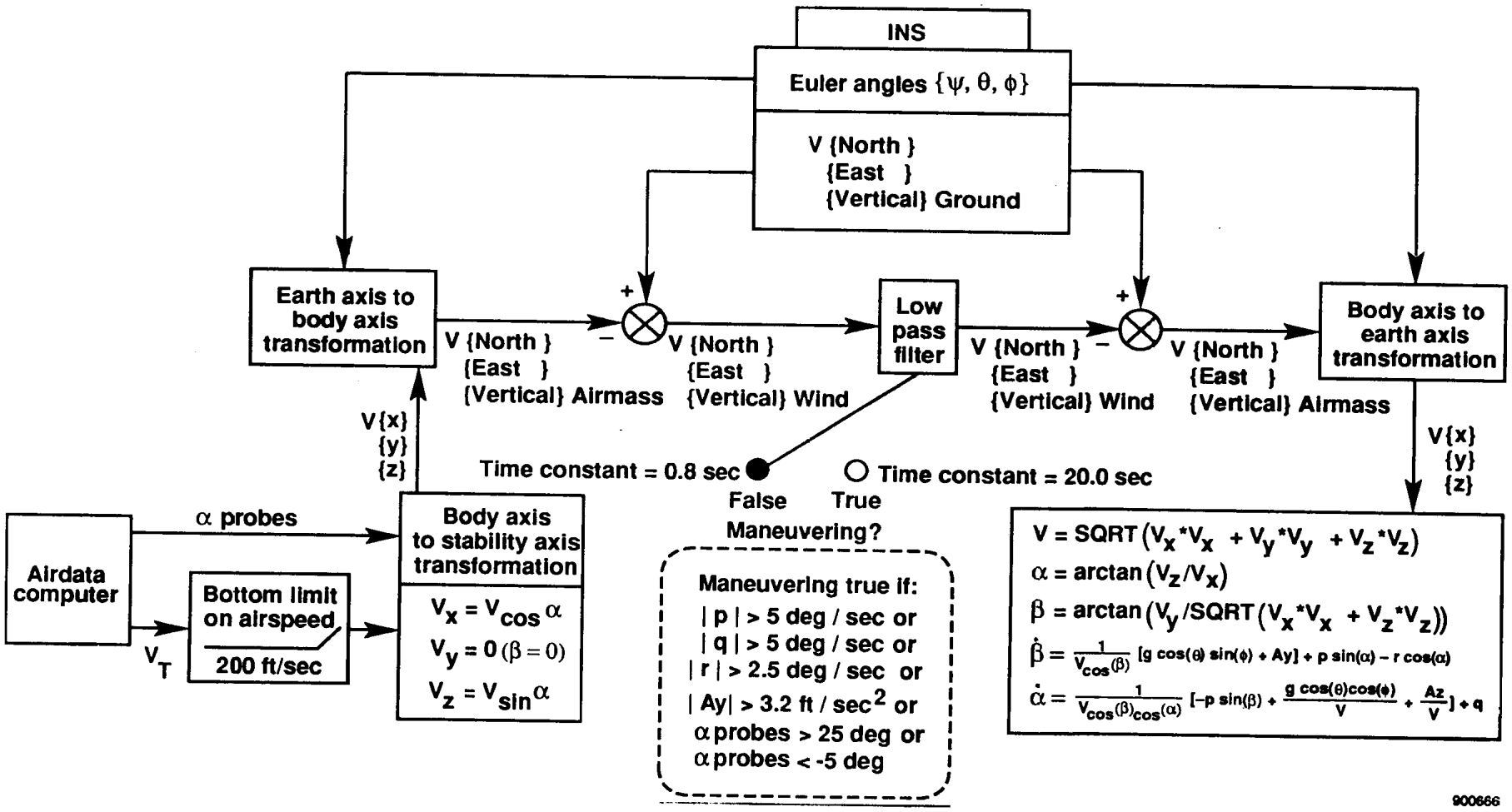

Figure 7. Inertial navigation system airdata algorithm.

The performance of the INS angle-of-attack algorithm was evaluated using INS parameters recorded from an earlier HARV flight. Figure 8 shows the calculated INS angle of attack compared with "corrected" angle of attack that

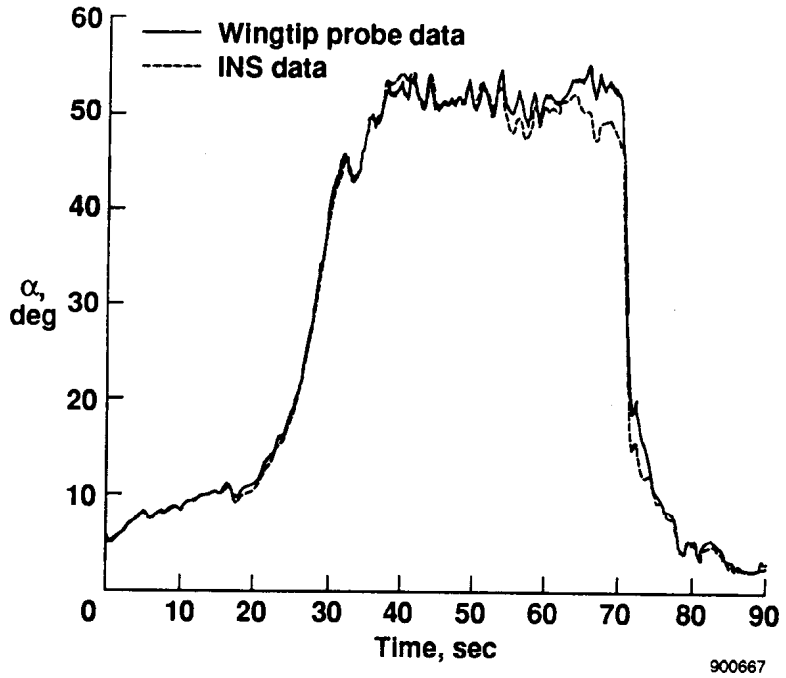

Figure 8. Flight data comparison of angle of attack from INS and calibrated wingtip probes.

was obtained from the calibrated wingtip probes (ref. 8). The relative error is less than 5°, while the maneuver maintains angle of attack above 40° for more than 40 sec.

All INS parameters have simplex redundancy (single string) since only one MC is operating at any time, and the HARV is equipped with a single INS. Computing airdata parameters in the MC eliminated the need for software modifications to the complex input signal management of the basic system, but at the cost of increased system complexity and time delay (approximately 60 msec).

The RFCS design also required the modification of existing sensor signals. Pitch rate and yaw rate signals were rescaled to accommodate the increased maneuvering capability. The HARV TVCS is expected to experience pitch and yaw rates greater than the 60 deg/sec maximum rates used by the basic F-18 system. Therefore, the pitch rate and yaw rate gyro signals were run through additional A/D interfaces to provide 100 deg/sec maximum rates to the RFCS without affecting the normal gyro signals provided to the basic F-18 system.

Minor modifications to the pilot displays were required for RFCS implementation. Sideslip angle and RFCS status are now displayed on the heads-up display (HUD), and vane deflection information was added to the existing control system page available to the pilot on the digital display interface. The RFCS can produce yaw rates that would be considered a spin by the basic F-18 control system, which would then normally activate a spin recovery display. With the RFCS engaged however, the spin recovery display is not activated. As a result, the word SPIN was added to the HUD display when the RFCS is engaged to warn the pilot that an activation of the spin-recovery mode logic would occur after a downmode from the RFCS to the basic system. A spin arrow similar to that in the spin recovery display was also added to the HUD to indicate the direction the pilot would be required to move the stick for spin recovery.

INITIAL CONTROL LAWS

The first set of RFCS control laws were developed by McDonnell Aircraft Company to demonstrate the research utility of the TVCS, and to allow RFCS flight envelope expansion (ref. 9). The control laws were designed for large amplitude maneuvering as well as stabilized flight at high-angle of attack for data acquisition, integrating both aerodynamic and propulsive controls. Initial design emphasis was placed on the stabilized flight task. The maneuvering performance guidelines were not used directly in the design techniques used for the control law development, but results were checked after final design iterations. Considerable effort was required to translate the initial linear control laws into a workable, nonlinear design.

A modular approach to the design and implementation of the RFCS control laws was used whenever possible. A modular approach simplifies future modifications, such as the design of a single axis control law, without a complete redesign of the existing system. A key element in the development effort was the use of Ada to implement the control law design. Ada source code is divided into modules, is readable, and is easy to transport. The same Ada source code developed for batch and piloted simulations was used as the flight code release and eventually compiled for the microprocessor used by the RFCS. Although the use of Ada reduced the development time and simulation integration effort, the amount of software verification testing required was unchanged.

The RFCS Ada control law software can be separated into longitudinal, lateral–directional, thrust vane mixer, and gross thrust estimation modules as shown in figure 9. These modules will be discussed in more detail in the following

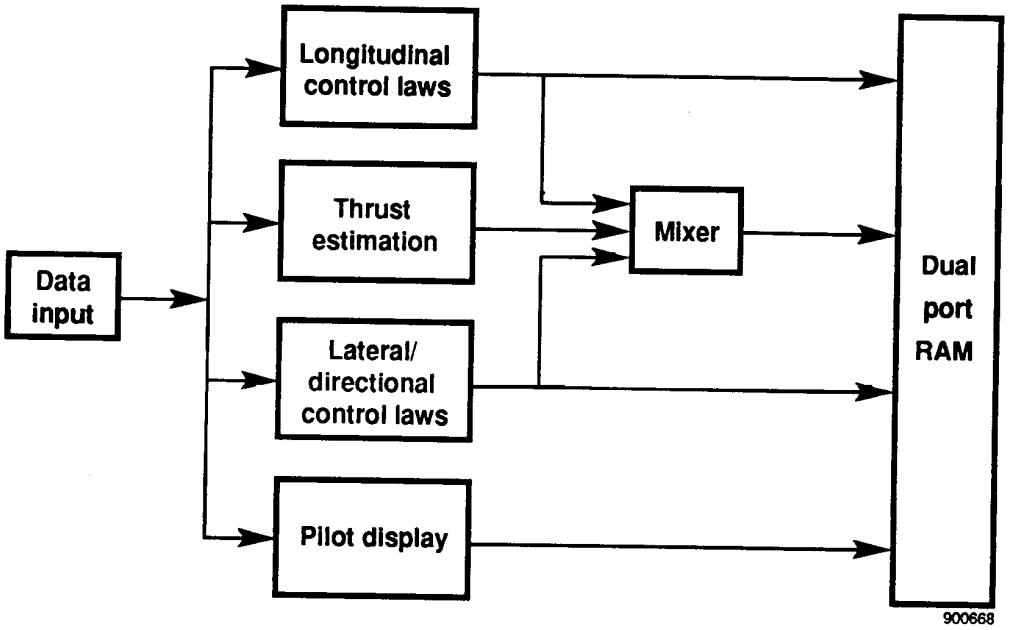

Figure 9. Research control system software modules.

sections. Additional modules provide instrumentation parameters to the MIL-F-1553 bus, provide a remotely augmented vehicle (RAV) capability (ref. 10), and an interface to the pilot's displays. Propulsion system functions are located in the thrust estimation and vane mixer modules. In this way, modifications to the more standard longitudinal–lateral–directional control law functions could be made without requiring complete knowledge of the complex interactions and gain scheduling associated with the thrust vanes and engines.

Longitudinal Control Laws

The RFCS longitudinal control is an angle-of-attack command system using pilot stick position, angle of attack, pitch rate, and inertial coupling feedback (p*r) as inputs. A simplified block diagram is shown in figure 10. Inertial coupling feedbacks are used to counteract undesirable cross-axis motion generated at high angular rates. Both stabilator and pitch thrust vectoring are used for rapid commands, but steady-state vectoring is driven to zero (washed out) if collective stabilator is not saturated. This helps to minimize thrust loss caused by vectoring, and reduces thermal loads on the vanes. Trimmed flight above approximately 55°-angle of attack will require a nonzero steady-state pitch thrust vectoring because of stabilator saturation.

The longitudinal control laws were designed using a contractor developed technique (ref. 9), which is a form of model-following suited for matching a desired closed-loop, lower order system. The control system gains are derived as explicit functions of the difference between a desired closed-loop transfer function and an approximation to the actual closed-loop system that ignores actuator and sensor dynamics. A short-period approximation to the longitudinal transfer function is used to model the unaugmented airframe. The desired closed-loop system is derived from a short period frequency and damping ratio selected from the level 1 range given in MIL-SPEC 8785C. A simple model (similar to a simulation model) of the unaugmented airframe longitudinal aerodynamic parameters is carried in the control laws as a function of Mach number and angle of attack. This model is used to approximate the actual bare airframe characteristics at any given flight condition. The approximate characteristics and the desired short-period characteristics are then used to compute the actual and desired closed-loop transfer functions. Specific control system gains are computed by equating the numerator and denominator coefficients of the two transfer functions.

Lateral–Directional Control Laws

The lateral–directional control laws use stability axis roll and yaw rate, lateral acceleration, sideslip rate, and inertial coupling (p*q, directional only) as feedback signals.A simplified block diagram is shown in figure 11. Differential stabilator, aileron, differential trailing-edge flaps, rudder, and yaw vectoring are used for stabilization, coordination, and maneuvering flight. Differential leading-edge flaps are not used. Differential stabilator command is limited as a function of angle of attack and symmetric stabilator command to maintain pitch command priority. Lateral stick commands stability axis roll rate. The initial RFCS design is a "feet on the floor" implementation, requiring no rudder pedal input for roll coordination. An early design used rudder pedal to command pure sideslip (with no roll rate), but this was viewed as unnatural during piloted simulation. A more traditional approach similar to the production F-18 control system is now in place. Pure sideslip may be commanded with rudder pedal and opposing lateral stick.

The design goals for the lateral–directional axis were a first-order response for stability-axis roll rate as a function of lateral stick, and a second-order sideslip response (with corresponding roll rate) due to rudder pedal. An eigenstructure assignment technique was used to design the lateral–directional control laws (refs. 11, 12, 13). Eigenstructure methods are well suited to the lateral–directional axis, since the desired surface interconnects and signal crossfeeds are intrinsic to the design technique. Eigenvalues were specified for the roll and dutch roll modes, and desired eigenvectors were derived from a simplified system model. A performance simulation was used to ensure that the desired eigenvalues and eigenvectors could be achieved with the control power available.

The lateral–directional gains are a function of angle of attack and impact pressure. At low-angles of attack and higher Mach numbers, the lateral–directional surface commands from the basic F-18 control laws are used by the RFCS with some yaw thrust vectoring added to augment rudder power. The capability to use basic F-18 surface commands to augment (or replace) RFCS commands without additional time delay was a by-product of the embedded system approach. This capability has also proved to be beneficial during ground testing of both the RFCS and the basic system.

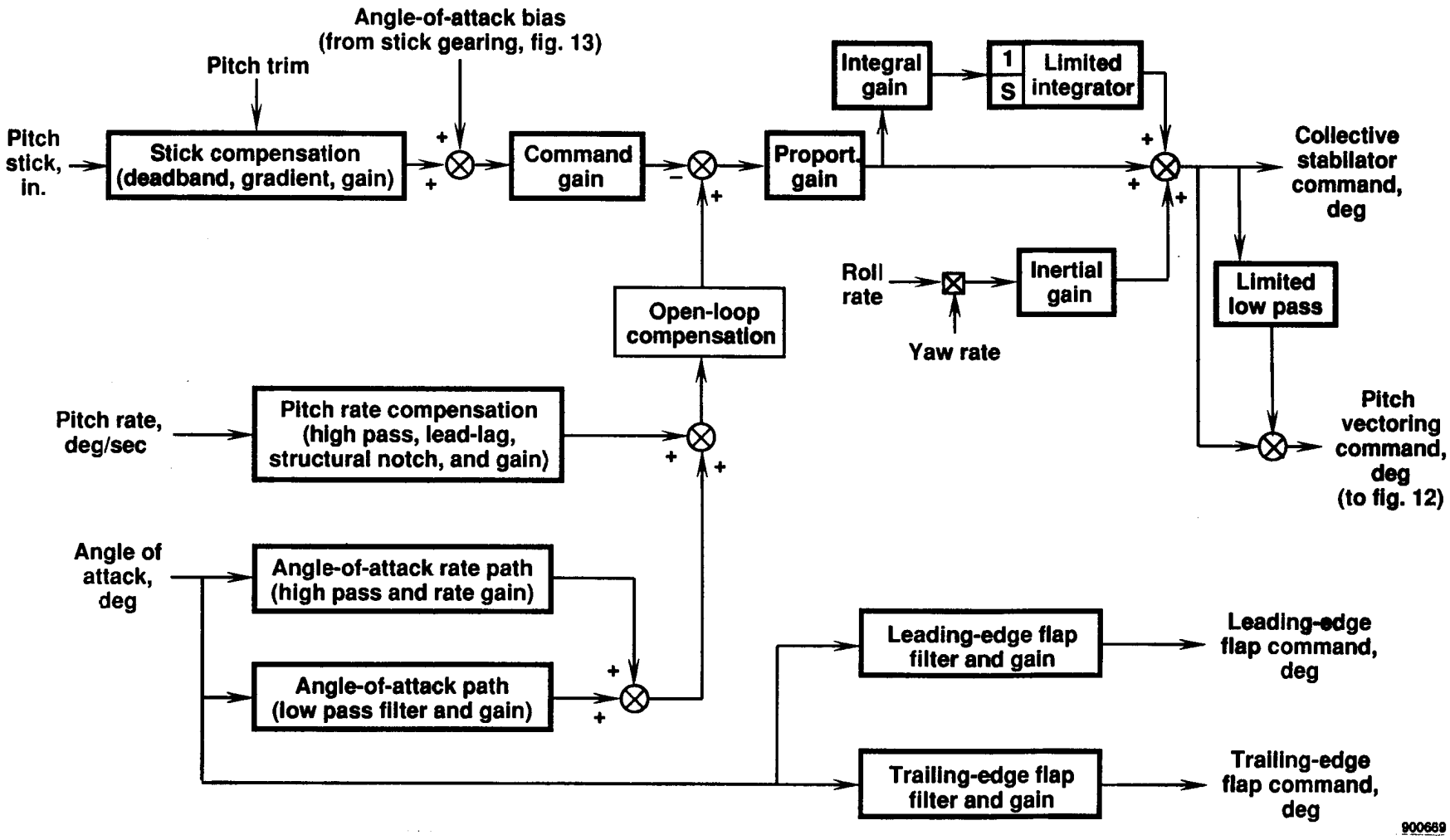

Figure 10. Simplified RFCS longitudinal control laws (angle-of-attack command).

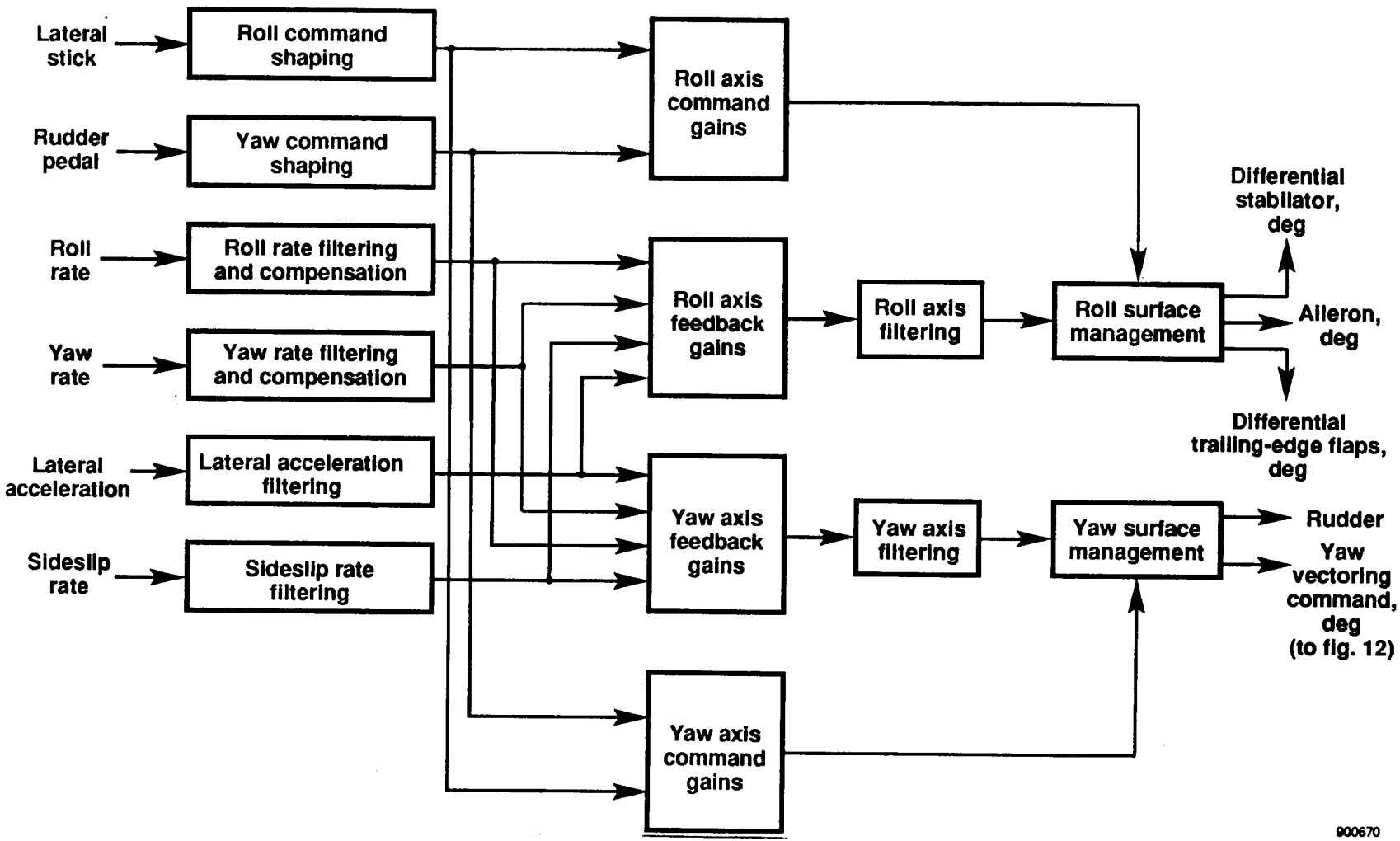

Figure 11. Simplified RFCS lateral–directional control laws.

Thrust Estimation and Vane Mixer

The surface effectiveness of the six thrust vanes that make up the TVCS is a complex relationship dependent on many parameters including gross thrust, flight condition, nozzle exit radius, nozzle pressure ratio, vane deflection, and positions of the other vanes situated around the same engine. Figure 3 shows the nonaxisymmetric vane placement and larger upper vane, factors that further complicate determining the vane deflections needed to achieve a desired vectoring result. Scheduling control law gains as functions of engine parameters greatly complicates the preliminary control law design process. One solution is to group the functions dependent on engine parameters apart from the inner-loop control laws. In this way, the control laws command pitch and yaw vectoring moments and it is left to a separate software module to determine the proper thrust vane deflections required to achieve those moments. This module, referred to as the vane mixer, was designed to generate the vane positions for the desired pitch and yaw vectoring commands (ref. 14, fig. 12).

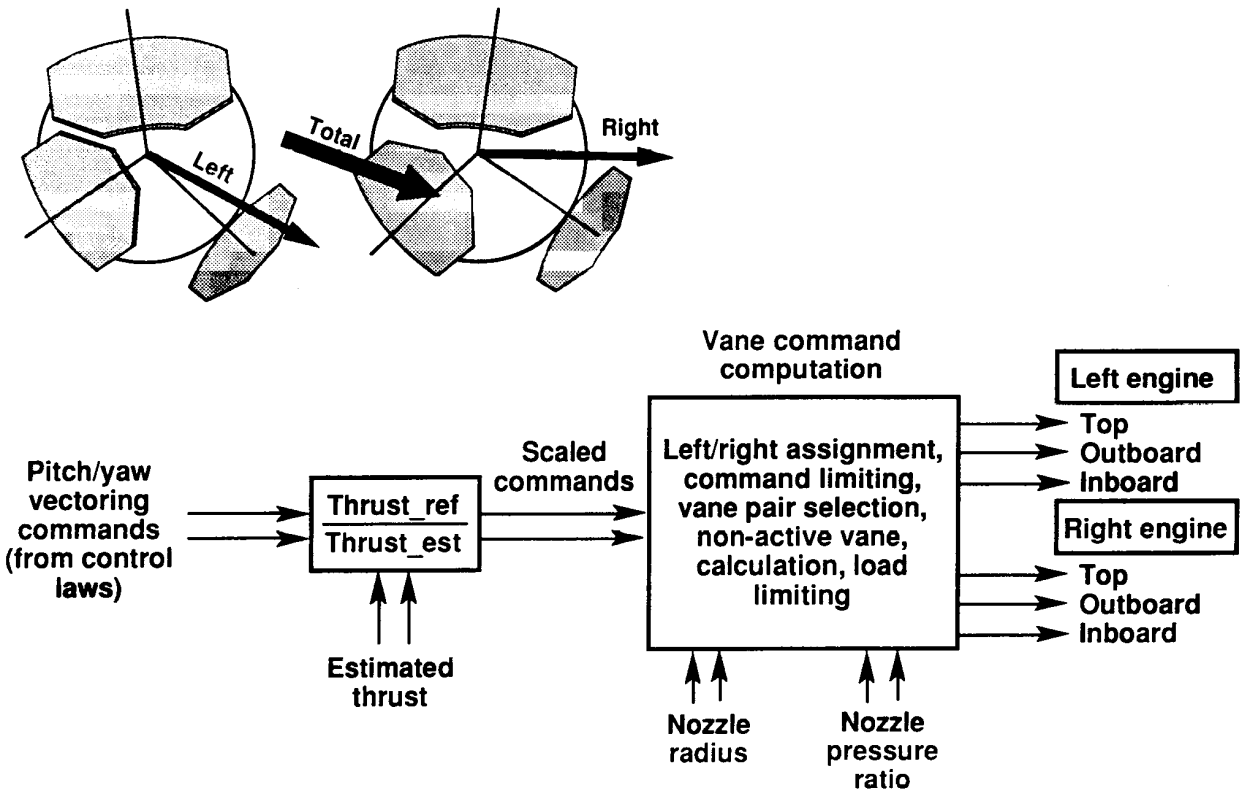

Figure 12. Simplified thrust vane mixer function.

The mixer function was developed by the contractor from the results of a high-pressure cold-jet test conducted at Langley Research Center using a 14.25-percent scale nozzle of the HARV TVCS. The moments commanded from the control laws are based on a constant reference gross thrust. The mixer uses the results of a real-time thrust estimation algorithm to scale the commanded thrust vectoring moments to the thrust available. In this way, the apparent thrust vectoring effectiveness is independent of engine thrust (within the range of the vane position limits). Gross thrust for each engine is estimated individually from the respective nozzle exit radius, engine pressure ratios, and power lever angle for the left and right engine. The mixer requires nozzle pressure ratio, estimated gross thrust, and nozzle exit radius from each engine, and the desired vectoring commands to produce the six thrust vane actuator commands.

Separating the thrust vectoring functions from the inner-loop control laws has an additional benefit in that the mixer and thrust estimator are generic modules common to all future control law designs. The performance of any thrust vectoring control law, however, will be dependent on the capability of the mixer to accurately predict the thrust vectoring performance in flight. Some of the primary control research objectives in the initial RFCS flight-test phase are to determine the actual performance of the thrust vectoring system and to update the existing models and control laws based on flight data.

Nonlinear Simulation

The preliminary linear control laws were implemented in a nonlinear batch simulation and also a piloted real-time simulation to further develop and refine the initial control law designs. Cross-axis coordination and surface interconnects were refined or limited when required. Gain schedules were finalized and faders were added to reduce gain transients. The lateral–directional strategy of using basic system surface commands as well as the longitudinal stick gearing strategy were developed after initial nonlinear batch and piloted simulation trials.

One of the more difficult tasks in the longitudinal axis design was developing a pilot stick strategy that would be acceptable both in the low-angle-of-attack region where stick position would normally command pitch rate and N_z, and at high angle of attack where stick position commands angle of attack. Physical modifications to the pilot stick feel system were not considered as a solution to this problem for RFCS, since the basic system (including the stick) was designed to be functionally the same as the production F-18 control system. Pitch stick throw was maintained at 2.5 in. forward to 5.0 in. aft.

Early in the longitudinal control law development effort, an angle-of-attack command system and an N_z command system were designed separately with faders used to smooth the transition between the two modes. When satisfactory results were not obtained, the system was changed to an angle-of-attack command system throughout the envelope. At low angles of attack, when an N_z command system is desirable, commanded N_z is converted to an angle-of-attack command by computing the angle of attack required to produce the desired N_z using a simple model of the lift curve at a fixed nominal gross weight. The angle-of-attack command is thus a function of stick position, dynamic pressure, and angle of attack as shown in figure 13. This stick gearing algorithm,

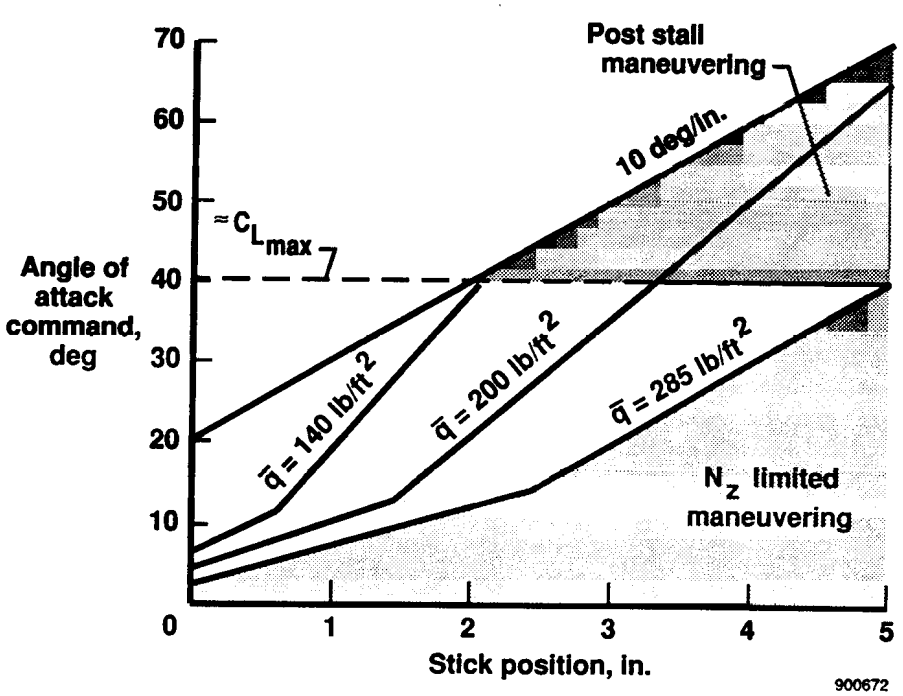

Figure 13. Pitch stick gearing for blended angle of attack and normal acceleration command.

although somewhat complex, provides the desired N_z command system for normal maneuvering with a smooth transition to an angle-of-attack command with a reasonable stick sensitivity for post-stall maneuvering up to 70°-angle of attack.

Figure 14 shows the response of the basic F-18 (dashed line) and the HARV/TVCS (solid line) to a 3.5-in. step (α = 54°) in pitch stick. The initial conditions are M = 0.35, 25,000 ft. Notice the improved damping and the angle-

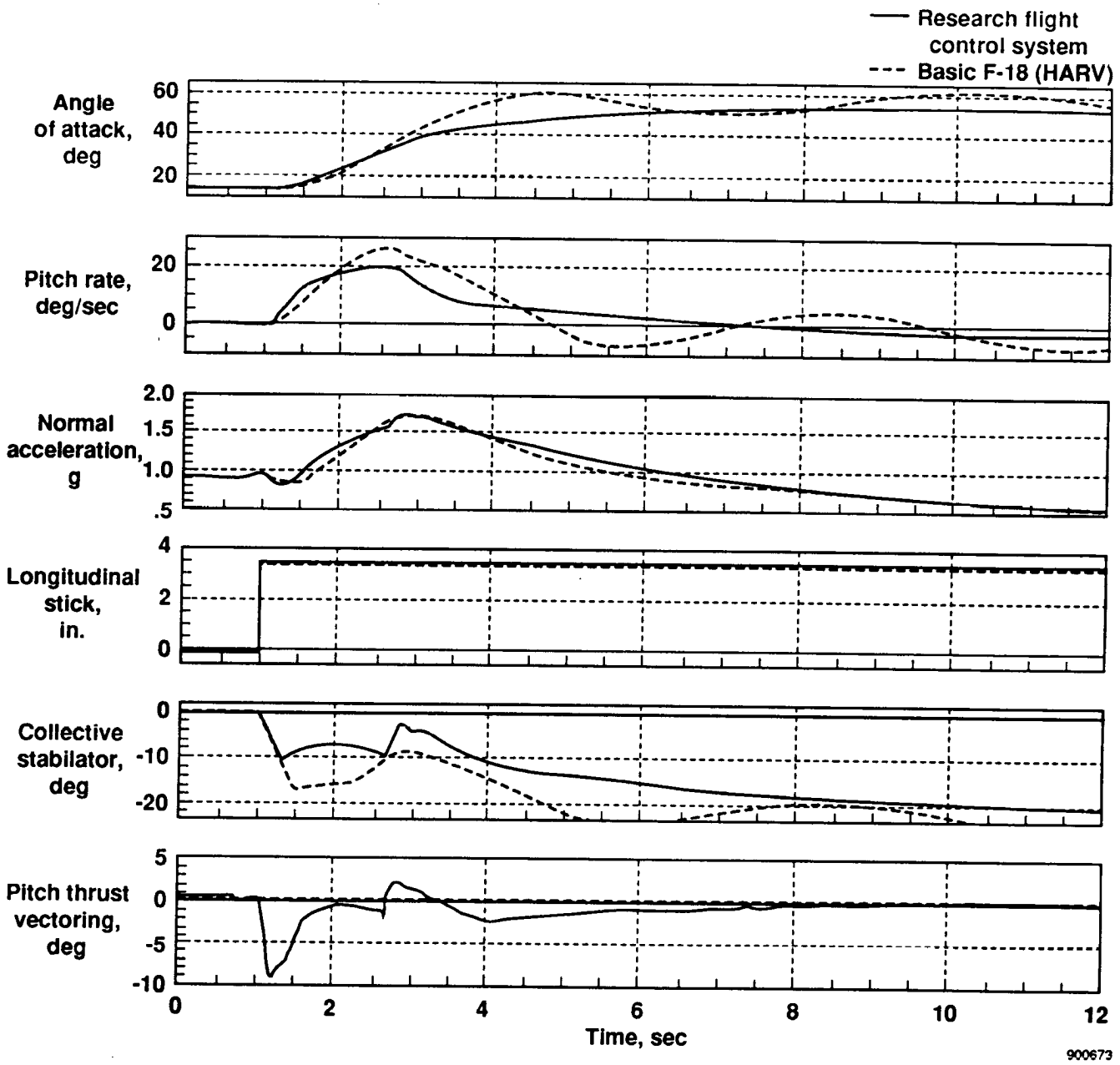

Figure 14. Simulated response of the HARV for a 54° angle-of-attack capture.

of-attack capture in the HARV/TVCS response, as well as the increased pitch acceleration at the onset of the step command.

Figure 15 shows the response of the basic F-18 (dashed line) and the HARV/TVCS (solid line) to a 2-in. lateral stick doublet. The initial conditions are $\alpha = 35°$ at 25,000 ft. The HARV/TVCS has more than twice the roll rate

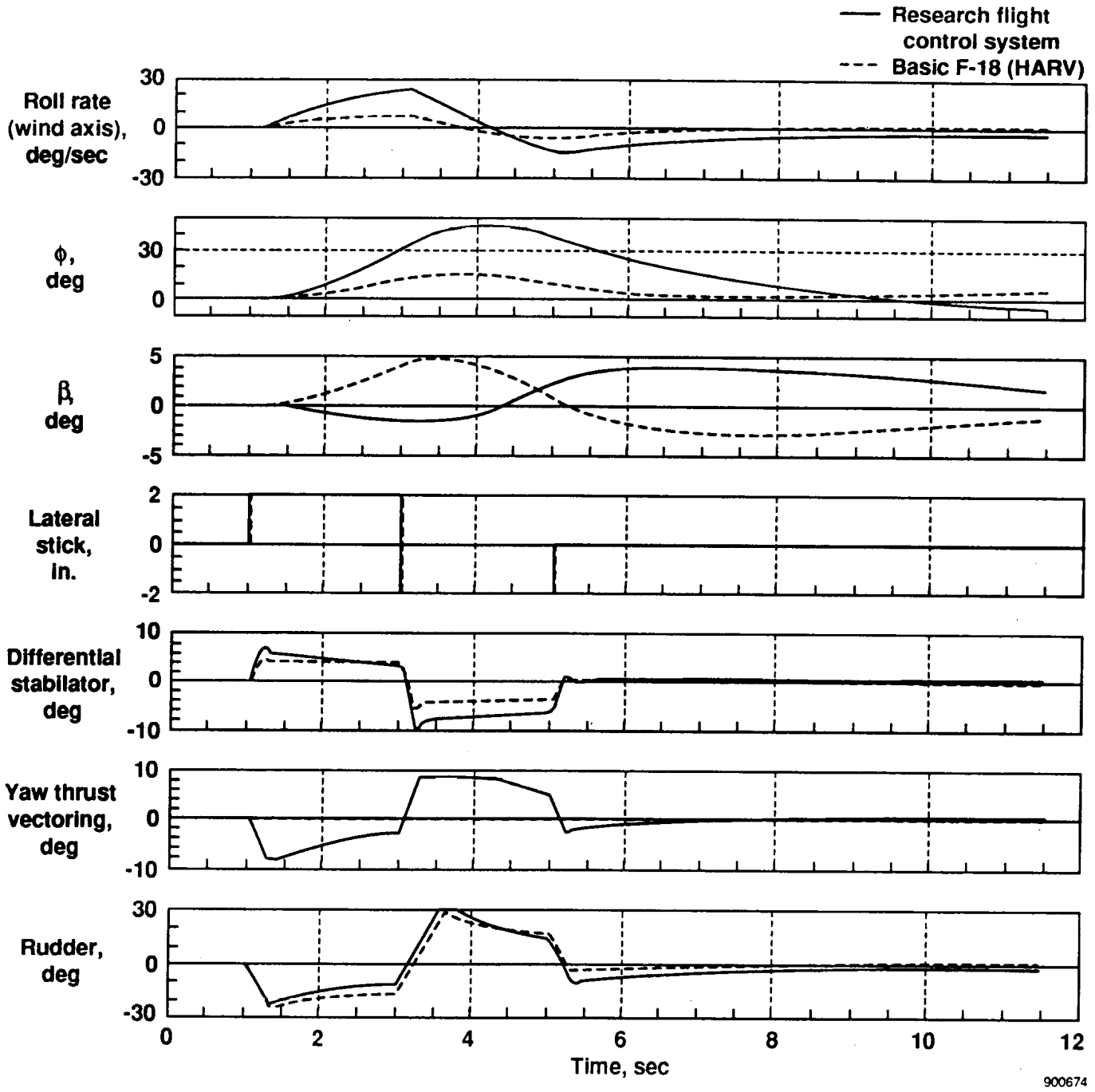

Figure 15. Simulated response of the HARV for a 2-in. roll doublet at 35° angle of attack.

response of the basic F-18, with smaller sideslip excursions. The six thrust vane positions and resulting pitch and yaw vectoring angles are shown in figure 16 for the same lateral stick doublet shown in figure 15. Some pitch vectoring is required to maintain the initial angle of attack throughout the maneuver. Figure 16 clearly indicates the complex relationship between the vane positions and the resulting thrust deflection angles.

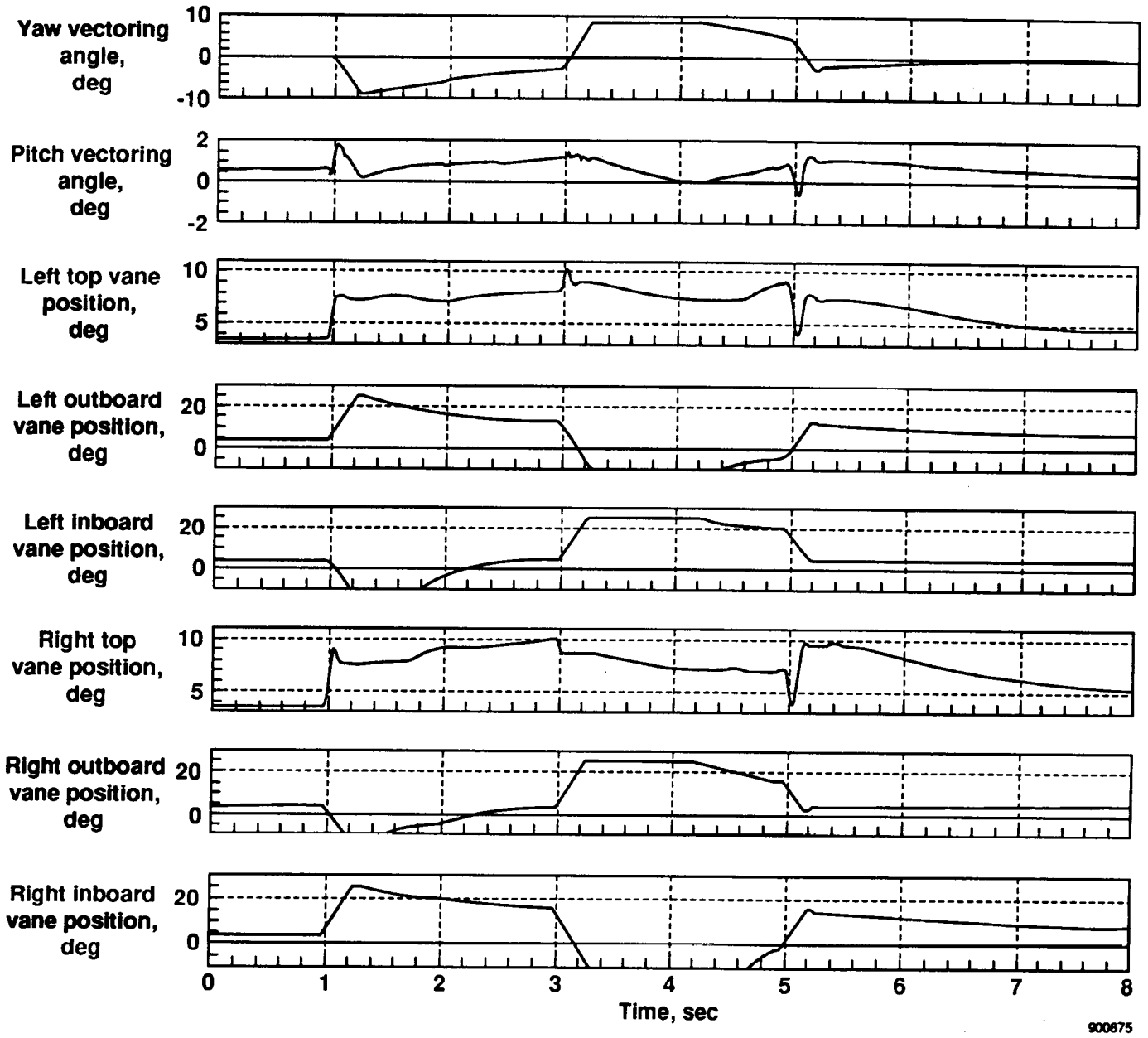

Figure 16. Simulated response of the HARV thrust vanes to a lateral stick doublet.

PLANNED FLIGHT RESEARCH USING THE TVCS

The first step in the flight program will be to evaluate the limited flight envelope with the basic F-18 flight-control system with the increased weight and inertia for structural loads and aeroservoelastic clearance. Since this is the recovery mode for any failures or downmode of the RFCS, it will be necessary to insure that adequate recovery

from high angle of attack, including recovery from departures and spins, exists with aerodynamic controls alone. After clearing the basic airplane envelope, the RFCS will be engaged and a normal envelope expansion program will be conducted to a stabilized angle of attack of 70°. During this phase, turning vane effectiveness and structural loads will be evaluated as well as control system stability margins. With the RFCS envelope cleared, the research flight-test phase will begin.

The initial research flight phase will begin to explore many of the research objectives of the NASA HATP (ref. 5). One area of interest to the flight-control system area will be the aerodynamic and thrust vectoring parameter identification. From this identification, the vane effectiveness characteristics will be determined and incorporated into an updated mixer algorithm for the research flight-control laws. In addition, during this phase the full maneuvering capabilities with the turning vane system will be evaluated in terms of handling qualities, agility, and performance using the initial research control laws. This evaluation will provide a preliminary assessment of high-angle-of-attack handling qualities and flight-control design criteria and an assessment of current agility metrics. After completing this phase, specialized research control laws will be required to fully validate the many technologies being developed in ground facilities.

FUTURE RESEARCH CONTROL LAWS

The F-18 HARV was designed so that alternate control laws could easily be implemented in the RFCS for various research investigations. The initial research control laws were designed to demonstrate the many options available with the RFCS. There are several areas in which highly specialized control laws can be used effectively to enhance research objectives. Potential candidates for future research control laws would include

control laws highly optimized for maneuverability and agility,

nonlinear control designs for high angle of attack,

control laws for parametric variations of handling qualities parameters,

control laws tailored to enhance identification of aerodynamic and thrust vectoring parameters, and

control law functions for on-board excitation of structural modes.

Depending on the size and complexity of these control laws, several control laws could be available to the pilot during any given flight which would greatly enhance the productivity of the high-angle-of-attack flight research program.

CONCLUDING REMARKS

The design of an experimental research flight-control system, and integration with the basic F-18 control system was a key element in the development of a high-angle-of-attack flight platform for controls, aerodynamic, and thrust vectoring research. The embedded research control system can be easily modified with alternate control laws without affecting the basic system. Research control laws were designed to demonstrate the increased maneuvering capabilities using the thrust vectoring system. An eigenstructure technique was used to design control laws for the lateral–directional axis, while a novel model-following technique was used to design an angle-of-attack command system for the longitudinal axis. A thrust vane mixer was developed to coordinate the deflections of the vanes to achieve the desired pitch and yaw vectoring commands. Inertial navigation system data and the mission computer were required for synthesis of required flight-control parameters not available from the basic system, making the avionics an integral part of the control system architecture. Simulation results indicate that the turning vane system in conjunction with the research flight-control system will provide a very good capability to perform the high-angle-of-attack research experiments of the NASA High-Angle-of-Attack Program. Flight tests of the thrust vectoring control system are currently planned to begin in early 1991.

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16. Abstract

The F-18 high alpha research vehicle was recently modified by adding a thrust vectoring control system. A key element in the modification was the development of a research flight-control system integrated with the basic F-18 flight-control system. This paper discusses design requirements, system development, and research utility of the resulting configuration as an embedded system for flight research in the high-angle-of-attack regime. Particular emphasis is given to control system modifications and control law features required for high-angle-of-attack flight. Simulation results are used to illustrate some of the thrust vectoring control system capabilities and predicted maneuvering improvements.

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