

Advanced flight control research and development at Boeing Helicopters

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1. Introduction

Boeing Helicopter's role in the technology advancement of full-authority digital fly-by-wire systems was spurred by requirements to improve handling qualities and mission effectiveness, and reduce weight and maintenance activities. The transition of Boeing research programs into production readiness is illustrated in Fig. 1. Development efforts on the Tactical Aircraft Guidance System (TAGS), Heavy Lift Helicopter (HLH) and Advanced Digital/Optical Control System (ADOCS) demonstrator programs form the basis for design of the V-22 and RAH-66. Currently, the V-22 is progressing through a 5 year engineering manufacturing development (EMD) contract for further refinement and demonstration of a production design. The aircraft is being co-developed by Boeing and Bell Helicopter Textron. Lessons learned from the V-22 flight test program are influencing design of the RAH-66 prototype. The first flight occurred in January 1996. The Comanche is being co-developed in a teaming arrangement between Boeing Helicopters and Sikorsky Aircraft Division of United Technologies Corporation. Boeing has lead responsibility for the flight control system development and mission equipment integration on both programs.

Safety is the primary objective of the flight control system development activities at Boeing. System design concepts are guided by a 'safety first' design philosophy, wherein a highly reliable control path is always maintained, thereby minimizing and constraining the effects of system failures. Production-type safety requirements are imposed at the outset of the design process, and although backup systems have been available on some programs, the design has never relied on them for flight safety.

Requirements for flight control systems integration at Boeing Helicopters have broadened and cover a wide range of technology disciplines. With higher levels of integration, advanced flight control systems have taken on a centralized role and have been renamed vehicle management systems. Significant emphasis has been directed toward achieving the following:

- *Improved flight safety and reliability* through the implementation of an architecture which minimizes the effects of system failures through intelligent fault detection algorithms.

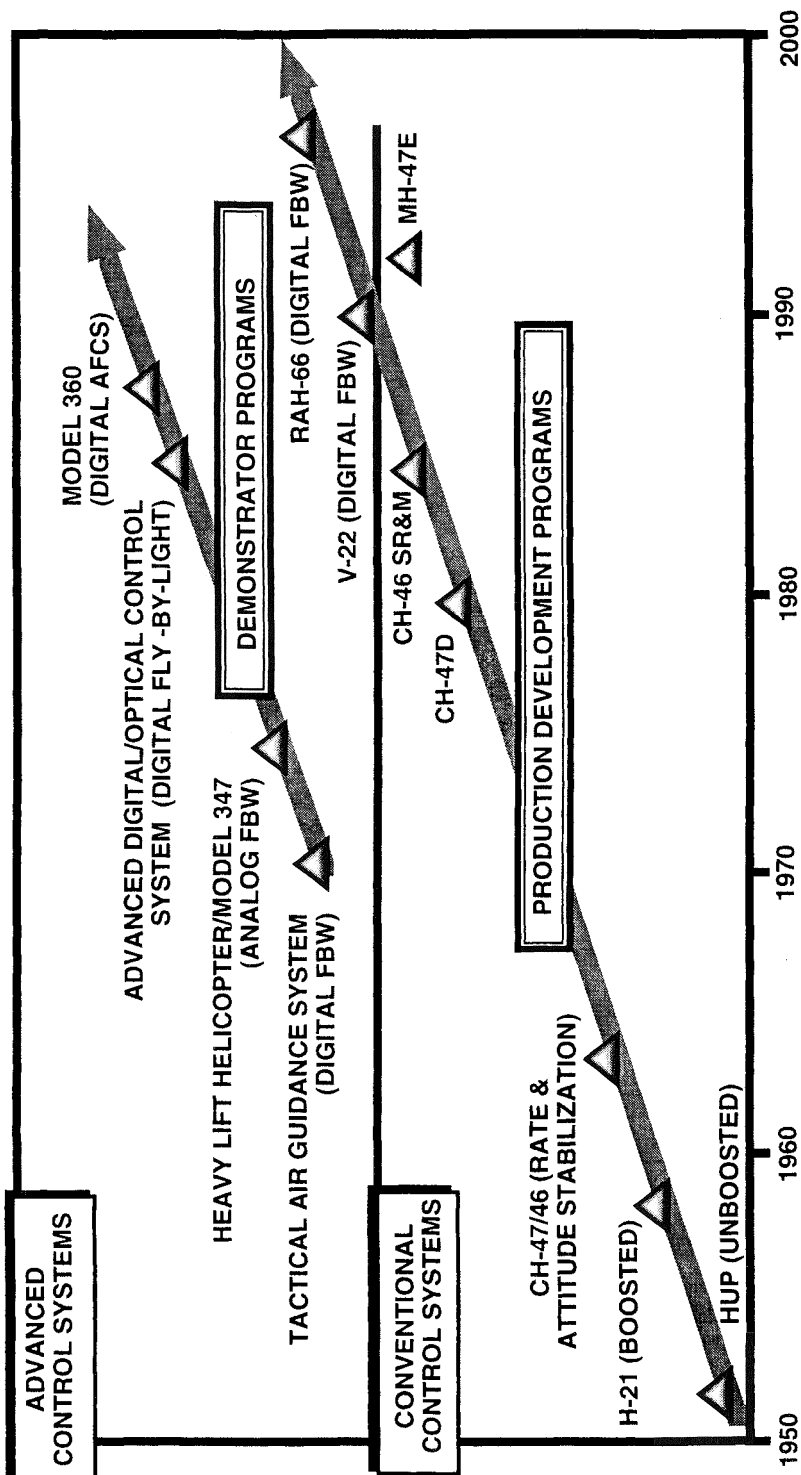


Figure 1. Boeing Helicopters flight control technology advancement.

- *Advanced control law techniques* using model-following control applications for tailoring of the aircraft response to achieve favorable handling qualities and structural loads characteristics.
- *Increased integration of mission-required functions* within the control system including engine, navigation and fire control systems, along with integration of advanced cockpit controllers.
- *Enhanced mission effectiveness* through selectable control law moding which allows optimization of control characteristics for each task, and automatic modes, such as programmed evasive maneuvers, to counteract known threats.

The purpose of this chapter is to highlight the advances in flight control design which will provide mission-capable rotorcraft for the future. Important developmental programs conducted at Boeing over the last several decades are summarized. A detailed discussion of vehicle management system design approaches provides insight into the control law architecture/implementation used in Boeing rotorcraft. Integration of subsystems to enhance efficiency and optimization of control law moding are highlighted as features required for a mission-capable aircraft. The control law design process employed to develop these features is provided for reference. The culmination of this experience as related to the RAH-66 Comanche and the V-22 Osprey programs is discussed in detail.

2. Development program overview

The broad experience accumulated at Boeing Helicopters is summarized in Fig. 2. The experience base established is backed up with extensive flight testing to verify system design concepts. On all programs, Boeing developed and refined an approach to control law architecture and redundancy management which took advantage of the benefits of model-following control laws. Significant experience with the integration of sidestick controllers was obtained, leading to a production-ready design. The flight control system has taken on a more centralized vehicle management system role through its integration with other subsystem functions, including navigation, engine, and fire control. This section provides an overview of the major flight control research and development programs conducted at Boeing Helicopters. Technology achievements of each program are discussed.

2.1. Tactical Aircraft Guidance System

Fly-by-wire efforts at Boeing began in the late 1960s with the Tactical Aircraft Guidance System (TAGS) research program. TAGS incorporated a triplex full-authority digital system using a three-axis sidearm controller. Advanced control concepts developed on TAGS included ground-referenced velocity vector control, command modeling and sensor complementary filtering. These concepts formed the basis of many flight control features included in the RAH-66 and V-22.

2.2. Heavy Lift Helicopter

Advancements in flight control technology were demonstrated from 1971 to 1974 as part of the US Army Heavy Lift Helicopter program (Davis *et al.* 1977). A dual-fail operational, full-authority, triplex fly-by-wire flight control system was

	PROGRAM FLIGHT HOURS				
	TAGS	HLH	ADOCS	V-22	RAH-66
VMS Technology	139	316	551	1000+	FIRST FLIGHT JAN 1996
Explicit Model Following	●	●	●	●	●
Multi-mode Control Laws	●	●	●	●	●
Sidestick Controllers	●	●	●		●
Integrated FCS / Navigation			●	●	●
Integrated FCS / Engine				●	●
Integrated Fire & Flight Control					●
Advanced Redundancy Management	●	●	●	●	●
Integrated Diagnostics				●	●

Figure 2. Boeing Helicopters vehicle management system experience.



Figure 3. Advanced flight control research and development programs at Boeing.

designed and flight tested on the Boeing Model 347 HLH demonstrator helicopter shown in Fig. 3. It was the first fly-by-wire helicopter with no mechanical backup control system. The aircraft had a retractable, rear-facing, load-controlling crew station equipped with a four-axis sidearm controller. As described in Landis *et al.* (1975), reconfigurable automatic flight control system (AFCS) modes provided Level 1 handling qualities along with a fully automatic approach to hover capability that enabled the pilot to perform rapid and precise external load operations in all weather conditions. With the hover-hold mode engaged, the aircraft demonstrated position hold to within 7.0 inches (18 cm) in steady winds of 12 knots, gusting to 24 knots. The load-controlling crew member, using the four-axis sidearm controller and operating through the hover-hold mode, demonstrated an impressive capability to control the aircraft precisely for rapid hookup and precision placement of external loads. An automatic load stabilization system provided a significant increase in load damping, both in hover and forward flight, to decrease pilot workload and improve performance during external load operations.

2.3. Advanced Digital/Optical Control System (ADOCS) demonstrator

Under a US Army contract during the 1980s, Boeing designed and flight tested an Advanced Digital/Optical Control System called ADOCS. Over 500 hours of testing with the digital fly-by-optics control system were accomplished on a modified UH-60A Black Hawk (Fig. 3). The ADOCS program was sponsored by the Army Aviation Applied Technology Directorate (AATD), Fort Eustis, Virginia, to demonstrate a battlefield-compatible helicopter with a flight control system that would enhance aircraft mission capabilities through decreased pilot workload and

improved handling qualities. An increasing hostile ballistic environment, along with consideration of the effects of lightning and electromagnetic interference on the battlefield of the future, led to the selection of fibre optic technology for the ADOCS flight control system. The application of multimode, mission-tailored control laws to improve scout/attack helicopter handling qualities, and the development of sidestick controller technologies, were advanced to a state of readiness for the RAH-66 Comanche.

The early stage of ADOCS development included a comprehensive piloted simulation study (Landis and Glusman 1984) of sidestick controller configurations and levels of system command/stabilization for use under both day and night-time conditions. Various sidestick controller designs (Fig. 4), ranging from a right-hand four-axis controller to a conventional $(2 + 1 + 1)$ configuration, were evaluated for numerous attack helicopter flight control tasks. The test matrix also evaluated controller compliance characteristics ranging from rigid force controllers to compliant small-displacement controllers. As a result of this simulation study, rigid force controller configurations were eliminated prior to flight test. For the flight demonstrator program, design improvements were made to the cockpit controllers, culminating with the flight demonstration of a small-displacement four-axis sidestick configuration and a $(3 + 1)$ controller configuration. Figure 5 shows the sidestick installed in the Black Hawk cockpit, as modified for the ADOCS demonstrator program. The $(3 + 1)$ configuration, comprising a three-axis small-displacement sidestick for pitch, roll and yaw control, and a left-hand medium-displacement collective controller with 4.0 inches (10 cm) of travel, was identified as the best configuration, leading to a similar application in the RAH-66.

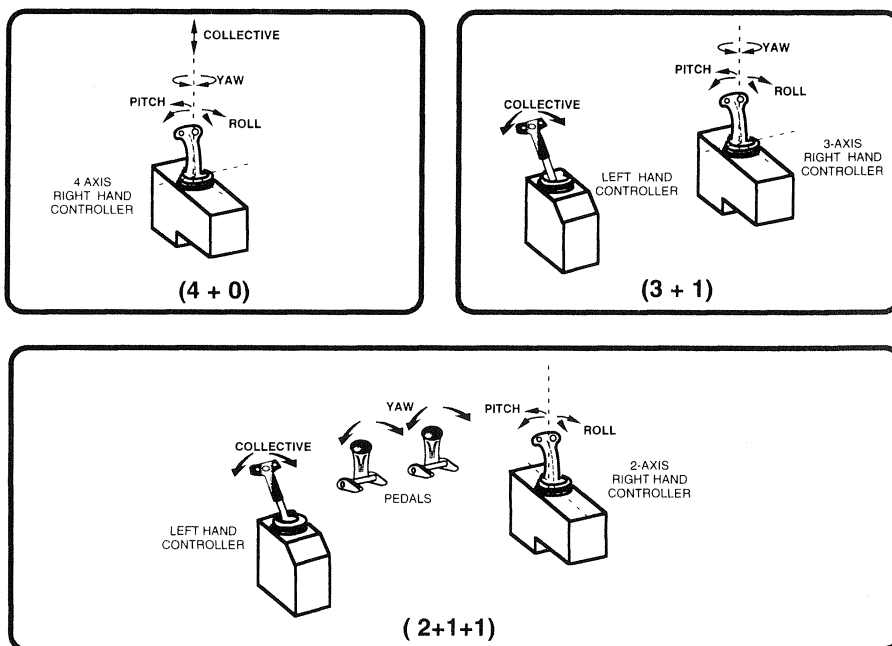


Figure 4. ADOCS sidestick controller configurations.

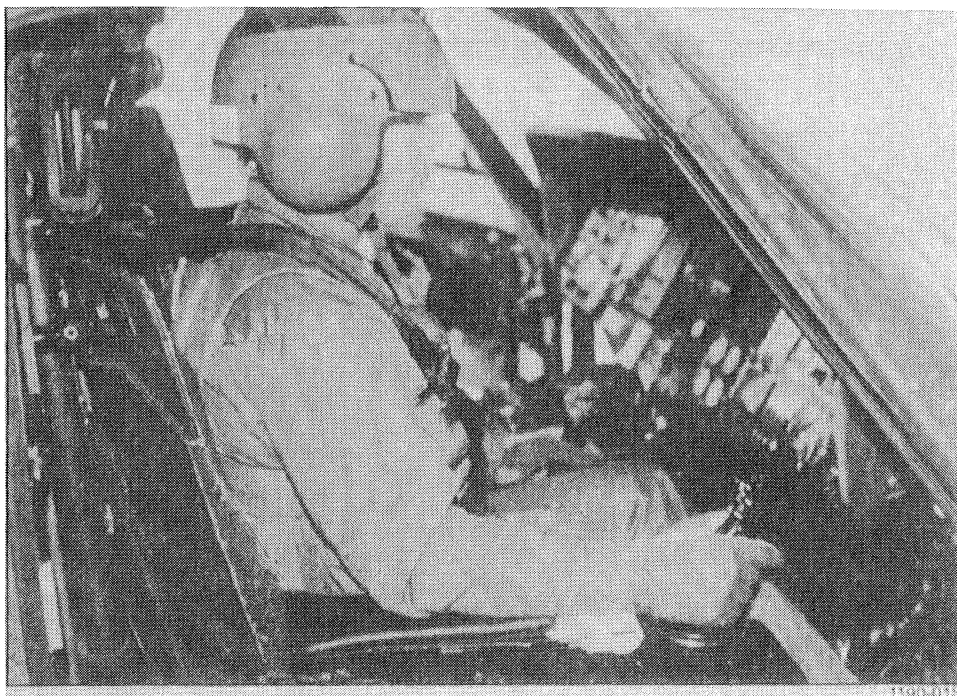


Figure 5. Advanced Digital/Optical Control demonstrator sidestick controller.

The ADOCS demonstrator aircraft provided an excellent test bed for the demonstration of major advancements in multimode explicit model-following control laws to enhance scout/attack helicopter mission performance. The reconfigurable digital fly-by-light control system provided the capability to evaluate a wide variety of selectable control laws. Overall success of the ADOCS control law design in providing excellent scout/attack helicopter mission performance and handling qualities was demonstrated in 1987 during nap-of-the-earth (NOE) flight testing conducted by the Army Aviation Engineering Flight Activity (AEFA) at the Army Fort Indiantown Gap test facility. Figure 6 compares pilot ratings for the ADOCS with the preferred (3 + 1) sidestick configuration and the UH-60A with conventional helicopter controls for a number of low-speed evaluation tasks. The flight test data shows the performance of the ADOCS with a sidestick controller configuration to be better than the conventional controls for a wide variety of tasks. Documentation of the ADOCS demonstrator design and flight test results can be found in Glusman *et al.* (1987, 1990).

2.4. RAH-66 Comanche

The ADOCS program preceded two pivotal events in the helicopter handling-qualities community, namely the initiation of the RAH-66 scout/attack helicopter program and the definition of a new handling-qualities specification (Aeronautical Design Standard ADS-33C, August 1989). The RAH-66 Comanche as shown in Fig. 3 will be the first helicopter to be procured under the new ADS-33 handling-qualities specification. Designed to be the next-generation scout/attack helicopter,

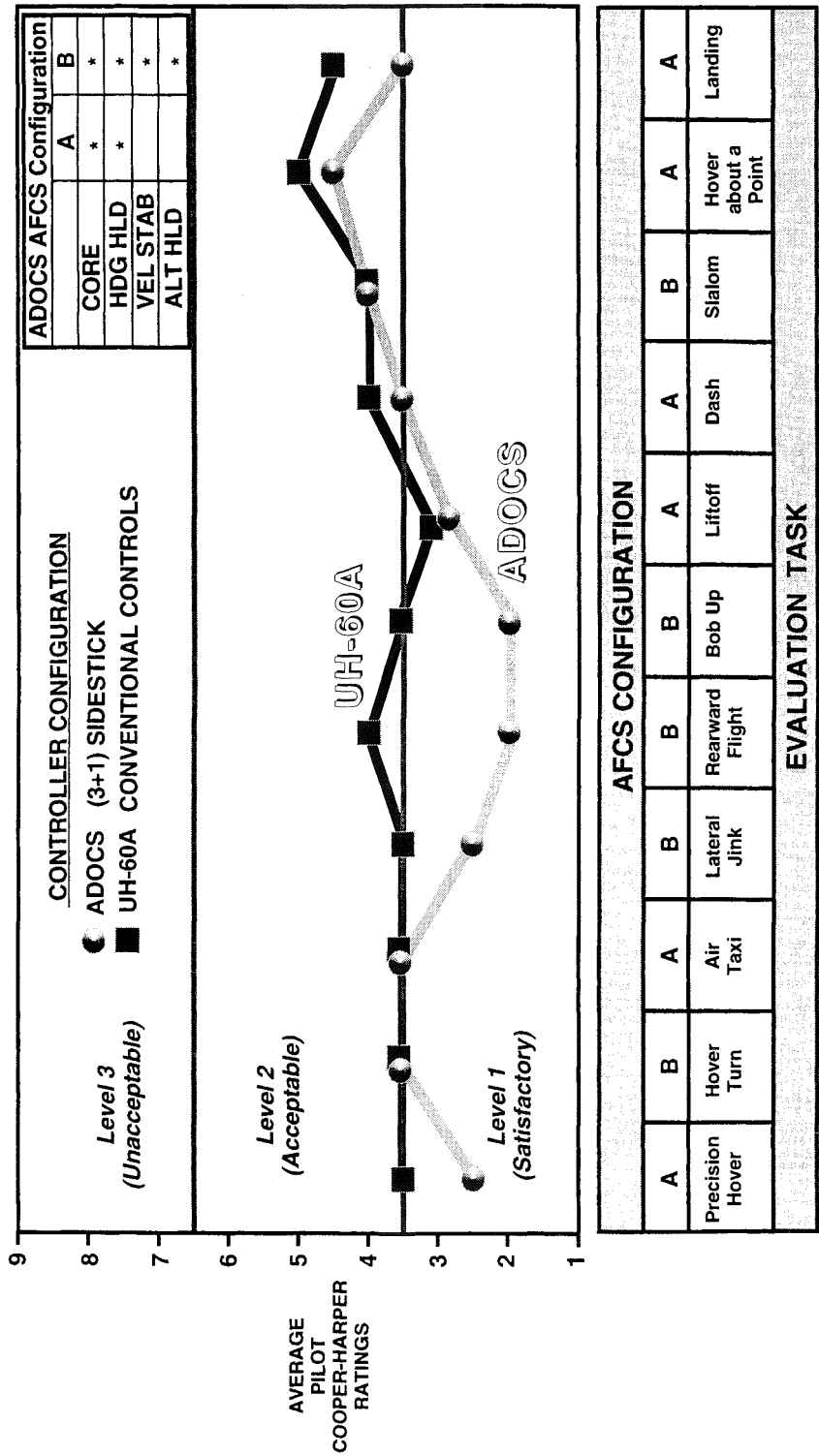


Figure 6. ADOCS demonstrator low-speed handling-qualities evaluation.

the Comanche incorporates many advanced technology features, including a FANTAIL anti-torque system and a bearingless main rotor with high equivalent flap hinge offset. It will also be the first US Army helicopter with a fully digital fly-by-wire control system and a three-axis sidestick controller. The flight control system technology base developed during the ADOCS program was well suited for direct extension to the Comanche design.

The Comanche flight control system utilizes a multimode control law design that enables the pilot to select flight control system characteristics according to the handling-qualities demands of each mission. In satisfying the requirements of ADS-33, the default (normal-mode) control laws are designed to achieve Level 1 handling-qualities ratings in day/VFR conditions (usable cue environment (UCE) = 1 in the nomenclature of ADS-33). Selectable modes and vision aids allow the Comanche to remain Level 1 under degraded visual conditions (UCE = 2 and 3), and provide further handling-qualities enhancements for automated navigation and targeting. In addition, adequate (Level 2) handling qualities are provided for safe return-to-base capability in the unlikely event of multiple flight control system (FCS) failures.

The Comanche flight control system capitalizes on many advanced design technologies. To meet stringent weight and cockpit ergonomic specifications while providing the desired handling qualities, the primary pilot controller for the longitudinal, lateral and directional axes is a small-displacement sidestick controller, a direct outgrowth of the ADOCS program. Full-time vertical control is provided by a left-hand medium-displacement collective lever having a total travel of 6.0 inches (15 cm). When the altitude-hold mode is engaged, a limited small-displacement vertical control axis provided on the right-hand sidestick frees up the pilot's left hand for cockpit management tasks. The Comanche also uses a binocular helmet-mounted display (HMD) as its primary instrument display to allow the pilot to keep 'eyes out of the cockpit' at critical times. A visual and aural cueing system reduces workload and allows the pilot to access full aircraft capability throughout the flight envelope while not exceeding limits.

2.5. V-22 Osprey

The V-22 Osprey (Fig. 3) is an advanced technology tilt-rotor aircraft developed for multiservice use in a wide variety of missions. It is capable of airspeeds ranging from 45 knots rearward in VTOL mode to 345 knots forward in airplane mode. The aircraft, described in detail in Rosenstein and Clark (1986), is characterized by a high forward-swept wing and H-tail empennage. The tilting nacelle at each wingtip is comprised of an engine, transmission and three-bladed rotor and rotor swashplate controls. The rotors are mechanically interconnected for continuous power transmission during single-engine operation. The V-22 flight control system is a full authority, two-fail operative, triplex digital fly-by-wire system. Control of the V-22 in the hover/low-speed regime is achieved through cyclic and collective inputs to the swashplate and power demand signals to the Allison T406 engines. Thrust vectoring is achieved by variation of the nacelle incidence between 0° in airplane mode and 97.5° (7.5° aft of vertical) in helicopter mode. Conventional airplane control surfaces (elevator, rudder, flaperons) are active throughout the flight envelope, while helicopter swashplate controls are phased out in forward flight as nacelle incidence is

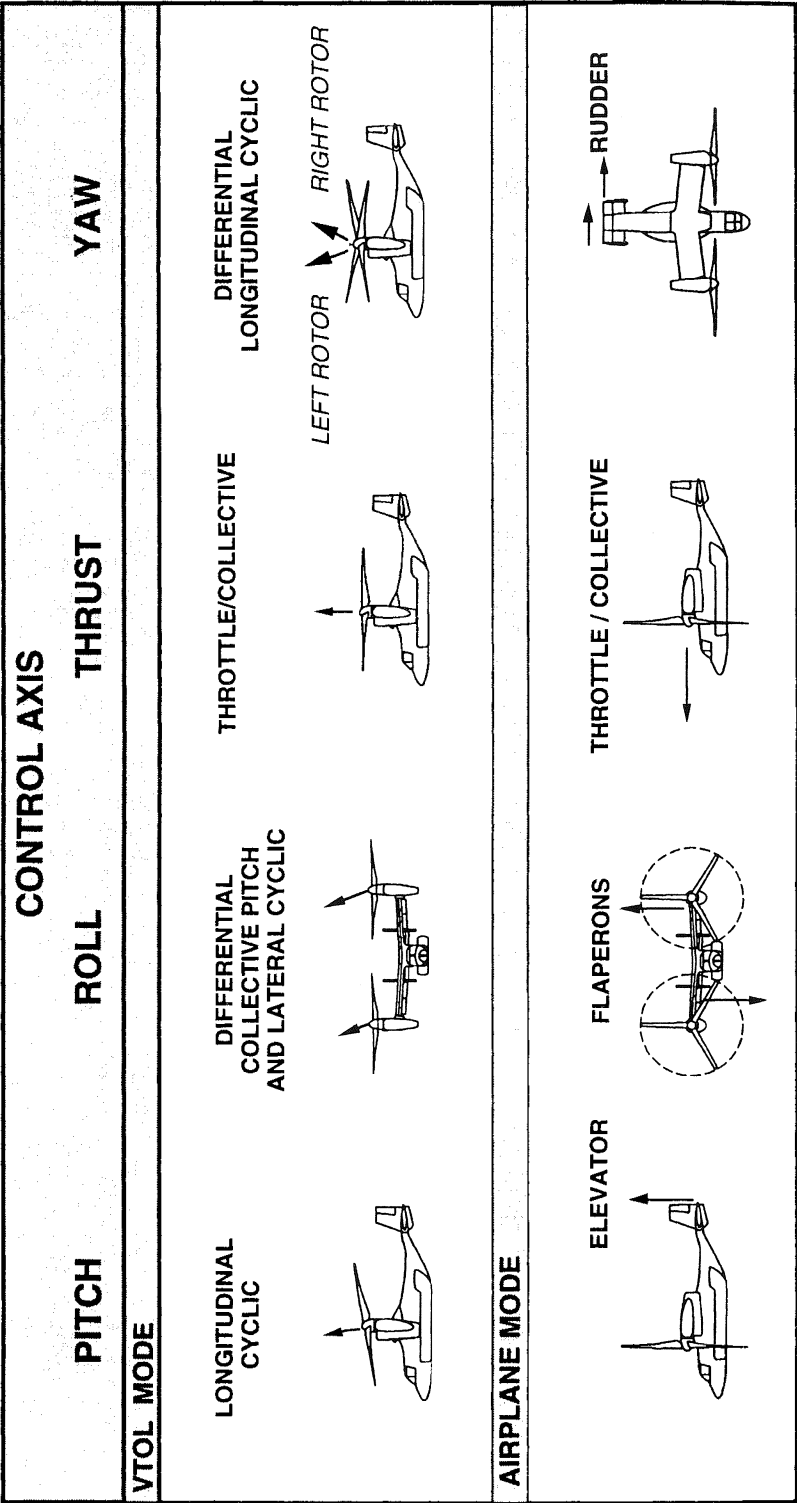


Figure 7. V-22 flight control configuration.

decreased. Figure 7 summarizes the V-22 control mechanisms used in the helicopter and airplane flight modes.

The cockpit controls of the V-22 include a conventional displacement center-stick, directional pedals and a small-displacement thrust control lever (TCL) having a total travel of 4 inches (10 cm). A programmable force-feel system provides airspeed-scheduled force-feel characteristics throughout the flight envelope. Early in the full-scale development program, a design study was conducted to evaluate conventional cockpit controls versus a 2 + 1 + 1 sidestick controller configuration. In this study, handling qualities were judged to be similar with either control configuration design. Although weight and control system complexity are reduced with a sidestick configuration, conventional controls were selected for the V-22 aircraft to reduce program risk and provide for an easier transition of pilots from other VTOL aircraft.

Development of the V-22 has involved a balance between handling qualities, structural and aeroservoelastic stability requirements (Dabundo *et al.* 1991). The stringent V-22 design requirements of Military Specification SD-572 mandate a maneuver envelope to 4-0g at speeds up to 345 knots. These requirements, along with the wide range of flight conditions within the operational flight envelope, present design challenges not seen in conventional helicopters or fixed-wing airplanes. The aircraft components must provide the performance to hover at 47 500 lb (21 205 kg) gross weight, the agility to attain Level 1 handling qualities for aggressive operational mission tasks, and the strength to withstand maneuvering at maximum aerodynamic capability as limited by the FCS. Further challenges are imposed by aeroservoelastic stability characteristics of the V-22 due to the proximity of structural and rigid-body mode frequencies. The flexibility offered by digital flight control systems has enabled the achievement of an effective design for the V-22 which satisfies all requirements.

3. Vehicle management system design

The integration of systems and subsystems is a key element of the vehicle management system (VMS) design process. Figure 8 illustrates the major technologies involved in the development of an integrated VMS. There is an increased demand for improving aircraft effectiveness through functional integration of flight control, engine control and fire control systems. In addition, simultaneous tailoring of handling qualities, structural design and aeroservoelastic (ASE) stability characteristics is required to meet design specifications. Some of the system architecture and control law features developed at Boeing which have proven to be successful include:

- Explicit model-following control incorporated within an architecture designed to maximize safety.
- Manual/automatic reconfiguration to tailor the handling characteristics and/or control functions to the task at hand.
- Control law implementation to integrate conventional or sidestick cockpit controllers in a fly-by-wire control system.
- Forward-loop control shaping to quicken the aircraft response to pilot inputs.
- Airspeed/nacelle gain scheduling to tailor aircraft stability and control characteristics throughout the flight envelope.

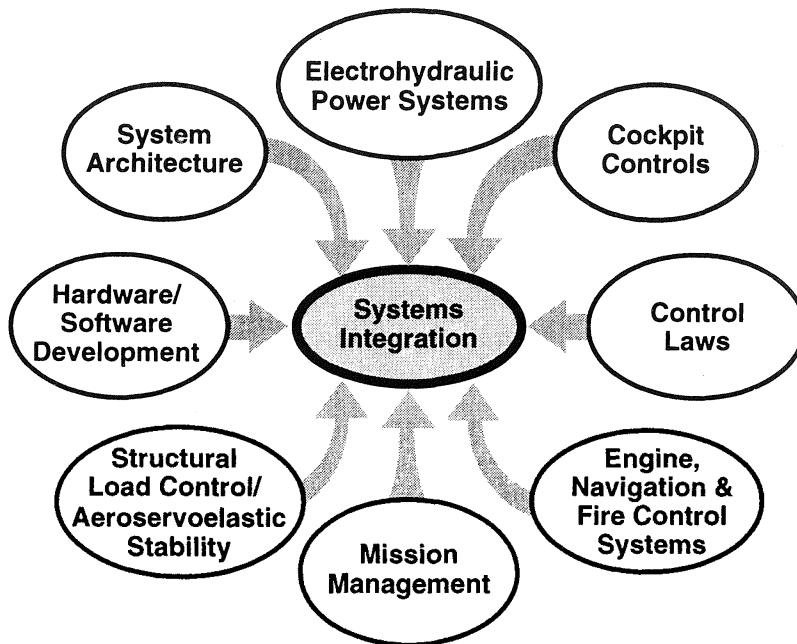


Figure 8. Elements of flight control system integration.

- Control command filtering to eliminate pilot biomechanical feedback for acceptable closed-loop structural mode damping.
- Structural load control algorithms embedded in the flight control laws to provide acceptable maneuvering flight loads throughout the operational flight envelope of the aircraft.

The following sections highlight the design approach used to integrate these features while satisfying overall air vehicle design requirements. Examples of the integration of system control functions in the design of the V-22 and RAH-66 flight control laws are also provided. In addition, the importance of ASE modeling and analysis to achieve a satisfactory total aircraft design is discussed.

3.1. Control law architecture

3.1.1. PFCS/AFCS architecture. Through the development programs described earlier, Boeing has designed an architecture which maximizes safety and reliability by partitioning flight-critical and mission-critical control laws. As shown in Fig. 9, the control laws are functionally separated into a primary flight control system (PFCS) and an automatic flight control system (AFCS). Each level is also physically separated using its own processor. The PFCS provides flight-critical control laws and possesses a higher level of reliability than the mission-aiding AFCS. The PFCS provides the minimum required flight capability in the event of multiple system failures, while the AFCS provides enhanced handling qualities for mission performance under all conditions. The required level of PFCS reliability is achieved through the use of redundant hardware and software processing, minimization of sensor inputs and reduced control law complexity.

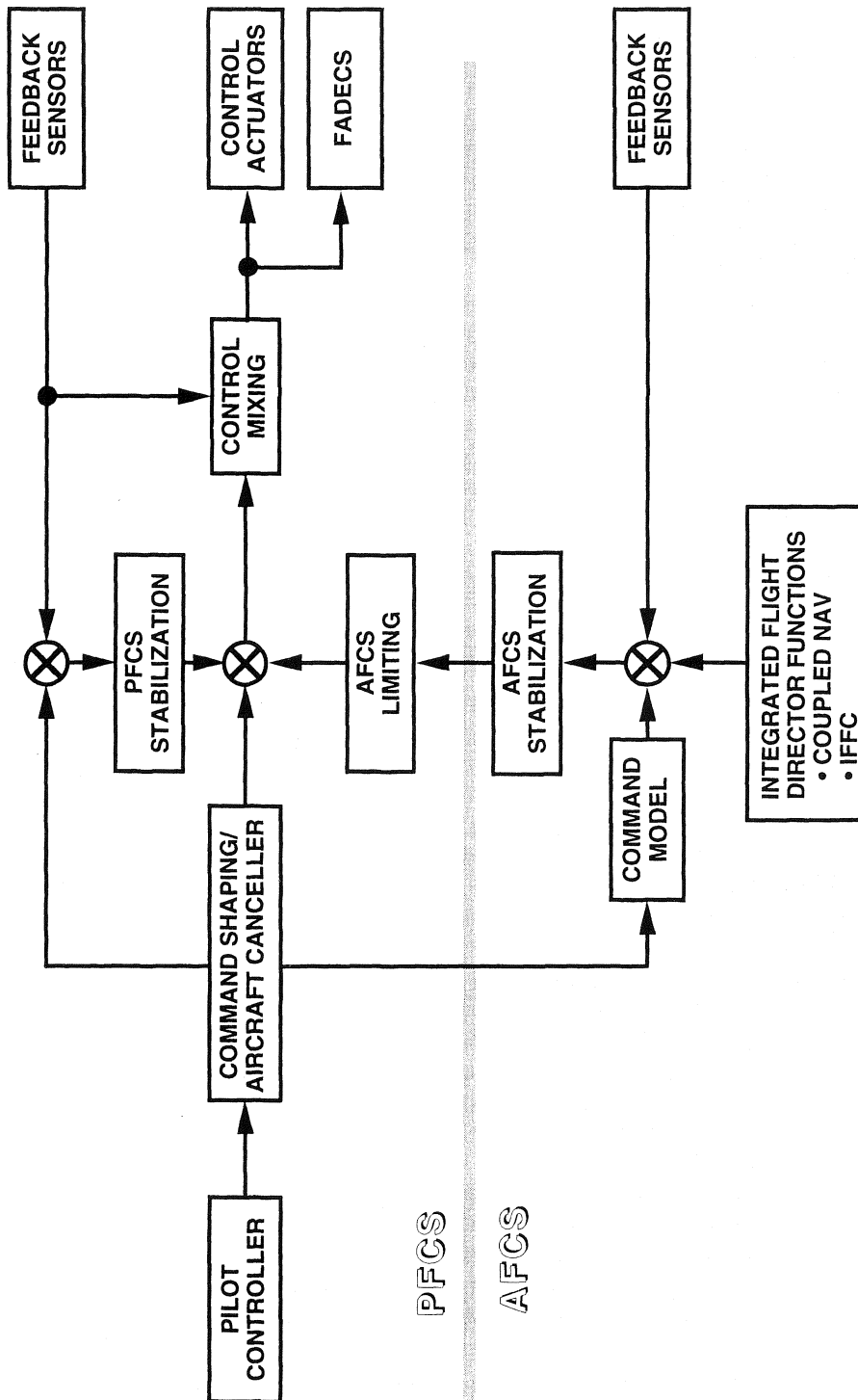


Figure 9. Flight control law architecture.

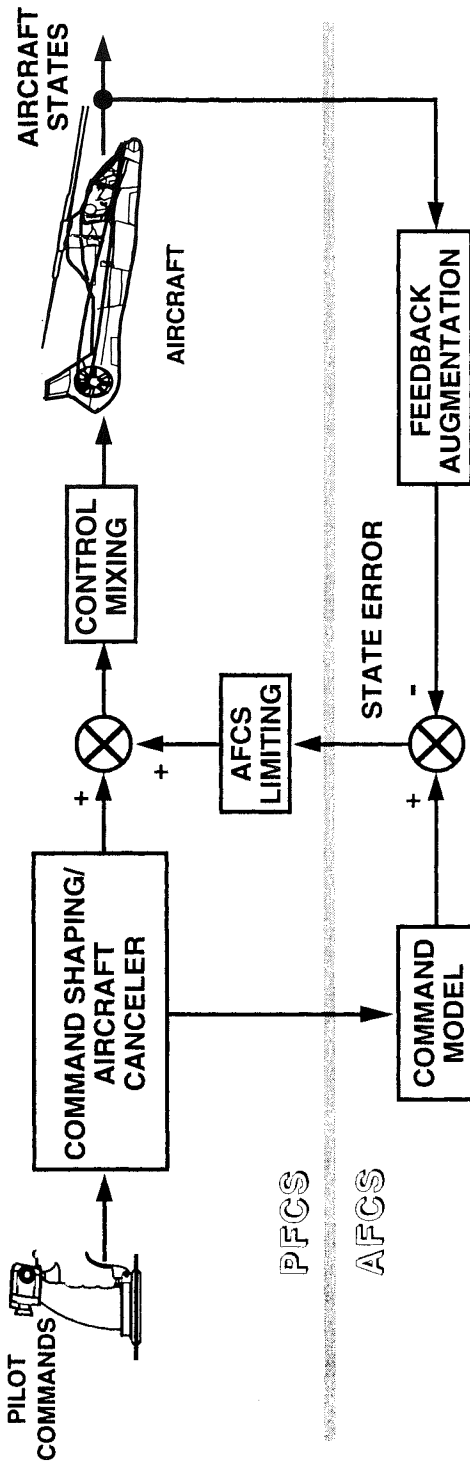
The AFCS processor interfaces to the PFCS through a limit and switching function denoted as *AFCS port limiting*. This function is designed to provide adequate control authority for the operation of model-following control laws, while isolating the AFCS in the unlikely event of multiple system faults.

3.1.2. *Control mixing/scheduling*. Mixing of the cockpit controllers and the AFCS commands to generate the required rotor, control surface, and engine commands is performed in the PFCS. The capability to vary mechanical mixing and rotor control gearing gains of current production helicopters, e.g. the CH-47 Chinook and UH-60 Black Hawk, is limited, thereby restricting the optimization of control response and coupling characteristics.

Alternatively, the Comanche features airspeed-scheduled control mixing with a fully populated mixing matrix to formulate rotor control commands in the aircraft control axes. In this manner, the highly coupled high hinge offset rotor is decoupled as a function of airspeed, providing desirable control responses in all axes over a wide range of flight conditions. V-22 mixing is programmed to provide optimal use of both rotor and control surface commands. The mixing gains are scheduled with both airspeed and nacelle angle to provide consistent handling characteristics throughout the helicopter, conversion and airplane flight envelope.

3.1.3. *Explicit model following*. Explicit model-following control laws (Fig. 10) are well suited for implementation in fly-by-wire digital control systems which provide the flexibility for tailoring of control law characteristics. The model-following design approach has been refined at Boeing to provide a control law implementation within the PFCS/AFCS architecture which is both safe and effective. In the design of model-following control laws, a cancellation of the inherent aircraft response is accomplished in the PFCS by the command-shaping function. The command model, located within the AFCS, is used to generate the desired state response of the aircraft. The desired response is then compared to the sensed states to form state errors for stability and command response augmentation. Primary attributes of the model-following control approach are: (1) aircraft response consistency over the complete range of ambient conditions and aircraft configurations, (2) independently designed stability and command response characteristics since sensor feedback is used only to augment the trajectory with respect to the commanded aircraft state, and (3) robust full-time feedback stabilization by minimizing errors between the desired and actual control response. Since the feedback signal in each axis is an error signal based on commanded minus actual response, the reduced control sensitivity typical of a conventional SAS with high rate feedback is overcome. Furthermore, synchronization and loss of attitude stabilization while maneuvering is avoided, and mode-switching transients associated with a conventional synchronized attitude feedback system are eliminated.

As shown in Fig. 10, the AFCS error signal is passed through a port-limiting/switching algorithm which fails safely in the event of multiple system failures. The port is designed to provide adequate control authority for operation of the model-following control laws. The ADOCS design implemented all feedback augmentation within the AFCS, resulting in AFCS port saturation for large-amplitude maneuvers. To remedy this situation, the RAH-66 design incorporates the feedforward angular rate response command models and the associated feedback loops in the PFCS as illustrated in Fig. 9. The rate feedback loops are only active when the AFCS is



MODEL FOLLOWING ATTRIBUTES

- CONSISTENT AIRCRAFT RESPONSE OVER COMPLETE RANGE OF FLIGHT CONDITIONS AND CONFIGURATIONS
- STABILITY AND COMMAND RESPONSE CHARACTERISTICS DESIGNED INDEPENDENTLY
- FULL TIME FEEDBACK STABILIZATION AND GUST REJECTION DURING MANEUVERS
- NO CONTROL LAW SWITCHING TRANSIENTS

Figure 10. Model-following control law architecture.

operational but, by being resident in the PFCS, they are not subject to port limiting. By providing control response fidelity with respect to the rate-command model in the PFCS, desired levels of control augmentation (i.e. attitude-command/hold functions) can be implemented in the AFCS with a minimum port authority. Improved redundancy management algorithms to detect and eliminate failure modes of the PFCS provide the required degree of system safety.

3.1.4. Attitude-command model following. As discussed above, the model-following control law approach allows command response characteristics of the vehicle to be tailored based on mission requirements. Figure 11 describes the command/stabilization characteristics implemented on the RAH-66 Comanche. Since the Comanche is designed for aggressive air combat maneuver scenarios, its control laws must operate to extreme aircraft orientations. Although the angular rate sensors are based in the aircraft body axes, the attitude references need to be inertially based for large-amplitude maneuvers. Thus, the attitude signals must be accurately transformed for precision attitude control during extreme maneuvers. To address this requirement, the Comanche design performs Euler angle transformations on the attitude signals within the model-following control law structure. The attitude errors are then inversely transformed back into the body axis, where the aircraft control is referenced. Since the Euler angle reference system inherently possesses singularities at $+90^\circ$ and -90° of pitch attitude, the control laws are synchronized within a narrow cone about these orientations to eliminate divergence of the attitude signal.

3.2. Cockpit controller integration

Control law functionality for landing/takeoff and control trim operation is based on the selected cockpit controller configuration. Implementation strategies for both conventional large-displacement centerstick controls and unique-trim sidestick controllers are discussed below.

RAH-66 COMMAND RESPONSE / STABILIZATION					
CORE AFCS			SELECTABLE AFCS (VELOCITY STAB / ALT HOLD)		
AXIS	HOVER & LOW-SPEED	HIGH SPEED FORWARD FLIGHT	HOVER	LOW-SPEED	HIGH-SPEED FORWARD FLIGHT
LONGITUDINAL	RATE / ATTITUDE		VELOCITY COMMAND/ POSITION HOLD	ATTITUDE COMMAND/ ATTITUDE HOLD	ATTITUDE COMMAND/ AIRSPEED HOLD
LATERAL	RATE / ATTITUDE		VELOCITY COMMAND/ POSITION HOLD	ATTITUDE COMMAND/ ATTITUDE HOLD	RATE COMMAND/ ATTITUDE HOLD
DIRECTIONAL	RATE / HEADING	RATE / HEADING WITH AUTOMATIC TURN COORDINATION	RATE COMMAND/ HEADING HOLD	RATE COMMAND/ HEADING HOLD WITH AUTO-TURN COORDINATION BASED ON GROUNDSPEED	RATE COMMAND/ HEADING HOLD WITH AUTO-TURN COORDINATION
VERTICAL	RATE OF CLIMB		RATE OF CLIMB	RATE OF CLIMB /ALTITUDE	

Figure 11. RAH-66 Comanche command response/stabilization characteristics.

3.2.1. *Automatic trim transfer.* Regardless of the type of controller selected for the aircraft, the explicit model-following approach may result in control trim building up in the AFCS. Therefore, control laws are required to automatically transfer control trim offsets from the limited-authority AFCS to the PFCS.

The conventional displacement controller used on the V-22 has a relatively large range of control motion. Stick positions are sensed electronically by LVDTs and passed to a digital flight computer which processes rotor and control surface commands. Pitching moment variation due to changes to longitudinal center-of-gravity and nacelle position creates a wide range of possible trim elevator positions at a given airspeed. As illustrated in Fig. 12, parallel backdriving of the longitudinal stick is utilized to avoid storing trim within the limited-authority AFCS, thereby reducing the potential for port saturation. The low-frequency component of the AFCS port signal is fed to a backdrive actuator which smoothly drives the stick to reduce the AFCS offset to zero. In a trim condition, the AFCS port is centered, and the cockpit stick trim position provides the pilot with a tactile cue of the actual aircraft rotor and control surface position.

Apart from the obvious physical differences with respect to conventional displacement controls, sidestick controllers are unique in the manner in which aircraft trim is represented. The unique-trim sidestick controller, because of its size and mechanical simplicity, cannot provide sufficient motion to reflect both trim and maneuvering commands. Therefore, the sidestick uses a common, or unique, centered reference position to represent trim for all flight conditions. The actual trim control surface position must be stored within the control laws. The low-frequency component of trim resident in the AFCS output is continually transferred to the PFCS so all trim resides at a single point in the PFCS regardless of augmentation level. In this manner, the transients associated with deselection or loss of the AFCS are minimized.

3.2.2. *Landing and takeoff/ground handling.* Since displacement cockpit controllers provide a direct relationship between cockpit stick position and the resultant control surface position, the pilot is provided with tactile cues to establish a control strategy for landing and takeoff. Pilots rely on experience to anticipate the magnitude of control displacement required for a smooth transition between a ground and fly state. In contrast, unique-trim sidestick controllers do not provide such cues. With a sidestick controller the pilot can no longer judge control surface position based on stick deflection since the trim is stored in the FCS and not at the pilot controller. This sidestick limitation is of no consequence for hover or forward-flight operations where the pilot adjusts the control input based purely on aircraft response. In addition, pilot workload with both controller configurations is increased during landing or takeoff since the pilot must compensate for a change in control responsiveness which occurs upon transition from a ground- to fly-state condition.

Sidestick controller handling qualities during landing and takeoff maneuvers were identified as an area of risk during ADOCS demonstrator flight testing. A detailed design study, including piloted simulation along with flight testing on the SHADOW aircraft, was conducted for the Comanche to resolve key control law issues regarding the landing and takeoff tasks. The study, discussed in Bauer (1993), produced new control law features for the Comanche to improve pilot kinesthetic cues, resulting in reduced workload and improved task performance for landing and

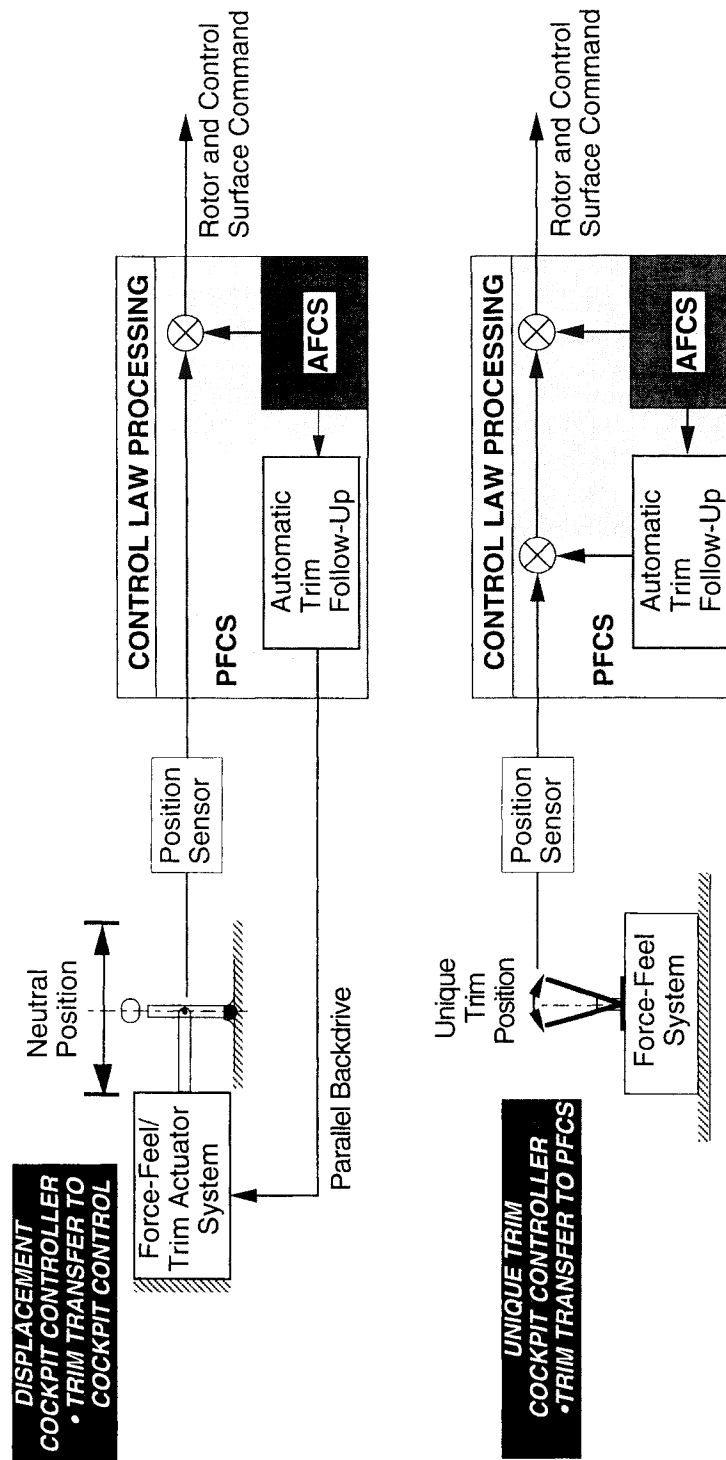


Figure 12. Automatic trim transfer implementation.

takeoff maneuvers. To accomplish this, in-flight control laws are progressively altered to a ground-state mode, based on the combinations of landing gear constraint imposed by ground contact. Weight-on-wheel switches are installed in each landing gear strut to sense ground and flight states. The sensed weight-on-wheel state is filtered to prevent rapid toggling between logic states during a light-on-gear condition.

The combinations of gear contact, listed sequentially for a landing maneuver, include:

- initial contact of any landing gear;
- individual aircraft axis (pitch, roll or yaw) constrained by the ground;
- initial contact of all gear with the ground plane;
- aircraft heavy on all gear.

These combinations, illustrated in Fig. 13, are used to transition control law functions for feedforward shaping, rate stabilization, attitude stabilization, automatic trim follow-up and rotor reference position with respect to cockpit control position. For example, upon contact of any gear with the ground, the feedforward dynamic shaping functions required to achieve desired fly-mode control response characteristics are changed to proportional control for ground operations. Additionally, upon any gear contact, the trim follow-up function in each axis is held so that the constant-gain forward path allows the pilot to judge accurately control requirements based on stick position. All AFCS stabilization, i.e. attitude, velocity or position, is also eliminated at this time through transient-free switching to prevent degradation of aircraft controllability resulting from false command model errors which may arise due to ground contact.

To enhance handling qualities during the transition between the ground and in-flight states, rate stabilization is retained in each control axis if the associated rotational degree of freedom is not fully constrained by gear contact. When an individual axis becomes constrained, the corresponding rate feedback channel is faded to zero. The elimination of rate stabilization when constrained is essential for

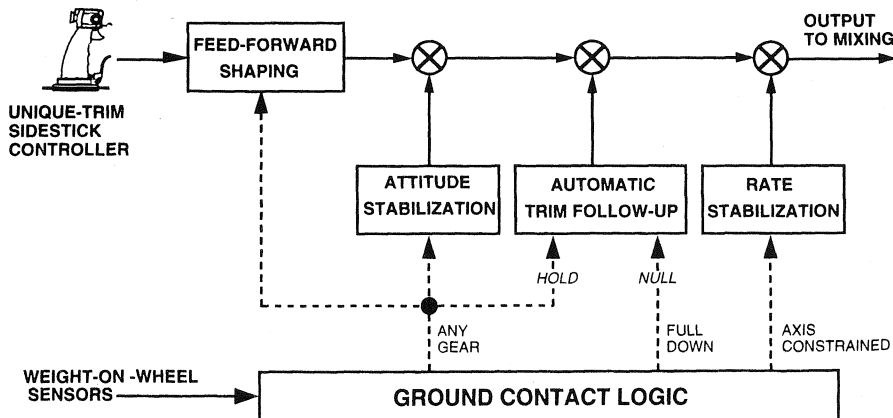


Figure 13. Landing/takeoff control laws.

shipboard operations where deck motions must not be transferred to the rotor while the aircraft is on the deck.

When the aircraft is fully down on the ground (heavy on all gear), the rotor control rigging position is referenced directly to the sidestick controller neutral position. The reference positioning process is initiated when the collective stick has been lowered 5% below the point at which all gear initiated ground contact. Trim follow-up in all axes is also nulled as the rotor reference position for ground operation is acquired. The setting of all stored trim values to zero restores an attribute inherent with conventional large-displacement controls, i.e. a fixed relationship of cockpit controller position and rotor control position while on the ground.

3.3. Control law moding

The experience base with multimode control laws accrued from the TAGS, HLH, ADOCS and V-22 programs was transferred to control law moding design requirements for the RAH-66 Comanche scout/attack mission. The PFCS modes are designed to minimize handling-qualities degradation when multiple failures result in loss of the AFCS. AFCS control laws are designed to allow the pilot to tailor handling qualities to mission requirements with minimal cognitive effort. AFCS moding enhances handling qualities based on the usable cueing environment (UCE) available to the pilot. Thus, a wide range of enhancing control modes are made available with minimum pilot interaction.

The pilot interface to the multimode control laws is through the FCS panel located in the center of the cockpit console. Figure 14 illustrates the FCS panel and levels of augmentation available to the pilot ranked from highest to lowest. The system powers up in the core AFCS configuration, shown as the center level of control augmentation. Higher levels of stability augmentation, i.e. velocity stabilization/hover hold and altitude hold, are selected by the pilot. The flight director can be selected to provide a maximum level of augmentation and to automate many facets of navigation and weapons delivery to reduce pilot workload and improve mission effectiveness.

3.3.1. Core/mission PFCS. During the definition of design criteria for degraded control mode operation, fully attended nap-of-the-earth (NOE) flight was identified as a primary design driver for the PFCS control laws. Based on simulation studies, yaw rate stabilization, as a minimum, was required to provide Level 2 handling-qualities ratings for NOE flight on PFCS (Fig. 15). Thus, the *mission PFCS* design employs yaw rate feedback layered on top of a minimal set of flight-critical control laws and allows the pilot to return to base using an NOE flight profile. As illustrated in Fig. 14, the mission PFCS is engaged manually by pilot deselect of the AFCS, or automatically by loss of the AFCS due to a sensed second failure. The *core PFCS* provides the minimum control laws required for Level 2 handling qualities for up-and-away flight, and landings on level, sloped and shipboard sites. Reversion to this mode will occur only in event of failure of three yaw rate sensors in the PFCS. Using four yaw rate sensors for redundancy, a two-fail operative capability is provided to meet PFCS system-level reliability requirements.

3.3.2. Core/selectable mode AFCS. The *core AFCS* is the normal flight control mode for the Comanche. It is designed with rate-command/attitude-hold functions

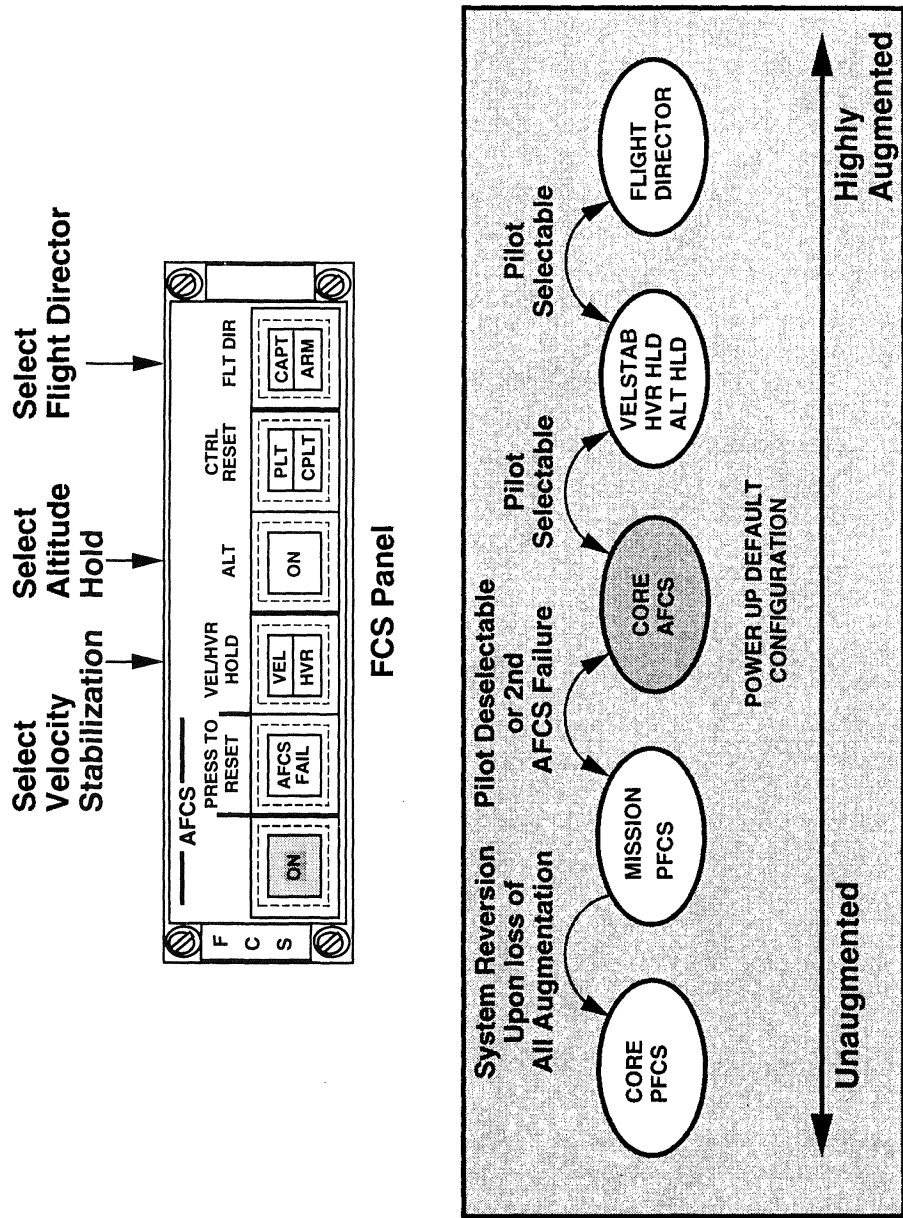


Figure 14. Pilot interface with RAH-66 flight control system.

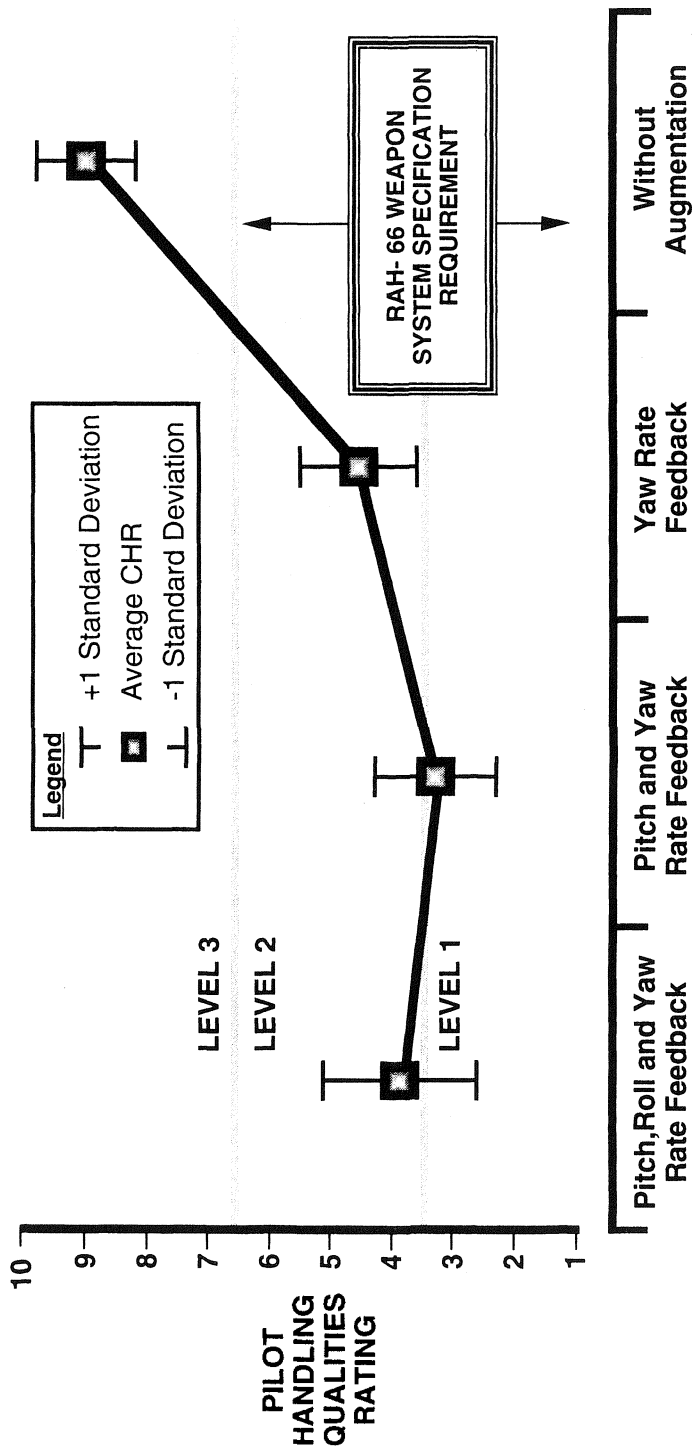


Figure 15. Effect of stability augmentation on handling qualities for nap-of-earth flight.

in pitch, roll and yaw to allow the pilot to maximize maneuverability and agility of the Comanche. Automatic turn coordination is provided at airspeeds above 60 knots to improve handling qualities through reduced workload. Figure 11 provided a description of the command response and stabilization characteristics of the core AFCS as a function of airspeed. Additional details of the design are given in Fogler and Keller (1992).

Two *selectable AFCS mode* sets (altitude hold and velocity stabilization) are available to the pilot from the FCS panel for mission enhancement. *Altitude hold* provides a blended sensor hold function that uses a radar sensor reference while the aircraft is at low altitude and a barometric sensor reference for high-altitude flight. When the pilot desires operation with a specific sensor reference, the blended altitude reference function may be overridden through the MEP. The *velocity stabilization* mode provides the highest level of platform stabilization available to the pilot. Figure 11 depicts the features of these control laws, which vary according to groundspeed and airspeed. Hover hold is a submode of velocity stabilization which automatically engages when the aircraft is brought to hover to provide a hands-off position-hold capability. As seen in Fig. 14, the velocity stabilization button features a split-lamp indicator to annunciate when the hover-hold submode is active. Altitude hold is automatically enabled when the hover-hold submode is engaged. Additional information on the design of the Comanche selectable modes can be obtained from Dryfoos and Gold (1993).

3.4. Integrated flight control law design

3.4.1. Flight control system/engine integration. Traditionally, helicopters use engine governing, where the pilot sets blade collective and the control system adjusts engine power to maintain rotor rpm. This control approach provides a predictable pilot control response in hover since thrust response to collective is of relatively high bandwidth. Airplanes, on the other hand, generally use 'beta' governing where the pilot sets engine power and the governor adjusts propellor angle of attack to maintain rpm. This control approach is generally acceptable for airplanes since the pilot operates the thrust controller at relatively low frequencies.

The design of a rotor speed governor was an interesting challenge on the V-22. Precise height control for hover operations and shipboard landings is required in helicopter mode, while tight airspeed control and gust rejection are important in airplane mode. Precise power control and rotor speed governing are required in all flight modes. The throttle-governing approach typical of helicopters was not practical for the V-22 owing to the large sensitivity of mast torque to collective pitch at high inflow ratios in airplane mode.

Unique engine control requirements for the V-22 (Schaeffer *et al.* 1991) are met through incorporation of the thrust power management system (TPMS), which utilizes a collective ('beta') governor in all modes of flight. Acceptable hover characteristics are achieved using TCL quickening in the control laws, with high-frequency thrust control response actuated through collective blade pitch and low-frequency thrust commands provided through the engine response. Figure 16 provides an overview of the integrated V-22 engine/rotor control system, i.e. the TPMS. Pilot commands are input through the engine control levers (ECLs) during startup operations, and through the thrust control lever (TCL) during flight operations. The TPMS, which is integrated within the primary flight control system, provides

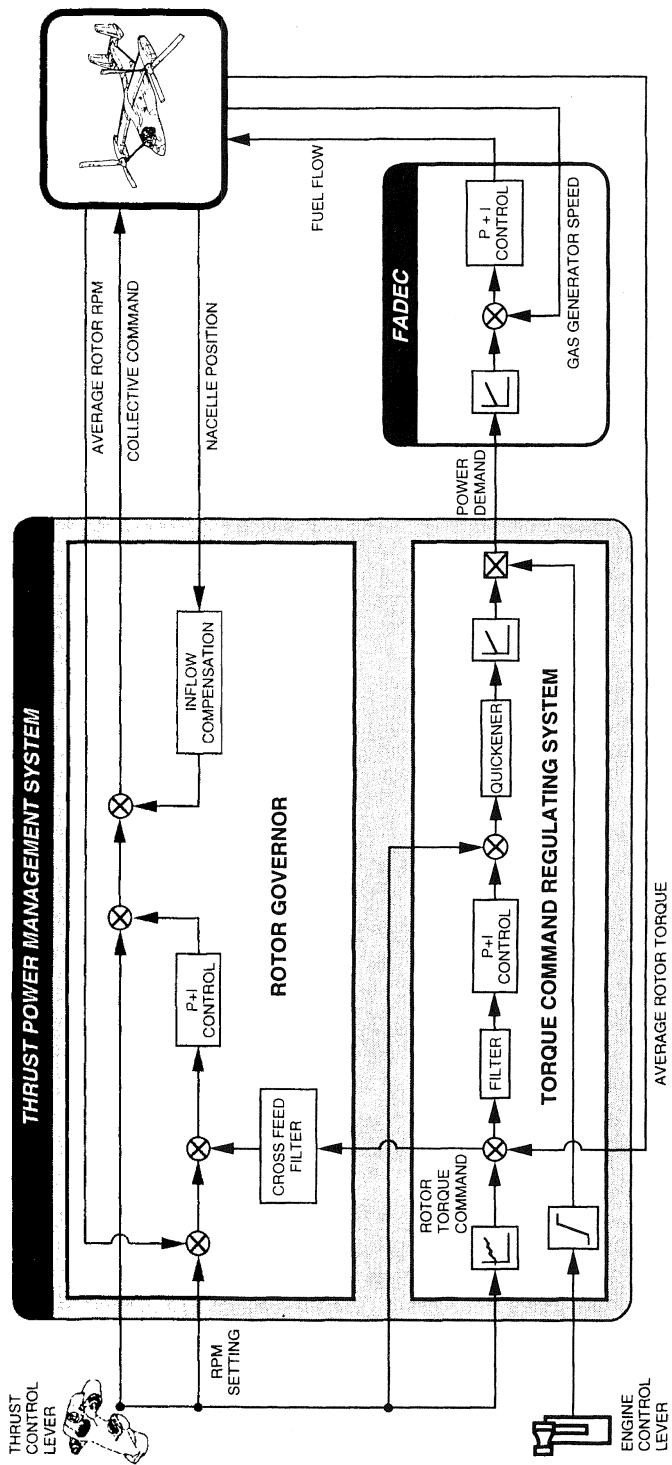


Figure 16. V-22 thrust power management system.

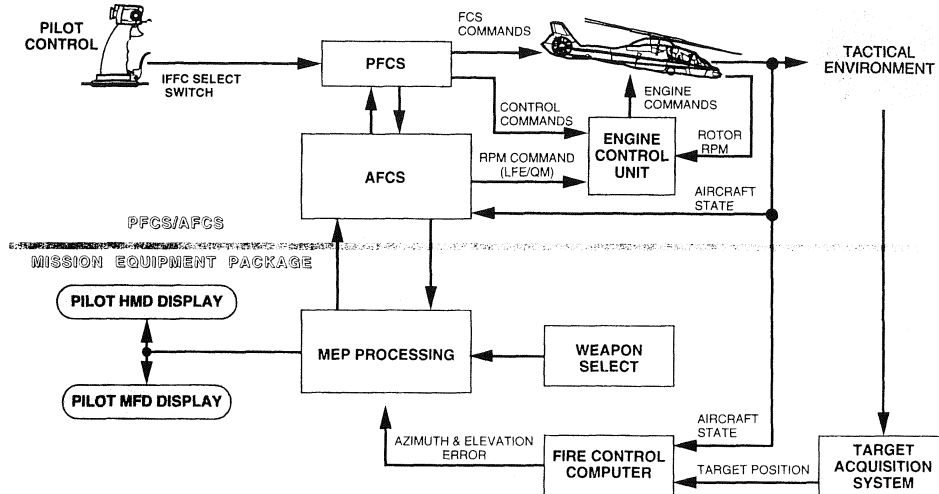


Figure 17. Flight/engine/fire control system integration.

command quickening, rotor governing, and torque regulation during all modes of flight. Key TPMS parameters are scheduled with nacelle angle and airspeed to provide desired characteristics throughout the flight envelope. Inflow compensation is provided to offload rpm governing requirements as the nacelle is varied. The primary outputs of the VMS are the collective command to the rotor for rpm governing, and the power demand to the FADEC (Full-Authority Digital Engine Control) to regulate rotor torque. The FADEC modulates fuel flow to the engine based on power demand and a proportional-plus-integral (P + I) regulator which governs gas generator speed. Extensive flight testing of the TPMS has demonstrated satisfactory performance and good handling qualities throughout the flight envelope.

Collective, lateral, and directional control commands typically couple with rotor torque demand to degrade targeting precision for single-rotor helicopters. Precise regulation of rotor rpm during targeting operations has been shown to be critical during adaptive fuel control flight testing (Sweet 1989). The Comanche is powered by twin LHTEC T800 engines controlled by a FADEC. To minimize rpm excursions during targeting maneuvers, Comanche flight control commands are directly coupled to the FADEC rpm governing control laws (Fig. 17) to provide engine response quickening and compensation. This alleviates undesired coupling and enhances handling qualities.

Integration of the flight and engine controls on the Comanche also includes two selectable modes that allow the pilot to change engine set speed. The *quiet mode* (QM) reduces main rotor rpm to 95% nominal to reduce the Comanche's acoustic signature. The *load factor enhancement mode* (LFE-mode) automatically increases the main rotor rpm to 107% nominal to enhance the normal load factor envelope and to reduce control loads at high speeds. These additional rotor speed options expand the mission capability of the RAH-66.

3.4.2. Integrated fire/flight control (IFFC). Fire control systems typically operate autonomously from other aircraft systems. Wide-regard weapons such as seeker

SYSTEM ATTRIBUTES

- TARGET ACQUISITION AND "LOCK ON" ASSISTANCE
- MODEL FOLLOWING ATTITUDE CONTROL LAW AUTOMATICALLY DRIVES AZIMUTH AND ELEVATION ERRORS TO ZERO
- WEAPON RECOIL COMPENSATION TO MINIMIZE AIRFRAME DISTURBANCES
- FLIGHT SAFETY ENHANCED THROUGH AUTHORITY LIMITS/ "DEAD MAN" SWITCH

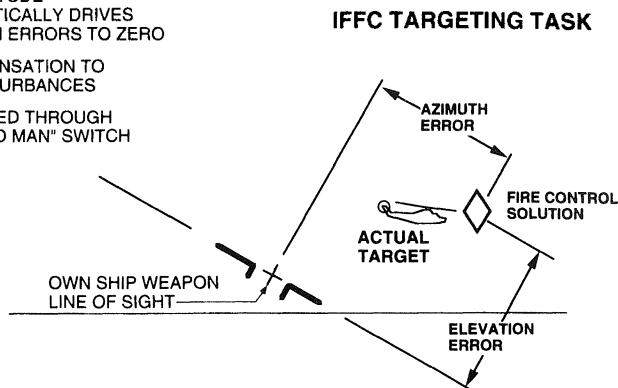


Figure 18. RAH-66 IFFC functionality.

guided missiles, e.g. HELLFIRE, do not require significant aircraft maneuvering, since the fire control system automatically compensates for aircraft motion. With unguided limited-regard weapons, the success rate is directly affected by the crew's ability to coordinate the aircraft trajectory within target sight constraints. Therefore, handling qualities and hence the aircraft control laws directly influence the successful accomplishment of the targeting task. The launch precision accuracy of unguided limited-regard weapons is affected foremost by crew targeting errors, and secondarily by the accuracy of the fire control solution.

The Comanche fly-by-wire digital system architecture (Fig. 17) is well suited for integration of the weapons' fire and flight control systems to reduce pilot workload associated with weapons aiming. When the IFFC system is engaged, the fire control solution is presented as a maneuvering command on the helmet-mounted display (HMD). The IFFC maneuvering command is also coupled to the flight control system by referencing the rate and attitude state variables to the fire control solution. The authority of the IFFC control is highest when the aircraft is closely aligned with the target. As the aircraft attitude is moved outside of the engagement window, the IFFC authority is reduced to zero. In this manner, the pilot is provided with a 'sticky pipper' to improve basic targeting accuracy. The IFFC system is designed to allow the aircraft to be stabilized within $\pm 0.1^\circ$ of the fire control solution. The pilot command path remains active, so that the pilot can override the system at all times. The IFFC system is easily disengaged by release of a grip switch which must be depressed at all times when using IFFC. Functionality and attributes of the Comanche IFFC system are illustrated in Fig. 18. The design and development of IFFC control laws is discussed in Fowler *et al.* (1992).

3.5. Structural loads limiting

The unique requirements of the V-22 mandate flight operations to the maximum aircraft aerodynamic capability is limited by the FCS. The V-22 design requires a maneuver envelope to $4.0g$ at speeds up to 345 knots (Fig. 19). However, the aerodynamic capability is greater than $4.0g$ above 260 knots. Since the strength of struc-

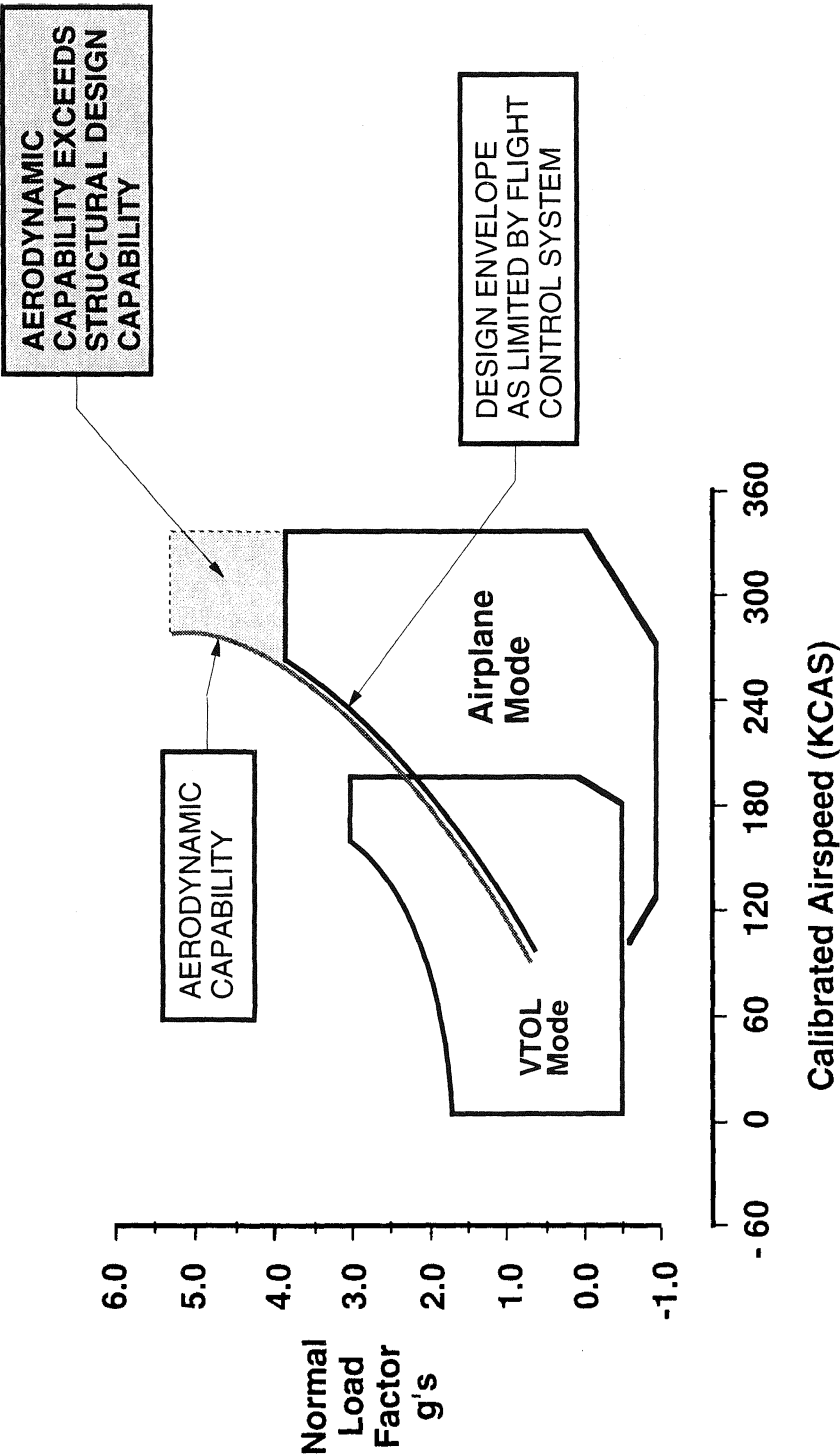


Figure 19. V-22 structural design envelope.

tural components is constrained by weight, size and cost considerations, the control laws were optimized to alleviate trim/maneuver loads as described in King *et al.* (1993). The V-22 system design ensures that structural component limit and fatigue loads are not exceeded for the full range of aircraft maneuvers, while retaining Level 1 handling qualities. The digital flight control system provides a cost/weight effective means of meeting both structural loads and handling-qualities requirements throughout the flight envelope.

Two examples of structural load-limiting control laws are presented, namely (1) the use of roll-rate feedback applied in airplane mode and (2) the implementation of a longitudinal flapping limiter in the VTOL/conversion flight mode.

- (1) *Roll-rate feedback.* The V-22 rotor system is comprised of counter-rotating rotors mounted at the wingtip, connected by an interconnect drive shaft which maintains equal rotor rpm at both rotors. During roll maneuvers in airplane mode, aircraft roll rate induces an effective increase in the rate of rotation of the downward rolling rotor and an effective decrease in the rate of rotation of the upward rolling rotor. This variation in the effective rate of rotation on the left and right rotors causes a torque split which is transmitted through the interconnect drive shaft during maneuvers. These maneuver-induced loads are a design concern with respect to the fatigue and limit-loading characteristics of the shaft.

To minimize weight and cost of the drive system, roll rate to differential collective pitch feedback is provided in airplane mode to alleviate cross-shaft loads during roll maneuvers. By sensing roll rate and making the appropriate differential collective pitch change, the torque split between the rotors, and thus the loads carried through the interconnect shaft during maneuvers, can be minimized. Figure 20 presents simulation and flight test

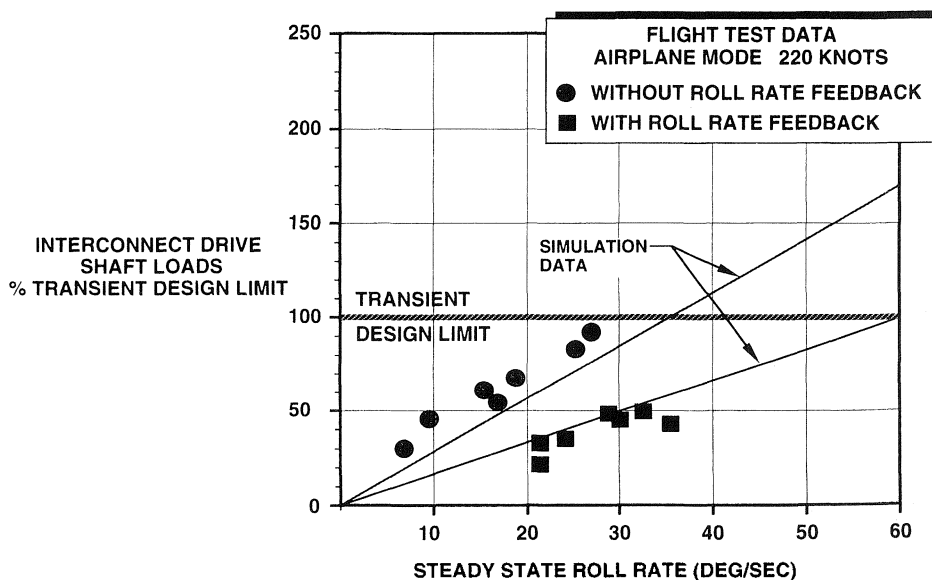


Figure 20. Effect of roll-rate feedback on roll maneuver capability.

data showing the benefit of roll-rate feedback in reducing interconnect drive shaft torque for roll maneuvers. With structural load limiting, i.e. roll-rate feedback, the maneuvering capability of the V-22 as limited by transient design limit loads is increased from 30° to 60° per second.

- (2) *Flapping limiter.* The relatively small disk area of the V-22 rotor results in operation at relatively high thrust coefficients in VTOL/conversion-mode forward flight. Regions of blade stall can develop at moderate speeds which induce increased blade flapping and rotor yoke chord bending loads. Furthermore, the aircraft operates over a large range of nacelle/airspeed and c.g. conditions. At the envelope extremes, trim flapping increases, thereby presenting fatigue issues in trim and limit flapping issues during maneuvering flight.

A control law was developed to feed rotor blade flapping to the elevator in order to reduce trim flapping of the rotor in both VTOL and conversion flight modes. A frequency splitter was also implemented in the longitudinal stick command path to alleviate high-frequency longitudinal cyclic inputs which can lead to excessive flapping during aggressive pitch maneuvers. The frequency splitter, which modifies the command split between the rotor and elevator, was set to maintain required control power throughout the conversion envelope. Flight test results indicate that this control law was successful in reducing trim and maneuver flapping throughout the V-22 envelope, while maintaining acceptable handling characteristics.

3.6. *Aeroservoelastic stability*

Aeroservoelastic (ASE) stability characteristics have become a significant consideration in the design of modern aircraft as the requirement to minimize weight and maximize maneuverability becomes more critical. Analysis, design and testing of ASE stability characteristics are key tasks in the development of air vehicle characteristics. Both the V-22 and RAH-66 programs have shown that the flight control system provides a powerful tool to meet weight and maneuverability design requirements.

The large roll/yaw inertia of the V-22 coupled with the relatively soft wing/fuselage interface (induced by the wing fold mechanism) creates a situation where the frequencies of the aircraft's structural modes are relatively low (less than 5.0 hertz) and in proximity of the rigid-body modes (Fig. 21). As described by Parham *et al.* (1991), flight testing of the V-22 identified three conditions where the pilot/control system tended to couple with the aircraft, resulting in a pilot-assisted oscillation (PAO). Each case of PAO involved a destabilizing acceleration feedback through the pilot/control stick at a rigid-body or structural mode frequency shown in Fig. 21. Initial ASE analyses for the V-22 did not include a model of biodynamic feedback and, therefore, did not predict the PAOs. Subsequently, generalized pilot/control models were established using measured data taken from ground-shake tests and in-flight excitations of the aircraft/pilot. These models were correlated to measured stability data and then used to design system enhancements as described below.

The initial PAO experienced during V-22 testing occurred while light on the gear and is attributed to coupling of lateral pilot motion with a 1.4 hertz rigid-body mode, known as the high focus mode. This coupling, illustrated in Fig. 22, involves

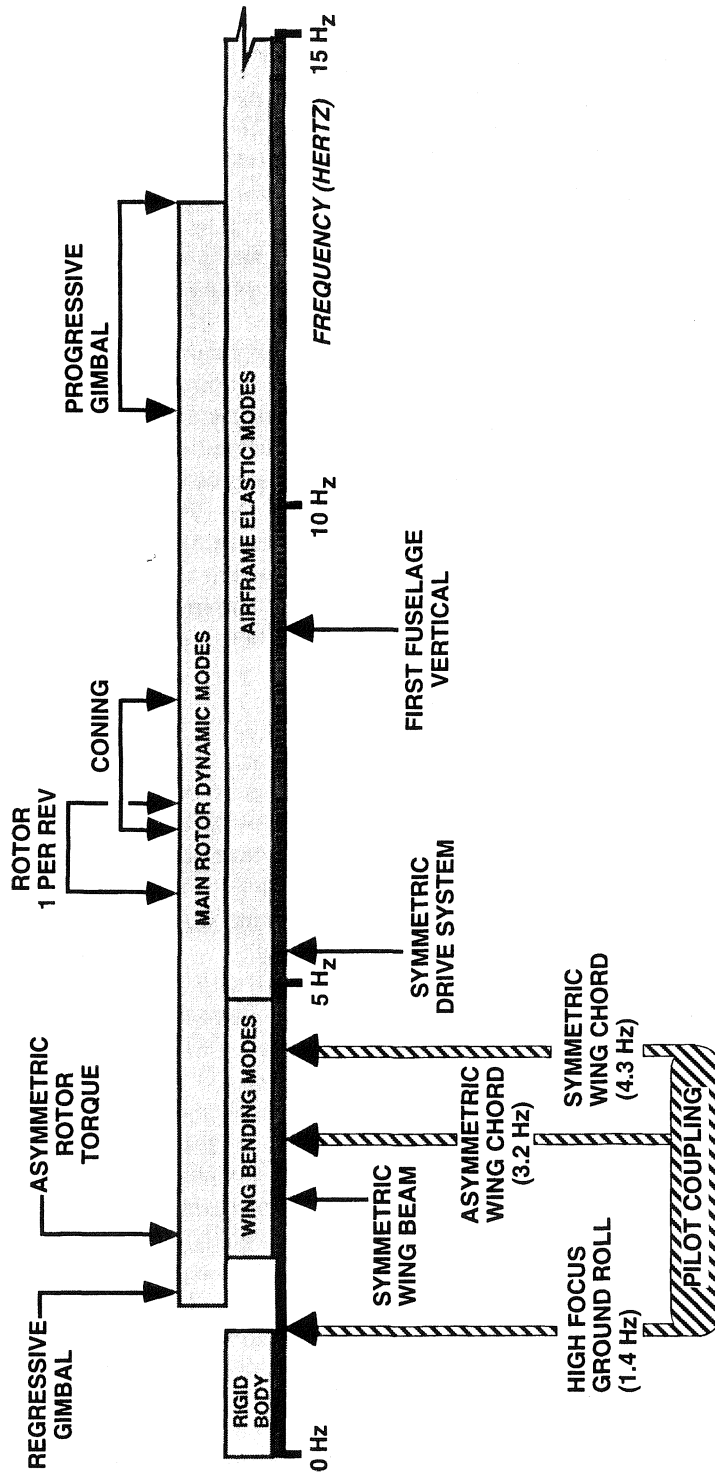


Figure 21. Spectrum of V-22 dynamic mode frequencies.

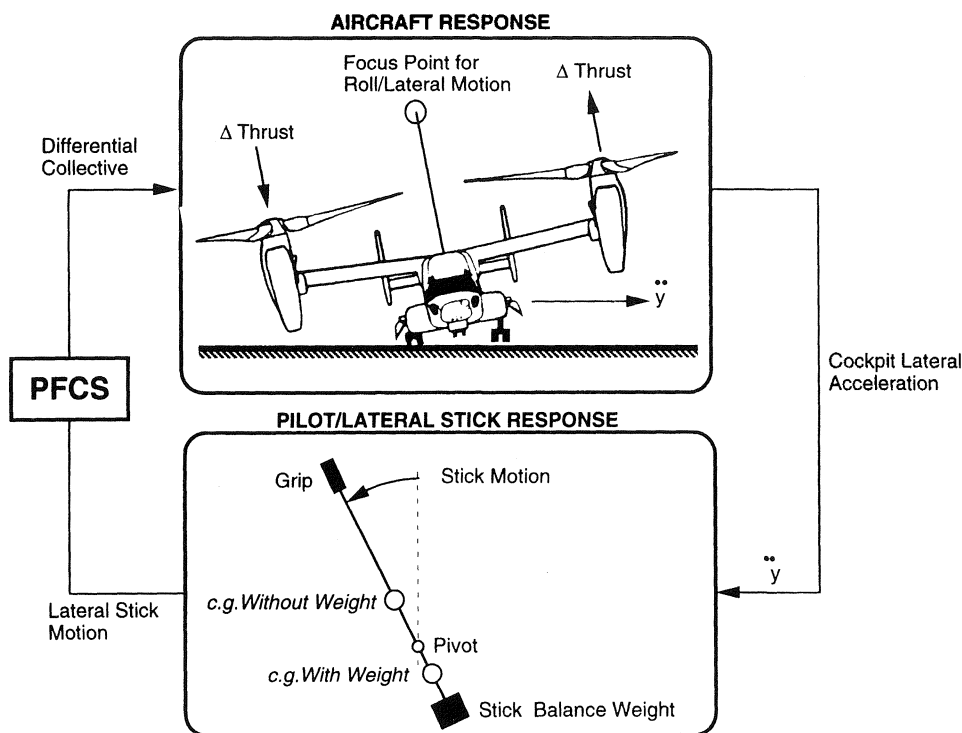


Figure 22. High focus roll mode/pilot biomechanical coupling.

both lateral and roll motion about a focus point above the aircraft. When the aircraft oscillates, lateral control motions are introduced by the pilot inertial reaction to cockpit lateral acceleration. The gain of this loop with the pilot gripping the stick tightly was large enough to destabilize the high focus roll mode. Mass balancing of the cockpit lateral control (a large-displacement centerstick), i.e. lowering the stick c.g. below the pivot point, reduced the gain from lateral acceleration to pilot/stick input and effectively eliminated this mode.

Two in-flight occurrences of PAO were encountered which involved a destabilizing pilot/control system feedback loop at a structural wing-bending mode frequency. These PAOs were present in airplane mode and involved: (1) a coupled pilot/control system response to lateral acceleration at the asymmetric wing chord (AWC) mode frequency (3.4 hertz) at speeds greater than 250 knots, and (2) a coupled pilot/control system response to longitudinal acceleration at the symmetric wing chord (SWC) mode frequency (4.2 hertz) at speeds greater than 300 knots. Both in-flight PAO cases were addressed by incorporating digital 'notch' filters in the feedforward command path to effectively break the feedback loop at the critical structural mode frequency without inducing unacceptable phase lag in the handling-qualities frequency range.

The dynamics associated with the 4.2 hertz SWC mode are illustrated in Fig. 23. The thrust control lever (TCL) commands increased thrust, which causes elastic deformation of the wing in the chord axis. This motion results in fore and aft longitudinal acceleration at the cockpit, thereby closing the biodynamic feedback loop

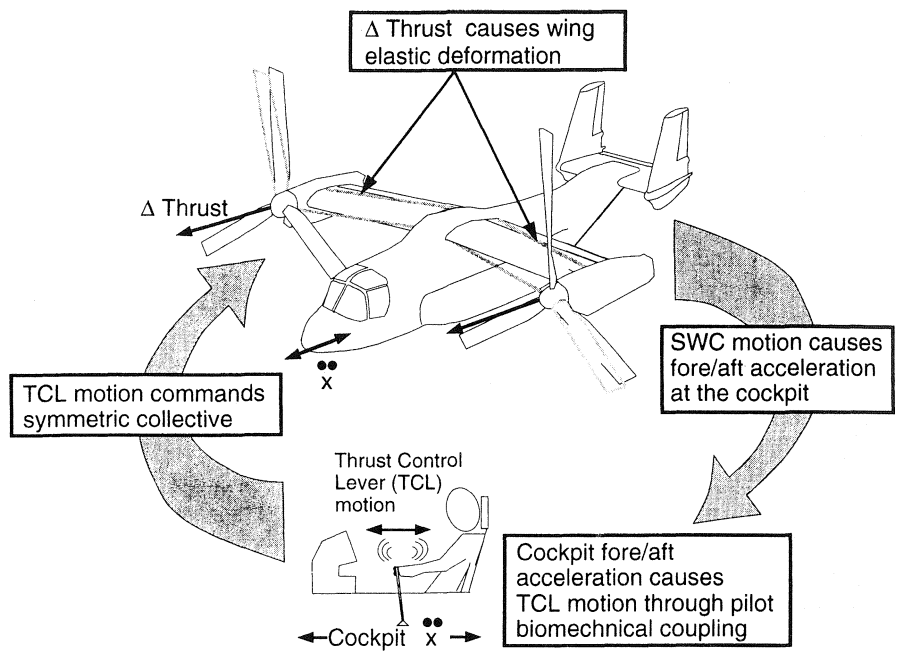


Figure 23. Symmetric wing chord mode/pilot biomechanical coupling.

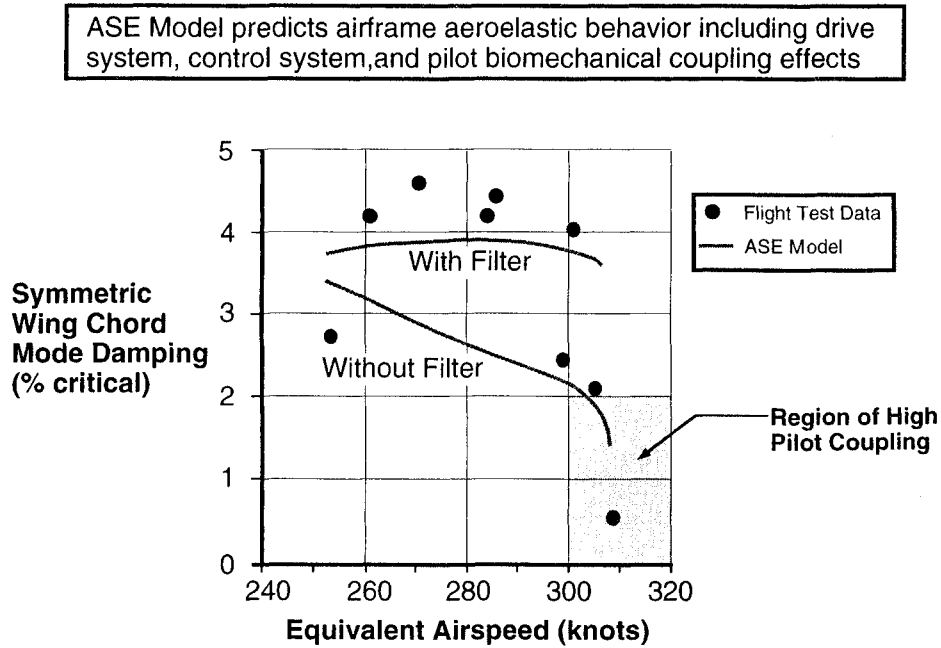


Figure 24. Effect of control system filter on symmetric wing chord damping.

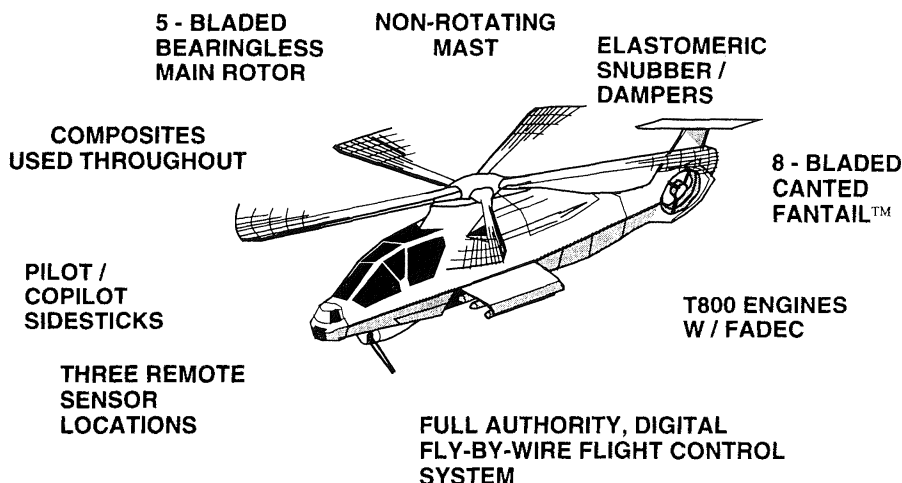


Figure 25. Key sources of RAH-66 aeroservoelastic coupling.

through the pilot. As seen in Fig. 24, this loop closure has a large effect on the SWC mode damping above 300 knots. A model update to include this loop was incorporated and used to design a notch filter that eliminated the destabilizing coupling through the pilot without adversely affecting handling qualities. The effect on SWC damping as shown in Fig. 24 illustrates the effectiveness of this filter.

Extensive use of composites throughout the Comanche to reduce weight has led to the lowest fuselage structural modes being in close proximity to the rotor 1/Rev frequency. The analysis of the complex interactions between the various sources of aeroelastic forces was performed at an early stage of the Comanche program due, in part, to lessons learned on the V-22 program. Figure 25 summarizes elements of the Comanche design which drive the requirement for a comprehensive ASE analysis. Pilot inputs into the control system come from a small-displacement sidestick and medium-displacement collective controller. Accurate empirical models of pilot biodynamic feedback with the RAH-66 pilot controller configuration were developed using motion-base simulation. A comprehensive ASE analysis tool, including the modeling of pilot biodynamic feedback, was developed and utilized throughout design of the Comanche VMS to meet all design requirements while minimizing cost and weight of the aircraft structure.

4. Control law design process

The control law design process employed at Boeing Helicopters has evolved from experience with major flight control research and development programs. Advanced computer analysis, design and simulation tools have been developed over the course of these programs, thereby increasing overall quality and productivity of the design process. The flight control law design process, highlighted in Fig. 26, includes four phases: namely, preliminary design, detailed design, implementation/verification/validation and acceptance testing.

The *preliminary design* process begins with the development of design criteria based on air vehicle specification requirements. An iterative process is applied in

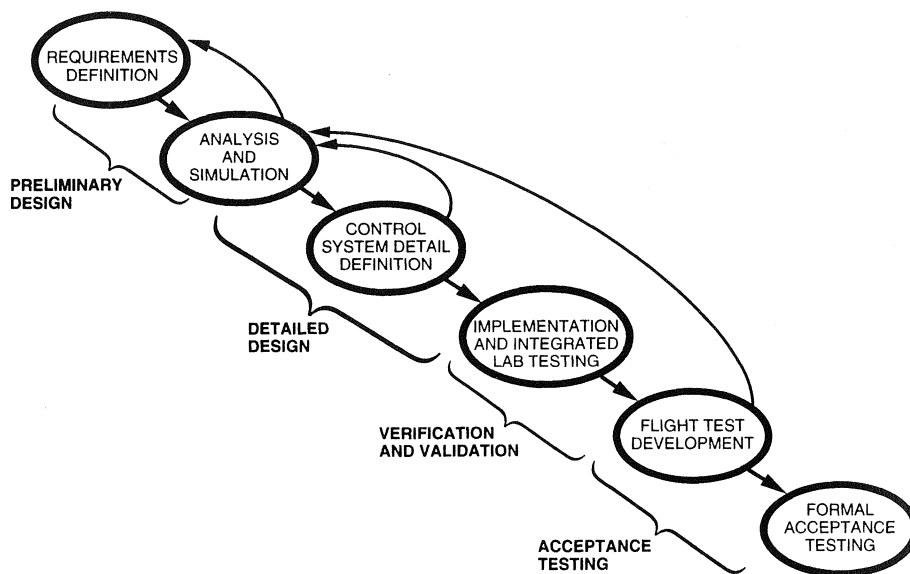


Figure 26. Vehicle management system design process.

which the combined vehicle/system characteristics are analyzed, simulated and assessed against the air vehicle specification requirements for handling qualities, structural loads and aeroservoelastic stability. This phase of development establishes the control law architecture, sensor requirements and system component bandwidth requirements. For example, the handling-qualities specification may quantify the minimum required level of dutch roll damping. An assessment of the vehicle's inherent stability and control characteristics may indicate that artificial stabilization is required to increase yaw damping to meet the established design criteria. The need for stabilization will then flow down a set of requirements for the system architecture, sensor characteristics and actuator performance.

Once the preliminary control law design process is complete, a *detailed design* phase is conducted. Again, an iterative process is applied which utilizes extensive analysis and piloted simulation evaluations to ensure acceptability of the control laws for a wide range of maneuvers. Mission effectiveness of the aircraft is assessed for specific mission task elements based on the handling-qualities requirements defined during the preliminary design phase. The detailed control law development process ensures that all handling-qualities, system and structural requirements are simultaneously met.

Comprehensive models are developed during detailed design to assess rigid-body and elastic stability characteristics, along with their interaction with the coupled pilot/flight control system (Fig. 27). Aeroelastic stability analyses are conducted to ensure that no ground or air resonance conditions occur in the coupled rotor/fuselage/drive/landing gear system. These analyses are considered to be 'open loop' in the sense that the control surfaces remain fixed. Aeroservoelastic (ASE) stability analyses, however, examine the stability of the 'closed-loop' system where the control surfaces respond to control law commands, elastic structural deformations at the hub or sensors, and any undesired pilot inputs created by the biodynamic

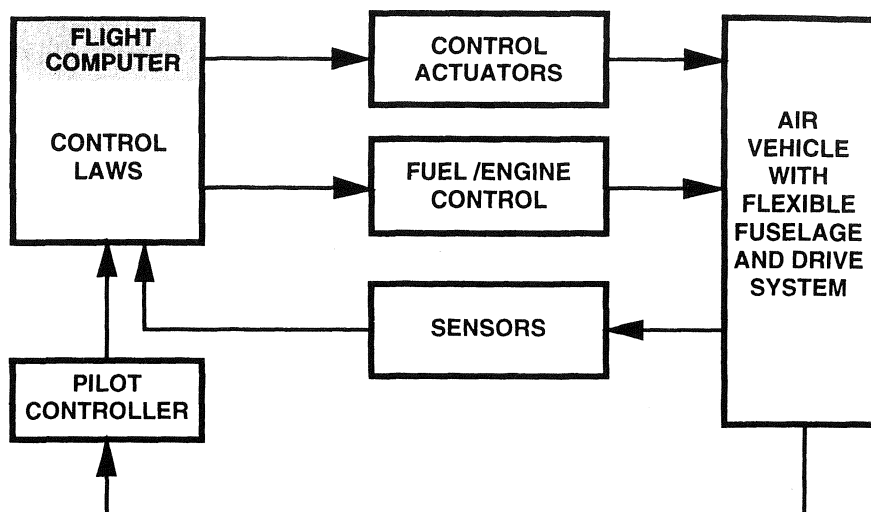


Figure 27. Rotorcraft analytical model overview.

transmission of pilot seat accelerations to the control sticks (also called ‘pilot-assisted oscillations’).

Figure 27 shows the primary components of the rotorcraft linear model used to analyze stability and control, ASE, and structural loads characteristics. Using this model, the ASE stability of the closed-loop system including pilot dynamics is determined and compared to the gain and phase margin guidelines established in Military Specification MIL-F-9490D. Components of the analytical model are discussed below.

The *air vehicle model* is a linear representation of the vehicle dynamics of interest including fully coupled rigid-body dynamics, rotor dynamics, landing gear dynamics and flexible fuselage and drive systems. This model is based on the same full-force, non-linear aircraft model used for real-time piloted simulation. The air vehicle model provides outputs to represent the linear accelerations felt at the crew stations, and sensor feedback signals referenced to sensor package locations in the flexible fuselage. Structural loads models are also included for real-time assessment of loads during batch and piloted simulation of control response characteristics.

The *sensor models* receive the feedback signals from the air vehicle model and calculate the dynamic response characteristics of each individual sensor package. Location of the sensor packages and the design of their mounting structures are important variables that influence the ASE stability characteristics.

The *pilot models* are linear transfer functions representing the pilot and copilot biodynamic transmission of seat accelerations through the body to the control sticks. Ideally this model should account for accelerations in all three orthogonal axes and produce control motions in all axes simultaneously, but single-axis models have proven adequate. These models are developed empirically from flight- or ground-based shake test data. Although defined as ‘pilot’ models, this element of the model represents the dynamics of the combined pilot/seat/controller system.

The *control law model* provides a detailed representation of the flight control system. In addition to the feedback stabilization loops, all feedforward control paths

are included since the biodynamically closed acceleration feedback paths are of primary importance. Since total loop computational delay has a significant effect on levels of stability, all input, processing and output delays must be represented accurately.

The *fuel control and engine model* couples the flight control laws with the flexible drive system and rotor dynamics. Accurate modeling of fuel control and engine dynamics is essential to insure a high-fidelity model.

The end product of this phase of the detailed design process is the definition of a complete set of integrated control laws. A formal control law definition process ensures that a rigorous and disciplined review of the system is accomplished and that a valid control law definition results prior to coding flight-critical control system software. Over the past 20 years Boeing Helicopters has developed numerous computer design tools to streamline and shorten the time required for detailed design. These tools are packaged in a workstation environment to maximize efficiency of the process.

Verification and validation of the total flight control system, including the control laws, is performed to insure that system integrity is maintained. Verification of the control laws insures proper coding to the requirements by testing at the unit, module and function levels. Implementation errors are effectively eliminated by using the exact flight control element algorithms in the design phase. Validation of the flight control software involves an assessment at the system level. Non-piloted, open-loop test conditions are run in the Flight Control System Integration Rig (FCSIR) to evaluate the overall system response. These runs are compared to expected results generated by the FCS simulation. After successful open-loop testing

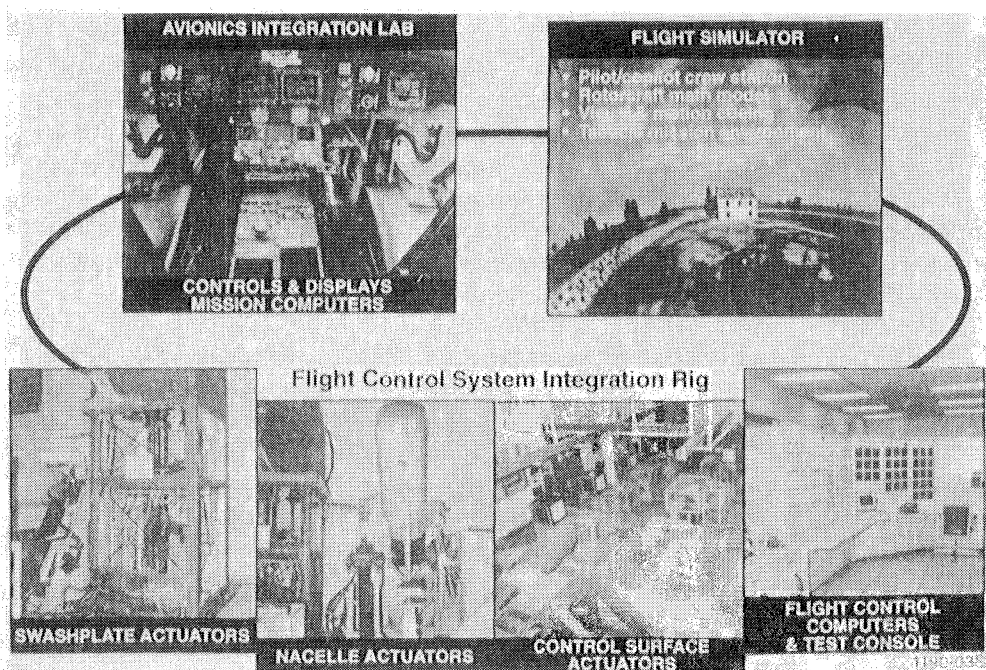


Figure 28. Hardware-in-the-loop simulation.

is accomplished, the simulator is interfaced with the FCSIR and Avionics Integration Laboratory (Fig. 28) to conduct a formal final pilot acceptance test of the total system as described for the V-22 in Robinson *et al.* (1989). A wide range of maneuvers and flight conditions are evaluated. System failures are introduced to evaluate failure-mode effects and degraded mode handling qualities with hardware-in-the-loop. The validated software is then installed on the aircraft, and a flight assessment of the aircraft is made to demonstrate that handling-qualities, system and structural requirements are met prior to delivery of the aircraft to the customer for acceptance testing.

5. Summary

Advanced flight control system technology at Boeing Helicopters has matured over two decades of developmental programs, culminating with integration of advanced technologies in the RAH-66 Comanche and V-22 Osprey. An integrated design is achieved by applying a balanced approach using state-of-the-art analysis tools and real-time piloted hardware-in-the-loop simulation.

The PFCS/AFCS system architecture provides a safe approach to control partitioning for explicit model-following control laws. This approach has proven to be adaptable to a wide range of aircraft configurations, providing the flexibility to address new directions in handling-qualities requirements. Enhanced mission effectiveness is achieved through integration of stability and control augmentation and structural load alleviation control law functions. Integration of these control law functions, along with advanced cockpit displays and controls, engine control and fire control systems have proven to be key in providing a VMS capable of meeting future military requirements.

6. Future development trends

Research into advanced flight control techniques continues at Boeing Helicopters. Future control system designs will be optimized for multiple missions and configurations, and provide increased levels of stability and command augmentation throughout the flight regime, with intelligent system reconfiguration to compensate for failures. System bandwidth will be increased through control system algorithms that provide active stabilization of fundamental airframe and rotor modes. Control algorithms based on rotor-state feedback and individual blade sensing will provide means of extending usable bandwidth and improving gust rejection and stability characteristics. Integrated design approaches will simultaneously optimize handling qualities, maneuver control and aeroservoelastic stability while minimizing airframe and rotor structural loads.

Advances in computing speed are enabling adaptive compensation for changing aircraft configuration, flight condition and level of aggressiveness through the application of real-time system identification techniques. Increasingly sophisticated analytical redundancy techniques (including real-time system identification methods) will be used for failure prognosis detection and isolation. These analytical redundancy techniques will also provide improved failure tolerance with less physical hardware. Computer speed advances will also make digital control algorithms feasible for active vibration suppression, higher harmonic and individual blade control, and active modal damping enhancement. Parallel on-line computing will

allow the implementation of high-order controller structures using finite impulse or neural techniques.

Integration of cockpit displays, sensors, stability augmentation and flight director functions will allow the pilots of the future to survive an increasing array of threats while improving mission effectiveness. Automatic control system technologies will be applied to on-line mission planning and flight director functions based on more accurate navigational, threat and obstacle avoidance information provided from phased-array radars, forward-looking infrared (FLIR), video and global positioning sensor (GPS) technologies.

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