BOEING 234 FLIGHT CONTROL DEVELOPMENT

James J. Morris
Technology Manager, Commercial Chinook
Boeing Vertol Company
Philadelphia, Pennsylvania

Abstract

The Boeing 234 is the commercially certified derivative of the CH-47 Chinook. The automatic flight control system and flight director with coupler have been designed to reduce pilot workload for missions of approximately six hour duration during VFR, IFR, day and night conditions. The AFCS system for the 234 is essentially the same system as developed for the CH-47D, which has airspeed hold, attitude hold, and maneuver enhancement in all three axes. The system also has the capability to couple to the Sperry Helcis flight director system which provides for enroute navigation and landing approaches. Certification testing has been completed, by both the FAA and CAA, to FAR Part 29 for Transport Category Rotorcraft and BCAR Section G: Rotorcraft. The aircraft was certified for civil operation in June 1981.

Introduction

The Boeing 234 is the commercial derivative of the CH-47 Chinook tandem rotor helicopter which has accumulated over one and half million hours of flight. The aircraft (as shown in Figure 1) is designed to carry 44 passengers for a distance of 574 nautical miles with IFR fuel reserves at its maximum internal load gross weight of 48,500 pounds. FAA and CAA certification was received in June of 1981. Revenue service with the initial customer, British Airways Helicopters (BAH), began on July 1, 1981.

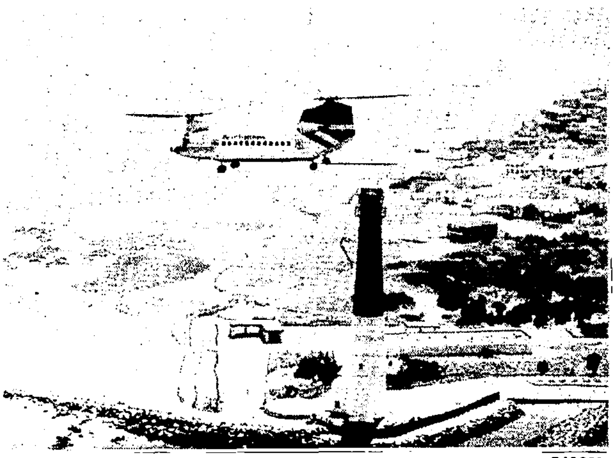

Figure 1. Boeing 234 Helicopter

Figure 2 shows a typical offshore oil mission for the 234 in which advantage is taken of its range capability to go directly from Aberdeen, Scotland to the Dunlin oil platform. This replaces the previous practice of flying fixed wing from Aberdeen to Sumburgh in Shetland Islands, and then flying by helicopter from Sumburgh to the Dunlin platform. The 234 handling qualities and flight control systems have been designed to accommodate this type of mission under IFR, VFR, day, and night conditions. This paper will describe the 234 flight control system, the criteria which led to this system, and the results of testing the aircraft.

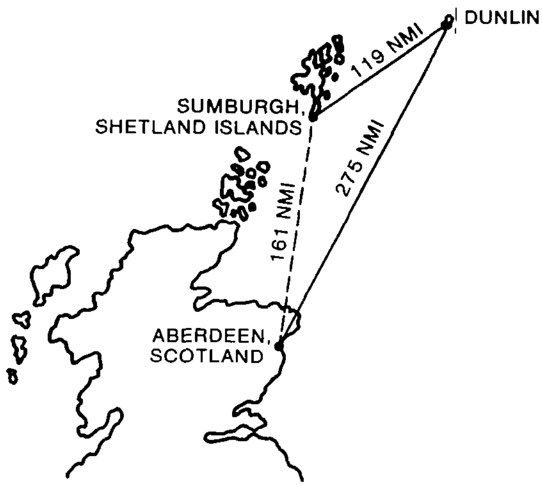

Figure 2. Typical Offshore Oil Mission

Flight Control System Development Criteria

Development of the 234 flight control system encompassed three considerations which had to be satisfied in order to achieve a satisfactory system for civil operation.

The first consideration was that the applicable civil regulations had to be satisfied since it was a program requirement to be certified by FAA and CAA. The relevant FAA documents were FAR Part 29 and the interim IFR standards dated December 15, 1978. The applicable CAA documents were BCAR Section G: Rotorcraft, and for IFR working papers, number 612 (Instrument Flight) and number 615 (Automatic Flight Control and Stability Augmentation Systems). These defined a minimum level of flight characteristics during normal and degraded mode operations, the criteria used to judge the system during certification flight testing, and a minimum level of reliability for system operation. Table I summarizes the pertinent criteria (in a general sense) to which the 234 was certified and shows that, for the basic stability and controllability criteria, the FAA and CAA requirements are very similar. For AFCS failures, the CAA requirement is significantly more stringent with a maximum time delay of five seconds compared to the FAA maximum of three seconds. With regard to what failures are to be evaluated, the FAA is more stringent with their 10^{-9} probability of occurrence compared to the CAA requirement of 10^{-7}.

TABLE I. HANDLING QUALITIES CERTIFICATION CRITERIA FOR VFR AND IFR FLIGHT

ITEM	FAA	CAA
Controllability and Maneuverability	The rotorcraft must be safely controllable and maneuverable	The rotorcraft shall be safely controllable and maneuverable
Trim Control	Must be able to trim out steady forces No undesirable discontinuities in control force gradients	Must be able to trim out steady forces No undesirable discontinuities
Static Longitudinal Stability	Must demonstrate static longitudinal stability from hover through V_{NE}	Must demonstrate static longitudinal stability from hover through V_{NE}
Static Lateral Directional Stability	Must demonstrate static lateral directional stability throughout IFR envelope	Must demonstrate lateral directional stability throughout IFR envelope
Dynamic Stability	Must demonstrate dynamic stability characteristics Stability level varies with frequency of oscillation	Must demonstrate dynamic stability characteristics Stability level varies with frequency of oscillation
AFCS Failures	Must demonstrate failures with time delays varying from normal pilot reaction to 3 seconds, depending on flight condition	Must demonstrate failures with time delays varying from 1.5 seconds to 5 seconds, depending on flight condition
Probability of Failure which would Prevent Continued Safe Flight	Extremely improbable (10^{-9})	Extremely remote (10^{-7})

The second consideration was that two specific operational requirements had to be satisfied. The first requirement was to provide for an approximate six hour flight over water during IFR and VFR, day, and night conditions. The second was to be able to operate in adverse atmospheric conditions – specifically cross winds of up to 50 knots. This criteria is especially necessary for operation in the North Sea, where in winter months it is not unusual to have winds up to 50 knots.

The final consideration was the systems had to be acceptable by pilot qualitative evaluation. Included in these pilot evaluations were handling qualities evaluation during VFR, IFR, and flight in turbulence for normal AFCS operation and degraded mode operation. During these evaluations trimability, stability, control cross coupling, and dynamic stability were evaluated. The criteria of acceptability by pilot qualitative evaluation determined the signal paths and the gain levels and shaping in each of the signal paths for the basic AFCS.
Evaluation of these requirements resulted in the definition of an AFCS system which provides full time attitude and airspeed hold, maneuver enhancement, and vernier trim capability, and includes the incorporation of a flight director and coupler which has navigation capture and tracking, approach guidance capture and tracking, altitude hold, vertical speed hold, heading hold and course select.

Chinook Flight Control History

The Boeing 234 configuration is a result of over 20 years of development of the flight control system as well as the evaluation of requirements. The history of the development of the Chinook flight control system is interesting in that it parallels the development of the state of the art of flight control systems.

Table II summarizes the features of the automatic flight control system for the CH-47A, B, C, and D. On the CH-47A the SAS was essentially a rate damping system which improved the stability characteristics and provided a short term hands-off capability through a pseudo pitch attitude hold (lagged pitch rate). A scheduled airspeed input into a differential collective pitch actuator was provided to obtain a positive longitudinal stick gradient with airspeed. The CH-47B maintained the same basic configuration of the SAS but modified the signal shaping in the pitch axis and the yaw axis. On the CH-47C a Pitch Stability Augmentation System (PSAS) was incorporated which added the features of airspeed and pitch attitude feedback for improved pitch stability. The CH-47D and 234 are the current step in the automatic flight control system (AFCS) development. As shown on Table II, continuous airspeed and pitch attitude hold and stability has been added; bank angle hold logic has been changed from a wings level hold to a capability to hold any bank angle; heading and altitude hold and maneuver enhancement in the pitch, roll, and yaw axes has been added. Cross coupled feedbacks have been added to the pitch, roll, and yaw extensible links for improved failure characteristics. With this generation of the Chinook automatic flight control system a hands off capability has been obtained.

TABLE II. CHINOOK AUTOMATED FLIGHT CONTROL SYSTEM CAPABILITY

HANDLING QUALITIES FUNCTION	CH-47A (SAS)	CH-47B (SAS)	CH-47C (PSAS)	CH-47D (AFCS)	234
Rate Damping	All Axes	All Axes	All Axes	All Axes	All Axes
Pitch Attitude Hold and Stability	Pseudo Attitude Hold	Pseudo Attitude Hold	About Trim	Continuous	Continuous
Roll Attitude Hold	No	No	Wings Level	Any Bank Angle	Any Bank Angle
Heading Hold	No	No	No	Yes	Yes
Airspeed Hold	No	No	About Trim	Continuous	Continuous
Altitude Hold	No	No	No	Yes	Yes
Maneuver Enhancement	Yaw (Turn Entry Only)	Yaw (Turn Entry Only)	Yaw (Turn Entry Only)	Pitch, Roll, and Yaw	Pitch, Roll, and Yaw
Cross Coupled Feedback for Improved Failure Characteristics	No	No	No	Pitch, Roll, and Yaw	Pitch, Roll, and Yaw
Flight Director	No	No	No	No	Yes

Automatic Flight Control System (AFCS) Configuration

The control system configuration is shown schematically in Figures 3 through 7. The AFCS is in general dualized; i.e., input signals, signal conditioning, and differential actuation. The collective parallel actuator has not been dualized. Philosophy of the system mechanization has been to dualize differential actuation paths which influence basic handling qualities and maintain a single system for parallel paths which do not affect basic aircraft handling qualities. Mechanization of the system is such that the handling characteristics of the aircraft are essentially unchanged on single or dual AFCS.

The pitch axis of the AFCS (Figures 3 and 4) is comprised of two parts – dualized high rate, low authority, hydraulically powered, extensible links for pitch damping; and dualized low rate, high authority, electromechanical Differential Airspeed Hold (DASH) actuators for pitch attitude and airspeed hold. Dual system authority for the extensible links is ± 25 percent of cockpit control and for the DASH is 50 percent of cockpit control. Also included in the control laws for the DASH system is a longitudinal stick pick off for maneuver enhancement. Data signals used by the AFCS for the pitch axis are pitch attitude (from which pitch rate is derived), airspeed, and longitudinal stick position.

The roll axis of the AFCS is shown on Figure 5. It consists of signal paths for roll rate damping, roll attitude hold with synchronization logic so that any commanded bank angle can be held, lateral stick position feedback for maneuver enhancement,

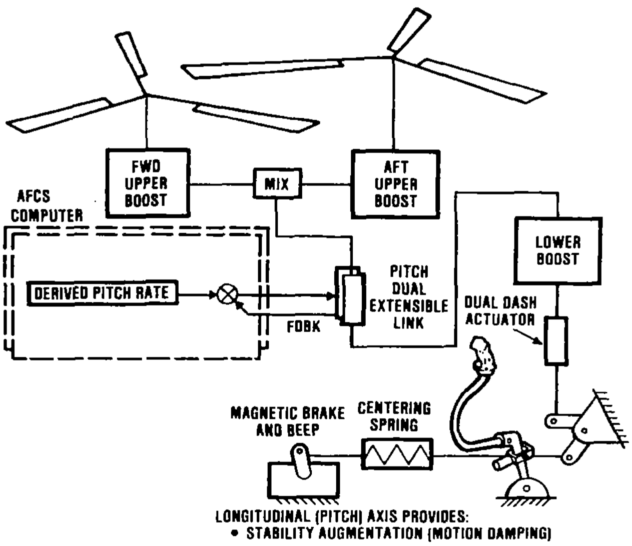

Figure 3. Pitch AFCS Mechanization

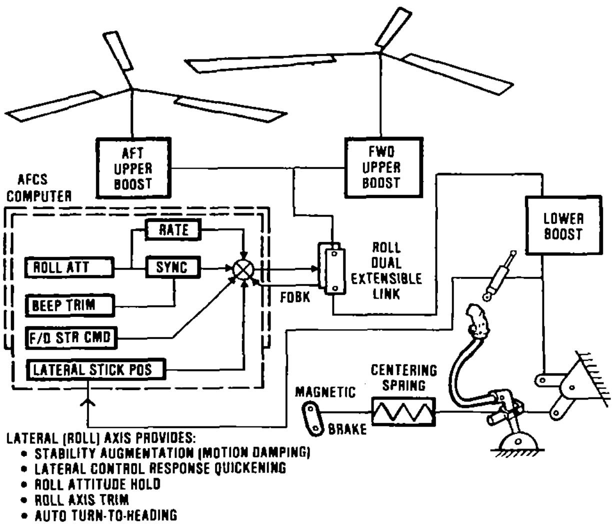

Figure 5. Roll AFCS Mechanization

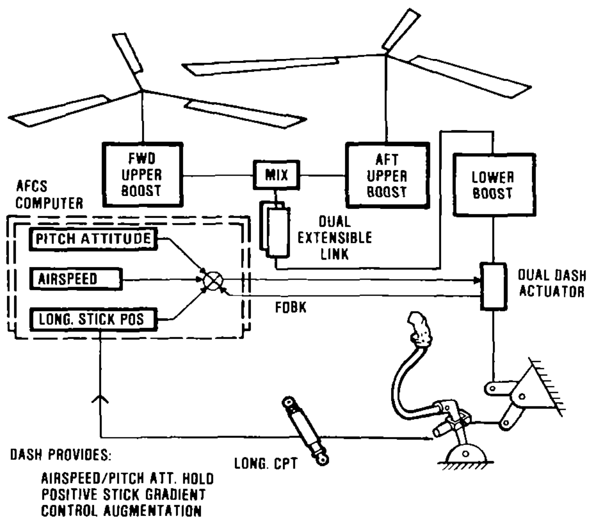

Figure 4. Pitch AFCS (Dash) Mechanization

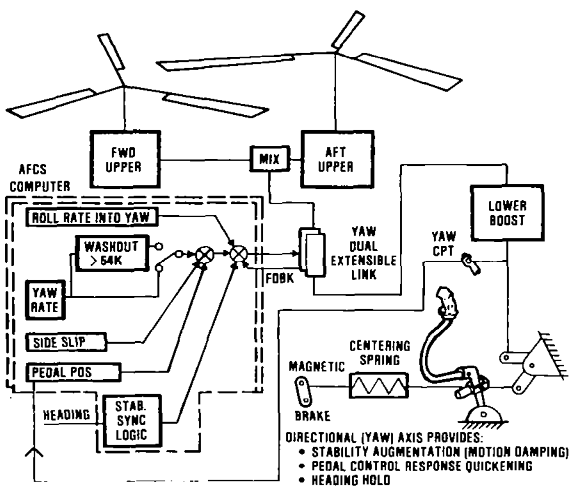

Figure 6. Yaw Axis Mechanization

roll attitude beep for vernier attitude control, and flight director steering commands. Actuation for the roll axis AFCS is provided by dualized hydraulically powered extensible links. Dual system authority for the extensible links is ± 26 percent of cockpit control authority. Data signals used by the roll AFCS are roll attitude (from which roll rate is derived), lateral stick position, flight director steering command, and beep trim command.

The yaw axis of the AFCS is shown on Figure 6. It consists of signal paths for yaw damping, heading hold, sideslip stability, pedal position for maneuver enhancement, and roll rate into yaw for turn entry coordination. Actuation for the yaw axis is provided by dualized hydraulically powered extensible links. Dual system authority for the extensible links is ± 30 percent of cockpit control. Data signals used by the yaw axis are heading, sideslip angle from sideslip transducers on the nose of the aircraft, yaw rate from rate gyros, roll rate derived from roll attitude, and pedal position. Logic for the operation of the yaw damping and holding hold signal paths varies in the yaw axis depending upon flight condition. For yaw damping at low speed there is full time rate damping. At high speed (above 54 knots) the rate damping is washed out with a four second time constant so that the yaw AFCS is not saturated during turns. For heading hold at low speed, the heading hold function is synchronized with pedals out of detent so that the aircraft may be turned with pedals and relatches when the pedals are returned to detent and the yaw rate is less than one and a half degrees per second. At higher speed (above 54 knots) the heading hold circuit synchronizes for lateral stick or pedals out of detent so that the aircraft can be turned with the stick or sideslipped with pedals. Heading hold relatches when the stick

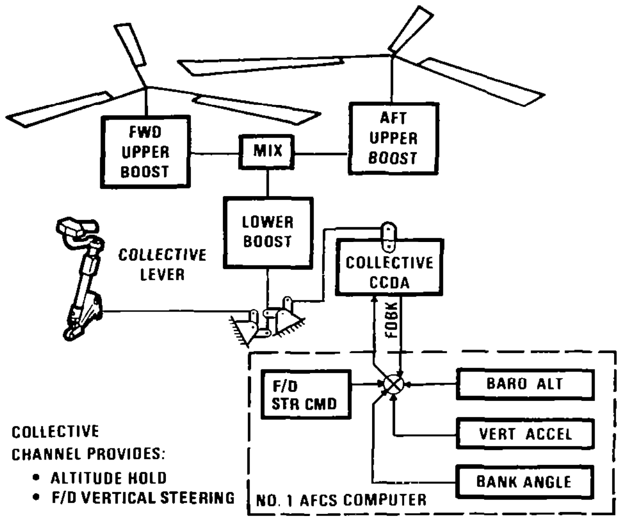

Figure 7. Collective Axis Mechanization

and/or pedals are back in detent, roll rate is less than one and a half degrees per second, yaw rate is less than one and a half degrees per second, and roll attitude is less than one and a half degrees.

The collective axis of the AFCS is shown on Figure 7. It consists of a parallel actuator with signal paths for flight director commands and for altitude hold. The collective axis is not redundant and operates through the Number 1 AFCS unit.

The flight director with its interfaces is shown on Figure 8. The flight director is the Sperry Helcis system which provides for enroute navigation and landing approach with the capability for coupling into the automatic flight control system for lateral steering commands through the aircraft roll control and vertical steering command through the collective parallel actuator. *The system can be used in the coupled or uncoupled mode.*

The flight director system consists of a mode selector panel (Figure 9) and a computer with sensor inputs provided from radio navigation, attitude, acceleration, and air data devices. The flight director mode selector panel provides the controls for engaging/disengaging and displaying the status of any available flight director mode. The modes provided are as shown in Table III.

TABLE III. FLIGHT DIRECTOR SELECTOR PANEL MODES

	Lateral Axis	Collective Axis
Heading Select Mode (HDG)	X	
Navigation Mode (NAV)	X	
Instrument Landing System Mode (ILS)	X	X
Back Course Mode (BC)	X	
Go-Around (GA)	X	X
VOR Approach Mode (VOR APR)	X	
Altitude Hold Mode (ALT)		X
Vertical Speed Hold Mode (VS)		X
Standby Mode (SBY)	–	–

Heading Select Mode (HDG)

The Heading Select Mode is selected by pressing the HDG *button on the mode selector. In the HDG mode, the flight di*rector computer provides inputs to the roll steering pointer to command a turn to the heading indicated by the heading bug on the HSI. When HDG is selected, it overrides the NAV, BC,

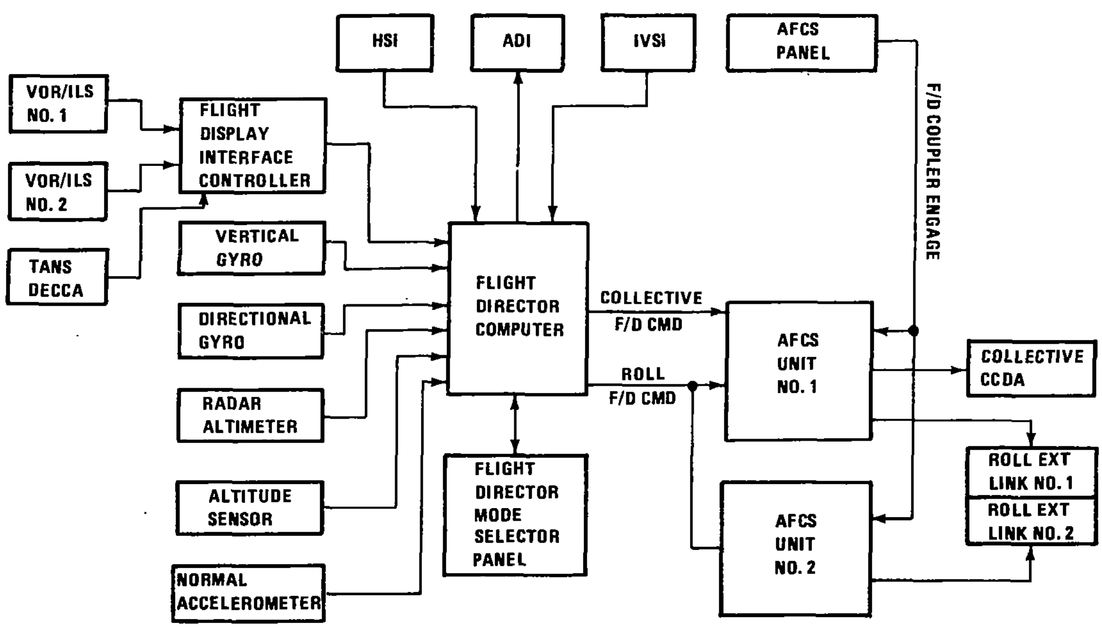

Figure 8. Flight Director/AFCS Interface

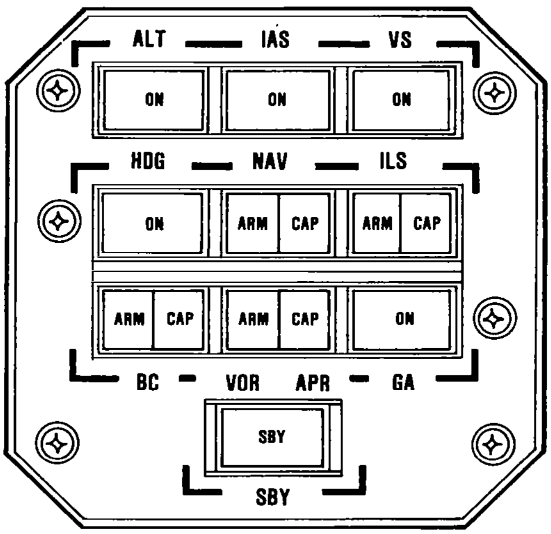

Figure 9. Flight Director Mode Select Panel

and ILS modes. In the event of a loss of valid signal from either the vertical or directional gyros, the roll steering pointer is biased out of view.

Navigation Mode (NAV)

The NAV Mode provides steering commands for both VOR and localizer navigation.

VOR Mode

Pressing the NAV button on the F/D MSP with the navigation receiver tuned to a VOR frequency engages the VOR mode. When outside the lateral bracket sensor trip point, the roll steering pointer receives a heading select command as described above, and both the NAV ARM and HDG mode annunciators are illuminated. Upon reaching the lateral bracket sensor trip point, the system automatically switches to the VOR mode – HDG and NAV ARM annunciators extinguish and the NAV capture NAV CAP annunciator illuminates. At capture, a command is generated to capture and track the selected VOR course. When passing over the station, an over-station sensor detects station passage, removing the VOR deviation signal from the command until it is no longer erratic. While over the station, course changes are made by selecting a new course on the HSI.

If the NAV receiver is not valid prior to the capture point, the lateral beam sensor will not trip and the system will remain in the HDG mode. After capture, if the NAV receiver, compass data, or vertical gyro go invalid, the roll steering pointer will be biased out of view.

Localizer Mode

The Localizer Mode is selected by depressing the NAV button on the MSP and being tuned to a loc frequency. Mode selection and annunciation in the LOC mode is the same as the VOR mode.

Instrument Landing System Mode (ILS)

The ILS Mode is used to make an ILS approach. Pressing the ILS button with a LOC frequency tuned, arms both the localizer and glideslope modes. In the ILS mode, both the NAV and ILS modes are armed to capture the localizer and glideslope, respectively. The initial localizer capture angle is set using the heading bug similar to the VOR mode.

With ILS mode armed, the collective axis can be in any one of the other collective modes, except Go-Around. When reaching the vertical beam sensor trip point, the system automatically switches to the glideslope mode. The collective mode and ILS ARM annunciators extinguish and ILS GS annunciator illuminates. At capture, a command is generated to intercept the glideslope beam. Capture can be made from above or below the beam.

Glideslope mode is interlocked so the localizer must be captured prior to glideslope capture. If the glideslope receiver is not valid prior to capture, the vertical beam sensor will not trip and the system will remain in the existing collective mode. After capture, if the glideslope receiver or vertical gyro become invalid, the collective steering pointer will bias out of view.

Back Course Mode (BC)

The Back Course Mode is selected by pressing the BC button on the Mode Selector. Back Course operates the same as the LOC mode with the deviation and course signals locked out when in the BC mode. When BC is selected outside the lateral beam sensor trip point, BC ARM and HDG will be annunciated. At the capture point, BC CAP will be annunciated with BC ARM and HDG extinguished.

Go-Around (GA)

The Go-Around Mode may be engaged by pressing either the GA button on the mode selector or the remote GA button located on the pilot's collective pitch lever. When selected, all other modes are reset and the GA annunciator is illuminated. The roll steering cue receives a roll zero command while the collective cue commands a positive rate of climb of 500 fpm.

VOR Approach Mode (VOR APR)

Pressing the VOR APR button on the mode selector with the navigation receiver tuned to a VOR frequency engages the VOR Approach Mode. The mode operates identically to the VOR mode with the gains optimized for a VOR approach.

Altitude Hold Mode (ALT)

The Altitude Hold Mode is selected by pressing the ALT button on the mode selector. When ALT is selected, it overrides the ILS GS, GA, or VS modes and the altitude at time of selection will be maintained. In the ALT mode, the collective command is proportional to altitude error relative to the engage reference. Once engaged in the altitude hold mode, the collective steering pointer will bias out of view if either the VG or altitude sensor goes invalid, and the collective AFCS will revert to manual control.

Vertical Speed Hold Mode (VS)

The vertical speed hold mode is engaged by pressing the VS button on the mode selector. When VS is selected, it overrides the ILS, GA, and ALT modes. A vertical speed reference is set by the bug on the pilot's vertical speed indicator. Once engaged, if either the vertical gyro or altitude sensor go invalid, the collective steering pointer will be biased out of view.

Standby Mode (SBY)

Pressing the SBY button on the Mode Selector resets all the other flight director modes and biases both flight director command bars from view. While depressed, SBY acts as a lamp test, causing all mode annunciator lights to be lit and the flight director warning flag on the ADI to come in view. When the button is released, all the other mode annunciator lights extinguish and the flight director warning flag retracts from view.

Handling Qualities Characteristics

The handling qualities of an aircraft are quantitatively evaluated by its static and dynamic stability characteristics. Because of the tandem rotor design and the configuration of the AFCS the handling characteristics of the 234 are essentially independent of variations in gross weight, center of gravity, and density altitude. Representative static longitudinal stability characteristics are shown in Figure 10. There are several characteristics which should be noted. First the longitudinal stick gradient is essentially independent of flight condition with cruise being slightly more stable. Second, varying airspeed is a longitudinal axis task only — there is no significant cross-coupling with the lateral or directional axis. Third, the true stability level of the aircraft to external disturbances is masked due to the longitudinal stick pickoff which cancels part of the airspeed feedback. The stability level to external disturbances is approximately four times that shown. Representative lateral directional static stability characteristics are shown in Figure 11. Note that the stability level is essentially independent of flight condition and that there is no cross coupling with the longitudinal axis. Dynamic stability characteristics in cruise are shown in Figure 12. The response to pitch, roll, and yaw control pulses are well damped. Note that in the pitch axis the system is designed for a return to trim capability, but the logic in the roll and yaw axis is such that when the stick is returned to detent a new attitude is held.

AFCS failures from dual system operation are mild due to the cross coupled feedback scheme on the extensible links (Figure 13). The effect of this mechanization is to obtain immediate relief from a number 1 or number 2 system actuator hardover. Figures 14 and 15 show typical failure characteristics in cruise in the pitch, roll, and yaw axes. Failures from single system operation are more abrupt and are characterized by delay times of one to two seconds and maximum pitch, roll, or yaw rates in the axis of failure of 10 to 15 degrees per second.

Crosswind trim characteristics are shown in Figure 16. The tandem rotor configuration is especially suited for this type of operation because of its insensitivity to wind direction. Note from the figure that low speed control is a one axis control task — lateral stick. There is essentially no cross coupling with longitudinal or directional control.

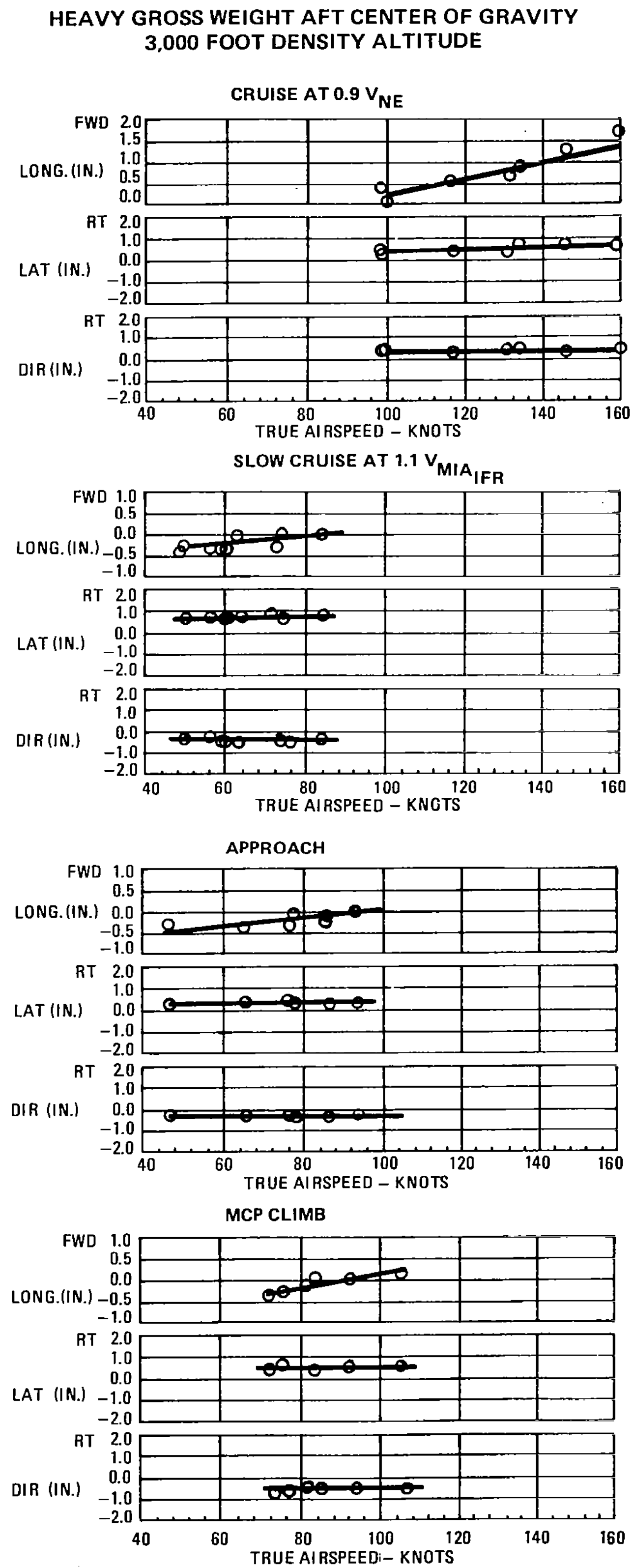

Figure 10. Static Longitudinal Stability

HEAVY GROSS WEIGHT AFT CENTER OF GRAVITY 3,000 FEET DENSITY ALTITUDE

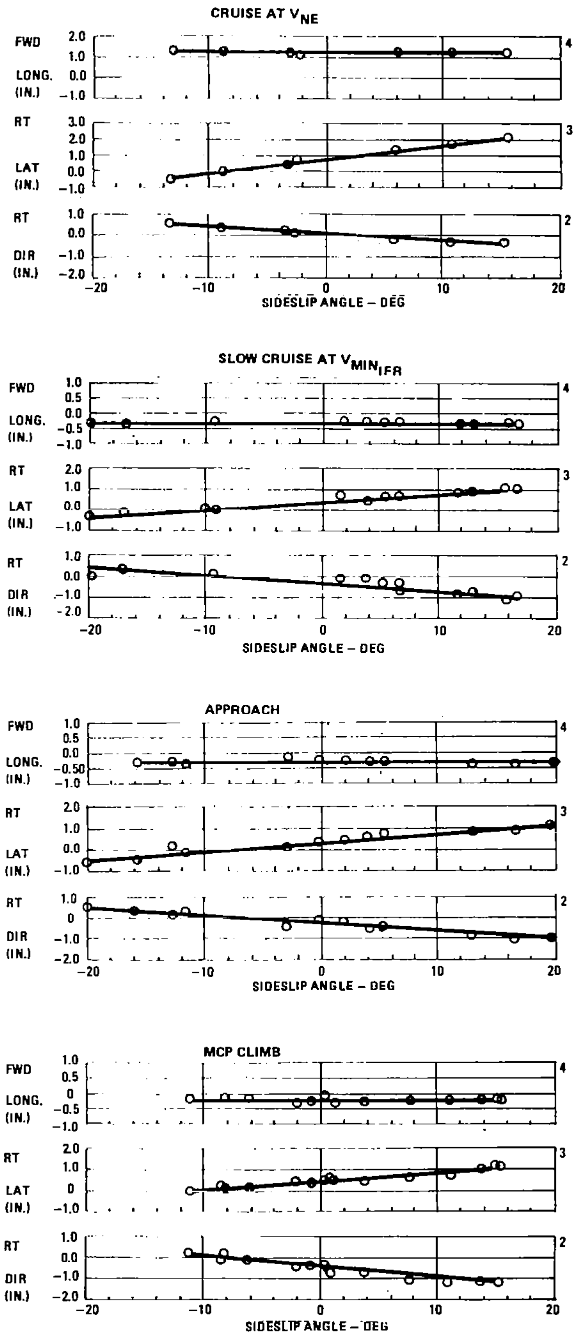

Figure 11. Static Lateral Directional Stability

HEAVY GROSS WEIGHT AFT CENTER OF GRAVITY

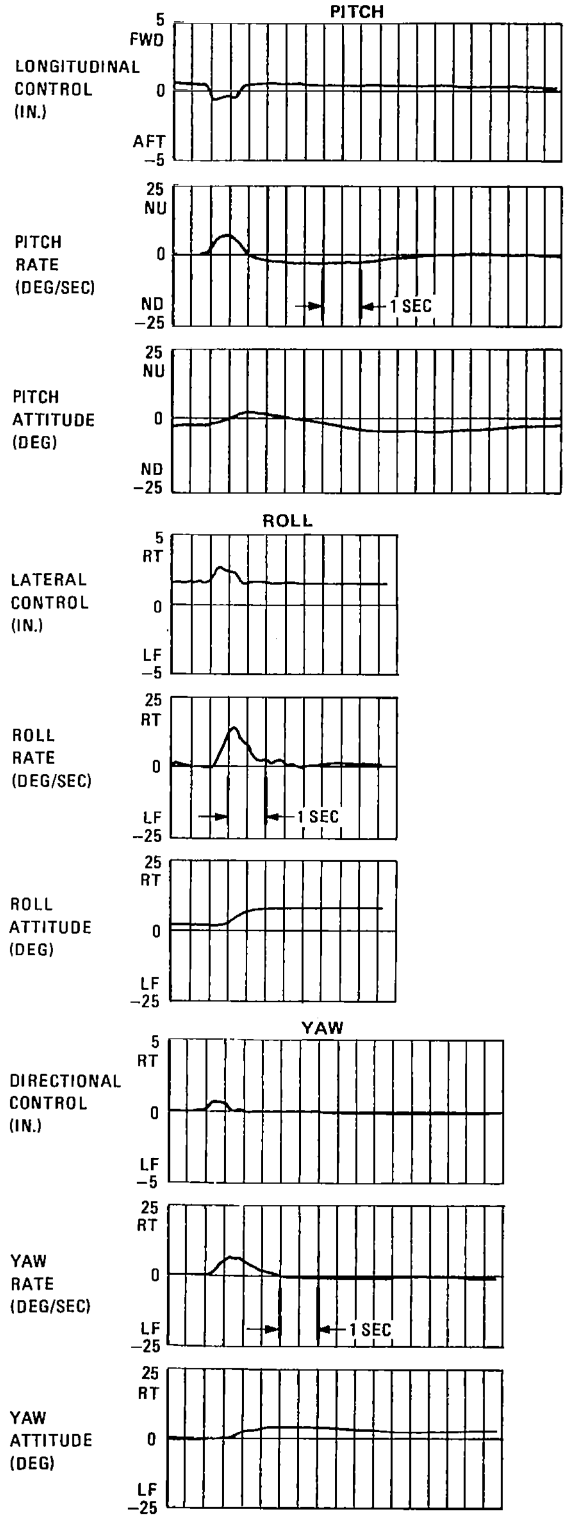

Figure 12. Cruise Dynamic Stability

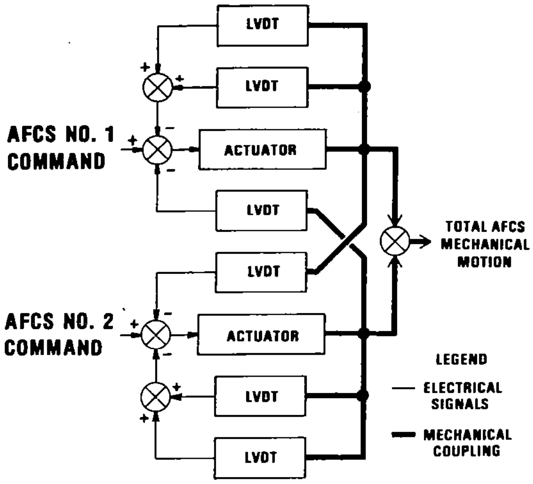

Figure 13. Extensible Link – Cross Coupled Feedback

HEAVY GROSS WEIGHT AFT CENTER OF GRAVITY CRUISE AT 135 KNOTS

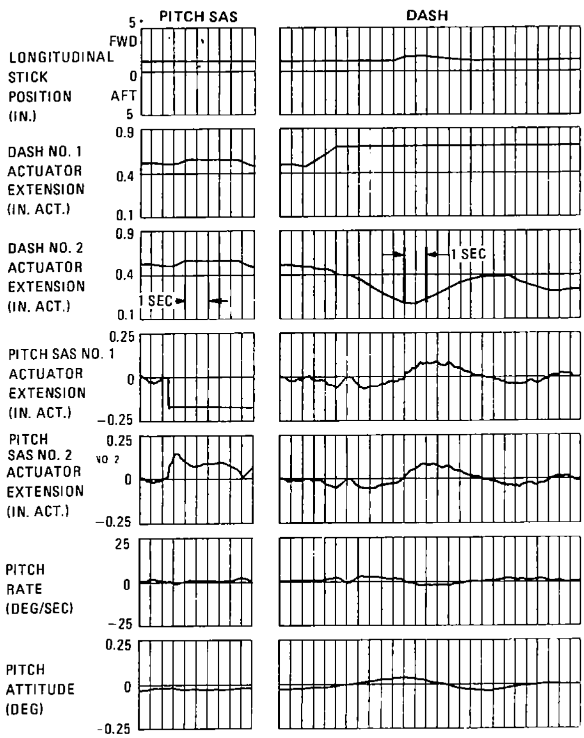

Figure 14. AFCS Failure Characteristics – Pitch Axis

HEAVY GROSS WEIGHT AFT CENTER OF GRAVITY CRUISE AT 135 KNOTS

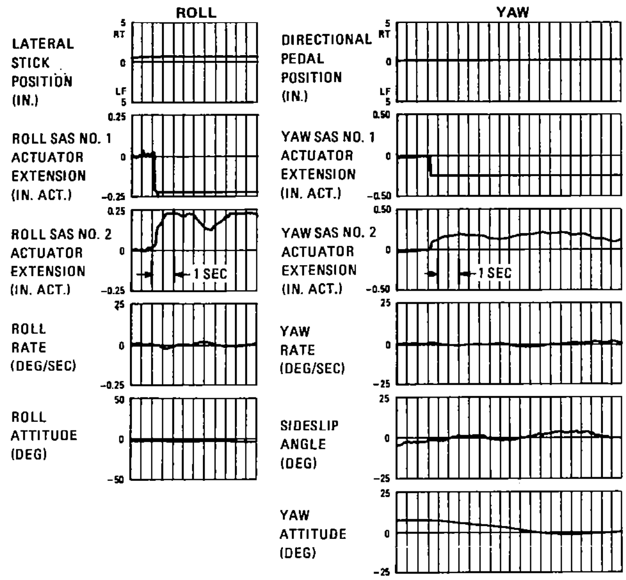

Figure 15. AFCS Failure Characteristics – Roll and Yaw Axis

HEAVY GROSS WEIGHT MID-CENTER OF GRAVITY

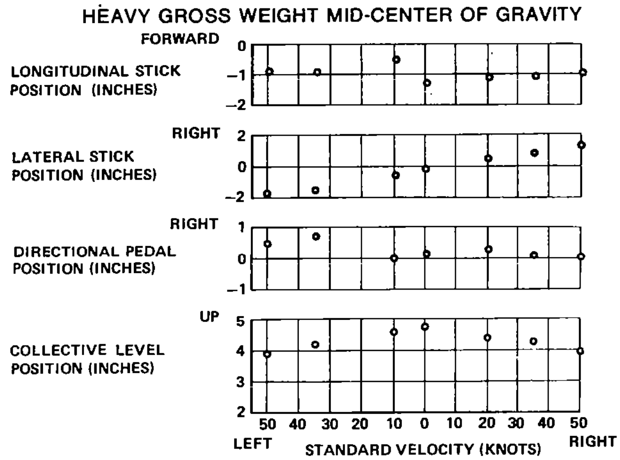

Figure 16. Slow Speed Controllability

Conclusions

Development of a flight control system for today's helicopters must consider the certification criteria for the countries in which it is to be operated; diverse operational criteria which include IFR, VFR, long duration missions, and high wind conditions; and addition of pilot aids such as a flight director and coupler to minimize the overall mission workload. For the Boeing 234 these criteria and needs have resulted in an AFCS with airspeed and attitude hold and maneuver enhancement and a flight director with a coupling capability.