TWENTYFIFTH EUROPEAN ROTORCRAFT FORUM

Paper n° H10

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SEPTEMBER 14–16, 1999
ROME
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFESA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

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1. INTRODUCTION

The Bell-Agusta BA 609 civil tiltrotor (Fig. 1) is poised to revolutionize light, transport-category commercial aviation. With accommodations for up to nine passengers, the BA 609 combines the speed and range of a turboprop airplane with the vertical lift capabilities of a twin-engine helicopter. Operators of the aircraft will be afforded the luxury of highly cost-effective point-to-point transportation at cruise speeds up to 275 knots (509 km/h) with ranges up to 750 nautical miles (1,389 km). The low-maintenance, flexible configuration will allow operators to use it for a wide variety of missions, including executive transportation, natural resource exploration, search and rescue, and emergency medical services.

Although tiltrotor development has been ongoing for several decades, as exemplified by the XV–3, XV–15, and V–22, the BA 609 will be the first of its type to achieve civil certification (Refs. 1 and 2). One of the design challenges of this pioneering effort is to provide a highly reliable flight control system (FCS), which will minimize pilot workload and satisfy a stringent set of handling qualities requirements and objectives. The BA 609 is being designed to flight standards that exceed those specified in the BA 609 aircraft Certification Basis. In legal terms, the BA 609 Certification Basis is a special condition under FAA regulations using an amalgam of FAR Parts 25 and 29 (Refs. 3 and 4) and any special requirements deemed necessary for a special class of aircraft as stated in FAR § 21.17(b). This paper presents advanced design features of the BA 609 FCS that are focused on the following objectives:

- ***Reduced pilot workload:*** Made possible by flight control design that allows the pilot to obtain desired aircraft responses and remain within the aircraft structural envelope by applying conventional control techniques, thus simplifying the transition from either airplanes or helicopters to tiltrotor aircraft.
- ***Improved flight safety and reliability:*** Through the use of redundant control mechanisms, real-time system monitoring, crew alerting, and a hierarchical mode structure that provide failure transient protection and automatic system reconfiguration.
- ***Reduced cost and weight:*** By a disciplined system development program that leverages state-of-the-art FCS technology and reduces risk through high-fidelity flight simulation combined with previous tiltrotor flight experience.

The paper first discusses the primary control of the BA 609, followed by a summary of the BA 609 handling qualities requirements with emphasis on those resulting in FCS design requirements and an overview of the fault tolerant design of the fly-by-wire FCS. Subsequent sections describe the cockpit controls and displays, aircraft control laws, and piloted simulation evaluations. The paper is focused on manual flight modes, relegating flight director and coupled mode flying as subjects for future reporting.

2. PRIMARY CONTROL OF THE BA 609

To accommodate the large tiltrotor flight envelope ranging from a 35 kn (65 km/h) tailwind hover to a 3*g* pullup at Mach 0.55, the BA 609 incorporates multiple control mechanisms. Fig. 2 depicts the mechanisms for primary force and moment control of the BA 609 at the extremes of its conversion capabilities: helicopter mode and airplane mode. For configurations in between, blending of aerodynamic and rotor controls ensures sufficient control power in all axes. In helicopter mode, rotor controls are used: pitch control is accomplished by symmetric application of fore/aft cyclic, yaw control by differential left-right fore/aft cyclic, vertical force control by symmetric collective, roll control by differential left-right collective (DCP).

One difference between the BA 609 and its predecessors, the XV–15 and V–22, is that it does not have lateral cyclic control. Lateral cyclic control is required for control of conventional single main rotor helicopters, but is an option for tiltrotors; it can provide side force control, roll control, and lateral flapping alleviation to minimize rotor loads. On the BA 609, the rotors have a fixed 2.5 deg inward lateral tilt that alleviates download in hovering flight by directing rotor downwash outward away from the wings. Another consideration in this fixed

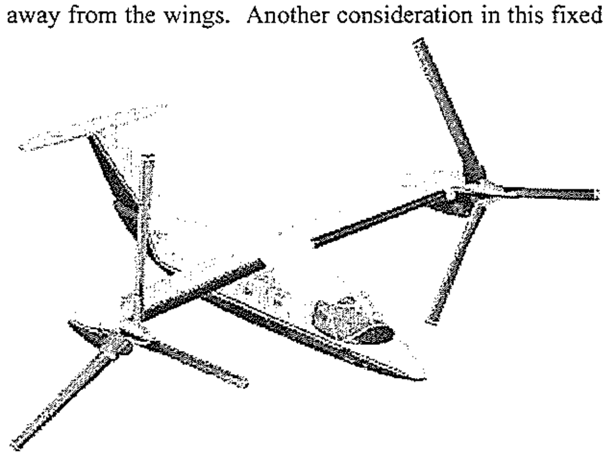

Fig. 1. The BA 609 tiltrotor aircraft.

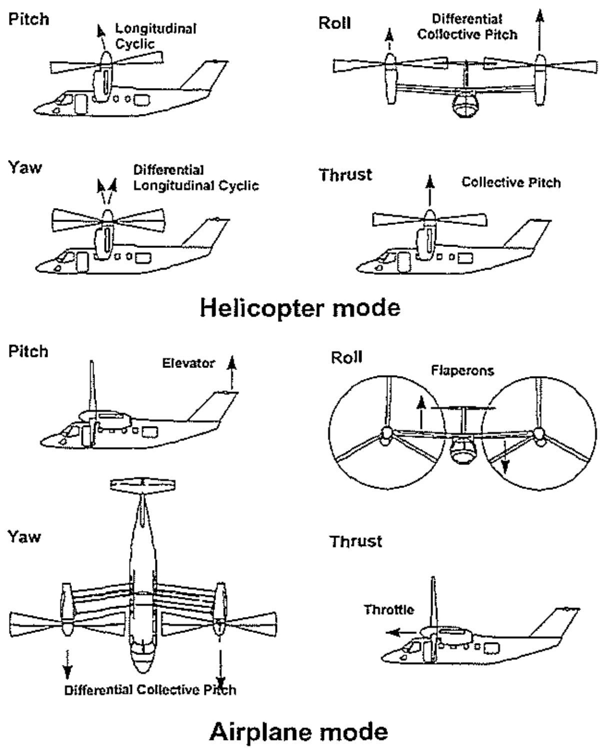

Fig. 2. BA 609 primary control mechanisms.

setting was lateral flapping throughout the flight envelope, which is a maximum inboard in rearward flight and a maximum outboard at approximately 40 kn (74 km/h) in helicopter mode. As a provision for possible future user requirements, space provisions for lateral cyclic actuators have been included in the nacelle design.

In airplane mode, tiltrotors have the option of using rotor controls or conventional aerodynamic control surfaces. BA 609 pitch control is accomplished with an elevator and roll control by differential deflection of the 78% span flaperons. Flaperons combine standard flap and roll control functions through an electronic summation of symmetric deflection (flaps) and asymmetric deflection (ailerons). Unlike the XV–15 and V–22, which control yaw using conventional rudder surfaces, the BA 609 foregoes a rudder and generates yaw moment with DCP. This alternative has been applied successfully in the Bell Eagle Eye Unmanned Air Vehicle (UAV) (Ref. 5) and has contributed substantial cost and weight savings for the BA 609 without compromising aircraft yaw control. The BA 609 rotor design allows rotor controls alone to produce sufficient yaw control power throughout the aircraft's conversion and airplane mode envelope. Transition from helicopter mode to airplane mode results in differential fore/aft cyclic pitch being phased out gradually as a function of nacelle angle and DCP being phased in simultaneously. Unlike dual engine turboprop airplanes, the BA 609 does not require rudder control power to offset asymmetric thrust from a single engine failure. The BA 609 engines are interconnected to both rotors via a highly reliable cross shaft installed in the wings, allowing a single engine to generate thrust at both rotors. The BA 609 yaw control power in airplane mode is sized to coordinate aggressive turns and generate a limited amount of sideslip.

3. HANDLING QUALITIES REQUIREMENTS FOR THE BA 609 FCS DESIGN

To be certified, the BA 609 must satisfy the handling qualities requirements in Subpart B – Flight Characteristics of the Certification Basis. These requirements are taken in most instances verbatim from existing FARs and relate to traditional measures of aircraft stability and control such as controllability, maneuverability, trim characteristics, static and dynamic stability, and stall characteristics. In addition to adopting these requirements as mandatory for the BA 609 handling qualities, a design objective was established to comply with the guidance relative to handling qualities ratings—"Satisfactory," "Adequate," and "Controllable"—provided by Advisory Circular AC-25-7A (Refs. 6 and 7). This section focuses on the translation of these handling qualities requirements and objective into FCS design requirements.

Table 1 is a compilation of the primary handling qualities-based requirements for the FCS design. Since one of the most fundamental requirements of any control system is to provide sufficient control power throughout the flight envelope, requirements for highly reliable actuators head the list. Almost of equal importance are the cockpit controls and displays, which provide the pilot interface with the FCS; these requirements are listed next and discussed in Section 5. Next on the list are requirements relating to the attainment of "Satisfactory" and "Adequate" handling qualities. Finally are requirements for additional automated functions that have been found to reduce pilot workload to an extremely low level for the tiltrotor mission, including flight in instrument conditions. These functions are to be provided to the most reliable level possible within the aggressive cost and weight constraints of the overall aircraft design.

Control power requirements for the BA 609 were gleaned from several military specifications and tiltrotor experience. For example, rotor cyclic fore-aft authority was set to be the same as the XV–15; helicopter mode roll control power was sized to meet the ADS-33D (Ref. 8) attitude quickness criteria for general tasks; airplane mode roll control power was sized to meet the MIL-F-8785C (Ref. 9) Level 1 Category B tasks requirement of attaining 45 deg of roll angle in 1.9 seconds; airplane mode pitch control was required to be sufficient to attain 1*g* stall and limit load factor at forward cg with an additional control margin of 1 rad/s^2; airplane mode yaw control was required to provide turn coordination for aggressive roll maneuvers. In addition, a requirement was imposed that the control power required at each flight condition be delivered at a minimum rate of 100%/s to protect against the possibility of aircraft pilot coupling (APC) due to actuator rate limiting (Ref. 10).

The guidance provided by the handling qualities assessment matrix in Advisory Circular AC 25-7A is a series of subjective handling qualities ratings (Satisfactory, Adequate, Controllable) related to the

Table 1. BA 609 FCS requirements based on primary handling qualities.

- Highly reliable rotor and surface actuators that satisfy control power and rate requirements
- Highly reliable nacelle angle control
- XV–15 cockpit arrangement and control travels
- Variable force feel system and trim actuator for cyclic stick
- Variable friction, torque limit tactile cueing, and trim actuator for collective stick
- Fixed feel system with magnetic brake release for pedals
- Tiltrotor-specific electronic flight displays showing envelope limits
- "Adequate" (Level 2) handling qualities with probability of failure less than 10^{-9}
  - Rate command control laws
  - Pitch, yaw, and roll rate damping
  - Lateral acceleration feedback
  - Nacelle angle gain scheduling
  - Automatic rotor speed governing
- "Satisfactory" (Level 1) handling qualities with probability of failure less than 10^{-5}
  - Attitude hold control laws
  - Automatic turn coordination
  - Airspeed gain scheduling
  - Torque command regulating system
  - Engine limit protection
  - Conversion corridor protection
  - Plus "Adequate" handling qualities requirements
- Automated heading hold
- Automated flaps
- Automated loads protection
- Autopilot capability

probability of encountering various turbulence levels (Light, Moderate, Severe), the portion of the flight envelope (Normal, Operational, Limit) in which the aircraft is operating, and the failure state (Normal, Probable, Improbable) of the FCS. The subjective ratings "Satisfactory," "Adequate," and "Controllable" are comparable to the Level 1, Level 2, and Level 3 handling qualities used in the military handling qualities specifications. The handling qualities input to the FCS design process derived from this matrix is the following: System failures resulting in an operational state with less than "Satisfactory" handling qualities must have a probability less than 10^{-5} (Probable Failure State), and system failures resulting in an operational state with less than "Adequate" handling qualities must have a probability less than 10^{-9} (Improbable Failure State).

Based on V–22 and XV–15 flight experience (Refs. 11 and 12), BA 609 high-fidelity simulation evaluations, and military specification (Refs. 8 and 9) guidelines, it was decided that "Adequate" handling qualities require a classical rate response to control inputs, lateral acceleration feedback, rate stabilization, nacelle-based control law gain scheduling, and automatic rotor speed governing. "Satisfactory" handling qualities require additional augmentation, including long-term attitude stabilization, airspeed-based conversion protection, airspeed-scheduled control laws gains, and more automatic control functions for workload reduction. Thus an FCS design requirement was established that attitude, airspeed, and engine torque sensing must have a failure probability less than 10^{-5} reliability, while angular rate, lateral acceleration, nacelle angle, and rotor rpm sensing must have a failure probability less than 10^{-9} reliability.

4. THE BA 609 FAULT TOLERANT FLY-BY-WIRE FLIGHT CONTROL SYSTEM

The triplex fault tolerant fly-by-wire FCS architecture of the BA 609 satisfies a myriad of requirements, in addition to those imposed by handling qualities. The flight control system architecture (Fig. 3) is driven primarily by flight safety requirements. Failure and safety analyses were completed early in the program to define the criticality of FCS functional failures and ensure that the system architecture provides the required level of reliability. As a result, the FCS is composed of three separate flight control channels. Each of these three channels is provided with separate and independent sources of electrical power, and makes use of separate and independent sources of hydraulic power for operating its actuation elements.

The actuation elements are sized so that any single flight control channel has sufficient capability to control the aircraft within a reduced flight envelope, allowing for safe flight and landing after loss of any two channels. The actuation capability of any two out of three channels operating provides full control power and rate. In addition, each channel is provided with "Adequate" handling qualities sensor data for other aircraft operating states to allow it to independently perform the necessary calculations for correctly positioning the flight control surfaces. During normal operations with all channels active, the

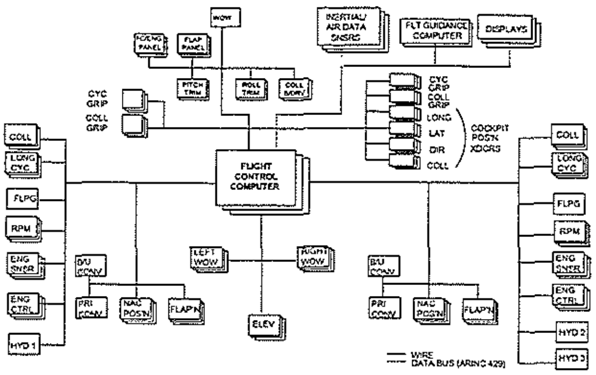

Fig. 3. Flight control system architecture.

data and calculations performed within the three computers are synchronized to provide improved performance and failure detection.

The primary cockpit control positions are measured at each crew station using three transducers per axis. Each of these measurements is made available to all three channels of the system. Similarly, secondary cockpit control positions, such as flap lever and engine condition lever, are measured and made available to all three channels. Aircraft state measurements are measured by a suite of four sensors which operate together to provide the required level of reliability for each FCS augmentation function listed in Table 1.

Control of the aircraft engines is via torque motor commands to the hydromechanical fuel control unit of each engine. Control of engine fuel flow and gas generator speed governing are provided within the fuel control unit. Each FCS channel can independently control the throttle position through the full power range for each engine. Essential engine operating parameters for each engine (such as torque, temperature, and power turbine speed) are measured and made available to all three channels. The FCS also provides commands to the engine starters and engine ignition system in response to pilot activation of the engine condition levers in the cockpit.

The nacelle conversion system consists of two telescoping ballscrew actuators, each powered by two redundant hydraulic power drive units (HPDU). Nacelle position is synchronized by a drive train connecting the two ballscrew actuators, which provides an added level of redundancy between the left and right HPDUs. The two HPDUs on each actuator are operated as a primary and backup drive for positioning the nacelles. Triplex redundant resolvers on the conversion actuators provide actuator position feedback. These sensors are used also for cockpit indication of nacelle position, system fault monitoring, and for scheduling the control laws. When the nacelles are close to airplane mode during conversion, conversion speed is slowed to reduce the force of impact with the downstop. Downstop strain gauges are used to detect when each nacelle reaches the downstop and to set the downstop pre-load and actuator brakes. Pre-loading and braking the nacelles provides enhanced whirl mode flutter stability in airplane mode.

To simplify aircraft control and minimize pilot workload, the BA 609 manual control laws have been designed with just two hierarchical modes: NORMAL and DIRECT. These are similar in concept to the flight modes of the Boeing 777 aircraft (Ref. 13). A summary of each mode is presented in Fig. 4, with more details provided in Section 6. The NORMAL mode is designed to provide "Satisfactory" handling qualities for all expected environmental conditions. The NORMAL mode control laws with all sensors available provide the necessary levels of stability augmentation and flight envelope protection functions to reduce pilot workload and provide enhanced pilot awareness of potential hazard conditions

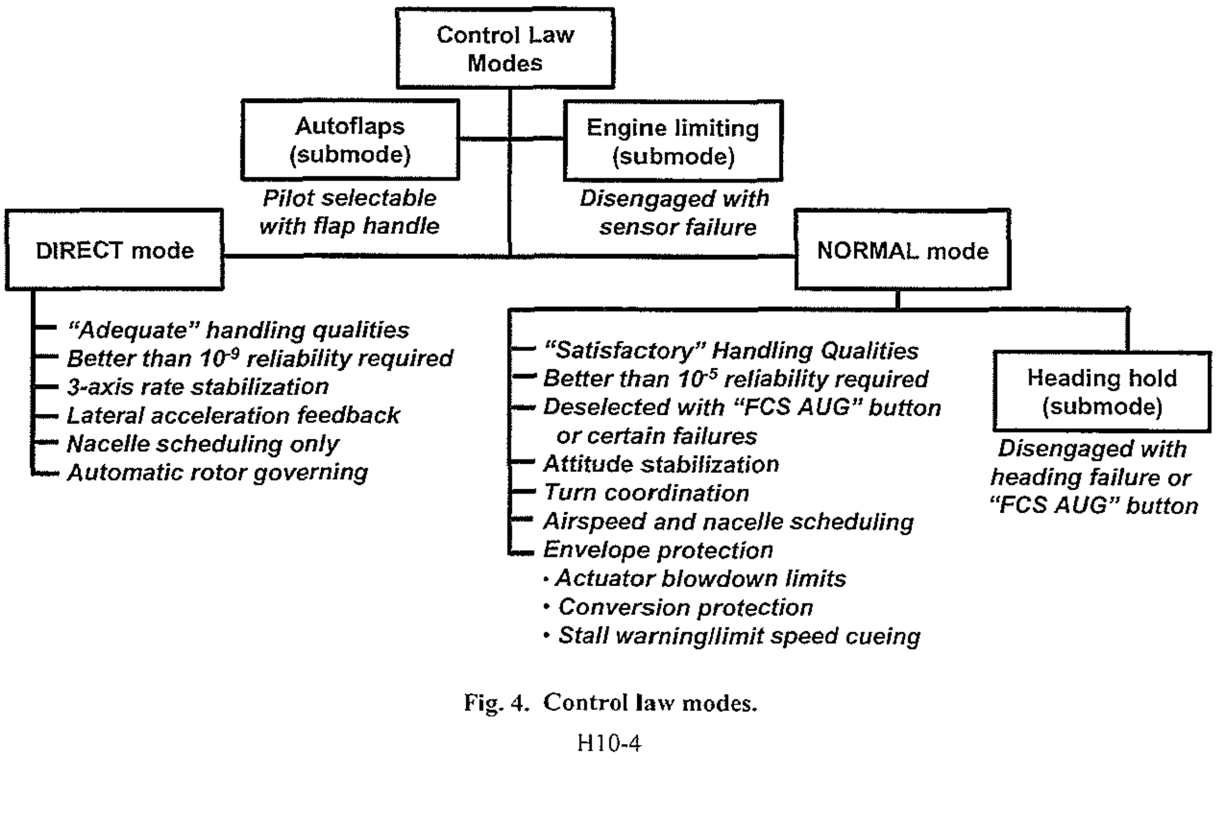

Fig. 4. Control law modes.

such as aircraft stall. The NORMAL mode also provides the capability to couple the flight control system to the aircraft flight guidance system.

Certain dual failure conditions (such as dual airspeed system failure) will automatically engage the DIRECT mode, or it can be manually selected via the FCS Augmentation switch on the overhead panel. The DIRECT mode provides the minimum set of control capabilities consistent with "Adequate" aircraft handling qualities—basic pilot control capabilities in all axes, nacelle tilt control, any required stability augmentation functions, rotor speed governing, trim functions, and engine operation capabilities. This configuration requires a more traditional approach to avoiding certain flight hazards such as aircraft stall, or limit speed exceedence, and pilot workload will increase accordingly.

5. COCKPIT CONTROLS AND DISPLAYS

The cockpit design philosophy for the BA 609 is to allow the pilot to apply conventional control techniques throughout the operational flight envelope and thus simplify the transition from either airplanes or helicopters to tiltrotors. This approach has been proven through flight experience with the conventionally configured cockpit of the XV–15 tiltrotor demonstrator, whose guest pilots from a variety of flying backgrounds have adapted quickly to flying a tiltrotor.

The BA 609 cockpit configuration is shown in Fig. 5. Manual control aspects of the design will be emphasized here. The primary controls—cyclic stick, collective stick, and pedals—are placed in a conventional helicopter arrangement at each crew station. The collective stick operates traditionally in that upward motion increases thrust and power. Cyclic stick travel is the same as for the XV–15, 9.6 inches (24.4 cm) both laterally and longitudinally, as is collective stick travel, 10 inches (25.4 cm). Pedal travel is ±2 inches (±5.1 cm), compared to ±2.5 inches (±6.4 cm) for the XV–15. The flap and landing gear handles are mounted on the front cockpit panel between the crew stations within reach of either crew member. The engine condition levers are mounted on the overhead panel, also within reach of either crew member. The nacelle control switch, unique to tiltrotors, is mounted on the collective stick.

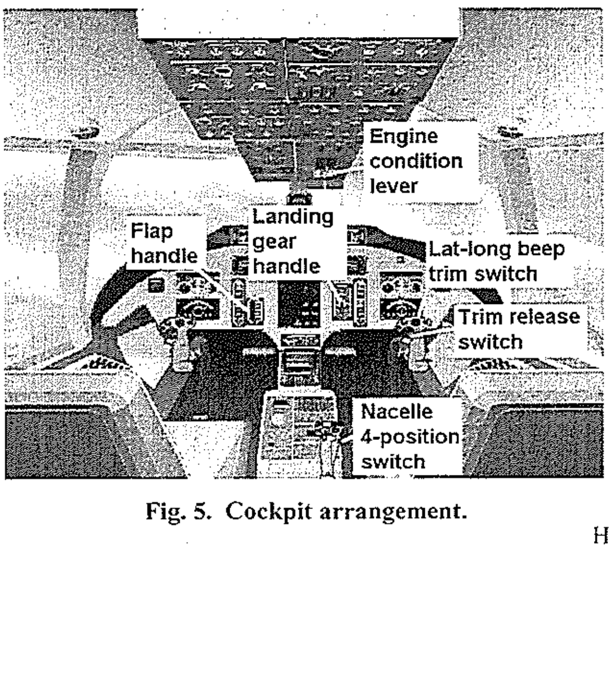

Fig. 5. Cockpit arrangement.

An artificial force feel system for the cyclic stick generates a variable spring gradient to accommodate the low 1.5 to 2.0 lbf/in (263 to 350 N/m) force gradients desired for the helicopter mode and the higher 5 to 7 lbf/in (876 to 1,226 N/m) gradients desired to produce Certification Basis compliant speed and maneuver force gradients in airplane mode. The cyclic stick is backdriven by a cyclic trim actuator during automated flight modes to enable the pilot to monitor system operation and quickly intervene in the event of failure. The backdriven controls also provide a one-to-one correspondence between cockpit control margin and available control surface margin.

The cyclic grip and its controls are shown in Fig. 6. The trim beeper is a standard-shaped four-way switch, spring-loaded to center. It enables the pilot to trim forces off the stick and, in the NORMAL mode, to slew the pitch and roll attitude references of the attitude hold loops. The force trim release button releases all forces on the stick and pedals when it is depressed. In airplane mode, it is programmed to release pedal forces only. When depressed, the autopilot disconnect switch disengages all of the active coupled flight modes controlled by the flight guidance computer.

The collective stick has an automated variable-friction actuator that provides tactile cueing of aircraft power limits to reduce pilot workload during the critical takeoff and landing flight tasks. This is accomplished by programming the actuator to set up friction detents when power limits are encountered. The detents do not prevent the pilot from pulling through them under emergency conditions. A high side friction detent is set to cue the pilot when transmission torque reaches 100%. The pilot can pull through the high side friction detent to tap into emergency power. When the collective is released in an overtorque position, it will backdrive to the 100%

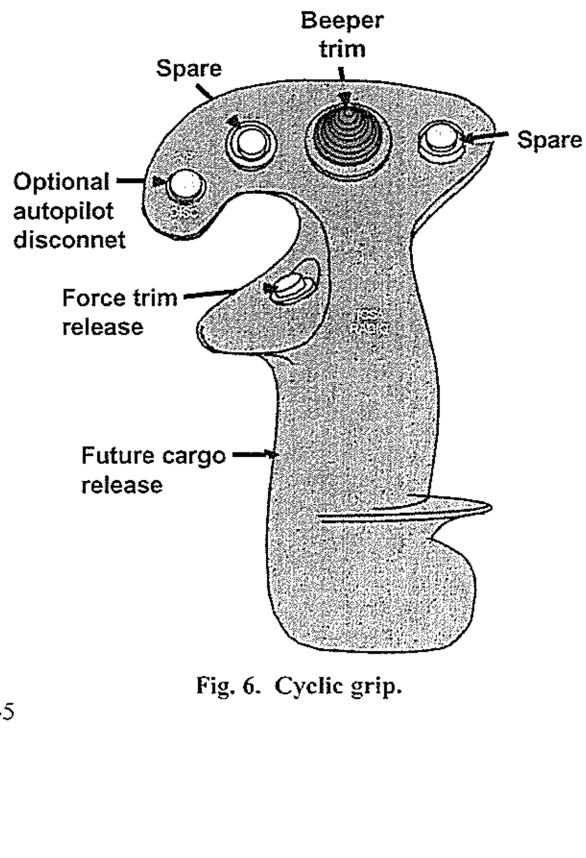

Fig. 6. Cyclic grip.

transmission torque position. The collective backdrive has proven to reduce power management workload substantially.

The collective stick grip is shown in Fig. 7. The nacelle controller is located under the pilot's left thumb. The only switches that require explanation are the OEI limit switch which reduces 30 second OEI power to 2 minute OEI power when it is depressed, and the "Go Around" switch which engages the "Go Around" mode of the coupled flight modes.

The nacelle switch geometry is shown in Fig. 8. It is a four-position switch spring loaded to the second position. Pushing forward to the first position commands the nacelles towards airplane mode. Pulling aft to the third position commands the nacelles towards helicopter mode at normal conversion rates (either 3 or 8 deg/s, depending on nacelle angle). The third and fourth positions are separated by a detent. The fourth position activates the emergency reconversion mode which commands the nacelles towards helicopter mode at the emergency conversion rate of 8 deg/sec. Further discussion of nacelle control and the provisions for keeping the aircraft within the operational conversion corridor (Fig. 9) are given in Section 6.5.

Fig. 10 shows the electronic flight instrument system (EFIS) monitor, centered at each crew station, which provides conventional aircraft displays of vertical speed, altitude, indicated airspeed, pitch ladder, roll angle, heading, and turn ball representation. In addition, it provides tiltrotor-specific displays such as the nacelle display in the upper left corner and an arc on the perimeter of the airspeed display that shifts with nacelle position to indicate the conversion corridor. The airspeed numbers and the indicator needle turn red if conversion corridor limits are exceeded. In addition to the conversion protection provided by the nacelle control laws, this feature aids in reducing the workload of remaining within the operational conversion corridor.

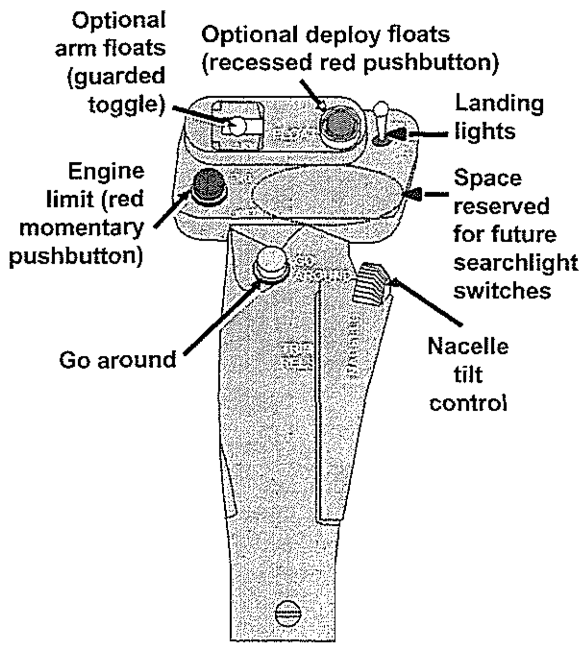

Fig. 7. Collective grip.

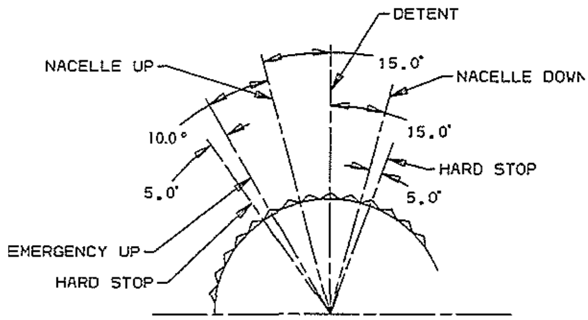

Fig. 8. Nacelle switch schematic.

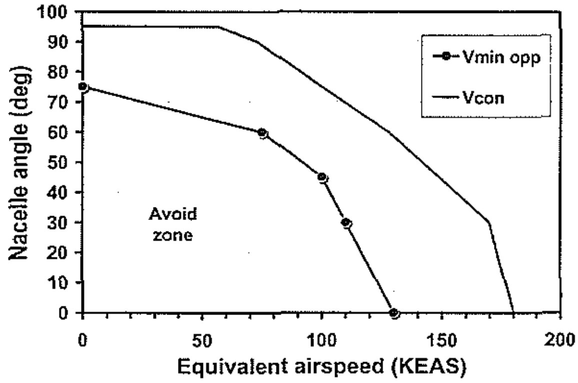

Fig. 9. Operational conversion corridor.

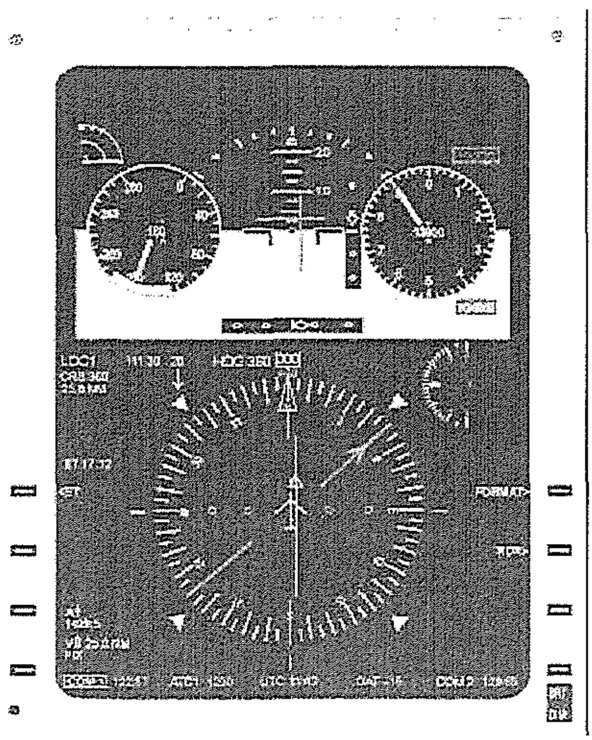

Fig. 10. Electronic flight instrument system monitor.

Fig. 11 shows the engine display monitor, which is centered between the two flight display monitors. It provides status information about engine and drive train operation, i.e., transmission torque, engine torque, measured gas temperature (MGT), rotor rpm, gas generator speed, and oil pressure. The transmission torque display cues the pilot relative to maximum continuous power (90%), the maximum allowed in the normal flight envelope, and takeoff power (100%), which can be used in helicopter mode. Caution, advisory, and warning messages concerning vehicle management system operation are displayed in the lower left of the viewing area.

6. AIRCRAFT CONTROL LAWS

The aircraft control laws functionality is discussed by axis in this section. The attitude hold features of the control laws contribute to a significant workload reduction in performing the precision tasks required by the many aircraft missions. Aircraft maneuverability for tasks requiring less precision and larger motions is maintained at a high level by suppressing the attitude holds when the pilot enters the loop. The turn coordination function eliminates the need for pedal inputs except when uncoordinated flight is desired. In addition to these primary control law functions whose operation is obvious to the pilot, there are others that operate in the background and relieve the workload involved to ensure that aircraft design loads are not approached without degrading handling qualities. Several automated load protection algorithms developed for the V–22 control laws (Refs. 14–17) have been adapted for the BA 609 and are discussed in Section 6.6.

6.1 Pitch Control Laws

A summary of the design features of the pitch control laws is given in Table 2. The primary outputs of the control laws are symmetrical fore/aft cyclic and elevator actuator commands scheduled with nacelle angle and airspeed. Full time (i.e., greater than 10^{-9} reliability) pitch rate stabilization is included. The rate command loop of both NORMAL and DIRECT modes is the same, except

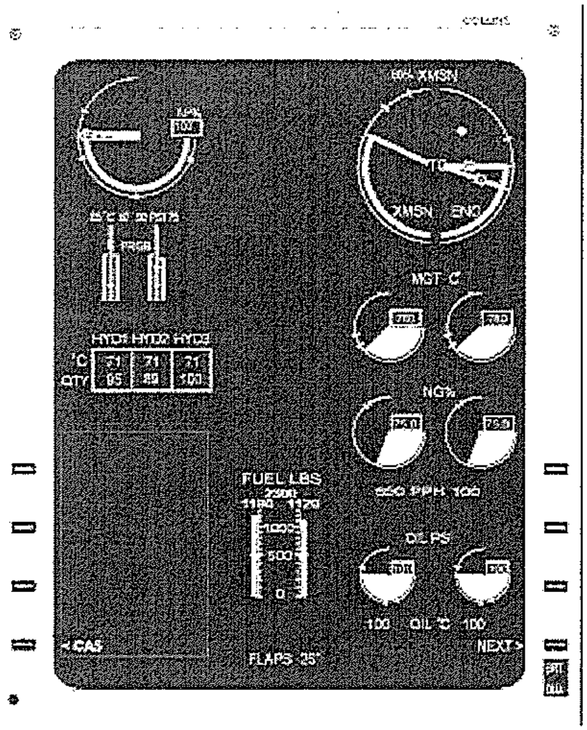

Fig. 11. Engine displays monitor.

that in DIRECT mode, airspeed scheduling is not available. In both modes, the control laws provide a classic pitch rate response when the longitudinal stick is out of the zero force detent (i.e., the pilot is in the loop). In the NORMAL mode, reference pitch attitude is held when the stick is returned to the detent (i.e., the pilot is out of the loop). The reference pitch attitude is set in one of three ways:

1. If the stick is in detent (zero force), the beep trim will slew the pitch attitude reference.
2. If the stick is out of detent and the beep trim is used to reduce forces, the pitch attitude reference is synched to pitch attitude and the reference is reset to the pitch attitude existing when the stick is returned to detent.
3. If the force trim release switch is depressed, the pitch attitude reference is synched to pitch

Table 2. Pitch control laws design summary.

- Common to both the NORMAL and DIRECT modes
  - Classical pitch rate response
  - Pitch rate command model
  - Full time pitch rate stabilization
  - Forward path shaping
  - Generate commands for symmetric fore/aft cyclic and elevator actuators
  - Nacelle-based gain and actuator command scheduling
  - Variable stick force gradient scheduled with nacelle angle
- NORMAL mode only
  - Pitch attitude hold with limited authority (suppressed when stick out of detent, returns to pitch reference when stick returns to detent)
  - Pitch reference set by pilot with beep trim or trim release
  - Nacelle and airspeed-based gain and actuator command scheduling
  - Trim transfer to stick trim actuator when stick in zero force detent (pilot out of loop)

attitude and the reference is reset to the pitch attitude existing when the switch is released.

The NORMAL mode pitch attitude hold loop uses a proportional plus integral structure. When the stick is in detent, the integrator output is transferred to the trim actuator. When the stick is moved out of detent, the pitch attitude loop is suppressed to prevent it from resisting pilot efforts to maneuver the aircraft.

Besides the workload reduction provided by the pitch attitude hold function, the pitch control laws also reduce the workload of flap management by incorporating automatic flap scheduling. Currently the flaps are scheduled with airspeed; they are commanded full down at 66 deg in helicopter mode to reduce download. They are fully retracted at 195 kn (361 km/h) in airplane mode. The schedule was established to maintain reasonably level trim attitudes at the center speed of the conversion corridor. The pilot can override the automatic flap function by selecting one of four manual settings (0, 20, 40, 66 deg) with the flap handle.

6.2 Roll Control Laws

The design features of the roll control laws are summarized in Table 3. The primary outputs of the control laws are differential fore/aft cyclic, DCP, and differential flaperon actuator commands scheduled with nacelle angle and airspeed. As in the pitch control laws, the rate loop providing full time rate stabilization is common to both NORMAL and DIRECT modes, the difference being the absence of airspeed scheduling in DIRECT mode. Both modes provide a classic rate response when the stick is moved out of detent. In NORMAL mode with turn coordination on (airspeed > 50 kn [93 km/h]), when the stick is returned to detent, the attained roll angle is held. A wing leveler feature is provided which changes the roll attitude reference to zero if the reference is less than 2 deg. A reference roll angle can be established also by depressing the force trim release switch and flying to a new roll attitude or using beep trim to slew the reference. Additionally, a heading hold function is activated in NORMAL mode with turn coordination on when roll attitude is less than 2 deg. This automated feature maintains the existing heading by rolling the aircraft. The heading hold is disabled when the stick or pedals are moved out of detent. In NORMAL mode with turn coordination off, the aircraft returns to the trim attitude as defined by the roll attitude reference. Similar to the pitch attitude implementation, the roll attitude loop uses a proportional plus integral structure which transfers the integrator output to the trim actuator when the stick is in detent.

6.3 Yaw Control Laws

The functionality of the yaw control laws, summarized in Table 4, depends on turn coordination status. The primary outputs of the control law are differential fore/aft cyclic and DCP scheduled with nacelle angle and airspeed. As in the pitch and roll control laws, full time rate stabilization is provided. Full time lateral acceleration feedback is provided also when turn coordination is on. In both NORMAL and DIRECT modes, when turn coordination is off, the pedals command a yaw rate response when out of detent. In NORMAL mode, when the pedals are returned to detent, a heading hold function is activated which holds the existing heading by yawing the aircraft. In DIRECT mode, returning the pedals to detent commands a zero yaw rate.

In both modes, when turn coordination is on, the pedals command a lateral acceleration when out of detent to produce an uncoordinated condition. When the pedals are in detent, the directional control laws maintain coordinated flight.

Table 3. Roll control laws design summary.

- Common to both NORMAL and DIRECT modes
  - Classical roll rate response
  - Roll rate command model
  - Full-time roll rate stabilization
  - Forward path shaping
  - Generate differential commands for collective, cyclic, and flaperon actuators
  - Nacelle-based gain and actuator command scheduling
  - Variable stick force gradient scheduled with nacelle angle

- NORMAL mode only
  - Roll attitude hold with limited authority
    - Turn coordination off: suppressed when stick out of detent, returns to roll reference when stick returns to detent
    - Turn coordination on: roll reference synched when stick out of detent, set to attained roll angle when stick returns to detent (i.e., rate command attitude hold implementation) wings leveled if roll reference less than ±2 deg
  - Roll reference set by pilot with beep trim or trim release
  - Heading hold with turn coordination on and roll reference less than ±2 deg
  - Nacelle and airspeed-based gain and actuator command scheduling
  - Trim transfer to stick trim actuator when stick in zero force detent (pilot out of loop)

Table 4. Yaw control laws design summary.

- Common to both NORMAL and DIRECT modes
  - Classical rate response when turn coordination off
  - Lateral acceleration response when turn coordination on
  - Yaw rate command model when turn coordination off
  - Lateral acceleration command model when turn coordination on
  - Full-time yaw rate stabilization
  - Full-time lateral acceleration feedback when turn coordination on
  - Forward path shaping
  - Generate differential commands for cyclic and collective actuators
  - Nacelle-based gain and actuator command scheduling
  - Fixed pedal force gradient
  - Limited capability turn coordination maintains zero lateral acceleration

- NORMAL mode only
  - Heading hold when turn coordination off: rate command heading hold implementation
  - Generate roll angle commands to hold heading when turn coordination on
  - Full capability turn coordination: generates airspeed, roll angle, and pitch-angle-dependent yaw rate and pitch rate commands for yaw and pitch axes
  - Nacelle and airspeed-based gain and actuator command scheduling

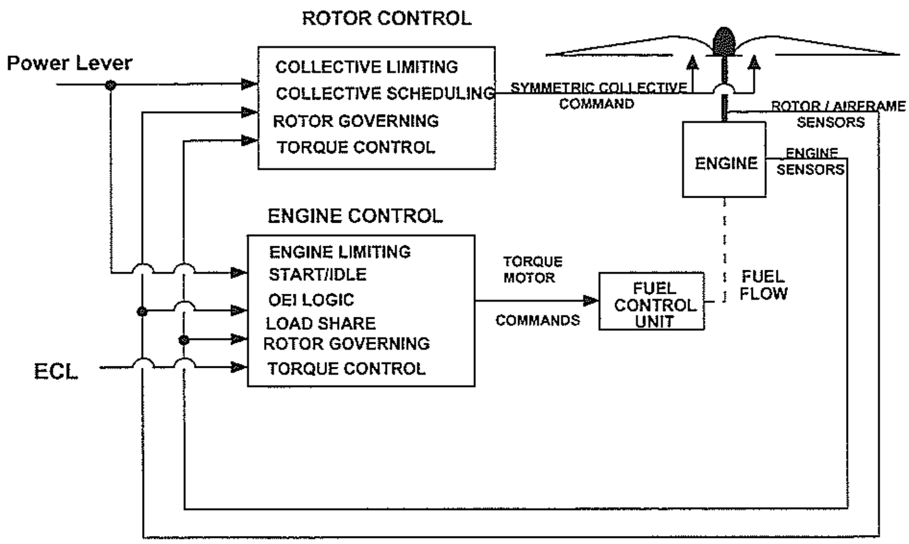

Fig. 12. Torque command regulating system control laws.

The turn coordination function of the directional control law maintains zero lateral acceleration in both NORMAL and DIRECT modes, and additionally, in NORMAL mode, generates yaw rate and pitch rate commands based on roll angle, pitch angle, and airspeed for the yaw and pitch control laws, respectively.

6.4. Torque Command Regulating System (TCRS) Control Laws

The multi-input/multi-output structure of the torque command regulating system control laws is indicated in Fig. 12. The control laws generate commands for the fuel control unit torque motor and rotor collective to maintain commanded torque as set by the collective stick position and to maintain tight control of rotor rpm. Proportional plus integral compensators are used in both the torque motor and collective command paths. Both paths receive inputs from both the rpm and torque command loop errors. The control law gains are set to favor engine control of rpm and collective control of torque in helicopter mode and vice versa in airplane mode. Because of the closed loop on engine control, automatic OEI compensation is inherent to the design in that increased fuel flow to the remaining engine does not depend on the generation of an engine fail discrete. This structure is similar to that in the V–22 control laws (Ref. 18), which has significantly reduced the torque management workload. Coupled with the collective tactile cueing described above, thrust/power management of the BA 609 is a low-workload task.

The BA 609 TCRS control laws are unique in that they incorporate engine control functions that are normally implemented in a separate full authority digital engine control (FADEC) computer. These include MGT limiter, idle governor, torque limiter, and load sharing algorithms. The engine control laws torque motor output command is selected from among the pseudo-FADEC algorithm outputs and the TCRS control laws.

6.5 Nacelle Angle Control Laws

The nacelle angle control laws have two primary functions: providing conversion protection (available only in NORMAL mode) and assisting the pilot to operate the nacelles in the recommended manner. As noted above, the operational conversion corridor limits (Fig. 9) are indicated to the pilot on the airspeed display, but are actively enforced by the conversion protection features of the nacelle angle control laws. As the aircraft is converted to airplane mode, enforcement of the low-speed limit of the corridor is activated. The nacelle angle is not allowed to move in the conversion direction if the airspeed is less than the corridor speed. The normal conversion rate of 3 deg/s is decreased to zero as the lower speed limit of the corridor is reached. On reconverting from airplane mode to helicopter mode, enforcement of the high speed limit of the corridor is activated in a similar manner: nacelles are stopped if airspeed is greater than the corridor speed and the conversion rate is decreased from 3 deg/s to zero as the corridor upper speed limit is reached.

Three detent nacelle angles (75, 60, and 0 deg) and a range of continuous control (75 to 95 deg), where the nacelle angle can be set at liberty, are provided. In the continuous control range, a forward push and hold to the first nacelle switch position will command the nacelles to move towards the 75 deg detent at 8 deg/s. When the switch is released, the nacelles will stop at the attained angle. Conversely, a backward pull and hold to the third switch position will command the nacelles to move towards 95 deg at 8 deg/s. Releasing the switch stops the nacelles at the attained angle.

Once a detent nacelle angle is reached, a momentary forward push to the first switch position will command the nacelles to the next lower detent at a rate of 3 deg/s while a momentary aft pull to the third position will command the nacelles to the next higher detent at 3 deg/s. A momentary push opposite the direction of nacelle movement to either the first or third switch position while the nacelles are moving between detent angles will stop the nacelles at the attained angle. A subsequent push or pull will command them to the next lower or higher detent angle.

A momentary pull to the fourth position activates emergency reconversion, commanding the nacelles to move towards 95 deg at 8 deg/s. If not stopped by a momentary push to the first switch position, the nacelles will continue unabated to 95 deg. Emergency reconversion is intended to move the nacelles as quickly as possible to the preferred angle for autorotation in the event of a dual engine failure.

When the nacelles are full down in airplane mode, an additional momentary push to the first switch position will command rotor rpm to the 84% airplane mode rpm. If this is not done before an airspeed of 200 kn (370 km/h) is reached, it will be done automatically by the control laws. Conversely, if the nacelles are in airplane mode, speed is less than 200 kn (370 km/h), and rotor rpm is at 84%, a momentary aft pull to the third switch position will command the rpm to the 100% conversion mode rpm. The rpm must be at 100% before a reconversion is permitted.

6.6 Aircraft Protection Control Laws

Several load limiting control law algorithms, developed for the V–22 and adapted for the BA 609, are discussed here. These algorithms reduce pilot workload by automatically protecting the aircraft from exceeding load limits.

6.6.1 Control Power Management System (CPMS)

The control power management system (CPMS) combines sensed rotor flapping with sensed fore/aft cyclic to estimate rotor blowback and generates dynamic limits on fore/aft cyclic commands to prevent commanding the rotor into flapping stops. Flapping is sensed by detecting deflection in the blade angle as a function of azimuth angle. CPMS operates on each rotor independently to protect against conditions where large pitch, roll, and/or yaw inputs are made simultaneously, resulting in large cyclic commands. In essence, CPMS maximizes the rotor control power available within the flapping constraints of the rotor.

6.6.2 Aeroservoelastic (ASE) Filtering

As the control laws evolve, aeroservoelastic (ASE) stability analyses are performed periodically to ensure that the control laws provide sufficient gain margin at structural and rotor modes frequencies to ensure that these modes are not excited by normal operation of the FCS (Refs. 15 and 19). Where required, structural notch filters are designed for inclusion in the control laws. Currently, the BA 609 has nacelle angle dependent ASE-designed filters on longitudinal, lateral, and collective stick inputs; roll, pitch, and yaw rate sensors; lateral acceleration sensor; and rpm sensor.

6.6.3 Active Cyclic

Active cyclic (Ref. 16) operates in airplane mode to reduce flapping and blade chord loads. It feeds back pitch rate through a series arrangement of a lag and washout to move fore/aft cyclic aft with positive pitch rate to reduce the sum of flapping rate and pitch rate, which is a major contributor to blade chord loads.

7. HANDLING QUALITIES EVALUATIONS

Piloted simulation evaluations have been, and will continue to be, a primary tool to evaluate the handling qualities achieved with the evolving BA 609 control laws.

These evaluations encompass precision flight tasks and large-amplitude maneuvers (Table 5) in the presence of failure modes and winds and turbulence throughout the flight envelope. Though formal pilot ratings have not always been solicited, all pilot commentary is noted and applied to evolve the control law functions and structures. At this time, the NORMAL mode handling qualities for the limited envelope used in control law development have been assessed as "Satisfactory" and the control law structure has been frozen for initial flight testing and FCS bench testing. DIRECT mode handling qualities have not been fully evaluated. Between now and first flight, the control laws will be evaluated throughout the flight and loading envelope to establish a predicted certification data base and identify problem areas that may require additional attention.

8. CONCLUDING REMARKS

Handling qualities requirements and objectives for the BA 609 have culminated in an FCS design that maintains conventional helicopter and airplane piloting techniques to ease the transition from either aircraft type to a tiltrotor. This objective is achieved by incorporating a simple control mode structure, full-time stability augmentation, automated aircraft envelope protection, and cockpit enhancements such as tactile cueing of power limits. The unique tiltrotor tasks of conversion and reconversion have been simplified greatly by conversion protection control laws, specialized cockpit displays, and automated nacelle control. The triplex fly-by-wire FCS design satisfies all handling qualities imposed requirements, facilitates the process of tailoring control laws to achieve desired handling qualities, and ensures safe operation in the event of failures.

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Table 5. BA 609 mission tasks used in handling qualities development.

Hover tasks	Conversion tasks	Airplane tasks
1. IGE precision hover	1. Pitch angle capture	1. Stalls and recoveries
2. OGE precision hover	2. Roll angle capture	2. *G* captures
3. Vertical reposition	3. Maneuver stability	3. Roll angle captures
4. Vertical landing/takeoff	4. Speed stability	4. Maneuver stability
5. Lateral reposition	5. Steady heading sideslip	5. Speed stability
6. Longitudinal reposition	6. Level reconversion/landing	6. Steady heading sideslip
7. Pedal turn	7. Approach to landing	7. Establish constant speed climb/descent
	8. Departure from hover	
	9. STOL landing/takeoff	
	10. Establish constant speed climb/descent	
	11. ILS tracking	

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