

UH-60M Upgrade Fly-By-Wire Flight Control Risk Reduction using the RASCAL JUH-60A In-Flight Simulator

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Abstract

The U.S. Army Aeroflightdynamics Directorate (AFDD), Sikorsky Aircraft Corporation (SAC), and the U.S. Army Utility Helicopter Program Office (UHPO) have completed rapid risk reduction development for the UH-60M Upgrade fly-by-wire flight control system using the RASCAL JUH-60A In-Flight Simulator and AFDD advanced flight control development tools. Analytic preparations included the development and validation of advanced dynamic models of the UH-60A and UH-60M flight mechanics, and optimization of the UH-60M Upgrade control laws with these models. The RASCAL aircraft was extensively modified to host key hardware and software elements of the UH-60M Upgrade flight control system, including prototype active cyclic and collective inceptors. The first flight of the system occurred on December 22, 2006, approximately one year after the UH-60M Upgrade System Requirements Review, and 15 months before the first prototype of the UH-60M Upgrade is scheduled to fly. Since that time, the control laws have been extensively matured on RASCAL during approximately 100 hours of flight test development; and significant improvements in handling qualities have been demonstrated relative to the UH-60A/L baseline. The RASCAL system and AFDD rapid flight control prototyping tools enabled quick implementation of the pre-production control laws in the world's only full authority fly-by-wire Black Hawk and the rapid evolution of the control laws in a fail-safe flight environment. This was accomplished early in the overall development of the UH-60M Upgrade, effectively reducing technical, programmatic, and flight safety risk for the program.

Nomenclature

AACVH	Attitude/Acceleration Command, Velocity Hold	HQR	Handling Qualities Rating
ACAH	Attitude Command, Attitude Hold	HRDH	Heading Rate Command, Direction Hold
AIS	Active Inceptor System	HWIL	Hardware In the Loop
ARCAH	Attitude/Rate Command, Attitude Hold	ICM	Inceptor Control Module
CAAS	Common Architecture Avionics System	IMU	Inertial Measurement Unit
CLAWS	Control Laws	INU	Inertial Navigation Unit
DF	Development Facility	IOP	Input Output Processor
DVE	Degraded Visual Environment	LVDT	Linear Variable Differential Transducer
EGI	Embedded GPS/INS	MTE	Mission Task Element
EP	Evaluation Pilot	MUCLAWS	UH-60M Upgrade Control Laws
FBW	Fly By Wire	NVG	Night Vision Goggles
FCC	Flight Control Computer	RASCAL	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
FCS	Flight Control System	RFCCA	Research Flight Control Computer Assembly
FDDCP	Flight Director Display Control Panel	RFCS	Research Flight Control System
GVE	Good Visual Environment	RVDT	Rotary Variable Differential Transducer
		SCU	Servo Control Unit
		SP	Safety Pilot
		UCE	Usable Cue Environment
		ϕ, θ, ψ	Aircraft Attitude Euler Angles, rad
		τ_p	Phase Delay, sec
		ω_{BW}	Bandwidth, rad/sec

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Introduction

UH-60M Upgrade Program

Sikorsky Aircraft is developing an upgrade to the UH-60M Black Hawk helicopter for the U.S. Army. A key element of the UH-60M Upgrade Program is the incorporation of a full-authority fly-by-wire (FBW) flight control system (FCS) into the UH-60M airframe, including advanced, multi-mode flight control laws (CLAWS), active cyclic and collective sticks, and integration with the Common Avionics Architecture System (CAAS). As shown in Figure 1, all existing mechanical control system components upstream of the primary servos will be replaced by the FBW FCS system. In addition, the primary servos, hydraulic system, and electrical system will be upgraded for performance and reliability. The UH-60M Upgrade FBW FCS will be implemented in a “triple-dual” architecture consisting of identical dual hardware and software channels within each of the three Flight Control Computers (FCC). The pilot control interface for the FBW FCS consists of electronically synchronized, active cyclic and collective enable the use of tactile cueing to provide control mode feedback to the flight crew. For forward flight, the UH-60M Upgrade implements fully coupled flight director functions integrated with the CAAS flight management functions for those functions not integrated into the basic control laws of the aircraft.

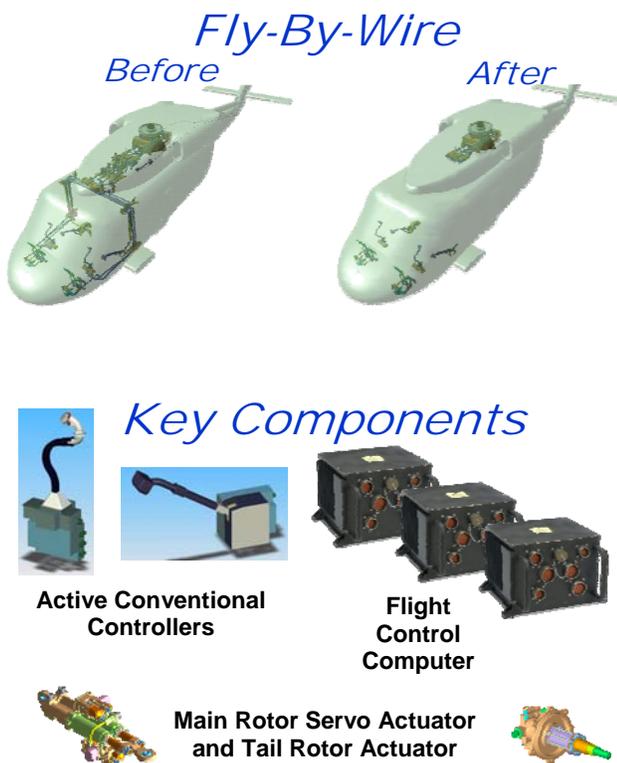


Figure 1. Key Features of the UH-60M Upgrade Fly-By-Wire Flight Control System

A key design goal for the UH-60M Upgrade FCS is to provide control laws which will enable Level 1 handling qualities at low speed and in degraded visual environments, without compromising the maneuverability

of the aircraft throughout the remainder of the mission environment. Sikorsky has translated this requirement into a set of multi-mode, attitude command control laws with functions such as low-speed and high-speed turn coordination, and automatic altitude, flight-path, hover, heading, velocity, and position hold modes. Automatic modification of control law response types and modes is handled using regime recognition and task tailoring with the aid of aircraft sensors and pilot vehicle interfaces, similar to the approach taken by the HACT FCS design [Ref. 1]. The system provides transitions between control modes based on aircraft state and pilot input without the need for the pilot to release the controls to select these modes. The active cyclic and collective enable the use of tactile cueing to provide control mode feedback to the flight crew. For forward flight, the UH-60M Upgrade implements fully coupled flight director functions integrated with the CAAS flight management functions for those functions not integrated into the basic control laws of the aircraft.

AFDD/RASCAL Risk Reduction

In order to reduce development risk for the UH-60MU, the Utility Helicopter Project Office (UHPO) sought to leverage the extensive rotorcraft flight control and handling qualities capabilities developed by AFDD over the past 20 years as part of the Army Science and Technology (S&T) development process. Through application to various research and development programs, AFDD has evolved these capabilities into the cohesive flight control rapid prototyping process shown in Figure 2. The RASCAL fly-by-wire JUH-60 [Ref. 2], shown in Figure 3, is a cornerstone of this process, enabling rapid prototype system implementation in a fail-safe flight test environment, and timely feedback into the system design from engineering measurements, pilot comments and handling qualities ratings.

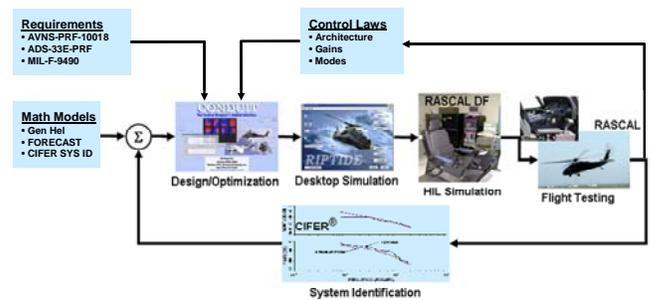


Figure 2. AFDD Flight Control Rapid Prototyping Process

Although many military aviation programs have recently adopted ADS-33E [Ref. 3] as a design standard for flight control evaluations during flight test, the UHPO also required, as part of the UH-60M Upgrade statement of work, the use of this comprehensive flight control rapid-prototyping process throughout the design and flight test process to reduce flight control law development time and reduce schedule risk. To facilitate this, UHPO entered a memorandum of agreement (MOA) with AFDD to

conduct early flight control analysis, modeling, and flight test development of the UH-60MU FBW control laws, developed by Sikorsky Aircraft, using AFDD advanced flight control development tools and the RASCAL JUH-60 in-flight simulator.



Figure 3. The RASCAL JUH-60A In-Flight Simulator

Over the course of the program, significant efforts were expended in each of the areas represented in the diagram of Figure 2. Early analytical preparations focused on updating and validating flight mechanics models for use in control law design, analysis, and simulation. The modeling effort included both the UH-60A and UH-60M aircraft, to support not only the analysis and optimization of the control laws on the RASCAL (JUH-60A) aircraft, but also to ensure successful migration of the RASCAL results to the UH-60M airframe.

Sikorsky began development of the UH-60M Upgrade control laws (MUCLAWS) in late 2005, and during the following 18 months, made six major and 11 minor incremental CLAW software drops to AFDD. Together with validated flight mechanics models, the CONDUIT[®] flight control analysis and optimization tool [Ref. 4] was used to guide control law development and optimize the performance of the control laws relative to flight control and handling qualities specifications. This process was applied iteratively throughout the program: before first flight as early CLAW drops were developed, during initial flight testing as MUCLAW integration with RASCAL was verified, and throughout flight test development as the CLAWS were updated based on flight test data and pilot comments.

The RASCAL JUH-60 aircraft was modified to host key elements of the UH-60M Upgrade FCS, including a prototype active inceptor system (AIS), a Honeywell H-764G Embedded GPS/INS (EGI), emulations of the CAAS primary flight displays, and the UH-60MU control laws. These modifications were also made to the RASCAL HWIL Development Facility (DF) to ensure the most effective use of the DF during system integration and development. Modifications were also made to the AFDD ADS-33 flight test course at Moffett Field, CA to support flight test development, including construction of a new hover tower.

A three-phase flight test approach was adopted for development and initial evaluation of the UH-60MU FCS on RASCAL. Phase 0 consisted of approximately 10 hours of flight time in which system integration was verified in the hover and low-speed flight regimes and analysis tools were validated. Phase 1 consisted of approximately 40 hours of flight time in which the control laws were iteratively developed following the process of Figure 2. The flight test envelope was expanded in this phase from 40 to 100 KIAS forward flight, and issues were addressed as they were discovered as the test team systematically explored the modes, mode transitions and flight regimes. Phase 2 was a first look at evaluating the handling qualities of the optimized system against quantitative handling qualities criteria and five Mission Task Elements (MTEs) from ADS-33E-PRF. Two Sikorsky pilots and three Army pilots evaluated the system during this phase. Four of the five pilots also flew the MTEs in a simulated Degraded Visual Environment (DVE) using specially modified Night Vision Goggles (NVG) to simulate a usable cue environment (UCE) of Level 2.

The objectives of this paper are:

1. To illustrate the application of the AFDD flight control rapid prototyping process, including the RASCAL flying laboratory, to the rapid development of advanced flight control and cockpit interface technologies of the UH-60M Upgrade FBW FCS.
2. To highlight key steps and technical details which are critical to the successful application of the rapid prototyping process for flight control development.
3. To provide initial quantification of the UH-60MU FCS performance and demonstrate the value of the UH-60MU RASCAL development in terms of improvements in handling qualities ratings relative to the UH-60A/L baseline.
4. To provide lessons learned from the RASCAL UH-60MU development that will be useful to future rotorcraft flight control development efforts.

These objectives will be met through the discussions in the remaining sections of the paper which roughly follow the processes shown in Figure 2. First, the key elements of the UH-60M Upgrade FBW FCS under development on RASCAL will be presented, followed by a description of the salient features of the RASCAL JUH-60A flying laboratory. The analytic development of the UH-60MU CLAWS will then be presented; including the development and validation of math models required for control law analysis and optimization, and the control law optimization process. The UH-60MU flight control test development process on RASCAL will then be described, focusing on some key areas of development, control law optimization results, and lessons learned. Finally, the results of the limited-scope handling qualities assessment will be presented and correlations between handling

qualities ratings (HQR), predicted handling qualities parameters, and analytical results will be discussed.

UH-60M Upgrade Flight Control System

Requirements and Design Goals

The UH60M Upgrade Fly-By-Wire control system was designed to significantly improve the following aircraft characteristics: system weight, handling qualities, system reliability, and maintenance time. This paper focuses on the handling qualities aspects of the system. The top level handling qualities requirement for the system is ADS-33E-PRF. This specification, coupled with inputs from the piloting community provided a basis for the design of the flight control system modes and response types. In order to further reduce pilot workload, the system was designed to automatically select basic flight control modes and appropriate response type. The mode selection scheme was divided into two distinct categories. The first category is for basic response type and mode selection and is called “automoding”. The second category, “task-tailoring,” is reserved for future expansion of the system. It is envisioned that task-tailoring algorithms will adapt the control system to specific aircraft configuration changes and distinct piloting tasks (such as air-to-air refueling). Extensive simulation work prior to risk reduction on RASCAL further refined the basic system modes and “automoding” algorithms.

Pilot Vehicle Interface

The primary pilot vehicle interface consists of unique-trim¹ pedals, unique-trim cyclic and displacement collective inceptors. The cyclic and collective inceptors include high bandwidth, variable force feel systems. The flight control system, via the variable force-feel system, provides several important cues to the pilot regarding aircraft state, flight control mode and control limits. Use of a high bandwidth force-feel system also allows electronic linking between pilot and copilot inceptors. The secondary pilot vehicle interface consists of cyclic and collective beepers, station deselect/reselect buttons and a flight director display control panel (FDDCP².) The functionality of cyclic and collective beepers varies with flight control mode, but in general they are used to allow precision control over currently held aircraft state.

Control Law Architecture

The UH-60M Upgrade control laws are executed in an explicit model following architecture, similar to that employed in the RASCAL system [Ref. 5] shown in Figure 4. The goal of the model-following control system is to make the aircraft respond to pilot commands following the dynamics of a simple low-order command model. To achieve this, the actual aircraft dynamics are partially cancelled with an approximate inverse of the aircraft dynamics in the forward loop. Since this

¹ The center of travel of the inceptor, or neutral position, always corresponds to the aircraft trim state.

² The FDDCP was not implemented on RASCAL

cancellation is not perfect, the error between the actual aircraft response and the command model response is also used to provide corrective feedback commands. The command model is delayed in the feedback path to compensate for un-modeled dynamics in the inverse plant.

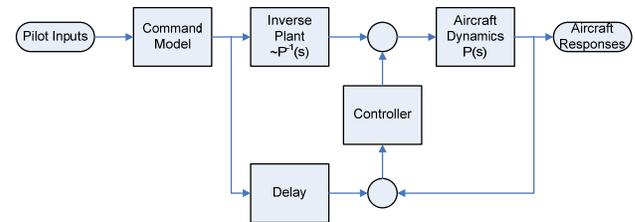


Figure 4. Model Following CLAW Architecture

UH-60M Upgrade Control Law Modes

Figure 5 summarizes the major UH-60MU FBW control modes and serves as a reference for the following functional description of the MUCLAWS.

Airspeed/Ground Speed Blending It has become a common practice in advanced rotorcraft flight control to switch flight control mode based on airspeed and/or ground speed. For this system, with many intermediate modes, it proved very challenging to consistently switch modes based on airspeed and ground speed in the presence of winds. The solution was to derive a blended speed. The speed blending algorithm blends air speed, ground speed and body acceleration to derive one speed value upon which all mode switching is based. Blended speed is also displayed to the pilot on the primary flight display.

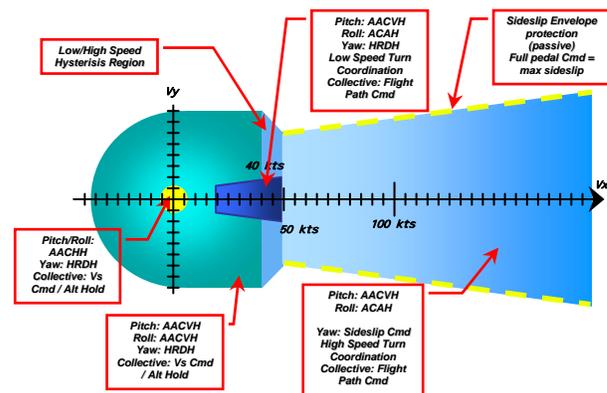


Figure 5. UH-60M Upgrade Fly-By-Wire Control Law Modes

Hover and Near Hover (<5 kts blended speed) In this portion of the envelope an attitude command/hover hold response type is provided in the pitch and roll axes. In this mode, displacement of the cyclic inceptor from center (in each axis) produces a change in attitude proportional to the amount of the inceptor displacement. When the pilot returns the cyclic to center, the aircraft decelerates to back to zero velocity in the corresponding axis. When the aircraft has attained a stable hover, the system acquires a new position reference and engages position hold.

A heading rate command/heading hold response type is provided in the yaw axis. In this mode, displacement of the pedals from the center position results in a heading rate that is proportional to the amount of pedal displacement. When the pedals are returned to the center position, the system arrests the yaw rate, acquires a new heading reference, and engages heading hold.

A vertical speed command/altitude hold response type is provided in the collective axis. In this mode, if no force is applied to the collective, radar altitude hold is engaged. Applying force to the collective results in a vertical speed proportional to the direction and amount of force applied. It should be noted that even though the collective is a displacement inceptor, in this mode the primary command is via force, but the collective pitch is still maintained via displacement. To synchronize force and displacement, the collective is back-driven to maintain a constant rate of climb/descent and the collective back-drive is adjusted to maintain constant force.

Low Speed (5 kts - 50 kts blended speed) At low speed an attitude and acceleration command/velocity hold response type is provided in the pitch and roll axes. In this mode, displacement of the cyclic inceptor from the center position (in each axis) results in an attitude change proportional to the displacement of the inceptor. When the pilot returns the cyclic to the center, a new velocity reference is acquired and velocity hold is engaged (per axes basis). If the pilot continues to hold the cyclic away from the center position, the response type slowly blends to acceleration command, and the aircraft acceleration (magnitude and direction) becomes proportional to inceptor displacement. There are several other sub-modes that modify the roll response type as described below.

The yaw axis has two sub-modes in this portion of the envelope. Below 20 kts, heading rate command/heading hold is provided. In this sub-mode, a transform is applied to current velocity references such that a constant velocity vector is maintained regardless of heading (if the cyclic inceptor remains centered). Above 20 kts, low-speed turn coordination becomes active (if the pedals remain centered). In this sub-mode, the roll response type is modified to be attitude command/zero inertial side-slip hold. Displacement of the lateral cyclic away from center results in an attitude change that is proportional to the amount of cyclic displacement. At the same time heading rate command is produced such that inertial side slip remains at zero. The yaw axis response type in this sub-mode is modified to be inertial side slip command/zero inertial side-slip hold. Displacement of the pedals from center position results in a change in side-slip proportional to the amount of pedal displacement. If the commanded aircraft side-slip exceeds a predetermined threshold, the low speed turn coordination sub-mode is shut off, and the system reverts to heading rate

command/heading hold mode. This allows the aircraft to be trimmed at non-zero side slip angles.

In this flight regime, a displacement collective command with multiple hold modes is provided in the vertical axis. In this mode, the variable force-feel system is used extensively to provide several important cues to the pilot. At all times a tactile cue for level flight is provided. Placing the collective inceptor in this detent automatically engages altitude hold. Once in the level flight detent, a vertical speed command/altitude hold response type is active. This response type is identical to the vertical speed command/altitude hold described above for the near hover regime. Moving the collective out of the level flight detent results in a conventional change of the collective pitch. Once the collective is stationary, outside of the level flight detent, a flight path angle reference is acquired and flight path hold algorithm is engaged. A flight path detent is also set, and the collective is back-driven as necessary as the system holds the reference flight path angle.

Forward Flight (>50kts blended speed) In forward Flight, an attitude command and acceleration command/velocity hold response type is provided in the pitch axis. This response type is identical to the one described above. A classical attitude command/attitude hold response type is provided in the roll axis. In this mode, displacement of roll cyclic from center results in attitude change that is proportional to the amount of cyclic displacement. Returning the cyclic to center results in a wings-level attitude.

The collective axis behavior is the same as the low speed mode. In forward flight, with pedals centered, high speed turn coordination is provided in the yaw axis. In this mode, when the pilot commands any angle of bank, yaw and pitch rate is generated such that lateral acceleration is kept at zero. Displacement of the pedals away from center results in side-slip that is proportional to the amount of pedal displacement. A passive side-slip envelope protection is also provided which limits commanded side-slip as a function of blended speed. Due to the use of estimated side-slip, the pilot still has responsibility of monitoring aircraft side-slip and not exceeding the side-slip envelope.

Direct Mode In case of multiple failures of sensors needed for full augmentation, a backup control mode is provided – direct mode. In this mode displacements of the inceptors command rotor cyclic and collective pitch directly. If the system is able to use rate sensors, rate augmentation is also provided. However the authority of rate augmentation is limited to 10% of the control range. A manual direct mode engage switch is provided in the cockpit to accommodate multiple failures in the weight-on-wheels sensors.

RASCAL JUH-60

System Description

The Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) is a modified JUH-60A Black Hawk helicopter developed by the US Army Aeroflightdynamics Directorate, NASA Ames Research Center and Boeing Helicopters [Ref 5]. The RASCAL facility has been in operation, in various research and development phases, since 1989. Now operated by AFDD as a fully qualified flight research facility, RASCAL features a full-authority fly-by-wire (FBW) flight control system, known as the Research Flight Control System (RFCS). The RASCAL system provides an easily reconfigurable, fully-programmable capability to investigate a wide range of flight control, cockpit display, and crew systems concepts, including integration of mission equipment.

RASCAL Architecture

A key feature of the RASCAL system is its fail-safe design, which maintains the mechanical controls and SAS of the UH-60A as a backup control system, as shown in Figure 6. When the RFCS is engaged, an evaluation pilot (EP) in the right seat flies the fly-by-wire research system while a safety pilot (SP) in the left seat monitors the back-driven mechanical controls. Control of the aircraft is transferred to the evaluation pilot by pressurizing the research servos and simultaneously depressurizing the JUH-60A pilot-assist servos and releasing the trim actuators. The safety pilot is pilot-in-command, and the evaluation pilot arms and engages the system at the direction of the SP. The system can be manually disengaged by either pilot or automatically disengaged by fault monitors in the Servo Control Unit (SCU). Upon disengagement of the RFCS, control is transferred back to the safety pilot by de-pressurizing the research servos and reactivating the pilot-assist servos and trim actuators. Flight safety is maintained through operational procedures (including envelope limits), system monitoring by the SP, a dual-redundant automatic safety monitoring system in the dual-channel SCU, and a highly reliable, analog electronic control transfer system.

Research Flight Control System

The heart of the RFCS is the Research Flight Control Computer Assembly (RFCCA). As shown in Figure 7, the RFCCA houses the single-thread Flight Control Computer (FCC) and the dual-channel SCU. The 32-bit FCC is equipped with a high performance (6MFLOPS/24MIPS) control law processor and four input-output processors to provide extensive analog, discrete, and digital I/O. The single-thread architecture of the FCC facilitates the programming flexibility required for flight control rapid prototyping and flight research applications.

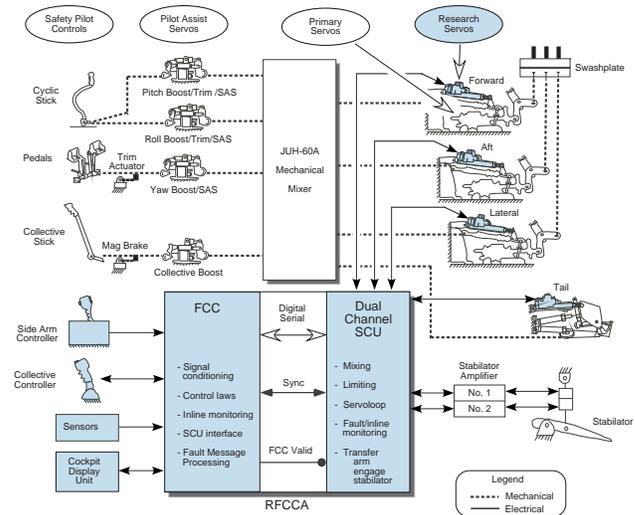


Figure 6. RASCAL System Architecture

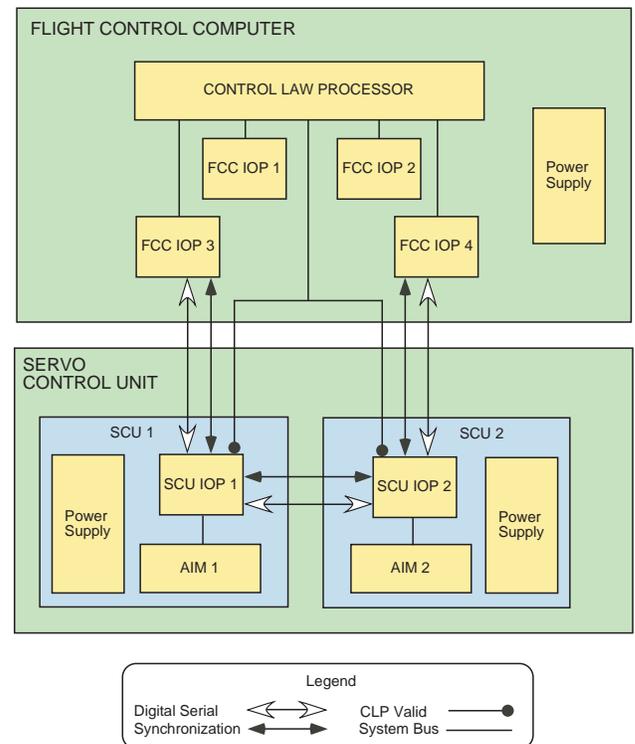


Figure 7. RASCAL Research Flight Control Computer Assembly

The SCU receives commands from the FCC, translates these into research servo commands, and provides closed-loop control and monitoring of the research servos. The SCU also includes an array of software safety monitors which check the validity of the commands from the FCC, monitor the responses of the servos, and disengage the system if predetermined thresholds are exceeded. The SCU is physically partitioned into two channels, and cross-channel comparisons are executed via a high-speed digital data link. The dual-channel architecture of the SCU and the relative stability of the SCU software are important factors in maintaining a high level of system safety with the single-thread research FCC architecture.

The RASCAL RFCS was designed to be versatile and accommodating of a wide range of control law applications. Autocoding tools such as Simulink[®] Real-Time Workshop[®] and Embedded Coder[™] have greatly simplified the task of creating C source code from block diagrams and state transition diagrams. Now the task of integrating new control laws primarily involves modification of the software interface between the system software and the control law application software. This interface consists primarily of state sensor feedback, pilot inceptor positions, and signal processing for these signals. For the UH-60M Upgrade program the interface was expanded to include communication with new active inceptors and a new EGI.

RASCAL Modifications for UH-60M Upgrade

The RASCAL JUH-60A was modified to closely emulate several key elements of the UH-60M Upgrade FCS. These modifications included the integration of active cyclic and collective inceptors and fly-by-wire pedals in the RASCAL cockpit, integration of a Honeywell H-764G EGI with the RASCAL avionics, and integration of emulated CAAS display pages in the RASCAL pilot display system. The aircraft was also outfitted with a modular ballast system to more closely emulate the primary gross mission weight of the UH-60M. The discussion here will focus on the modification of the evaluation pilot's inceptors.

The most significant modification to the RASCAL system was the integration of a prototype Active Inceptor System (AIS) on the aircraft. The AIS provides a high-bandwidth electro-mechanical force-feel system for the evaluation pilot cyclic and collective controllers. The cyclic stick has a standard, long-pole, center stick configuration; and the collective maintains the standard UH-60 mechanical configuration. Grip positions are identical to the UH-60A-M, and UH-60M grips and grip switches were fitted to the RASCAL AIS sticks.

The key elements of the RASCAL AIS system are shown in Figure 8, including the cyclic and collective motor drive units and the inceptor control module (ICM). The ICM is the system controller and communicates directly with the motor drive units to close the stick force-feel control loops. The ICM is under the supervisory control of the RASCAL FCC, from which it receives force-feel characteristic commands, and provides status information back to the FCC via the 1553 bus. Stick position commands are sensed by RVDTs in the motor drive units and communicated directly to the RASCAL FCC.

The RASCAL AIS is based on a Sterling Dynamics design, and was modified specifically for the RASCAL UH-60M Upgrade program by BAE Systems in Rochester UK. The system has been ruggedized for the helicopter flight environment, adapted to interface with the 1553 bus, and upgraded for reliability with triplex redundant RVDTs. This development path enabled emulation of the

production UH-60M Upgrade active sticks on RASCAL while the production sticks were still in early development.

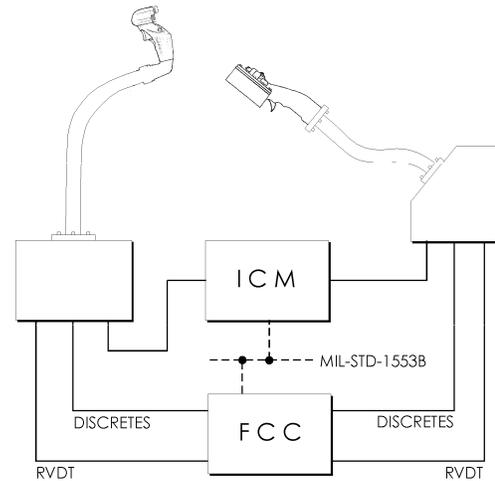


Figure 8. The RASCAL Active Inceptor System

As RASCAL was previously equipped with a three-axis side-arm controller, it was necessary to develop a new set of fly-by-wire pedals for this project. An additional requirement was to provide adjustable force-feel characteristics for the pedals so that a range of potential design characteristics for the UH-60MU could be evaluated in flight. Since the placement and geometry of the production UH-60MU pedals is similar to those in the UH-60A-M, the JUH-60A pedals themselves and part of the mechanism were retained in the new RASCAL design. As shown in Figure 9, the mechanism downstream of the pedal pivot point was modified and an adjustable spring cartridge and adjustable damper were added to meet these requirements. A triplex LVDT provides high-integrity measurements of pedal displacement to the RASCAL FCC.

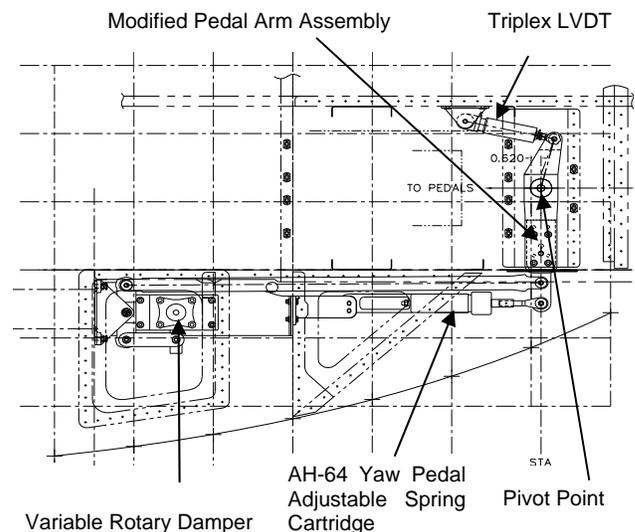


Figure 9. RASCAL FBW pedal force-feel mechanism

Flight Control Analytic Tools and Validation

Math Model Development and Validation

A significant effort was focused on the development and validation of accurate math models of the UH-60A and UH-60M aircraft for use in control law optimization, desktop simulation, and real-time piloted simulation. The importance of accurate models throughout the development process cannot be stressed enough, as this plays a central role in the accuracy of all analytic preparations before flight test, as well as analysis that guides development during flight test. Models can continue to be updated and refined as additional flight test data becomes available, but much can be accomplished ahead of first flight, particularly when the airframe is already flying with a legacy control system. Not only may flight safety be significantly improved, but analysis efforts can be accomplished much more efficiently if good models are available early in the FCS development process.

As part of the RASCAL-focused rapid prototyping process of Figure 2, AFDD has developed a suite of math modeling tools focused on the UH-60A aircraft, including full-flight envelope nonlinear simulation models, analytic high order-linear models, and system identification models. The foundation of this suite is the Ames Gen Hel simulation model [Ref. 6], which is based on the Sikorsky Gen Hel simulation model of the UH-60A [Ref. 7]. Ames Gen Hel is used for real-time simulation as part of the RIPTIDE simulation environment [Ref. 8] in the RASCAL DF and for desktop engineering simulation.

Another important tool is the FORECAST simulation model [Ref. 9], a restructured version of Ames Gen Hel developed jointly with the University of Maryland, which was used to produce high-order linear point design models for use in control law design and analysis. Both Ames Gen Hel and FORECAST have been extensively validated against flight test data, and were ready at the outset of the project for use in the development of the MUCLAWS on the RASCAL JUH-60A.

A sampling of the fidelity of the UH-60A version of Ames Gen Hel and FORECAST is shown the frequency domain comparisons with flight test data in Figure 10 and Figure 11. In Figure 10, the pitch rate to longitudinal cyclic frequency responses from Ames Gen Hel and FORECAST are shown to agree very well with flight test data from less than 1 rad/sec to more than 2 Hz. The accuracy of the models is somewhat degraded above 2 Hz due to deficiencies in modeling the main rotor lead-lag degree of freedom. This characteristic has been described by Curtiss in flight mechanics models of several articulated rotor aircraft, including the UH-60, CH-53, and AH-64 [Ref. 10].

In contrast to the pitch axis, Figure 11 shows that there are more significant discrepancies between Ames Gen Hel, FORECAST, and flight data in the yaw rate response

to pedals. The sources of the mismatches are currently under investigation, but the discrepancy was noted during control law optimization as a potential source of error in the analysis. In this case, the FORECAST model has more phase lag above the crossover frequency, making it conservative for the estimation of phase margins.

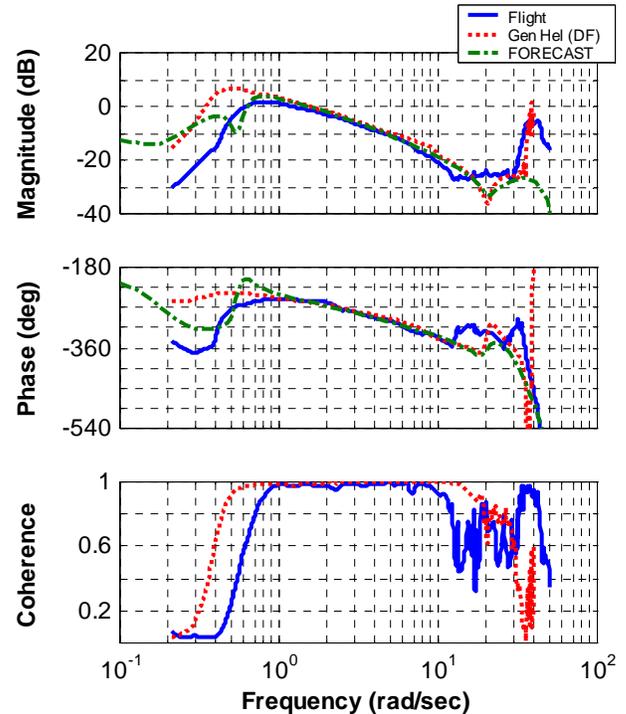


Figure 10. Pitch axis modeling fidelity of Ames Gen Hel and FORECAST

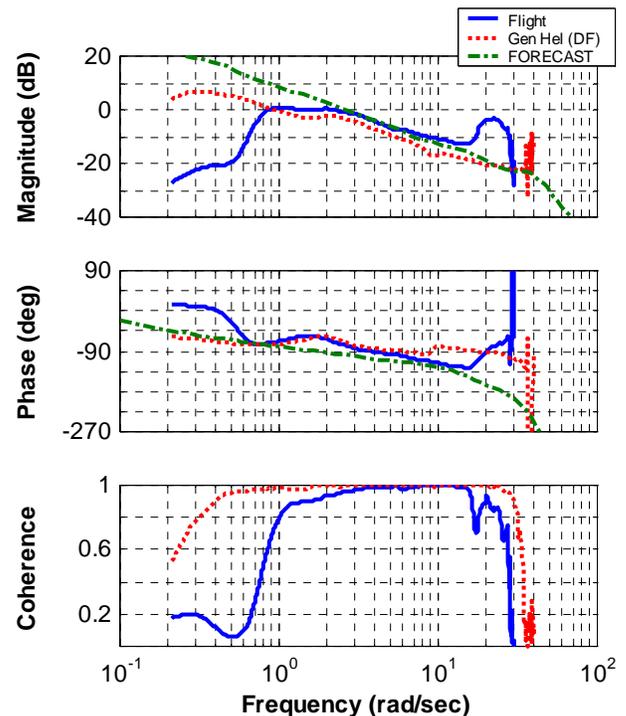


Figure 11. Yaw axis modeling fidelity of Ames Gen Hel and FORECAST

Although not directly related to the development of the MUCLAWS on the RASCAL aircraft, an important part of the AFDD support for the UH-60M Upgrade program was the development and validation of math models of the UH-60M aircraft, which will be used to continue the development of the control laws on the new airframe. UHPO sought to leverage considerable AFDD experience in this area to support model development at Sikorsky for use in control law design and to support model development at the Army Aviation Engineering Directorate (AED) for use in airworthiness analysis activities. To support this effort, the UHPO funded dedicated flight tests on the UH-60M Baseline test aircraft to provide sufficient flight test data for UH-60M model development and validation at hover, 80 kts and 120 kts.

As shown in Figure 12, the “model leveling” process began with the comparison of legacy Sikorsky and Ames Gen Hel math models of the UH-60A with existing RASCAL JUH-60A flight test data. The UH-60A models were then updated to reflect the physical characteristics of the UH-60M, including wide chord blades, and many minor updates. The resulting Sikorsky Gen Hel, Ames Gen Hel, and FORECAST models of the UH-60M were compared with each other, and UH-60M flight test data. The validated full-flight envelope simulation models were then ready for use in real-time piloted simulation, desktop engineering evaluations of the MUCLAWS, and for HWIL simulation in the Sikorsky flight control systems integration laboratory (FCSIL).

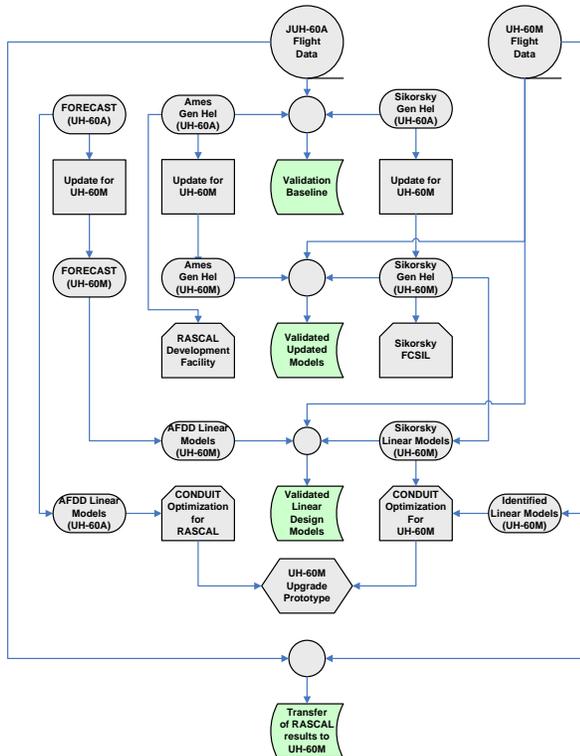


Figure 12. UH-60M Math Model Development and Validation Process

Linear point-design models were derived from the UH-60M configured FORECAST and Sikorsky Gen Hel, and were again compared with each other and with flight test data to validate the fidelity of the model linearization process. Once validated, this provided a capability to generate linear models as needed for use in flight control law design and analysis and sensitivity studies.

The next step in the model development process was to identify very high-fidelity linear models of the UH-60M flight dynamics directly from flight test data for a small number of key flight conditions. These models will be used in final optimization of the MUCLAWS before first flight of the prototype UH-60M Upgrade. The CIFER[®] system identification tool [Ref. 11] was used to conduct the identification in the frequency domain. A sample of the dynamic response of the identified UH-60M hover model to control inputs is compared with the high-order linear models derived from Sikorsky Gen Hel and FORECAST and hover flight test data in Figure 13. These results are illustrative of the general level of fidelity of the various models which all capture the on-axis response to pilot controls (e.g. p/δ_{lat} and r/δ_{ped}) very well.

However, the system identified model fits the on-axis responses extremely well, and matches the important coupled responses (e.g. p/δ_{lon} and r/δ_{col}) much better, as has been demonstrated in previous UH-60 identification studies UH-60 [Ref. 12].

Another advantage of developing the MUCLAWS on RASCAL aircraft is the presumed dynamic similarity between the UH-60A and the UH-60M and the implications this has for transferring the results of the RASCAL development to the prototype UH-60M Upgrade airframe. However, there were some concerns that significant upgrades to the engines and wide chord blade aerodynamics would yield significant differences in flight dynamics. Early comparisons between the UH-60A and UH-60M version of Gen Hel reduced these concerns, but direct comparisons of UH-60A and UH-60M flight test data were needed to increase certainty.

Figure 14 provides a direct comparison of key bare-airframe frequency responses identified from hover flight test data from the RASCAL JUH-60A and the UH-60M aircraft. This set is representative of the generally excellent match of both on and off-axis responses to pilot controls between the two aircraft, over frequency ranges with good coherence. For example, the on-axis yaw response to pedals and roll response to lateral cyclic and are extremely similar, with the effect of the regressing lead-lag mode on roll response at approximately the same frequency. The yaw rate response to collective, which is dependent on the engine/governor dynamics, is very similar between the UH-60A and UH-60M responses indicating minimal effect on flight dynamics from the engine differences between the two aircraft. The most significant difference is in the vertical response to

collective which is attenuated in magnitude at high frequency for the UH-60M. This could be due to differences in weight (~15,000 lbs for RASCAL and ~18,000 lbs for UH-60M). Nevertheless, the high degree of similarity between the two data sets provides

confidence that the results of MUCLAW development on RASCAL will be readily portable to the UH-60M airframe with the expectation of very similar performance.

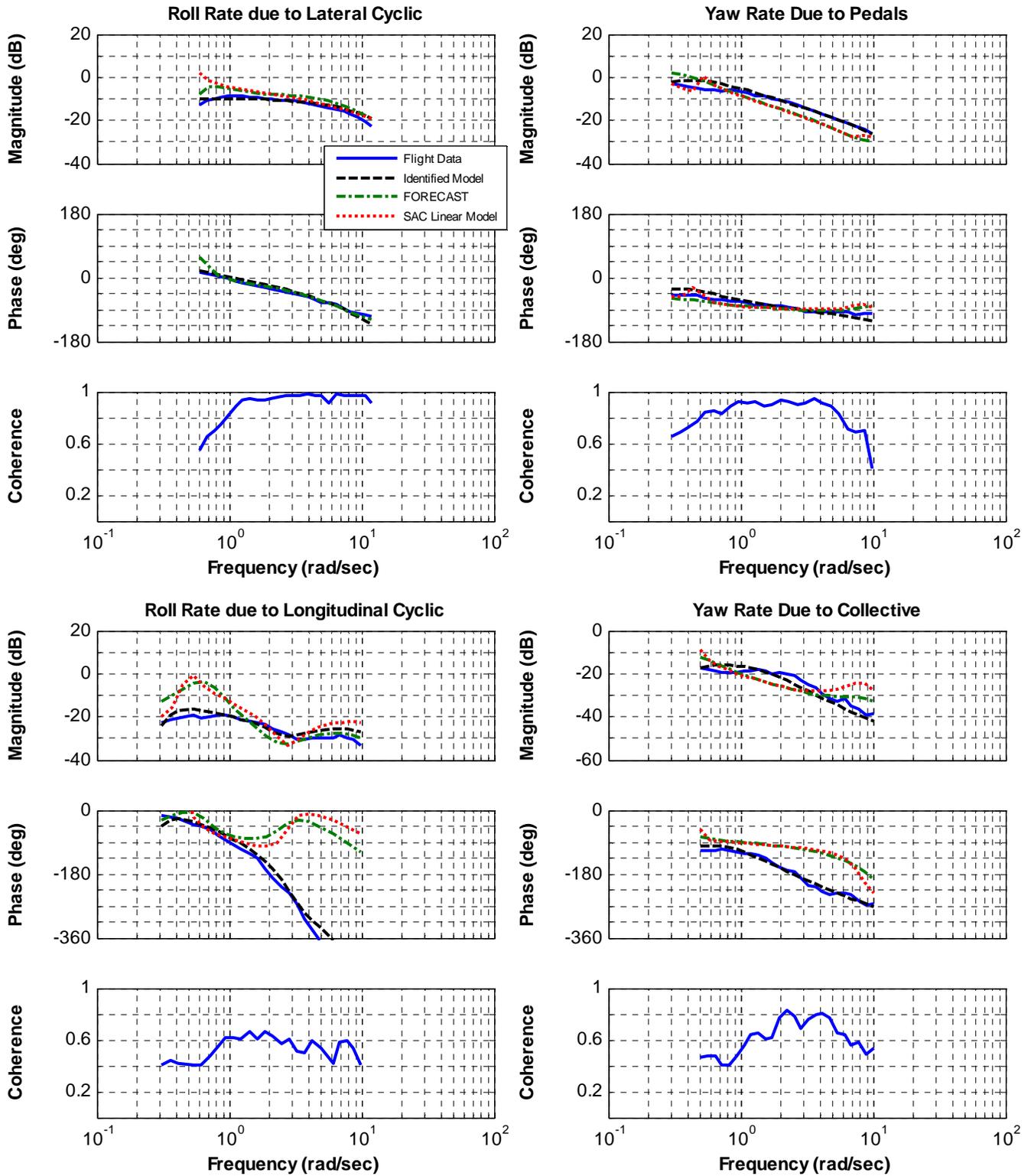


Figure 13. Comparison of UH-60M identified model with linear design models in hover

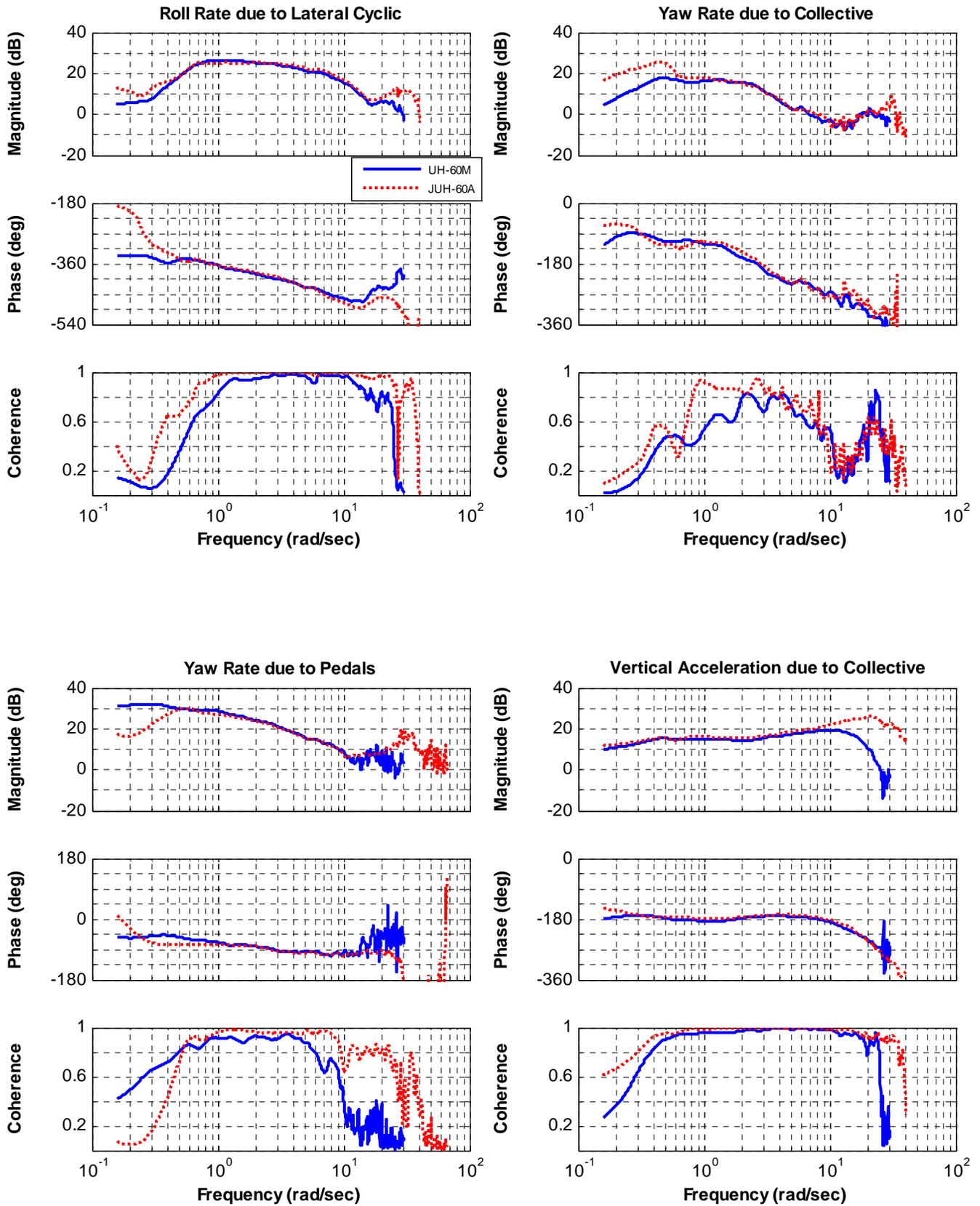


Figure 14. Comparison of JUH-60A and UH-60M Identified Frequency Responses in Hover

Control Law Software Implementations

Both Sikorsky and AFDD have adopted the Mathworks Matlab[®], Simulink[®] and Stateflow[®] tools for block diagram development and analysis, and the Real-Time Workshop[®] Embedded Coder[™] tool for the translation of block diagrams into embedded code. The availability of these tools enabled the decision early in the project to retain as much commonality as possible between the block diagrams used for control system analysis and for embedded code generation, to ensure correlation between what was being flown and what was being analyzed. However, this approach proved to be cumbersome for analysis because of the complexity of the UH-60M Upgrade block diagrams. The “full flight envelope” block diagrams, which were entirely appropriate for the embedded control application, contained many operating modes, complicated logic paths, complex gain scheduling, and nonlinear elements, which significantly complicated the process of analysis at particular operating points. Ultimately it was necessary to maintain a separate set of simplified block diagrams for analysis at each flight condition and to verify these against the embedded diagrams when updates were made.

The CONtrol Designers Unified InTerface (CONDUIT[®]) [Ref. 4] tool was used to perform linear analysis and optimization of the MUCLAWS to determine control law gains that satisfied the performance criteria set for the system. CONDUIT[®] interfaces with Simulink, and makes use of Simulink representations of the control law block diagrams and linear models of the aircraft dynamics. CONDUIT[®] allows the control system engineer to construct and solve a multi-objective function optimization problem, with control law design parameters (gains) as independent variables, and system performance relative to design specifications as dependent variables, subject to the constraints of the system defined by the mathematical representation of the control laws and aircraft dynamics. The size of the CONDUIT[®] optimization problem is a function of each of these factors, and can become very large when the control laws are complex and there are a significant number of design parameters, performance specs, and operating modes.

The complete MUCLAWS as implemented in Simulink[®] and State Flow form a very large system consisting of hundreds of block diagram pages, dynamics states, and decision paths. When combined with a significant number of design parameters and specifications to be evaluated for each control axis, control mode, and control loop closure, the optimization problem became intractable for routine use. With the complete control laws, a single evaluation of the system performance required more than 30 minutes to run on a state-of-the-art personal computer. Since tens of iterations can be required to arrive at an optimized solution, re-optimizing the system as often as needed to thoroughly analyze the system quickly became prohibitive.

The solution was to develop, simplified versions of the block diagrams, configured for specific operating conditions, thereby eliminating many of the complicated logic paths and lookup tables needed to accommodate the entire flight envelope. These were implemented in the same CONDUIT[®] structure that was used for the complete model and the responses and analysis results were compared to those of the complete model to ensure a good match. The verified simplified versions were then subsequently used for the analysis, reducing the computation time by more than two orders of magnitude.

Figure 15 compares the broken loop lateral response of the system in ACAH mode in hover as obtained from the complete model and the simplified model. These results are typical of the general trend, and indicate very good agreement between the complete and simplified control laws. The excellent agreement in the frequency range of crossover indicates that stability margins calculated using the two versions should be nearly identical.

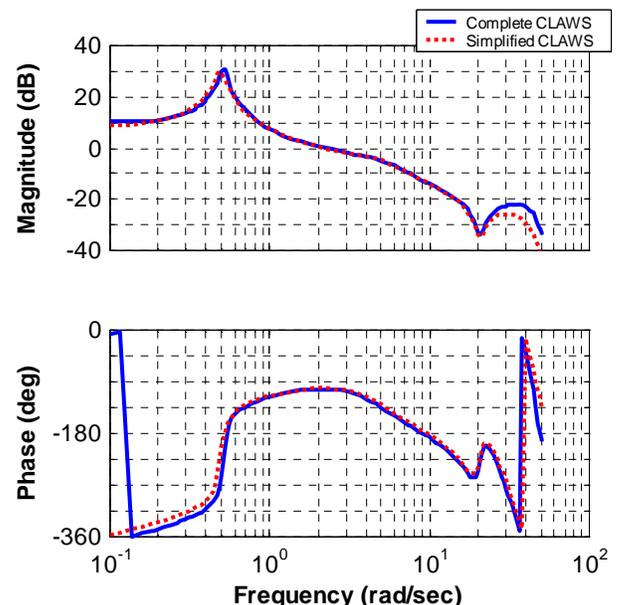


Figure 15. Comparison of complete and simplified lateral broken loop dynamics

Linear Analysis Verification

Before proceeding with the optimization, it was necessary to verify the accuracy of the analytic linearization employed by CONDUIT[®], namely the Matlab[®] linearize function. This function is relatively new, and had not been independently verified for use in CONDUIT[®] before.

Broken loop and disturbance rejection frequency responses from the Simulink[®] simulation model were evaluated both by sweeping the simulation in the time domain with automated chirp inputs, and in the frequency domain using the MATLAB[®] linearize function. Chirps were input into the mixer matrix for the broken loop and into the attitude sensor signal for disturbance rejection, and frequency responses were calculated from the time histories using CIFER[®]. Comparisons of the ACAH

lateral broken loop frequency response and the roll attitude disturbance rejection frequency response at hover from the two methods are shown in Figure 16. This confirmed that the linearization of the nonlinear blocks in the CONDUIT[®] simulation model was being handled correctly by the underlying Matlab[®] functions.

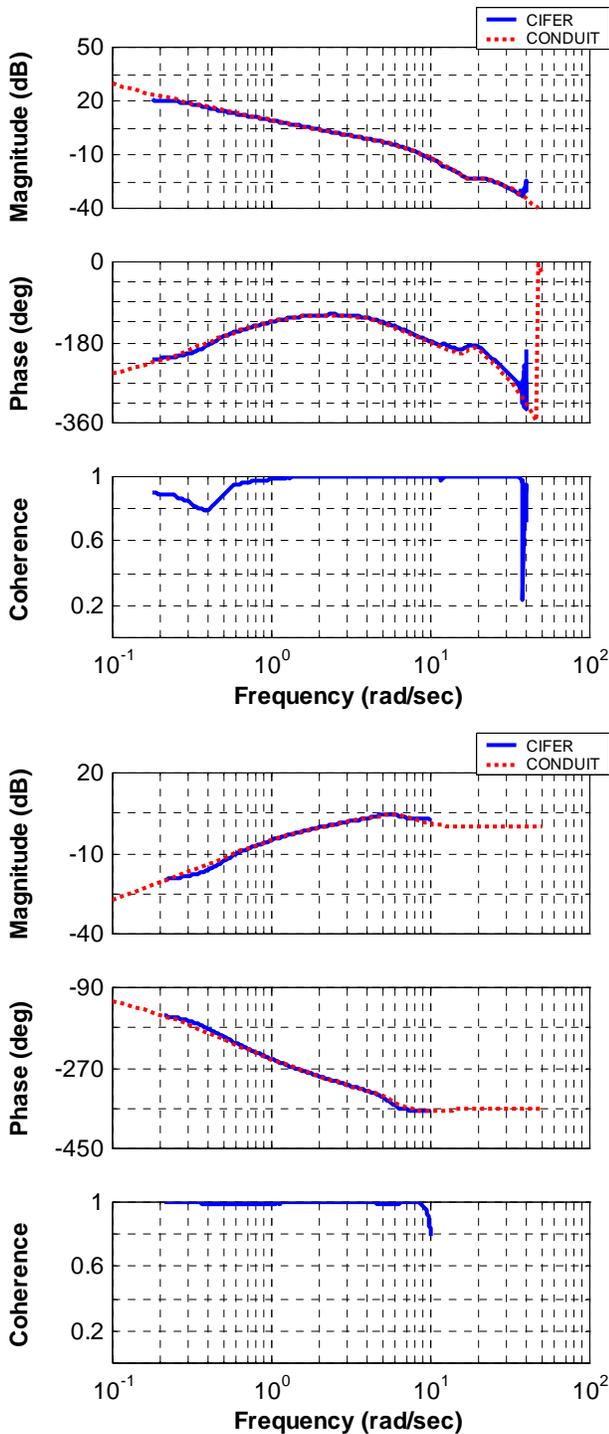


Figure 16. Lateral axis broken loop and disturbance rejection simulation validation

CONDUIT[®] Problem Setup

As mentioned previously, CONDUIT[®] was the primary tool employed for linear analysis and optimization of the MUCLAWS on RASCAL, and it was employed successfully throughout the program. Analysis of early software drops provided feedback to Sikorsky that supported basic control law design decisions. CONDUIT[®] continued to be valuable as an analysis and troubleshooting tool during initial integration and verification of the CLAWS on RASCAL, as will be discussed in a later section. And finally, CONDUIT[®] provided the primary guidance for optimization of the MUCLAW gains for flight test development on RASCAL. Throughout the program, the CONDUIT[®] problem was continuously updated as the control laws matured and as flight test data became available to refine aircraft flight mechanics, sensor and actuator models.

The major elements of the CONDUIT[®] problem are linear models of the relevant aircraft dynamics, SIMULINK[®] block diagrams of the control laws, selection of design parameters, and selection of a set of performance specifications for the system to optimize against. As mentioned above, FORECAST was used to generate linear models of the aircraft, and simplified versions of the MUCLAWS were used for analysis with CONDUIT[®].

The specifications selected included the UH-60M Upgrade System Specification, AVNS-PRF-10018A [Ref. 13], which includes many requirements from the ADS-33E Rotorcraft Handling Qualities design standard [Ref. 3]. Basic stability criteria from MIL-F-9490 [Ref. 14], model-following performance criteria, and developmental criteria for rotorcraft disturbance rejection performance were also included in the optimization. These were included for all response types and in both the inner and outer loops, where applicable.

The eigenvalue spec was used to verify that the closed loop system was stable. This was accomplished by checking that all the real parts of the eigenvalues of the system were negative or zero, ensuring that all the dynamics were stable or neutrally stable. In conjunction, stability margin specs were used to verify that satisfactory gain and phase margins were achieved for the broken-loop responses at both the actuators and at selected outer loop locations. Also, the bandwidth spec was included as key short-term response requirements in ADS-33 directly related to the step-response rise time for a piloted control input.

Disturbance rejection specs were included to check the disturbance rejection bandwidths, low frequency (steady state) disturbance response magnitudes, and the overshoot of the disturbance response curves which are direct measures of the damping of the responses. Disturbance response bandwidth is defined in CONDUIT[®] as the frequency at which the Bode magnitude plot of the

sensitivity function crosses the -3dB line. A higher disturbance-response bandwidth reflects tighter rejection of disturbances. The model following spec was used to ensure that the aircraft responses followed the command models as desired. Finally, the pitch/roll response coupling spec and the collective/yaw response coupling spec were used to ensure that the coupling responses remained within ADS-33E requirements.

In CONDUIT® each specification has three distinct regions corresponding to the 3 handling qualities levels (see [Ref. 4] for more details). The specifications themselves are divided into 4 distinct categories: Hard Constraints, Soft Constraints, Objectives, and Check Only. CONDUIT® optimization proceeds through three phases which each focus on different specification types.

In Phase 1, the optimization engine attempts to move all Hard Constraints into Level 1 while ignoring all other specifications. Specifications dealing with system stability and margins are generally selected as Hard Constraints.

After a set of design parameters are found that put all the Hard Constraints in Level 1, the design is usually stable and possesses satisfactory stability margins, but may not necessarily produce satisfactory handling qualities. In Phase 2, the optimization engine attempts to find a set of design parameters which also put all the Soft Constraints in Level 1 while ensuring that all Hard Constraints still meet the Level 1 requirements. Soft constraints are usually specifications relating to response characteristics and handling qualities.

When the design satisfies all the Level 1 requirements for both hard and soft constraints, a feasible, but not yet optimal, design solution is reached and the optimization process enters Phase 3. In Phase 3, CONDUIT® further tunes the design parameters to optimize the system based on minimizing the selected performance Objectives, such as broken loop crossover frequencies and actuator RMS, while ensuring the Phase 1 and Phase 2 requirements are still met. The goal of this phase is to ensure minimum over design.

Although CONDUIT® was used extensively for analysis and optimization prior to first flight of the MUCLAWS on RASCAL, those early results will not be presented here as they are not as relevant as later results. Instead, the use of CONDUIT® will be illustrated in the various phases of the flight test development, and final results will be presented in the section on flight test based optimization.

RASCAL UH-60MU Flight Test Development

A three-phase flight test approach was adopted for development and initial evaluation of the UH-60MU FCS on RASCAL consisting of: Phase 0 – system integration

and validation, Phase 1 – flight test development, and Phase 2 – limited scope handling qualities evaluation. Engineers and pilots from AFDD, Sikorsky, and UHPO participated in all phases. In addition, pilots from the U.S. Army Aviation Technical Test Center at Ft. Rucker, AL participated in Phase 2.

Phase 0 – System Integration and Verification

Phase 0 consisted of approximately 10 hours of flight time in which system integration and dynamic response were verified using system identification methods. The CONDUIT® model was also updated based on flight test data. The RASCAL DF played an important role in this process, allowing engineers to check out software integration with many of the RASCAL hardware systems before flight. However, flight testing with the actual aircraft dynamics, sensors, and actuators, serves as the ultimate verification for system integration. Phase 0 can be considered as the first iteration of the process shown in Figure 2.

A build up approach was employed in Phase 0, in which parts of the system were systematically integrated and verified, starting with core elements, and gradually adding complexity. This process began with check out of the active inceptor system using the existing RASCAL control laws. Although the RASCAL control laws were not configured to provide commands to the AIS, the basic functionality of the sticks and their interface with the RASCAL systems were verified, and initial tuning of stick force-feel characteristics, control sensitivities, and stick filters was accomplished. The EGI integration was also verified with the EGI operating in parallel with the legacy RASCAL INU during these early flights.

Integration testing with the MUCLAW software also followed a buildup procedure through the sequential closure of control loops from inside to out. Linear analysis was performed before flight, and stability margins greater than 6 dB (gain) and 45 deg (phase) were verified for each loop.

Testing began in “degraded direct” mode with all feedback loops open to verify basic control mixing, control sensitivities and forward loop shaping. Limited authority rate and lagged rate feedbacks were then enabled for “direct mode”, which approximates the level of augmentation in the UH-60A-M SAS. Attitude loops were closed next, which enabled attitude command attitude hold in pitch and roll and rate command heading hold in the yaw axis. Finally, the velocity and position loops were closed to provide velocity, altitude, and position hold functionality.

Oscillations Although the integration flight test approach was cautious and was supported by the best analysis available, significant undamped oscillations were experienced in the pitch and roll axes the first time that the velocity loops were closed. These oscillations were

not divergent, but the RFCS was quickly disengaged, and the flight was terminated.

Post flight analysis was conducted to determine the cause of the oscillations, which appeared to be associated with the lead-lag mode at approximately 34 rad/sec. Although the pre-flight stability analysis was based on FORECAST which includes lead-lag dynamics, the fidelity of the lead-lag degree of freedom is known to be deficient (see Figure 10 and [Ref 10]). In addition, comparison of key gains in the MUCLAWS with their analogs in the legacy RASCAL CLAWS revealed the pitch axis gains to be significantly higher in the MUCLAWS, leading to the possibility that the lead-lag mode was being destabilized by excessive pitch axis gains.

To explore this possibility, the CONDUIT[®] model was updated to include a pitch rate frequency response calculated from flight test data instead of the linear model. As shown in Figure 17, the broken loop magnitude response with the flight identified lead-lag dynamics included approaches the unity gain line at ~34rad/sec indicating a potential for instability at that frequency. The estimated phase does not precisely cross -180deg in this frequency range, as is required to assess the precise gain margin. However, the coherence is quite degraded in the vicinity of the lead-lag mode (due to reduced pilot excitation), and so there will be considerable uncertainty in the response – most in the phase estimate [Ref 11].

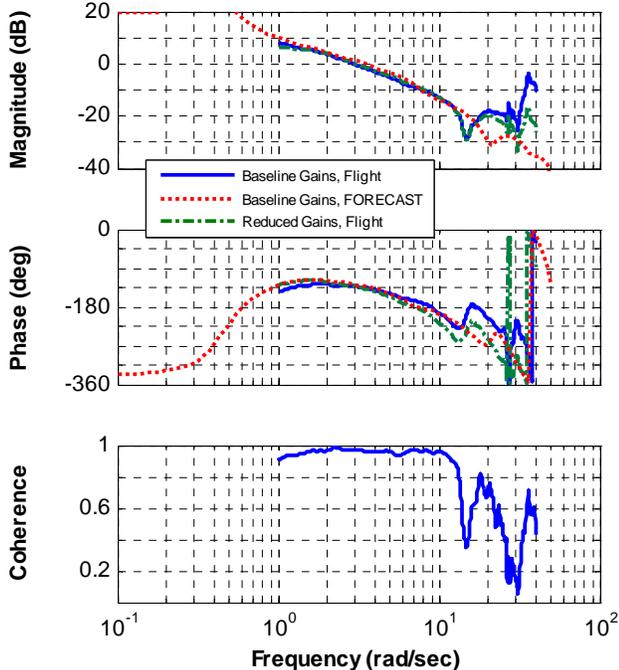


Figure 17. Improvement of pitch axis stability with optimization based on flight test measured response

As in the case of fixed-wing aeroservoelastic stability analyses, a more conservative approach is to calculate the gain margin based on the peak magnitude response (conservative estimate), resulting in a very low stability

margin, and thus corroborating the observed flight test behavior in this case. Reoptimization with the flight identified response yielded significant improvement in the gain margin and elimination of the oscillatory behavior.

This experience highlights the potential of high bandwidth, full-authority FBW systems to destabilize rotor modes, and the need to accurately model these modes in preflight analysis. It also demonstrates the value of developing new systems on an aircraft like RASCAL with the ability to revert to backup control system.

Final System Verification Once the MUCLAWS were fully operational on RASCAL a final verification of the completely integrated system was completed. Frequency response testing was conducted on the aircraft and in the DF, from which frequency responses were calculated with CIPHER[®] [Ref.11] and compared with linear analysis from CONDUIT[®]. Sweeps were input both at the pilot controls and at the actuators in order to calculate forward loop, broken loop, and closed-loop responses.

The verification was accomplished in two parts: verification of the broken loop responses (encompassing feedback paths in the control laws, aircraft dynamics, sensor dynamics and filters); and verification of the forward path (command model and inverse plant). The broken loop and forward path responses for the simulation model were obtained from CONDUIT[®]. The broken loop responses for RASCAL were obtained by injecting chirps into the actuators and processing the response time histories in CIPHER[®]. The forward path frequency responses for the RASCAL were obtained from piloted sweeps, and then processing the response time histories in CIPHER[®]. It should be noted that although the verification was conducted early in the program before the system was completely optimized, the process is illustrated below with results from the fully optimized system as it was flown for the handling qualities evaluation in Phase 2.

Figure 18 shows a comparison of the longitudinal broken-loop and longitudinal forward loop frequency responses from simulation and flight test (hover, stick in detent). Both the broken loop and forward path responses for the linear simulation (CONDUIT[®]) agree well with the flight test results. The differences at the high frequencies of the broken loop responses are due primarily to known deficiencies in the regressive lag mode model in Gen Hel and FORECAST.

The stability margins obtained from the broken loop responses from simulation and flight are summarized in Table 1. The good agreement between the broken loop responses and the stability margins ensured that the optimized gains generated by CONDUIT[®] would provide the expected performance in flight.

The disturbance rejection characteristics were determined by injecting automated chirps into the velocity sensor

signals v_x and v_y) for velocity hold mode, and the attitude sensor signals for attitude/heading hold mode (ϕ , θ , and ψ). So for example, to obtain the disturbance rejection frequency response for attitude hold mode in the lateral axis, a chirp (δ_{chirp}) is injected into the roll attitude signal (ϕ) at a point just before it enters the control laws, and the signal then becomes ϕ' . The disturbance rejection frequency response is then ϕ'/δ_{chirp} . The disturbance rejection bandwidth is defined as the frequency where the disturbance rejection frequency response crosses -3dB.

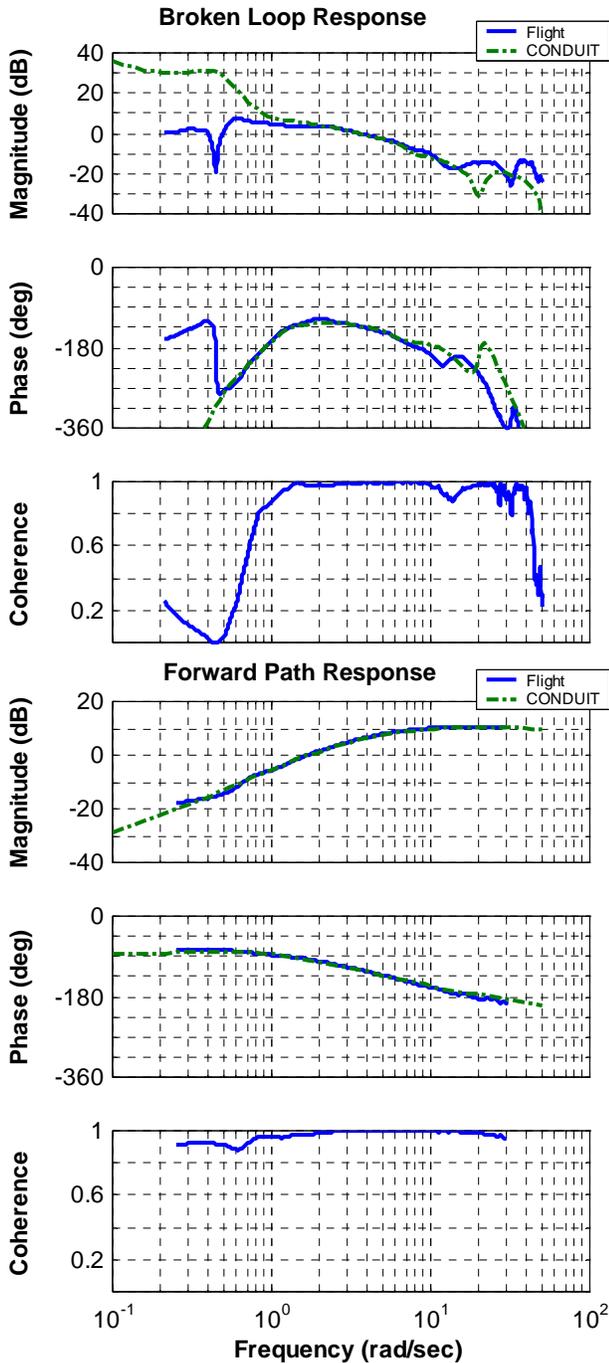


Figure 18. Longitudinal broken loop and forward path validation

Table 1. Identified Stability Margins

	CONDUIT®	Flight Test
Longitudinal		
ω_c	3.5	3.5
PM	49.7	48.4
GM	13.5	8.5
Lateral		
ω_c	4.2	3.4
PM	50.3	51.8
GM	8.1	7.3
Directional		
ω_c	5.7	6.2
PM	31.1	45.5
GM	8.2	6.7
Vertical		
ω_c	1.9	1.6
PM	74.6	64.5
GM	8.9	9.7

Figure 19 shows a comparison of the magnitude plots used to obtain the attitude disturbance rejection bandwidth from simulation and flight. As the figure shows, the agreement between the disturbance rejection bandwidths from simulation and flight is very good.

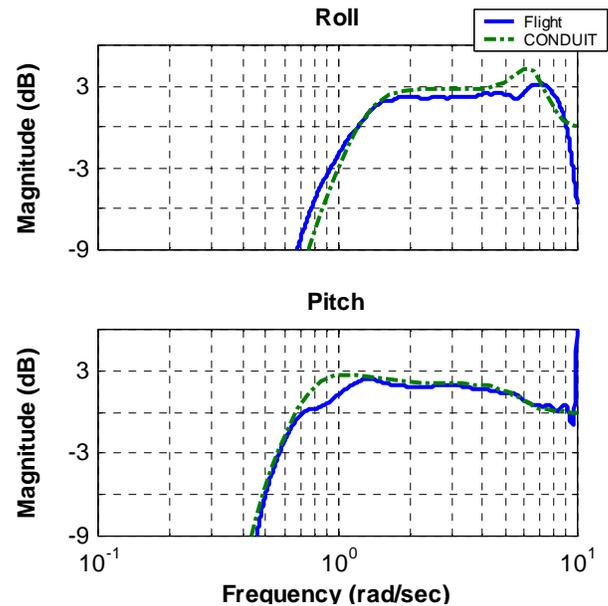


Figure 19. Comparison of attitude hold ϕ and θ and disturbance rejection

Conducting a thorough verification of the system integration in Phase 0 was essential. This not only ensured that the control laws had been correctly implemented on RASCAL; but also ensured that the analysis tools were correctly predicting the behavior of the real system. Verification provided confidence that RASCAL was flying with the intended CLAW design, and the analysis tools could be used with confidence to guide further flight test development and optimization of the MUCLAWS.

Phase 1 – Flight Test Based Optimization

Phase 1 consisted of approximately 40 hours of flight time in which the control laws were developed through further iterations of the process of Figure 2. This corresponded to approximately seven software drops. Both the flight control laws and the active stick characteristics were optimized as part of this process. Although engineers and pilots from AFDD, Sikorsky, and the UHPO participated in this process, Sikorsky had the role of technical lead for development of the MUCLAWS during this phase. AFDD provided support for the integration of the MUCLAWS in the CONDUIT® environment and conducted early optimization studies, which later transitioned to Sikorsky.

Flight Control Law Optimization Throughout the flight optimization phase, CONDUIT® was used as the primary analysis tool, and CONDUIT® optimized gains were used as a baseline at each flight condition for any further tuning based on pilot commentary or flight data analysis. For the RASCAL development, CONDUIT® analysis was performed for the hover/low speed and 80 KIAS flight conditions. Hover and low speed will be the focus of the results presented here.

Under ideal circumstances, post flight data analysis and pilot commentary would be used to make updates to the CONDUIT® optimization problem after each flight; and gains would be re-optimized based on changes made to the set of CONDUIT® design parameters, constraints, specifications, and individual specification boundaries. For example, the disturbance rejection bandwidth boundaries are often used as tuning parameters to find the correct balance between control response and disturbance rejection [Ref. 15].

However, schedule and manpower constraints made it impractical to repeat the CONDUIT® analysis after each flight; so this process had to be modified to meet these constraints while maintaining flight safety and making the best use of the guidance provided by the analysis. The solution was to repeat the analysis only when significant (structural) changes were made to the MUCLAWS or when it was desired to change gains that would directly impact stability. Again, the fail-safe nature of the RASCAL facility made this approach feasible without adversely affecting flight safety.

The hover/low speed results presented here reflect the final iteration of the CONDUIT® optimization including minor gain changes made to the yaw axis in subsequent flights. The predicted performance of this configuration relative to the selected set of specification criteria from CONDUIT® is shown in Figure 20 for the hover flight condition.

Note that only a subset of the criteria used for the actual analysis and optimization is shown here for brevity. The specifications dealing with system stability and margins are shown near the top and are designated as hard constraints. As mentioned earlier, this means that they are considered by the optimization engine in the first phase of optimization.

Gain and phase margins are calculated for each control loop closure including out-of-detent (AACAH) stability, in-detent stability (velocity hold), and stability with position/altitude hold loops closed. A Level 1 requirement of 45 degrees of phase margin and 6 db gain margin was enforced during the optimization. The pitch and roll margins are seen to be Level 1, but the yaw phase margins shown in Figure 20 for ACVH and ACAH are 31.6 and 33.7 degrees respectively. These results reflect increases in the yaw attitude and rate feedback gains made to improve heading hold performance after the final optimization iteration with CONDUIT®. As shown in Table 1, the final gain and phase margins determined from frequency sweep testing show that adequate margins were achieved in flight with the higher gains. The discrepancy between the analytic prediction and the flight test result is attributable to the mismatch of the phase responses of the linear model used for the analysis and the actual responses from flight as seen in Figure 11.

The case of the yaw axis tuning clearly illustrates the value of the thoughtful application of the flight control rapid prototyping process of Figure 2. Pre-flight CONDUIT® analysis was used to set control law gains to achieve safe stability margins, and prior model validation work made the team aware of potential weakness in the yaw axis of the analysis model. Subsequent frequency sweep testing corroborated the expected conservatism of the analysis, and careful in-flight tuning with the fail-safe RASCAL system was then carried out to improve performance. The final performance was then verified through frequency response testing.

In addition to the standard stability margin specs discussed above, Figure 20 shows the specialized stability margin spec (StbDaG1: Frequency Sweep Spec) which incorporates bare airframe responses from flight data, as discussed earlier. Inspection of this spec confirms that adequate margins (PM = 47.2, GM = 8.1) have been maintained. The fact that the progressive lead lag mode has not been adversely affected is also confirmed by the maximum broken loop magnitude spec (MagDaG1: Max. Mag. (Freq. Sweep)) which again uses bare airframe responses from flight data to calculate the maximum magnitude of the broken loop response in the frequency range of the progressive lead lag mode (30-40 rad/sec) and shows a satisfactory maximum magnitude of -16 db.

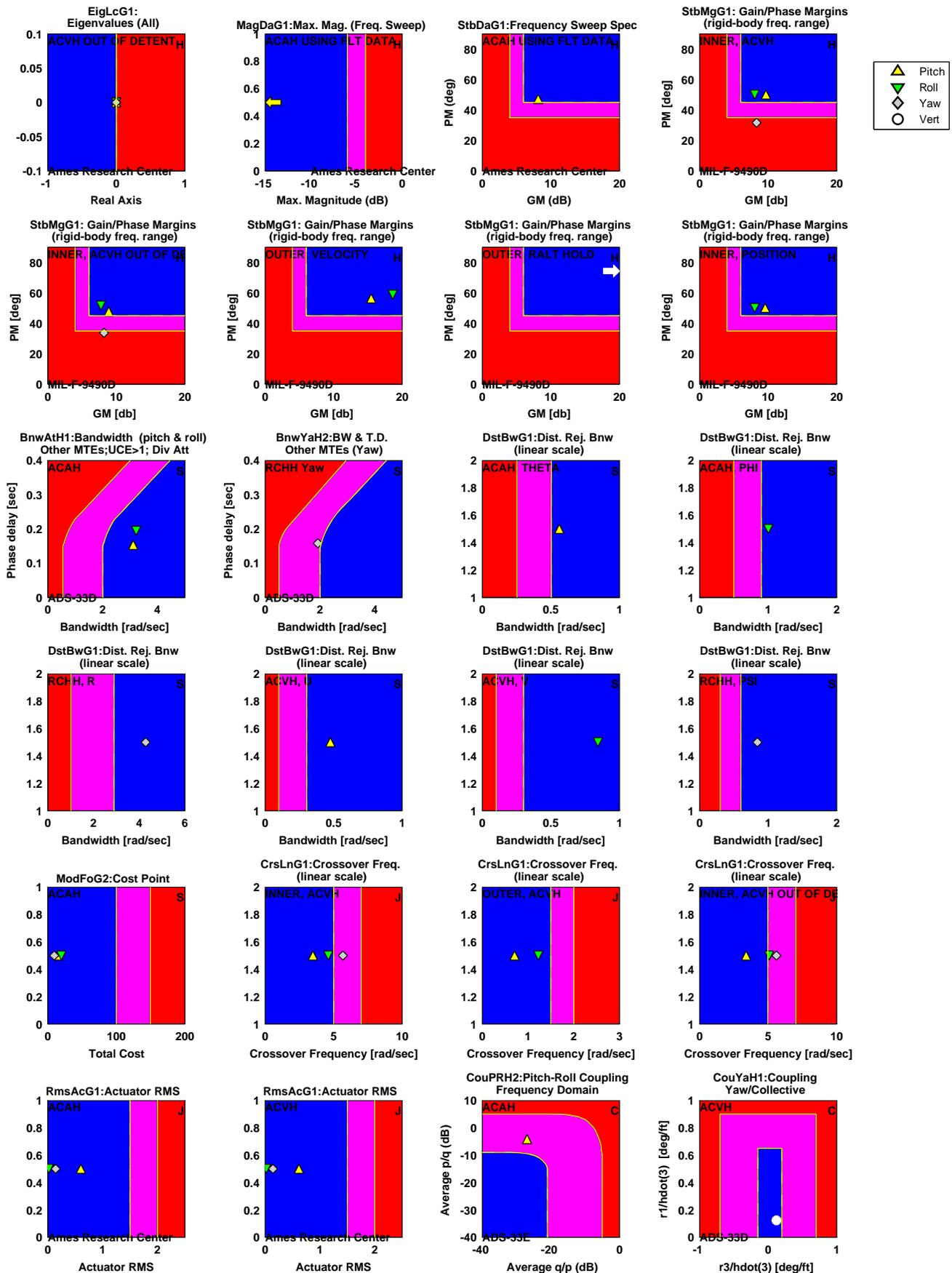


Figure 20. CONDUIT[®] Control Law Optimization Results for Hover/Low Speed

After the hard constraints, the soft constraints are considered by the optimization engine. These generally consist of handling qualities and disturbance rejection type of specifications. The top-most soft constraints shown in Figure 20 are the bandwidth specs from ADS-33E-PRF. For a model following system, the main contributor to the bandwidth of the system is the command model, though other factors, affect the final bandwidth and phase delay. As may be seen from the figure, the bandwidth specification is satisfied for the pitch and roll axes (ACAH case shown) while the yaw axis is slightly in Level 2 (RCHH case shown). This is consistent with the bandwidth specified for the yaw axis command model. This command model bandwidth was initially set at a much higher value, but was reduced to approximately two radians/sec based on pilot comments about the abruptness of the yaw response to pedals.

For a model following system it is also important to ensure that the closed-loop responses closely follow the command model responses. The model following spec (ModFoG2: Cost Point) was used to make this comparison to ensure a close match. As the figure shows, the cost values in all 3 axes are very low implying good model following performance.

The remaining soft constraints are the disturbance rejection specs. The location of the Level 1 boundaries of the disturbance rejection specs vary with axis, disturbance parameter, flight condition, and the response type being considered and are currently the subject of ongoing research. Nevertheless, best guesses for the initial location of the boundaries can be made based on previous work. The location of the boundaries can be used as a tuning knob during the analysis to extract maximum performance from the system. For the current work, the disturbance rejection specs were used only to verify good disturbance rejection performance and no attempt at further tuning was made. As Figure 20 shows, the system shows good disturbance rejection for all axes and parameters considered.

Following the soft constraints are the summed objective specs consisting of maximum crossover frequency and actuator RMS. In the case of summed objectives, the boundaries simply provide a direction for the cost function meaning that it's the lowering of the cost function that is of concern and not strictly achieving Level 1 for the boundary. As mentioned earlier, the summed objectives provide the means for optimizing the system such that all specifications are met with minimum over-design, as determined by low crossover frequencies and low actuator energy (as measured by actuator RMS). As may be seen from Figure 20, in some cases the final crossover frequencies were in Level 2 because the design parameters were modified post-optimization based on flight test results and pilot comments. Again, this is not an issue since achieving a specific crossover frequency is not required so long as the stability margins of the system are

satisfactory. Also, the actuator RMS specs are satisfied, indicating that actuator usage is not excessive and the system is not being overdriven.

Finally, note that the remaining specs are check only, which means that they allow certain characteristics of the system to be tracked without affecting the optimization process. The two check only specs used made it possible to track the pitch/roll and yaw/heave coupling of the system to ensure acceptable levels of coupling. As may be seen, the yaw/heave coupling is in Level 1 while the pitch/roll coupling is in Level 2. Pilots did not complain about excessive pitch/roll coupling in flight and therefore the gains were not further modified to reduce pitch/roll coupling.

Optimization of Active Stick Characteristics The force-feel characteristics of the active inceptors were optimized in a less analytic manner than the flight control laws for a number of reasons. A primary consideration was that the AIS control laws and dynamic models of the sticks were not available to the RASCAL MUCLAWS development team, which made it impossible to analyze the stick dynamics. In addition, very little has been published regarding performance requirements for active sticks against which one would analytically optimize the control laws. Therefore, the development team began with a baseline configuration similar to the force-feel characteristics of the UH-60A, and used the available stick configuration parameters to tune the characteristics based on pilot feedback, flight test experience, and the general guidance provided in ADS-33E-PRF.

The evolution of some of the cyclic stick force-feel characteristics during development is summarized in Figure 21. The baseline characteristics were chosen to emulate the gradients of the UH-60A-M force trim system with the addition of a shallow two-slope breakout to provide positive feedback of detent position to the pilot. During flight test development, uncommanded stick oscillations were encountered, which required increasing in the stick gradients to increase stick stability. The breakout forces were also increased to address pilot comments about the ease with which unintentional off-axis inputs could be made with the smaller breakout force.

The handling qualities evaluation of Phase 2 was conducted with these characteristics, and most pilots did not like the high force gradients, particularly in combination with the attitude command system and unique trim, which require holding the stick out of detent for longer periods of time than with a rate system. In addition, some pilots did not like the effect of the deep detent on aircraft response, which was described by one pilot as "like driving over a cobblestone" as one moves the cyclic through the neutral position.

After Phase 2, it was discovered that stick stability could be increased without increasing the force gradients.

Additional testing was conducted, and a lower gradient was selected for both the pitch and roll axes, as shown in Figure 21. It was also determined that a “zero width” detent with a one pound breakout force provided a very subtle indication of neutral position with no impact on aircraft response. In addition, the stick gradient ensures that the cyclic will always return to trim when released, introducing the possibility that a cue for trim is not necessarily a requirement with a unique-trim inceptor.

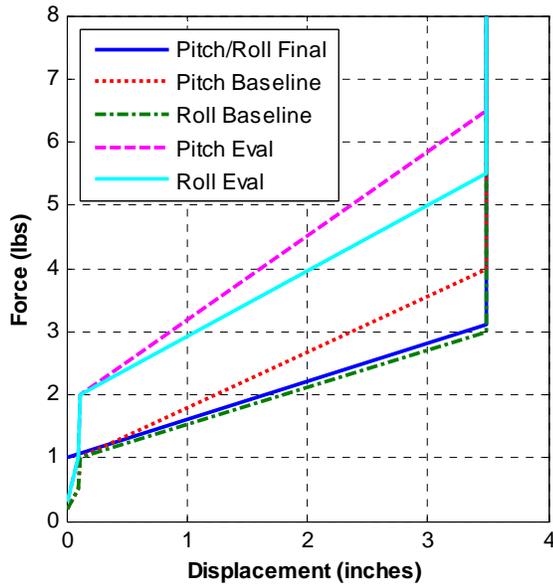


Figure 21. Active Inceptor Characteristics

Phase 2 – Limited Handling Qualities Evaluation

An initial assessment at the handling qualities of the optimized UH-60M Upgrade flight control system on RASCAL was performed during approximately 20 hours of flight testing in Phase 2. As specified in ADS-33E-PRF, overall handling qualities were investigated from both predicted handling qualities parameters and assigned handling qualities ratings (HQR) using the Cooper Harper Pilot Rating Scale [Ref 16]. Quantitative engineering maneuvers such as frequency sweeps and attitude quickness were flown to determine predicted handling qualities, and mission task elements (MTE) were flown to determine assigned handling qualities. MTEs were flown in both good visual conditions (GVE) and simulated degraded visual conditions (DVE) as described below.

Predicted Handling Qualities Evaluation A subset of the predicted handling qualities requirements of ADS-33E were selected to efficiently quantify and verify the results of Phase 1 optimization and to provide an initial assessment of predicted handling qualities of the system. The selected criteria focus on the small and moderate amplitude responses of the system to control inputs in each axis and one major coupled response.

Compliance of the optimized system with the small amplitude, short-term control requirements of ADS-33E was checked according to the requirements of paragraph

3.2.1.1 (pitch and roll) and paragraph 3.5.1.1 (yaw) for the hover flight condition. Frequency responses were calculated from both stick displacement and stick force measurements (for pitch and roll), as ADS-33 states that it is desirable to meet the requirements for both inputs. Although there is some disagreement within the handling qualities community as to whether the pilot closes the loop on stick displacement or force [Ref. 17], both calculations are shown here to provide bounds on the range of possible outcomes.

The flight identified pitch and roll bandwidth and phase delay data are plotted against the UCE>1 and/or divided attention criteria in Figure 22 along with the CONDUIT® analysis results from Figure 20. The roll axis is seen to be Level 1 for both displacement and force inputs. Although the pitch axis is seen to be Level 1 for displacement inputs, it is borderline Level 2 when evaluated from force inputs. The pitch axis analysis results agree very well with flight rest results, and although the roll axis analysis results do not agree as well, they are conservative.

It should be noted that ACAH criteria were used for this evaluation, and since the gain margin determined bandwidths were lower than the phase margin bandwidths, the aircraft could be PIO-prone for high gain tasks, which were not evaluated on RASCAL.

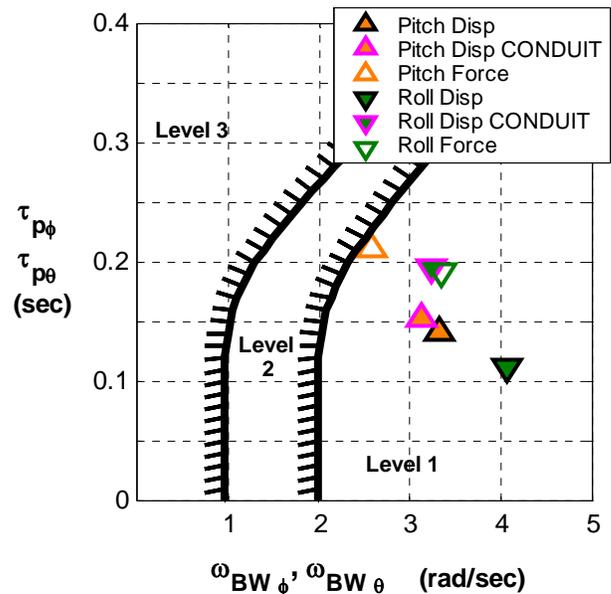


Figure 22. Pitch and roll bandwidth and phase delay, all other MTEs, UCE>1 and/or divided attention operations

The yaw axis bandwidth and phase delay calculated from pedal displacement is plotted on the ADS-33 criteria for all other MTEs in Figure 23. Although the predicted performance is just into the Level 1 region, the yaw axis control response was very quick, and some evaluation pilots felt that the yaw axis bandwidth should be reduced. Again the flight test result is very close to the result from

linear analysis, although it is just over the border into Level 1. The analysis result is again conservative.

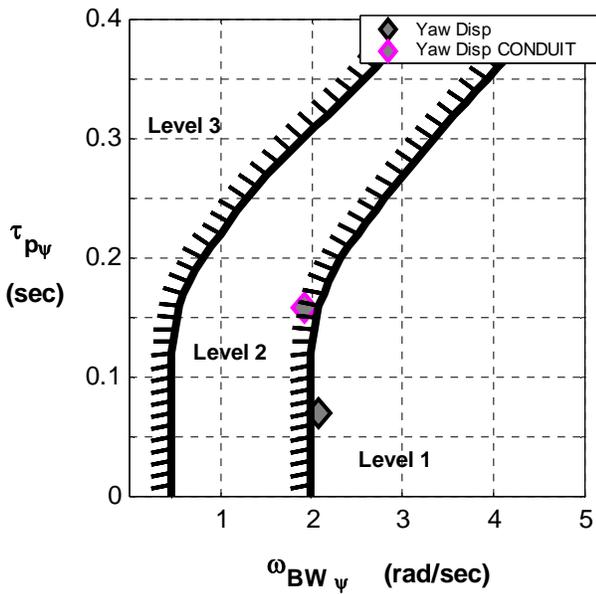


Figure 23. Yaw bandwidth and phase delay for all other MTEs

Compliance of the optimized system with the moderate amplitude, (attitude quickness) requirements of ADS-33E-PRF was checked according to the requirements of paragraph 3.3.2 (pitch and roll) for the hover flight condition. The results, shown in Figure 24 and Figure 25, satisfy Level 1 ADS-33 requirements for both pitch and roll, and indicate that the system should have adequate agility for moderate amplitude tasks.

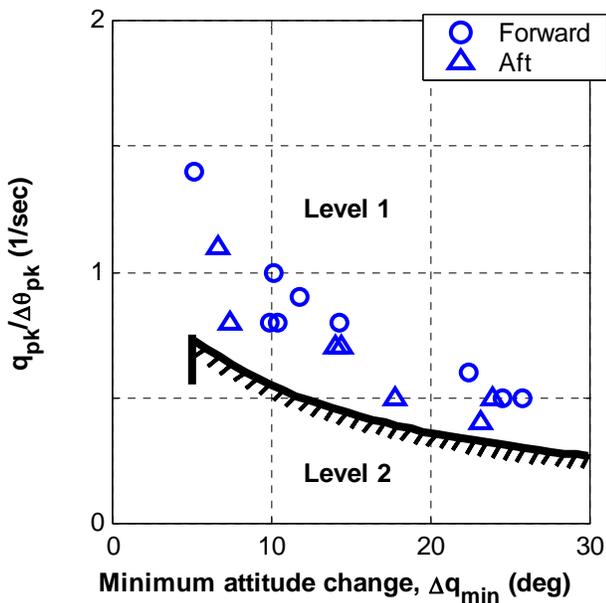


Figure 24. Pitch attitude quickness in hover

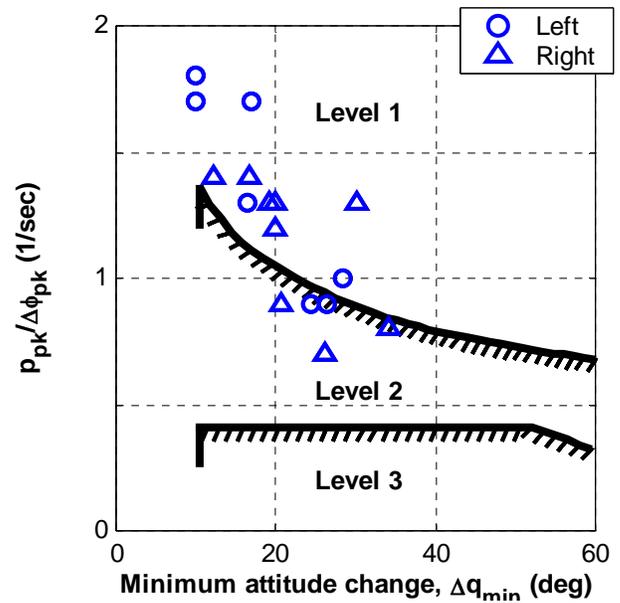


Figure 25. Roll attitude quickness in hover

The height response of the optimized system for the hover flight condition was checked according to the first order fit methodology specified in ADS-33E-PRF paragraph 3.3.10.1, as shown in Figure 26. The first order time constant of 5.0 seconds and equivalent time delay of 0.122 seconds meet Level 1 requirements.

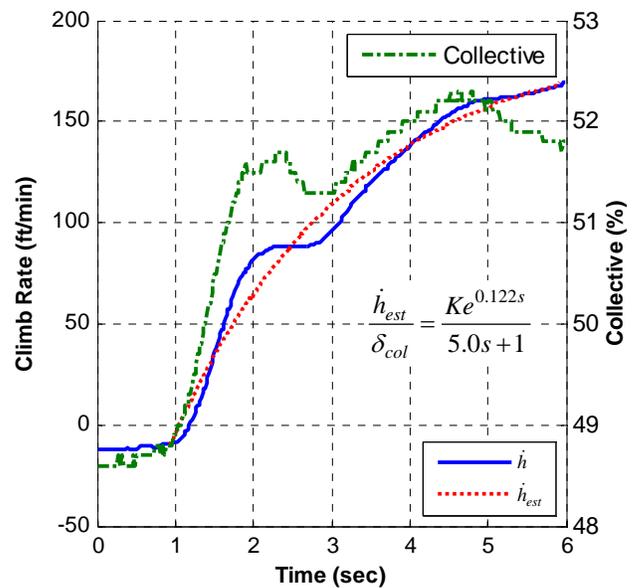


Figure 26. Vertical velocity response to collective in hover

The yaw due to collective inter-axis coupling was also checked according to the requirements of ADS-33E-PRF paragraph 3.3.9.1. Directional control workload due to collective inputs can affect the pilot's ability to perform collective tasks, so yaw excursions due to collective inputs need to be minimized for good handling qualities.

Figure 27 presents the yaw coupling due to collective for aggressive agility, and shows that the MUCLAWS on RASCAL exhibit Level 1 yaw due to collective coupling. Level 1 behavior was also predicted in the analysis of Figure 20, although the coupling was predicted with the opposite sign.

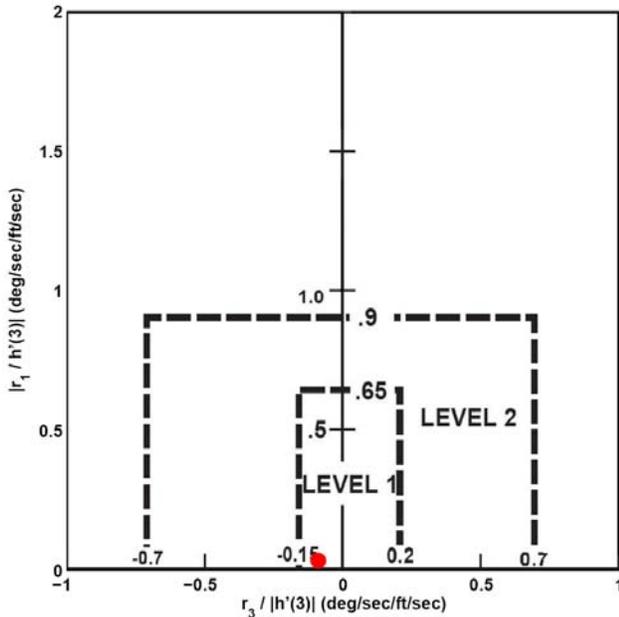


Figure 27. Yaw due to Collective Coupling for Hover and Low Speed

Although not all of the "quantitative" criteria from ADS-33 were checked, the criteria that were checked indicate Level 1 predicted handling qualities performance.

Assigned Handling Qualities Evaluation Five of the low-speed mission task elements specified in ADS-33E for the utility helicopter mission were selected for the determination of assigned handling qualities of the MUCLAWS on RASCAL. These included the Precision Hover, Hovering Turn, Lateral Reposition, Departure/Abort, and Vertical Maneuver, in both GVE and simulated DVE conditions. The same assigned handling qualities evaluation was also flown on the AFDD EH-60L aircraft in both visual environments as an experimental control.

The MTEs were modified slightly from the published ADS-33E descriptions for the RASCAL evaluation to maintain a safe altitude margin above the RASCAL RFCS-engaged minimum altitude of 25 ft above ground level (AGL.)

Prior to this project, the minimum RFCS-engaged altitude had been 50 ft AGL, but an extensive envelope expansion flight test was conducted to determine safe minimum altitudes for these five MTEs. The resulting starting altitudes for the modified MTEs are compared with those published in ADS-33E in

Table 2. The most significant altitude change for RASCAL is in the vertical maneuver, which provides sufficient altitude margin to allow the safety pilot to recover the aircraft from a hypothetical vertical axis downward hard-over at the end of the maneuver.

The ADS-33 test course at Moffett Field was modified to ensure that adequate visual cueing was maintained at the higher altitudes and in simulated DVE. A new hover tower and sight pole was constructed for the Hover, Hover Turn, and Vertical Maneuver. As shown in Figure 28, the new tower and the sight pole are equipped with adjustable targets and sights to provide visual cueing of vertical and lateral MTE performance for both GVE and DVE requirements. In response to pilot feedback from previous ADS-33 MTE testing, a similar device was constructed to provide additional longitudinal position cueing, as shown in Figure 29. The entire ADS-33 course was also updated with larger (36 inch tall) orange traffic cones to improve visibility at higher altitudes.

The five MTEs were flown both in a good visual environment (UCE=1) and a degraded visual environment (UCE=2). The UCE=2 condition was simulated by requiring the evaluation pilot to wear modified night vision goggles fitted with shrouding to prevent light from entering from the sides and above the goggles, as shown in Figure 30. The amount of light entering the NVGs through the lenses was adjusted with neutral density filters and an aperture disk to achieve visual resolution consistent with a starlit night (UCE=2) as described in Reference 18. This "predicted UCE" was validated by conducting a UCE evaluation on the AFDD EH-60L with the calibrated goggles for each of the DVE evaluation pilots at the beginning of each DVE flight.

Table 2. ADS-33 MTE Altitudes for RASCAL HQ Evaluation

Mission Task Element	ADS-33E-PRF Starting Altitude (ft)	ADS-33E Min Alt for Adequate (ft)	RASCAL MTE Starting Altitude (ft)	Minimum RFCS Engaged MTE Altitude (ft)
Hover	≤ 20	≤ 16	30	26
Hovering Turn	≤ 20	≤ 14	30	24
Vertical Maneuver	15	9	45	40
Depart/Abort	35	N/A	45	35
Lateral Reposition	35	20	45	30

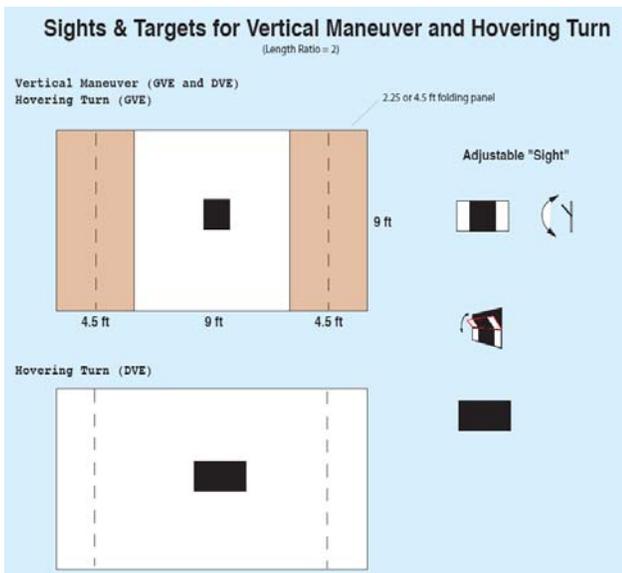


Figure 28. ADS-33 Hover Tower and Sight Pole



Figure 29. Longitudinal Position Reference Cue



Figure 30. Modified Night Vision Goggles for Simulation of Degraded Visual Environment (UCE 2)

Handling Qualities Ratings and Discussion Handling Qualities Ratings were collected following a systematic and uniform procedure which was designed to minimize training and procedural differences as sources of variation among pilots. Upon arrival at AFDD, each pilot followed a standardized course of training including classroom instruction on RASCAL systems and the UH-60M Upgrade flight control system and hands-on training in the RASCAL DF. Each pilot then flew the following six flights:

1. RASCAL/MUCLAWS familiarization flight
2. MTE familiarization and practice with MUCLAWS in RASCAL in GVE and simulated DVE (goggles)
3. GVE MTE evaluation with MUCLAWS in RASCAL
4. DVE MTE evaluation with MUCLAWS in RASCAL
5. GVE MTE evaluation in EH-60L
6. DVE MTE evaluation in EH-60L

During the MTE practice flights pilots were given feedback from flight test engineers on their performance

relative to ADS-33 criteria for each MTE. This allowed the pilots to become calibrated to the available visual cues on the course. Engineers on the ground were able to precisely monitor performance using differential-GPS tracking data and real-time computer displays of MTE performance parameters.

During the evaluation flights, engineers only provided feedback on MTE time performance, and the pilots were responsible for estimating other performance criteria. Engineers would only provide feedback on these criteria if the pilot's estimate was grossly in error. In practice, the pilots were able to judge their performance well during the evaluation flights.

Prior to providing a rating, the pilot was allowed to practice the MTE several times, until his performance was consistent. Pilots were then asked to provide an HQR by systematically following the decision tree in the Cooper-Harper handling qualities rating chart and providing a rating based on their consistent level of performance.

The average assigned HQRs for both the MUCLAWS on RASCAL and the EH-60L control are summarized in Figure 31 for both GVE and DVE conditions. Minimum and maximum ratings are also shown to provide an indication of scatter in the data. Five pilots provided ratings for the GVE averages, four pilots provided ratings for the DVE average on RASCAL, and three pilots provided ratings for the DVE average on the EH-60L. The lateral reposition and hovering turn were rated in each direction to control the effects of cross winds on the

ratings. Also shown in Figure 31 for reference are ratings from a 1999 handling qualities evaluation of the UH-60A flown at Ames Research Center in light winds [Ref. 19].

Average handling qualities ratings for the MUCLAWS on RASCAL in GVE were mostly Level 1. Average HQRs for the lateral reposition and depart/abort were borderline Level 1/Level 2, primarily due to difficulty maintaining altitude within the Level 1 tolerances. Some pilots also objected to the cyclic control forces required to hold the stick out of detent during these maneuvers, and difficulty in making precise off-axis corrections with the relatively large cyclic breakout force. As mentioned above, these characteristics were significantly improved after the assessment.

The position hold feature of the MUCLAWS made the hover turn and vertical maneuver single-axis tasks, significantly reducing pilot workload relative to the baseline aircraft. The hover capture became a two-axis task with the system taking care of altitude and heading maintenance. The average of all HQ ratings for the MUCLAWS on RASCAL in GVE was 2.76.

The handling qualities ratings for the EH-60L baseline were more uniform among the tasks, and resulted in an assessment of the aircraft as solid Level 2 for these tasks. Some degradation of the baseline may be attributable to slightly higher average winds during the EH-60 flights than were present during the RASCAL MUCLAWS flights. The average of all HQ ratings for the EH-60L in GVE was 4.25.

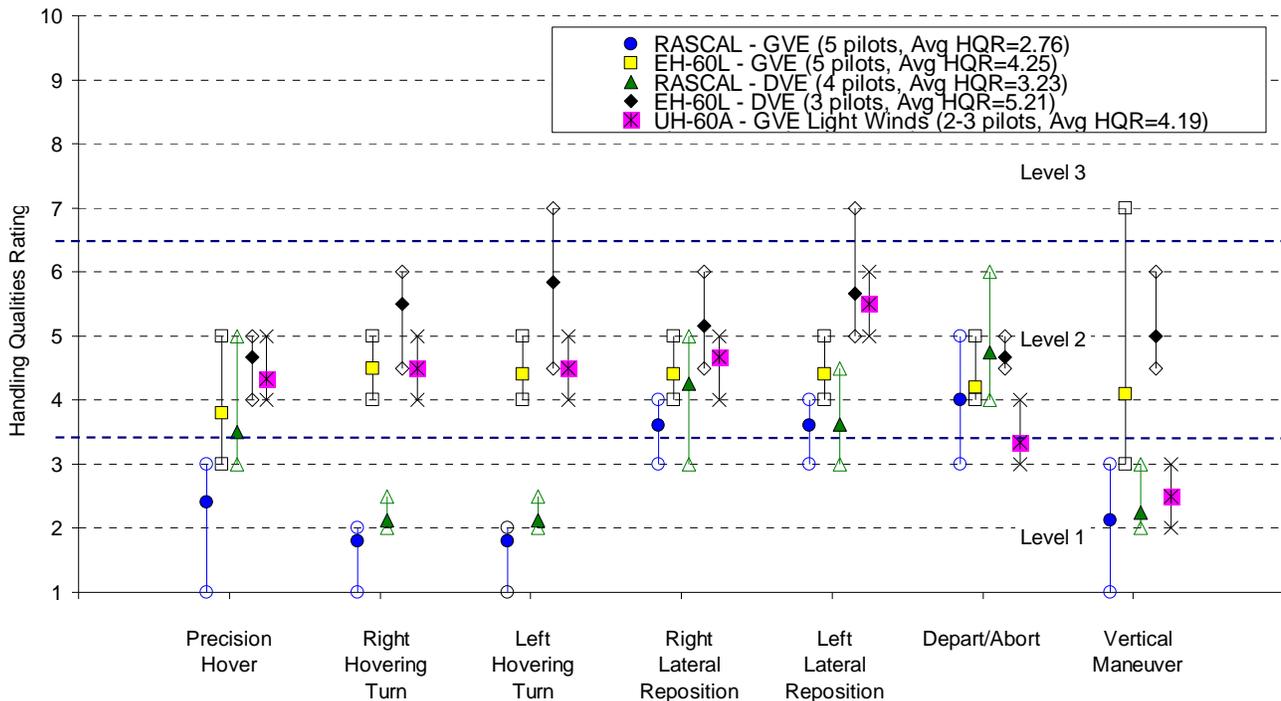


Figure 31. Handling Qualities Rating Summary

Comparison of the EH-60L GVE ratings with the UH-60A ratings in light winds provides some corroboration of the present data. Ratings for the hover capture, left and right hover turn and right lateral reposition are all within ½ HQR of the 1999 UH-60A data in light winds, and the average of all HQ ratings for the UH-60A is 4.21. However, there are significant discrepancies between the left lateral reposition, depart abort, and vertical maneuver ratings. The 1999 evaluation was flown at published ADS-33 altitudes, and this could have some effect on the ratings, particularly for the vertical maneuver. More credence should probably be given to the EH-60L GVE data for comparison with RASCAL GVE and EH-60L DVE due to its experimental proximity in time and method.

Handling qualities ratings for the MUCLAWS on RASCAL in DVE degrade only slightly from the GVE ratings from an overall rating average of 2.76 to 3.23 (+17%). This is due to the high level of platform stability and hold modes by the MUCLAWS, which provides a large enough workload reduction for the pilot to largely compensate for the reduction in visual cueing in the simulated DVE. In contrast, the overall rating average for the EH-60L increased from 4.26 to 5.21 (+22%) from GVE to DVE, indicating a higher sensitivity to the loss of visual cues and associated increase in workload with the baseline control system.

Overall, the assessed handling qualities agree well with the predicted handling qualities. Differences are attributable to the selected set of predicted handling qualities parameters not covering areas which were noted to require improvement during the MTE evaluations (e.g. altitude hold performance). Together with the predicted handling qualities results, the MTE evaluations provide a good first look at the handling qualities potential of the UH-60M Upgrade flight control system.

Summary and Conclusions

1. The AFDD flight control rapid prototyping tools (CIFER®, CONDUIT®, RITPIDE, RASCAL development facility and RASCAL in-flight simulator) provided a highly effective means to analyze and optimize a sophisticated multi-mode fly-by-wire flight control system. Excellent agreement was demonstrated between the handling-qualities predictions and flight test performance.
2. Math models used in flight control analyses and optimization for fly-by-wire flight control design must accurately represent the lead-lag dynamics to ensure satisfactory gain margin estimates. Flight test identified frequency-responses are useful for this purpose, when blade-element flight mechanics models are not sufficiently accurate.
3. The UH-60M Upgrade control laws provide significant improvements in hover and low speed handling qualities relative to the UH-60A/L baseline.

These improvements are achieved with the use of appropriate advanced command/response types and modes which provide increased platform stability and control decoupling. Handling qualities improvements are more pronounced in a degraded visual environment, where they will provide a greater benefit for modern military helicopter flight operations and safety.

4. The RASCAL development phase for the UH-60M Upgrade FBW FCS has significantly reduced risk for the program. It has achieved this by exposing key elements of the system to the rigors of implementation and optimization in a real flight environment early in the development process, when the design is less constrained, and changes are less expensive to make.

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References

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- [1] Miller, D. G., Einthoven, P. G., Morse, C. S., and Wood, J., "HACT Flight Control System (HFCS) Control Law Overview", Presented at the American Helicopter Society 58th Annual Forum, Montreal, Quebec, Canada, June 11-13, 2002.
 - [2] Moralez, E. III, et. al., "Flight Research Qualification of the Army/NASA RASCAL Variable Stability Helicopter," Presented at the American Helicopter Society 58th Annual Forum, Montréal, Canada, June 11-13, 2002.
 - [3] Anonymous, "Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft," ADS-33-E-PRF, 21 March 2000.
 - [4] Tischler, M. B., et. al., "CONDUIT – A New Multidisciplinary Integration Environment for Flight Control Development," NASA TM 112203, USAATCOM TR 97-A-009, 1999.
 - [5] Dones, F., et. al., "An Advanced Fly-By-Wire Flight Control System Designed for Airborne Research – Concept to Reality," *Proceedings of the American*

Helicopter Society 56th Annual Forum, Virginia Beach, Virginia, May 2-4, 2000.

[6] Ballin, M. G., "Validation of a Real-Time Engineering Simulation of the UH-60A Helicopter," NASA TM-88360, 1987.

[7] Howlett, J. J., "UH-60A Black Hawk Engineering Simulation Program: Volume I – Mathematical Model," NASA CR-166309, December 1981.

[8] Mansur, M., Frye, M., and Montegut, M., "Rapid Prototyping and Evaluation of Control System Designs for Manned and Unmanned Applications," *Proceedings of the American Helicopter Society 56th Annual Forum*, Virginia Beach, Virginia, May 2-4, 2000

[9] Kim, F. D., Celi, R., and Tischler, M. B., "High Order State Space Simulation Model of Helicopter Flight Mechanics," *Journal of the American Helicopter Society*, Vol. 38, No 2, October 1993.

[10] Curtiss, H. C. Jr., "On the calculation of the response of helicopters to control inputs," *Proceedings of the 46th Annual Forum of the American Helicopter Society*, Washington D.C., 1990.

[11] Tischler, M. B. and Remple, R., Aircraft and Rotorcraft System Identification, Engineering Methods with Flight Test Examples, AIAA Education Series, American Institute of Aeronautics and Astronautics, Reston, VA, 2006.

[12] Fletcher, J. W. and Tischler, M.B., "Improving Helicopter Flight Mechanics Models with Laser Measurements of Blade Flapping," *Proceedings of the 53rd Annual Forum of the American Helicopter Society*, Virginia Beach, May 1997.

[13] USAAMCOM, "System Specification for the UH-60M Upgrade Blackhawk Utility Helicopter," AVNS-PRF-10018A, September 7, 2005.

[14] Anonymous, "Military Specification, Flight Control Systems – Design, Installation and Test of Piloted Aircraft, General Specification for", MIL-F-9490D(USAF), 6 June 1975

[15] Harding, J. W., et. al., "Optimization and Piloted Simulation Results of the AH-64D Modern Control Laws," *Proceedings of the 63rd Annual Forum of the American Helicopter Society*, Virginia Beach, VA, May 2007.

[16] Cooper, G. E. and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

[17] Mitchell, D. G., Aponso, B. L., and Klyde, D. H., "Feel Systems and Flying Qualities," AIAA-95-3425-CP.

[18] Chalk, C.E.T, "Achieving the Degraded Visual Environment: A Novel Methodology for Handling Qualities Flight Test," presented at the 63rd Annual Forum of the American Helicopter Society, Virginia Beach, VA, May 1-3, 2007.

[19] Blanken, C. L., et. al., "Evaluation of Aeronautical Design Standard 33 Using a UH-60A Black Hawk," *Proceedings of the 56th Annual Forum of the American Helicopter Society*, Virginia Beach, VA, May 2-4, 2000.