Optimization of Partial Authority Automatic Flight Control Systems for Hover/Low-Speed Maneuvering in Degraded Visual Environments

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Abstract

A ground-based piloted simulation study of a Partial Authority Flight Control Augmentation (PAFCA) concept for the UH-60 Black Hawk helicopter was performed to assess options for potential in-service upgrades and to expand the knowledge base on optimization of PAFCA systems. Two pitch and roll command model gain sets were synthesized for a model-following, attitude-command attitude-hold (ACAH) control law: 1) a gain set optimized for Level 1 handling qualities with respect to the ADS-33D handling qualities specification, and 2) a gain set optimized for minimum mismatch between the open- and closed-loop frequency response. The resulting configurations were evaluated at 10 and 15 percent authority levels in four hover/low-speed tasks. Comparison was also made with the standard UH-60 SAS. The tasks were performed in a simulated degraded visual environment (DVE) using night vision goggles (NVGs). The simulated DVE was judged representative of night operation using NVGs and was assessed as a useable cue environment of two (UCE = 2). Series servo hardover recovery at the 10 and 15 percent authority levels was also assessed. The following summary points were noted:

- The ACAH control law was preferred to the UH-60 SAS for the tasks evaluated.
- The “frequency-matched” ACAH control law reduced series servo activity, reduced series servo saturation, and improved control predictability in the region of saturation as compared to the ADS-33D optimized gain set.
- Desired task performance was achieved with the frequency-matched ACAH control law using 10 percent series servo authority while increasing authority to 15 percent further improved handling qualities by one HQR.
- A 15 percent authority series servo hardover was rated one failure rating point worse than a 10 percent hardover, but all failures were recoverable and tolerable.

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Glossary of Terms

ACAH	Attitude Command, Attitude Hold
ACT	Active Control Technology
ADS-33	Aeronautical Design Standard-33
AFCS	Automatic Flight Control System
CONDUIT	Control Designers Unified Interface
DVE	Degraded Visual Environment
FBW	Fly-By-Wire
FPS	Flight Path Stabilization
HQR	Handling Qualities Rating
LART	Limited Authority Response Types
PAFCA	Partial Authority Flight Control Augmentation
PFCS	Primary Flight Control System
PIO	Pilot Induced Oscillation
PSD	Power Spectral Density
RCAH	Rate Command, Attitude Hold
SAS	Stability Augmentation System
SCAS	Stability and Command Augmentation System
UCE	Usable Cue Environment
VCR	Visual Cue Rating
VMS	Vertical Motion Simulator

Introduction

Impact of Handling Qualities on Mission Effectiveness

Handling qualities are a measure of the ease and precision with which a pilot is able to perform a particular mission task. Handling qualities encompass both the internal attributes of the helicopter (e.g., pilot, rotor, engines, controls, displays) and the external environment in which it operates (e.g., mission task, urgency level, weather, time of day). Formal requirements on handling qualities are specified in terms of three "Levels" of acceptability relating to task performance and pilot workload as shown on the Cooper-Harper Pilot Rating Scale[1] (Fig. 1).

Most, if not all, current military helicopters can only achieve Level 2 handling qualities in degraded visual environment (DVE) conditions for the most critical mission tasks, and can degrade to Level 3 in exceptional circumstances. Deficiencies which impact on the perceived task performance include control system-related attributes such as poor static and dynamic stability, strong cross couplings, together with external factors such as a degraded visual environment and strong atmospheric disturbances. The increasing emphasis on day/night all weather operations in military and civil applications further highlights shortfalls in the capabilities of current generation systems. Pilots can overcome many of these problems in normal flying conditions, but when operating in a high threat environment, degraded visual conditions or confined areas, the flying task can consume all of the pilot's spare capacity. This significantly reduces the pilot's situational awareness, degrades the mission effectiveness, and compromises flight safety.

Flight control is a key enabling technology for improving handling qualities. In particular, increased control augmentation is essential for providing the necessary level of handling qualities that allow mission tasks to be performed with increased agility and safety in degraded environmental conditions. In pursuit of this goal, the concept of PAFCA seeks to achieve a similar functionality to highly augmented Fly-By-Wire/Active Control Technology (FBW/ACT) systems, but with a particular emphasis on providing affordable options for potential in-service upgrades to current fleet aircraft within the constraints of the existing flight control system architectures.

Partial Authority Flight Control Augmentation (PAFCA)

Providing optimum handling qualities for all conditions is generally considered to be best achieved through full-authority FBW/ACT, whereby the pilot's commands are electrically or optically communicated to a flight control computer, which in turn synthesizes the appropriate collective and cyclic blade pitch demands. If Level 1 handling qualities are to be conferred on current

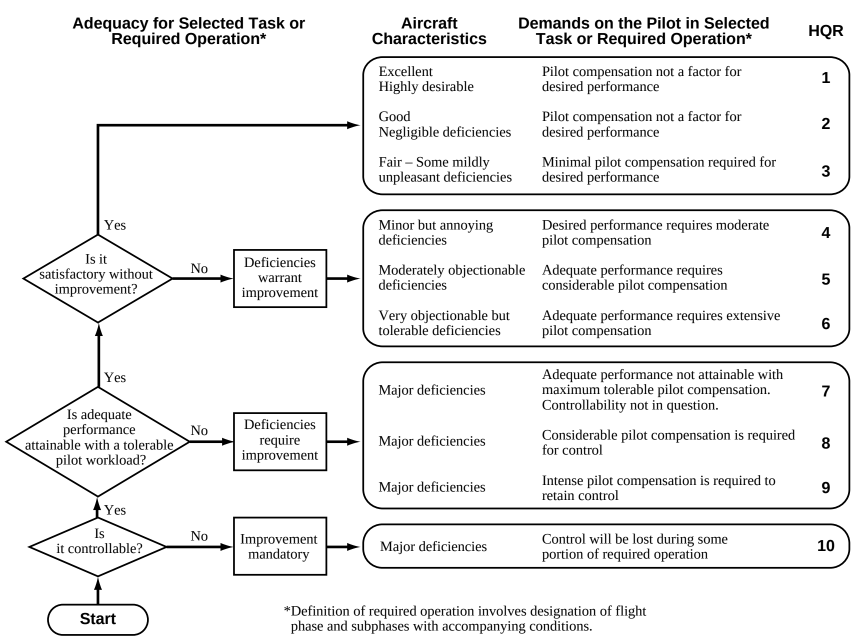

Fig. 1 Cooper-Harper Rating Scale.

in-service helicopters, then cost constraints will likely dictate that the equivalent functionality of a highly augmented FBW/ACT system will have to be sought within the bounds of the existing flight control system architecture—hence the concept of PAFCA.

The Primary Flight Control System (PFCS) typically consists of hydraulically boosted mechanical linkages (e.g., push-rods, bellcranks, cables, etc.) that connect the cockpit controls directly to the swashplate actuation system. Augmentation of the basic handling qualities is then achieved through the Automatic Flight Control System (AFCS) which can provide feed-forward command shaping and/or attitude and rate feedback stabilization via limited authority, high rate series servoactuators and autopilot hold and guidance functions via limited-rate, high-authority parallel servoactuators/trim motors (Fig. 2). Thus, the objective of PAFCA is to achieve maximum synergy from integration of the AFCS with the force-feel system, feedback sensors and series and parallel servos, particularly with respect to tailoring of the limited authority response type (LART) control laws.

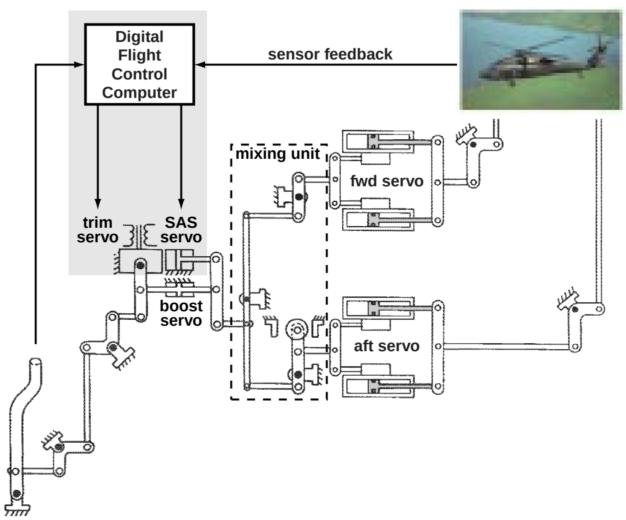

Fig. 2 PAFCA system.

Previous Work

The consideration of ADS-33 handling qualities requirements has, until quite recently, been examined purely in the context of full authority FBW/ACT and the potential for handling qualities improvement using partial authority augmentation has yet to be fully addressed.

A key study in this area was performed by Baillie et al.,[2] who describe an in-flight evaluation of LART control laws using the NRC Bell 205 Airborne Simulator. The experiment generated an initial database addressing whether limited authority ACAH response types could provide the necessary stabilization to maintain Level 1 handling qualities in a DVE. The handling qualities ratings (HQRs) and comments suggested that LART systems could provide borderline Level 1 handling qualities for hover/low-speed tasks. It was also found that series servo saturation did not always result in degraded handling qualities and could actually assist aggressive maneuvering. However, a few ratings and comments contrary to this result suggested that further investigation was required.

A previous ground-based simulation study conducted by the authors further explored the impact of AFCS saturation on handling qualities in ADS-33 hover/low-speed flight test maneuvers.[3] It was found that to avoid AFCS saturation, 35 percent pitch and 25 percent roll AFCS authority was required. (Note that these data relate to the maximum maneuver capability of an ACAH response type, with no auto-trim follow-up, in good visual conditions and with no prevailing atmospheric disturbances.) It was also seen that saturation was not always detrimental and borderline Level 1 handling qualities ratings could be achieved, even at maximum aggression, with a 25 percent pitch and a 15 percent roll AFCS limit. This point reinforced the findings of Ref. 2. Further, the data suggested that pilots were not perceiving saturation as such, but rather the magnitude and/or phase of the model-following error resulting from saturation. Additional simulation testing showed that matching the augmented and unaugmented dynamics in the frequency range of the pilot-aircraft closed-loop crossover resulted in more benign and predictable saturation characteristics. The concept of frequency matching was thus demonstrated to offer significant potential as a design philosophy for optimization of partial authority AFCS.

Although not mutually exclusive, the attributes of good handling qualities, minimal series actuator control activity, and benign saturation characteristics are highly interdependent; design guidelines distilled from the initial simulation study of PAFCA control systems are presented in Ref. 3. Further research is still required to generalize these data to different rotor systems, response types, series/parallel actuation architectures and environmental conditions, particularly DVE operations.

AFCS Authority Required to Meet ADS-33 Requirements

As a minimum requirement for DVE operations, the implementation of an ACAH response type in the pitch and roll axes requires inherently large series actuator authority. Most unaugmented aircraft will exhibit rate command response behavior and hence the effect of the series actuator displacement must be to exactly cancel the pilot's cockpit control displacement in the steady state in order to command a zero angular rate and hold a non-zero attitude. The magnitude of the resulting steady state attitude is obviously dependent on the level of series actuator authority, but also on the desired control power/control sensitivity.

For example, given a 10 percent authority limit and control sensitivity commensurate with an attitude change of 60–90 deg at maximum control deflection, the AFCS will only be able to maintain full-time ACAH response characteristics for attitude changes of 6–9 deg from trim (ignoring longer term stability effects). ADS-33D states that pitch and roll attitude changes in the range of 15–20 deg are required for Level 1 handling qualities in DVE operations and hence it is a question of when, not if, the AFCS series actuators will saturate in maneuvering flight. Auto-trim follow-up can be used to expand the available augmentation envelope, but it can also be shown that the associated parallel actuator or trim motor must exhibit similar rate/displacement "quickness" characteristics to the desired aircraft response in order to avoid rate saturation. In addition, previous research[2] has suggested that uncommanded cyclic stick motion during aggressive maneuvers have a detrimental impact on handling qualities (note that this does not preclude the use of auto-trim follow-up for autopilot functions).

It is therefore apparent that the design of the limited authority AFCS control laws must encompass more than the existing ADS-33D criteria, particularly given that both the stability and command augmentation may be ineffective for up to 50 percent of a maneuver due to saturation.

Study Objectives

The objectives of this study were:

- To design a limited authority ACAH control law for the UH-60 Black Hawk 1) optimized for performance relative to existing ADS-33D handling qualities specifications, and alternatively 2) frequency matched for reduced series servo activity, delayed onset of series servo saturation and improved predictability of control upon saturation.

- To evaluate the handling qualities of the control law options in a representative DVE on the NASA Ames Vertical Motion Simulator.

- To assess the potential for a UH-60 Black Hawk in-service upgrade.

- To expand the knowledge base on optimization of PAFCA systems for operations in degraded visual environments.

Description of PAFCA System

System Architecture

Figure 3 illustrates the top-level architecture of the PAFCA system and its integration with the UH-60 Black Hawk primary flight controls. Note that the PAFCA system did not make use of the parallel trim servo. The control law has a two-degree-of-freedom explicit model-following structure which takes the cockpit control deflections and sensor feedback as inputs and synthesizes the "ideal" pilot commands necessary to achieve the desired response characteristics. The output to the limited authority series servo is simply the difference between the ideal and actual maneuver commands.

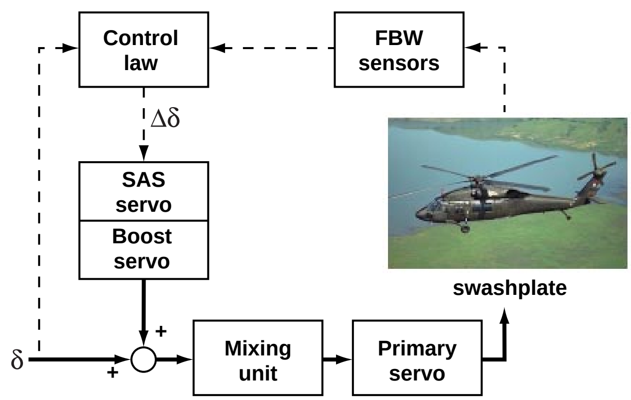

Fig. 3 UH-60 PAFCA system.

The control law was adapted from a generic rotorcraft full-authority model-following control law. The structure of the control law is shown in Fig. 4. A detailed description may be found in Ref. 4.

Figure 5 shows the transfer function model used to produce a first-over-third order attitude command response in pitch and roll, and a second order rate command response in yaw ($t_1 = t_2$). The first-over-third order structure replicates the classic hover cubic equivalent systems model and allows maximum harmonization of open- and closed-loop frequency responses for the frequency-matched control law.

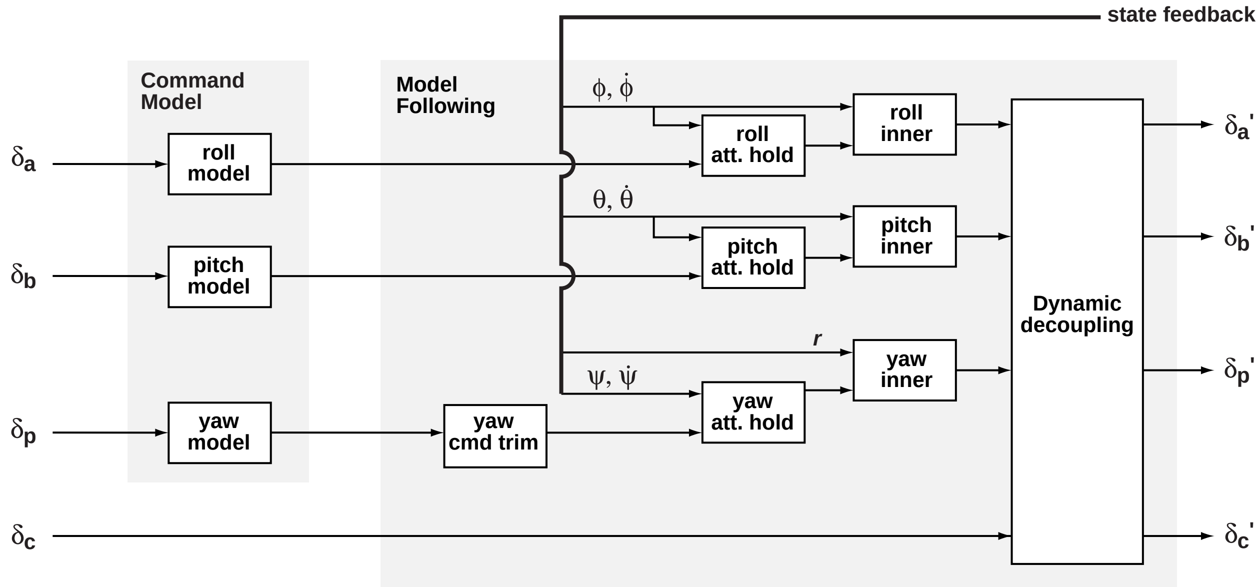

Fig. 4 General structure of the control law.

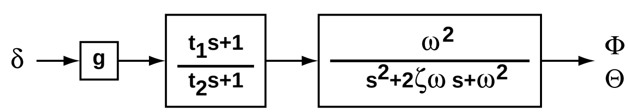

Fig. 5 Roll and pitch attitude command models.

The function of the attitude hold modules is to provide low gain integral action in addition to the rate and attitude damping provided by the inner loop modules. The inner loop modules provide most of the higher gain rate and attitude crossover feedback. The outputs from the inner loops are decoupled using a combination of static and dynamic mixing.

Control Law Optimization and the Resulting Response Characteristics

Two command model gain sets for the ACAH control law were synthesized : 1) "performance optimized" to achieve Level 1 handling qualities with respect to ADS-33D, and 2) frequency matched for reduced series servo activity, delayed onset of series servo saturation, and improved predictability of control upon saturation.

The control law gain sets were synthesized using the Control Designer's Unified Interface (CONDUIT) optimization tool.[5] CONDUIT is a graphical user interface for the commercial-off-the-shelf MATLAB and SIMULINK design, analysis, and simulation software packages and incorporates the multi-objective function optimization routine, CONSOL-OPTCAD.[6] CONDUIT allows the optimization of user-specified control system gains against a library of handling qualities and system performance specifications.

A 33-state linear model of the unaugmented UH-60 Black Hawk in hover was extracted from the FORECAST non-real-time representation of GenHel (Ref. 7) for the CONDUIT optimization. Inputs to the linear model included swashplate and tail rotor angles, and outputs included pitch, roll, and yaw attitudes and rates. Model states included rigid body rates and attitude, rotor flapping angles and flap rates, main rotor inflow, rotor speed, engine speed, and fuel flow rate.

The control system model outlined in Figs. 3 and 4 was coupled with the aircraft model, and the closed-loop simulation was submitted to the CONDUIT optimization package. The variables chosen for optimization were the command model frequency, damping, and lead-lag coefficients (ω, ζ, t_1, and t_2). For the performance-optimized configuration, t_1 was set equal to t_2, resulting in a simpler second order model structure. The natural frequency and damping were then optimized to give Level 1 handling qualities against the bandwidth and attitude quickness specifications.

For the frequency-matched configuration, additional criteria were added to the suite of ADS-33D specifications contained in CONDUIT. The frequency-matching criteria used two separate weighted cost functions to establish the least squares error in magnitude (expressed in decibels) and phase (expressed in degrees) between the closed-loop frequency response and a prespecified reference (in this case the open-loop frequency response):

$$\text{mag cost} = \frac{20}{N}\sum\left(\text{mag}_1 - \text{mag}_2\right)^2$$

$$\text{phase cost} = 0.01745\frac{20}{N}\sum\left(\text{phase}_1 - \text{phase}_2\right)^2$$

Equivalent "Level 1" and "Level 2" boundaries defining desired and adequate error tolerances were set qualitatively to give equal weighting to the handling qualities and the frequency-matching criteria. The cost functions were evaluated over the range of 1.0 to 10.0 rad/sec to ensure minimum saturation transients between closed- and open-loop dynamics in the region of the pilot/aircraft crossover frequency and to focus all available control authority on low-frequency stability augmentation (<1.0 rad/sec).

Table 1 and Fig. 6 contain the results of the optimizations. In the case of the performance-optimized configuration the requirement to meet the Level 1 attitude quickness specification drove the pitch and roll bandwidths significantly higher than was strictly required. Applying the frequency-matching criteria after the optimization shows a magnitude and phase mismatch deep within the "Level 3" region; i.e., to achieve the desired handling qualities performance required significant modification of the open-loop frequency response in the region 1.0 to 10.0 rad/sec.

For the frequency-matched configuration, absolute Level 1 handling qualities have been traded for harmonization between open- and closed-loop dynamics; the pitch and roll bandwidths are lower than for the performance configuration (the pitch bandwidth lies slightly within the

Table 1 Roll and pitch command model parameters.

	Performance		Freq. Match	
	Roll	Pitch	Roll	Pitch
ω	3.6	1.9	5.608	1.3092
ζ	0.7	0.7527	0.6067	0.6963
t_1			0.0741	0.0328
t_2			0.5794	0.1526

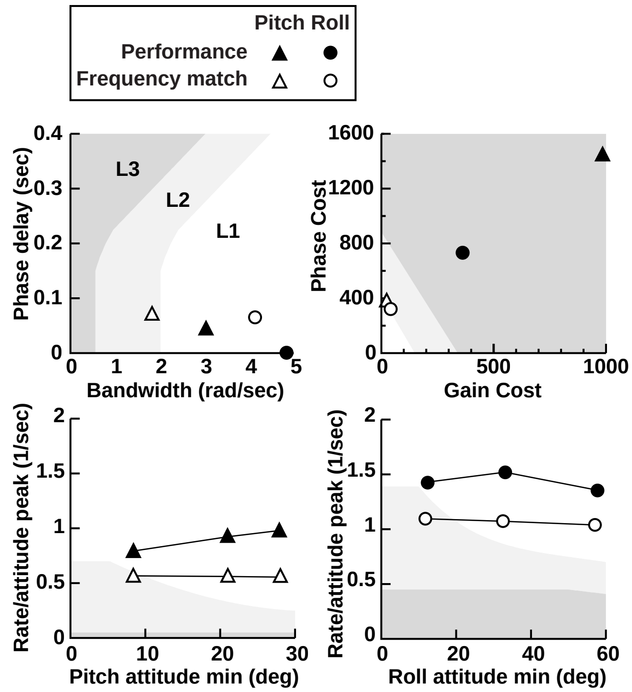

Fig. 6 PAFCA optimization results; clockwise from upper left: bandwidth, frequency-matching, roll attitude quickness, pitch attitude quickness.

Level 2 region) and the attitude quickness is correspondingly reduced. Figures 7 and 8 illustrate the differences between the two configurations in the frequency domain with the frequency-matched configuration being seen to

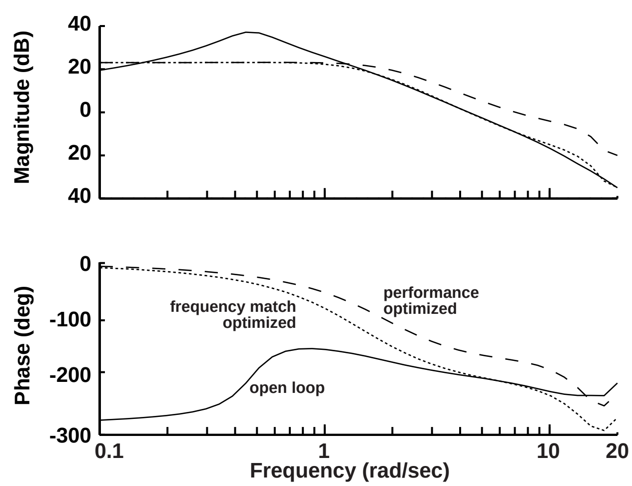

Fig. 7 Pitch frequency response (from linear model).

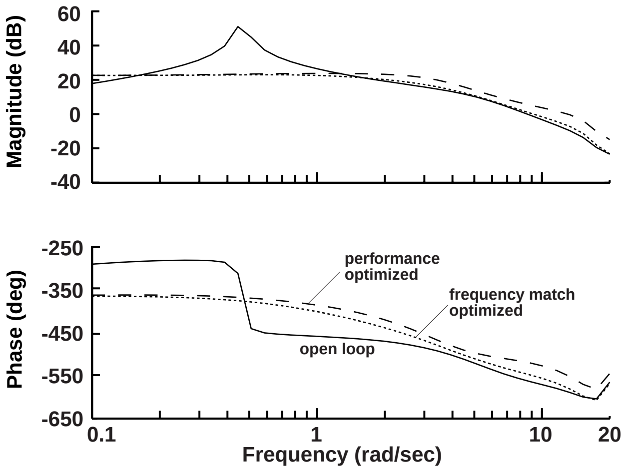

Fig. 8 Roll frequency response (from linear model).

track the open-loop system more closely in both magnitude and phase. The differences between the performance-optimized and frequency-matched configurations are slightly greater in the pitch axis than in the roll axis, which is supported by the frequency-matching specification results shown previously.

Figures 9 and 10 show the responses of the two configurations with both partial and full authority to a doublet input on the cockpit controls. The time histories show pitch and roll attitude, rate, and series servo displacement. It can be seen that the performance-optimized configuration requires more series servo displacement because it must augment the open-loop response more than is the case with the frequency-matched configuration. The performance-optimized configuration also saturates sooner and stays saturated

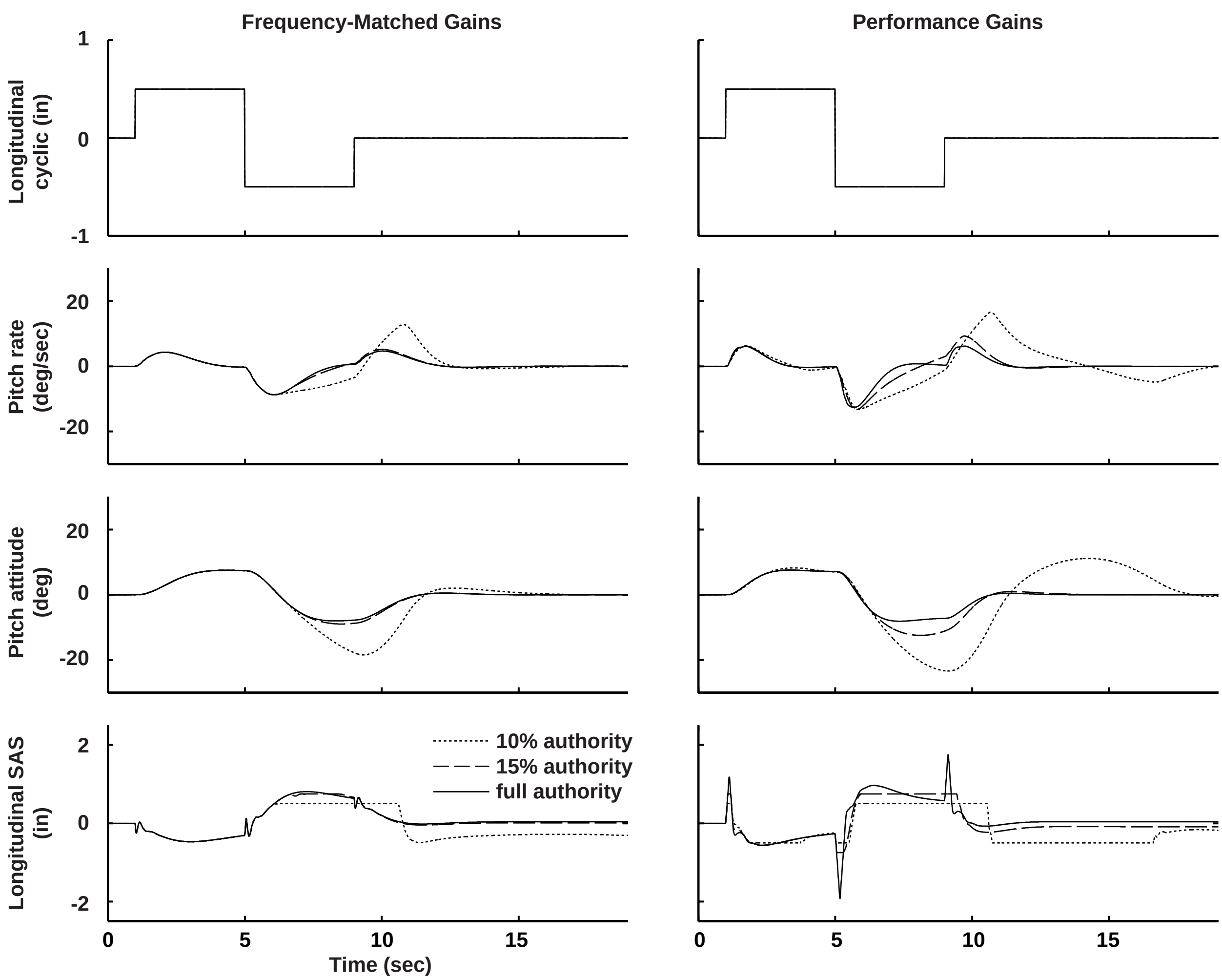

Fig. 9 Pitch doublet response (from linear model).

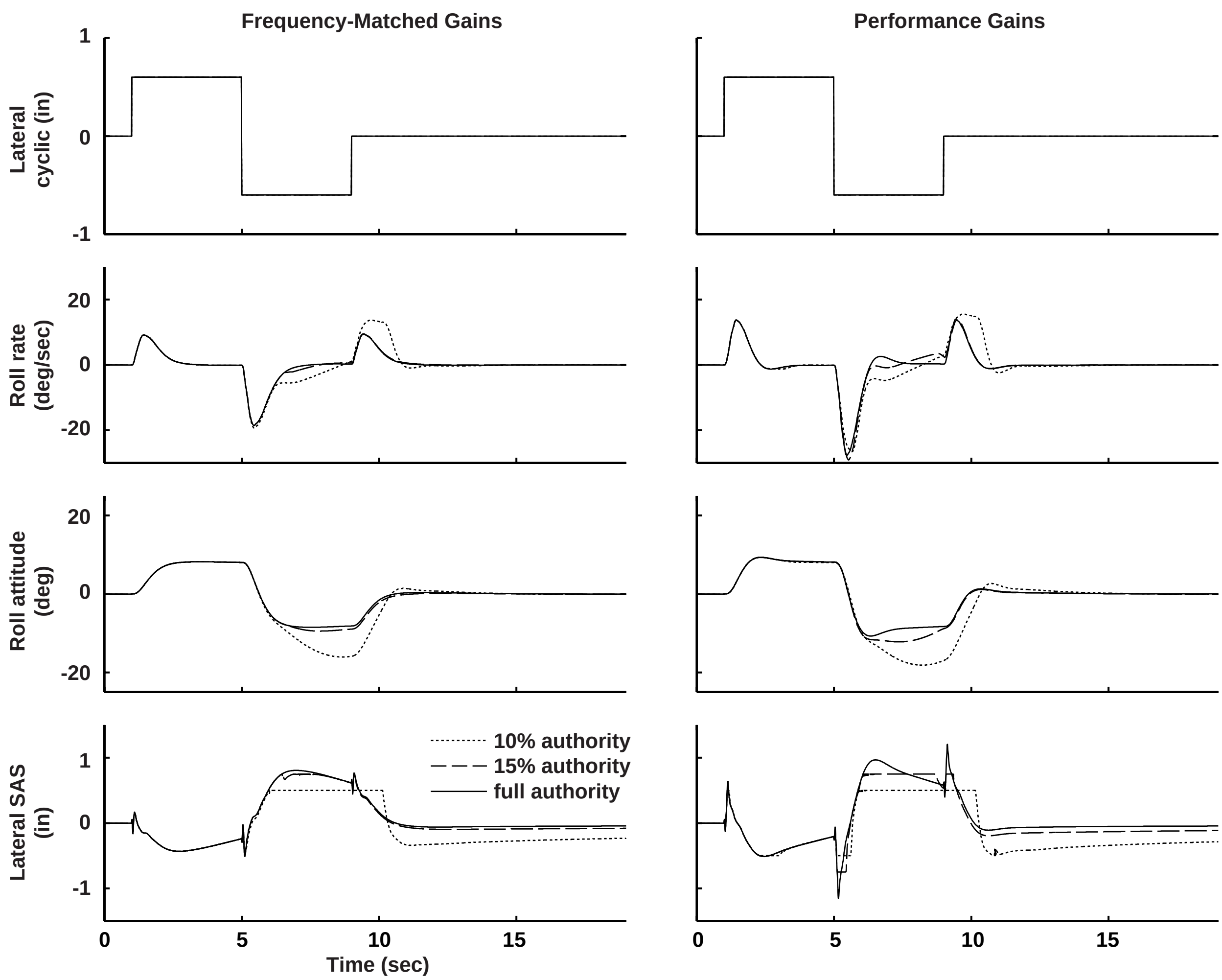

Fig. 10 Roll doublet response (from linear model).

longer than the frequency-matched configuration. These characteristics are more pronounced in the pitch axis than in the roll axis, as would be expected from the greater mismatch seen in the frequency domain.

The reduction in control activity achieved with the frequency-matching approach is also important when one considers the energy imparted to the rotor system. Previous work by Rozak and Ray suggests that significant rotor structural fatigue can be caused by the high-frequency actuator activity that results when trying to achieve high bandwidth.[8] By minimizing the difference between the open- and closed-loop systems, the series actuator activity has also been minimized in the mid- to high-frequency region.

Conduct of Piloted Simulation Trial

Trial Objectives

To evaluate the configurations described above, a piloted simulation trial was conducted on the Vertical Motion Simulator (VMS) at the NASA Ames Research Center.

The primary trial objective was to investigate the impact of AFCS series servo saturation on handling qualities in moderate aggression hover and low-speed maneuvers in a DVE. The two ACAH gain sets were evaluated at both 10 and 15 percent series servo authority levels. The parallel trim servo was not used. Assessment was made of both the handling qualities benefits to be gained from an increased level of authority and also the potential safety implications of a series servo hardover. Comparison was also drawn with a production UH-60 Black Hawk configuration which has a series servo SAS (high rate, 10 percent authority) to provide short term rate damping in the pitch, roll, and yaw axes and a parallel servo stick trim system (low rate, full authority) to provide attitude hold and autopilot functions.

A secondary objective was to accumulate knowledge that will assist in developing requirements for UH-60 Black Hawk in-service upgrades and, more generically, to expand the knowledge-base on optimization of partial authority AFCS.

Ames Research Center Vertical Motion Simulator

The investigation was conducted using the six-degree-of-freedom VMS with a rotorcraft cockpit (Fig. 11). The large motion capability of the VMS provides cues to the pilot that are critical to the study of helicopter handling qualities. The primary inputs to the motion base are the aircraft translational and rotational accelerations calculated by the math model for the pilot position. For this investigation the motion gains and washout frequencies were tuned for each individual task to make maximum use of the available travel.

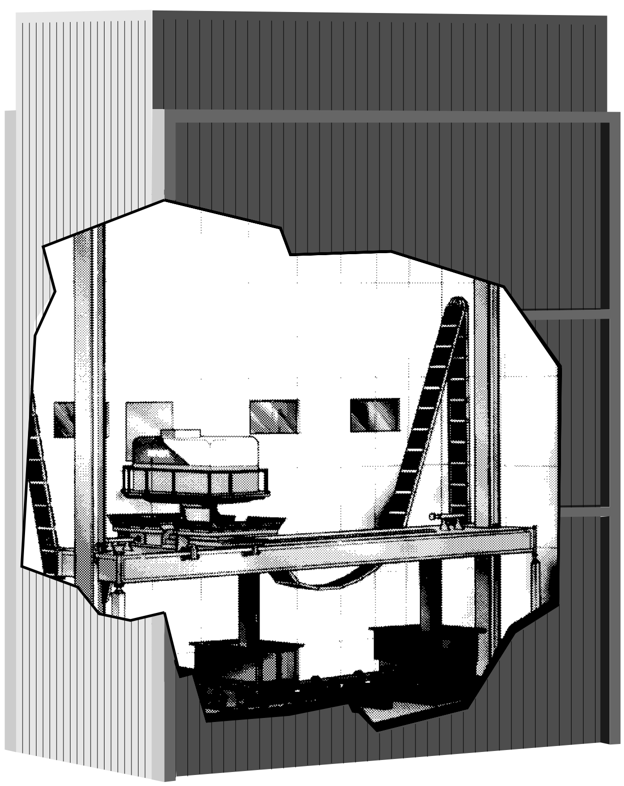

Fig. 11 NASA Ames Research Center Vertical Motion Simulator.

The control laws were integrated into the nonlinear GenHel UH-60 Simulation model. The model contains a blade element rotor model with flap and lag degrees of freedom, and static look-up tables for blade aerodynamic, rotor downwash, and fuselage aerodynamic forces. The rotor rpm degree of freedom and a component level T700 engine with rpm governor were also modeled as well as the nonlinear actuators, mixing box, and lead-lag damper systems.

The cockpit was configured for single pilot operation with conventional UH-60A Black Hawk cyclic and collective controls, analog instrument layout, and a four-window Evans and Sutherland ESIG 4530 computer generated imagery (CGI) display.

The image generator was set to a moonless night scene with a slight ambient light increase which gave a good qualitative appearance when used in conjunction with NVGs. The ANVIS-6 Generation III NVGs (Fig. 12) consist of two image tubes, which collect light and focus it on image intensifiers. Thus the NVGs work on the CGI display much as they would under normal operation; an example of the simulated night scene as viewed through the goggles is shown in Fig. 13. NVG compatible lighting was used to illuminate the instrument panel.

Fig. 12 ANVIS-6 Generation III night vision goggles.

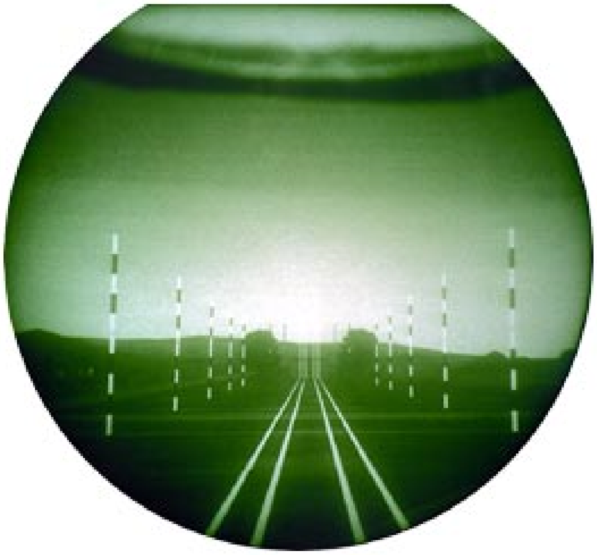

Fig. 13 Acceleration/deceleration course as viewed through night vision goggles.

Evaluation Tasks

This section describes the four tasks that were performed to assess the vehicle handling qualities. All four tasks were hover/low-speed tasks taken from ADS-33D. Position tolerances were measured relative to the pilot eyepoint. A headwind of 2 knots with light turbulence was added to each task to ensure that the pilot had to actively maintain vehicle position. Performance standards for each task are in given in Table 2 for operations in a good visual environment and in Table 3 for operations in a degraded visual environment.

Precision Hover. The objective of the precision hover was to check the ability to transition from translating flight to a stabilized hover with precision and a reasonable amount of aggressiveness in a DVE. The objective was also to check the ability to maintain precise position, heading, and altitude in a DVE.

Table 2 Summary of Day performance standards; desired (adequate).

	Hover	Accel/Decel	Sidestep	Pirouette
Transition time (sec)				45 (60)
Stabilize time (sec)	3 (8)		5 (10)	5 (10)
Hover hold time (sec)	30 (30)		5 (5)	
Longitudinal (ft)	± 3 (6)	0.5 (1.0) A/C length	± 10 (15)	± 10 (15)
Lateral (ft)	± 3 (6)	± 10 (20)	± 10 (10) of endpoint	± 10 (15) of start point
Vertical (ft)	± 2 (4)	< 50 (70)	± 10 (15)	± 3 (10)
Pitch (deg)		< "Acc" (–7) and > 30 (10)		
Roll (deg)			> 25 (25), <-30 (-30)	
Heading (deg)	± 5 (10)	±10 (20)	± 10 (15)	± 10 (15)
Notes:	No objectionable oscillations	95% power in 3 (1.5) sec; RPM within OFE/SFE; "pilot acceptable" nose down for desired	Overshoot of endpoint is ok, but final hover must be within ± 10 (10) ft tolerance	Nominal lateral speed is 8 (6) kts.

Table 3 Summary of DVE performance standards; desired (adequate).

	Hover	Accel/Decel	Sidestep	Pirouette
Transition time (sec)				60 (75)
Stabilize time (sec)	10 (20)		10 (20)	10 (20)
Hover hold time (sec)	30 (30)		5 (5)	
Longitudinal (ft)	± 3 (8)	0.5 (1.0) A/C length	± 10 (15)	± 10 (15)
Lateral (ft)	± 3 (8)	± 10 (20)	± 10 (10) of endpoint	± 10 (15) of start point
Vertical (ft)	± 2 (4)	< 50 (70)	± 10 (15)	± 4 (10)
Pitch (deg)		< -12 (-7) and > 15 (10)		
Roll (deg)			> 20 (10)	
Heading (deg)	± 5 (10)	±10 (20)	± 10 (15)	± 10 (15)
Notes:	No objectionable oscillations	RPM within OFE/SFE	Overshoot of endpoint is ok, but final hover must be within ± 10 (10) ft tolerance	Nominal lateral speed is 6 (5) kts.

The maneuver was initiated in a hover. The pilot would transition to a ground speed of between 6 and 10 knots with the target hover point oriented approximately 45 deg relative to the heading of the rotorcraft. The initial ground track was such that the rotorcraft arrived over the target hover point with minimum correction. Once stabilized over the target hover point, the pilot would hold the hover position for 30 sec. Figure 14 illustrates the precision hover task.

Acceleration and Deceleration. The primary objective of the acceleration/deceleration task was to check pitch axis and heave axis handling qualities for reasonably aggressive maneuvering in a DVE.

The maneuver was initiated in a hover. The pilot would then accelerate to a ground speed of at least 50 knots, and immediately decelerate to a hover over a defined point. The maximum nose-down attitude was to occur immediately after initiating the maneuver, and the peak nose-up pitch attitude was to occur just before reaching the final stabilized hover.

The test course consisted of two rows of pylons indicating the desired track during the acceleration and deceleration, and markers to denote the starting point and endpoint of the maneuver. The course included reference lines parallel to the course centerline to allow the pilot to perceive desired and adequate lateral tracking performance. The test course for this maneuver is shown in Fig. 15.

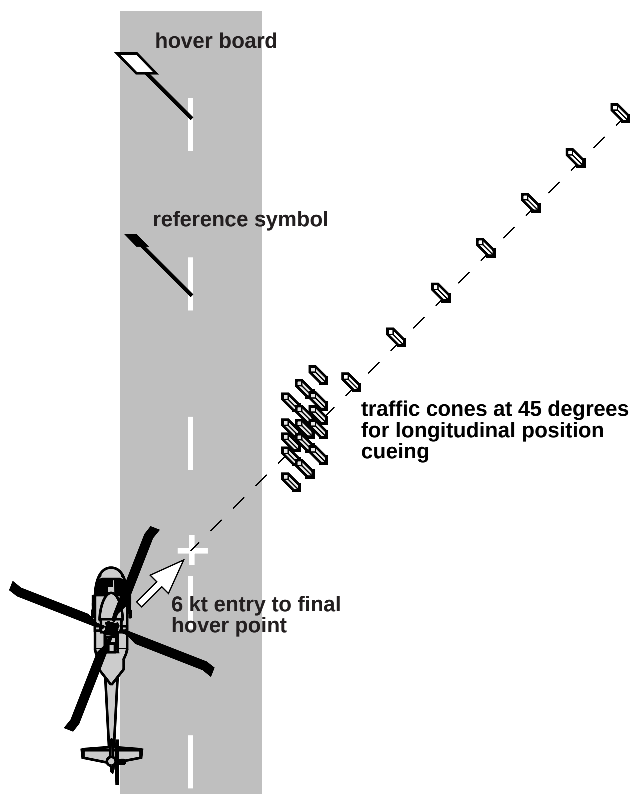

Fig. 14 Hover course.

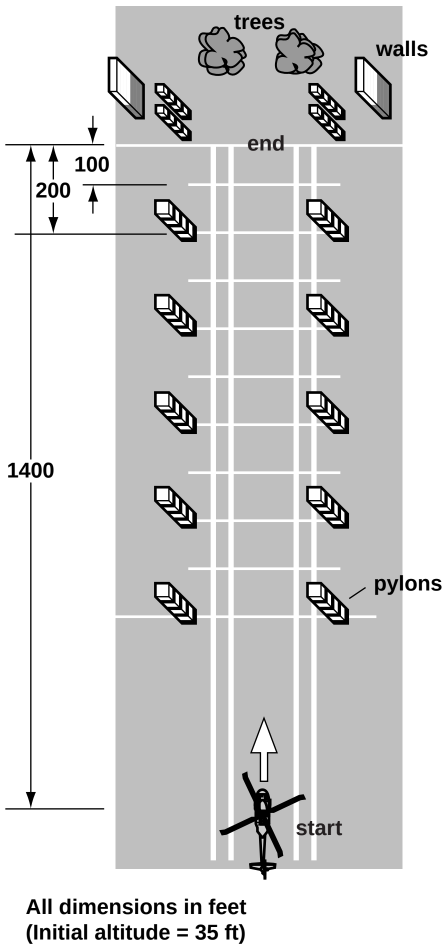

Fig. 15 Acceleration/deceleration course.

Sidestep. The primary objective of the sidestep task was to check lateral-directional handling qualities for reasonably aggressive lateral maneuvering in a DVE.

The maneuver was initiated in a hover with the longitudinal axis of the rotorcraft oriented 90 deg to a reference line marked on the ground. The pilot then initiated a lateral translation to approximately 17 knots, holding altitude constant with power. This was followed by a deceleration to laterally reposition the aircraft to a spot 400 ft down the course. The acceleration and deceleration phases were to be accomplished in a single smooth maneuver. The rotorcraft was to be brought to within 10 ft of the endpoint during the deceleration, terminating in a stable hover within this band. The pilot was then required to establish and maintained a stabilized hover for 5 sec. The maneuver was performed only to the right as that was found to be the more critical direction in terms of control authority and vehicle stability.

The test course consisted of a reference line on the ground indicating the desired track during the acceleration and deceleration, and markers to denote the starting and endpoint of the maneuver. The course also included reference lines parallel to the course reference line to allow the pilot to perceive the desired and adequate longitudinal tracking performance. The test course is shown in Fig. 16.

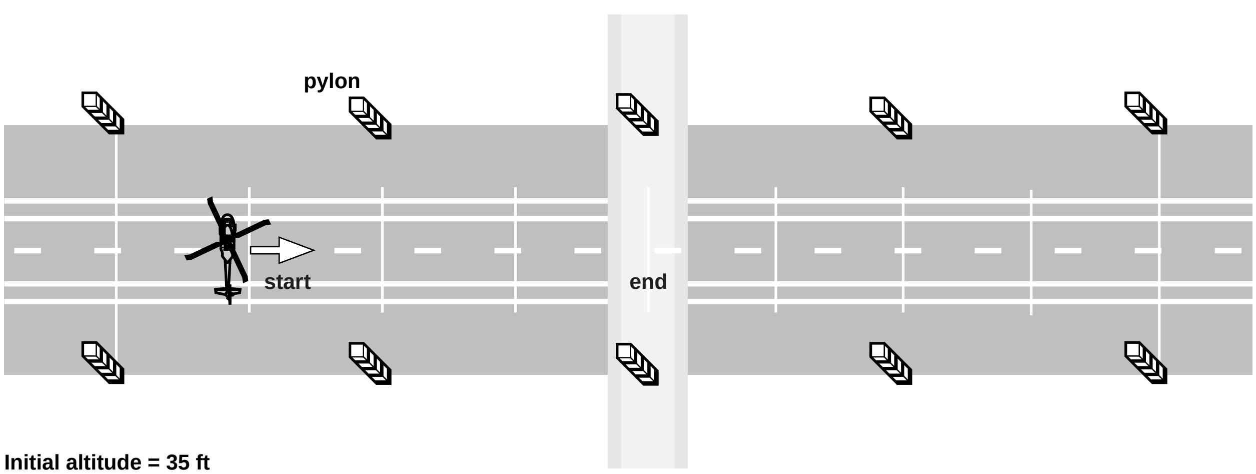

Fig. 16 Sidestep course.

Pirouette. The primary objective of the pirouette was to check the ability to accomplish precision control of the rotorcraft simultaneously in the pitch, roll, yaw, and heave axes in a DVE.

The maneuver was initiated from a stabilized hover over a point on the circumference of a 100 ft radius circle with the nose of the rotorcraft pointed at a reference point at the center of the circle, and at a hover altitude of approximately 10 ft. The pilot then executed a lateral translation around the circle, keeping the nose of the rotorcraft pointed at the center of the circle, and the circumference of the circle under the pilot eyepoint. The pilot was required to terminate the maneuver in a stabilized hover over the starting point. The maneuver was performed in a counterclockwise direction only because right-sideward flight was found to be more challenging than left-sideward flight.

The test course consisted of markings on the ground that clearly denoted the circular pathways that defined desired and adequate performance. The pirouette course is shown in Fig. 17.

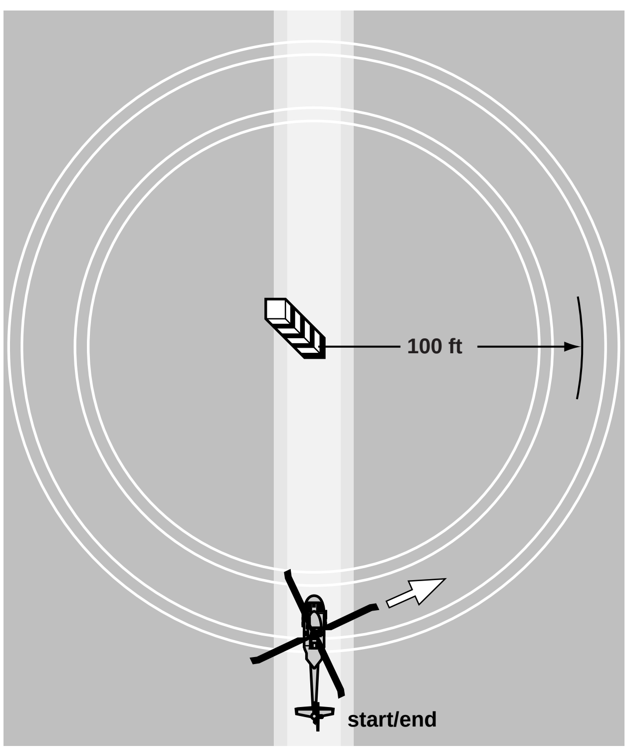

Fig. 17 Pirouette course.

Useable Cue Environment (UCE) Assessment

A UCE assessment was conducted in accordance with ADS-33D guidelines to calibrate the visual cues available to the pilot in performing the later handling qualities evaluation. In particular, confirmation was required that the combination of a simulated night scene with NVGs gave a UCE = 2 environment; i.e., that level of attitude and translational rate cues for which ADS-33D mandates an ACAH response type. Visual cue ratings (VCRs) for attitude and translational rate were given (Fig. 18).

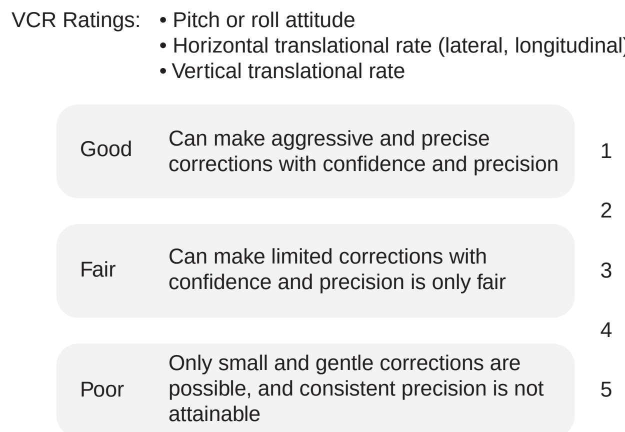

Fig. 18 Visual cue rating (VCR) scale.

The results of the UCE assessment are shown in Fig. 19 with each task represented by a shaded region indicating the 95 percent confidence interval for the VCRs assigned. Mean HQRs for the UCE assessment are also shown. The combination of NVGs with the night CGI scene worked well and was considered by all pilots to be a good representation of the real world. A borderline UCE = 1/2 rating was returned for the acceleration-deceleration task and a UCE = 2 rating for all other tasks. The horizontal field of view was restricted to approximately ±75 deg, which prevented the pilot from obtaining good fore and aft drift cues, particularly during the sidestep and pirouette tasks. In all cases, perception of fore/aft drift determined the UCE.

Interestingly, the acceleration-deceleration task was easier to fly in the simulated DVE because ADS-33D calls for only a 15 deg nose-up deceleration attitude as opposed to a 30 deg nose-up deceleration attitude in a good visual environment. This combined with a final fore/aft position tolerance of one-half of an aircraft length (±35 ft) made this the easiest task to fly. Conversely, the precision hover was expected to be the most benign task, but a fore/aft position tolerance of ±3 ft actually made it the most challenging.

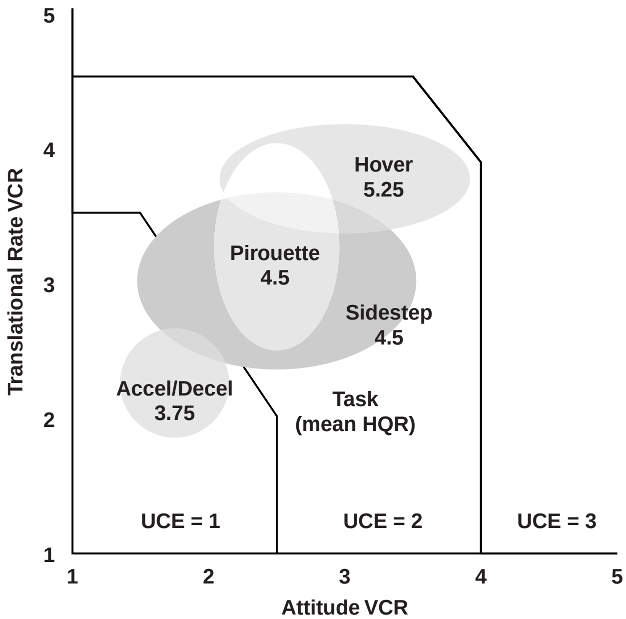

Fig. 19 Summary of UCE Ratings for hover and low speed tasks in simulated night + ANVIS-6 NVG operations.

The HQRs given for the four tasks closely reflect the respective VCR ratings which in turn reflect the respective fore/aft position limits, suggesting that task performance constraints had as much of an impact on the perceived cues as visual scene content, resolution, etc. With the exception of the acceleration/deceleration task, the tasks were found to lie sufficiently within the UCE = 2 region to justify proceeding with the handling qualities evaluation. The acceleration/deceleration task was retained with the understanding that the handling qualities results would need to be interpreted bearing in mind the fact that the task was rated borderline UCE = 1/2.

Trial Conduct

The simulation trial consisted of three main elements. The first was an assessment of the Usable Cue Environment described previously. The second was a handling qualities evaluation of the matrix of gain set and series authority configurations. The third was a comparison of the hardover failure characteristics of the 10 and 15 percent authority limited series servos. Subjective pilot commentary in response to a questionnaire was gathered as well as HQRs. In total, almost 1400 runs were performed by a combination of seven pilots (3 NASA, 2 U.S. Army, 1 U.S. Navy, 1 U.K. Army).

Discussion of Results

A summary of task performance and pilot opinion results is given in Fig. 20. Mean values and 95 percent confidence intervals are shown. Figure 21 shows the same statistics relative to the conventional UH-60 SAS configuration, with each statistic normalized by the standard deviation for all configurations.

The HQRs show that the ACAH configurations were generally preferred to the SAS/FPS system of the production UH-60. However, Level 1 ratings were rarely achieved, with pilot commentary indicating that the limiting factor was most often the poor visual cues for longitudinal positioning. Pilots expressed a desire for increased visual augmentation or a position hold function to improve the overall handling qualities ratings to Level 1.

The subjective HQRs show a one-point improvement for the frequency-matched configurations over the performance-optimized configurations and equivalent or slightly better objective task performance in terms of time to stabilize and longitudinal and lateral position errors. All pilots commented on the predictability of the frequency-matched configurations and whereas some pilots liked the crispness of the higher bandwidth performance-optimized configurations, others found it too abrupt. When questioned, pilots tended not to be aware that saturation had occurred, even though the series servo was limited for 30 to 40 percent of the time in the sidestep and up to 70 percent of the time in the acceleration/deceleration task. The pilots did comment, however, that the performance-optimized configurations had a tendency to be “ratchety” or “jerky” in these higher gain tasks and that pilot induced oscillations (PIO) could be excited if the pilot was “too tight in the loop.” It was noted that these comments correlated directly with occurrences of saturation, reinforcing the hypothesis that it is the relative mismatch between open- and closed-loop dynamics that pilots perceive upon saturation and that the magnitude of this mismatch relates directly to handling deficiencies. To this end, frequency matching improved handling characteristics such that desired performance was achieved consistently with moderate pilot compensation (HQR $\leq$ 4).

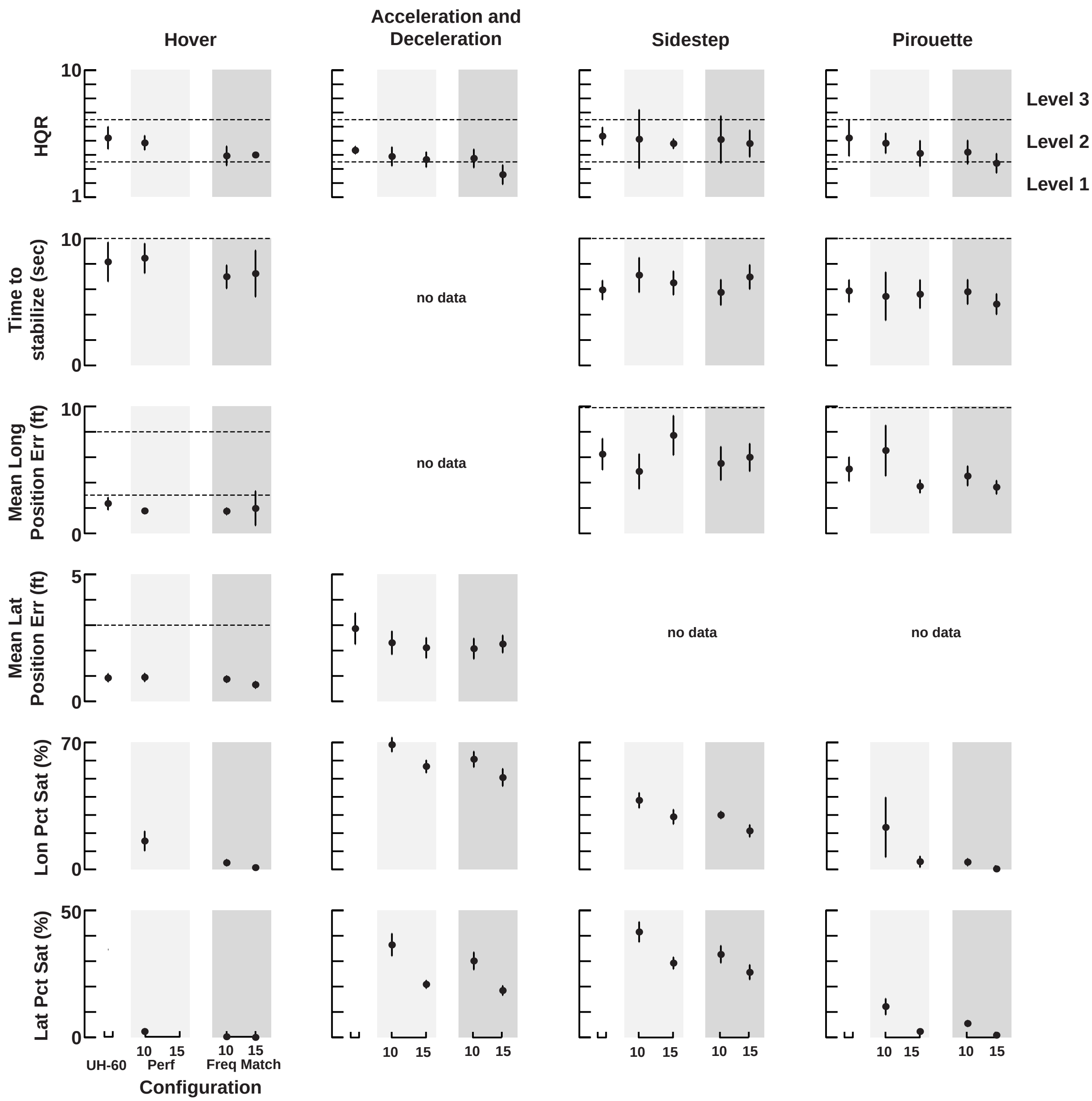

Fig. 20 Summary pilot opinion and task performance statistics.

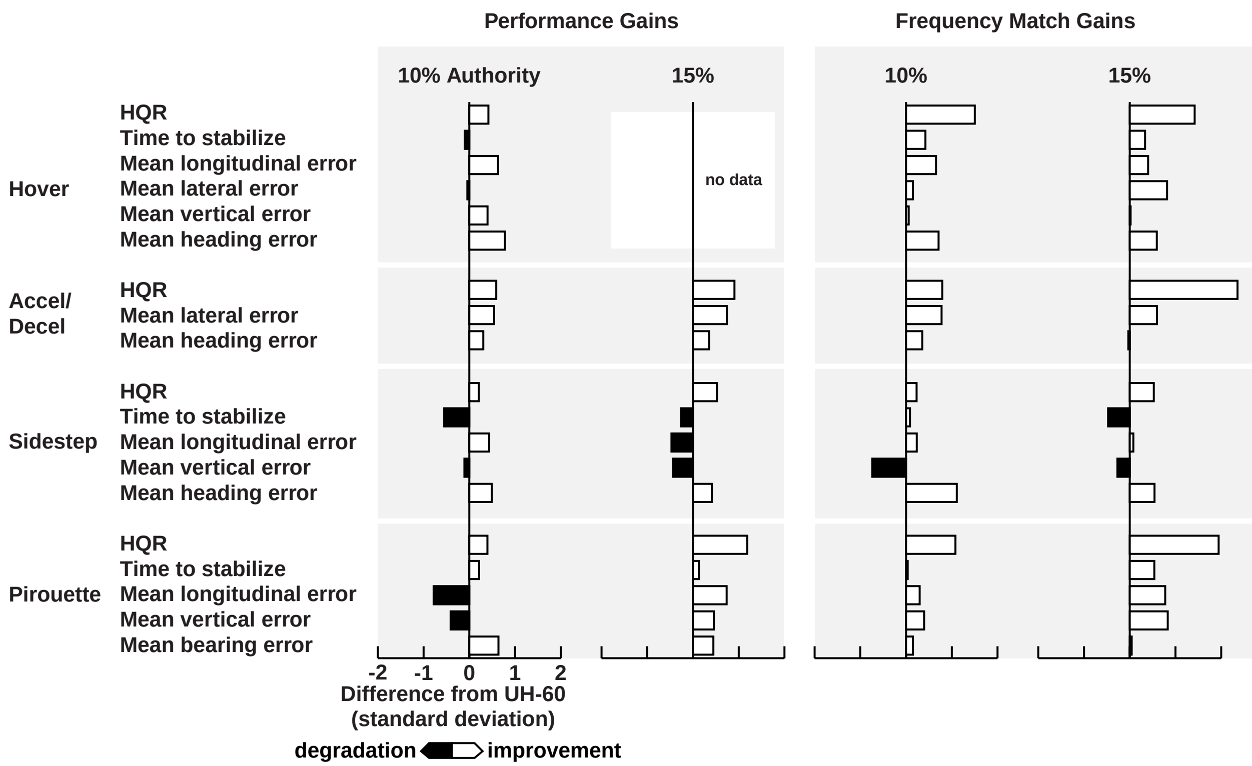

Fig. 21 Summary statistics.

Increasing series authority to 15 percent improved HQRs one-half to one rating in the acceleration/deceleration and pirouette tasks. In the hover task, saturation was not a factor even at the 10 percent level and so increasing it to 15 percent had little effect. In the sidestep, the ratings were dominated by pitch axis saturation effects that could not be accounted for even at the 15 percent level. These effects are described in more detail below.

Pitch Saturation Effects on the Sidestep Task

The handling qualities results for the sidestep task were dominated by saturation of the pitch axis series servo caused by the significant longitudinal stick trim requirement for sideward flight. Figure 22 shows the cyclic trim requirement for sideward flight as determined from the GenHel model. Assuming that the pilot does not manually retrim the cyclic during the maneuver, all trim changes must be taken up by the AFCS to maintain the commanded attitude. Hence for right-sideward flight, the pitch series servo limit will be reached at speeds slower than is typical for the ADS-33 sidestep task (Day UCE or DVE standards); approximately 10 and 15 knots for 10 and 15 percent authority, respectively.

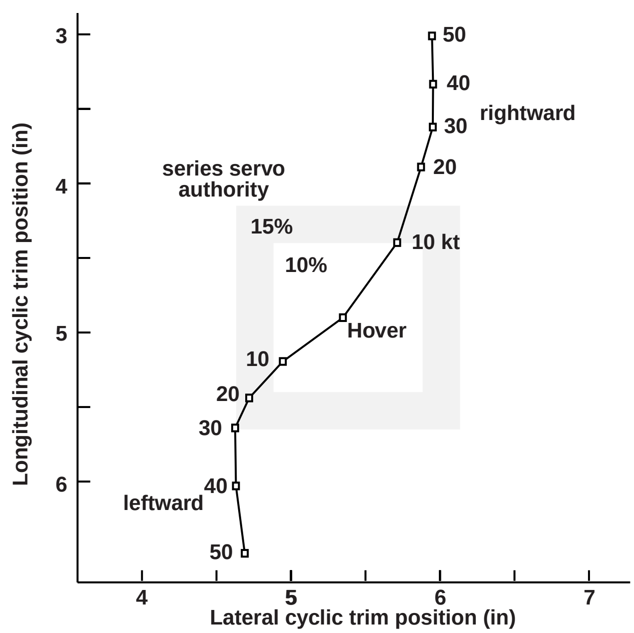

Fig. 22 Series servo authority required for trimmed sideward flight.

Since the pilot wasn't commanding a pitch attitude change while performing the sidestep, the pitch divergence resulting from saturation was viewed as highly undesirable. The solution to this problem would be to increase series servo authority or add a parallel trim follow-up, but from Fig. 22 it can be seen that as much as 25 percent pitch series servo authority would be required to avoid saturation in a right sidestep. Further work is required to validate this phenomenon against flight test data.

For completeness, the sidestep task was flown with the pitch series servo authority increased to 100 percent and, as expected, the pitch axis behavior was benign and the pilots returned handling qualities ratings of HQR = 3.

Series Servo Failure Evaluation

A series servo failure evaluation was performed to assess the relative ability of the pilot to recover from 10 versus 15 percent authority hardover failures. This portion of the trial was not intended as a comprehensive failure analysis, it was intended merely to expose hardover recovery issues that might arise if the existing series servo authority was increased.

Four pilots flew both the acceleration/deceleration and sidestep tasks with either a pitch or roll failure being injected at some point during the run. In each case the series servo was failed instantaneously to its fullest extent to simulate a dual-channel runaway. The system was also failed at three different points within each maneuver over a series of runs; i.e., initial pitch down/roll in, wings-level transition, and final pitch up/roll out. The pilot was required to complete the task “as best as possible” after each failure. The pilot gave a failure recovery rating using the scale presented in Ref. 9 The failure rating scale divides failures into three categories: 1) failures for which the recovery is tolerable, 2) failures for which safety of flight is compromised, and 3) failures which are catastrophic.

Mean values and 95 percent confidence intervals for the series servo failure evaluation are shown in Fig. 23. In general, all failures were recoverable with varying levels of urgency. Pitch axis failures tended to be one failure rating point worse than roll axis failures. Failures in the final pitch-up or roll-out phase of the maneuvers were the most demanding. Of most significance was the fact that 15 percent authority series servo failures were generally only one failure rating point worse than 10 percent authority failures. This small degradation in failure recoverability would be an important factor in any trade-off study assessing the benefits of increased authority.

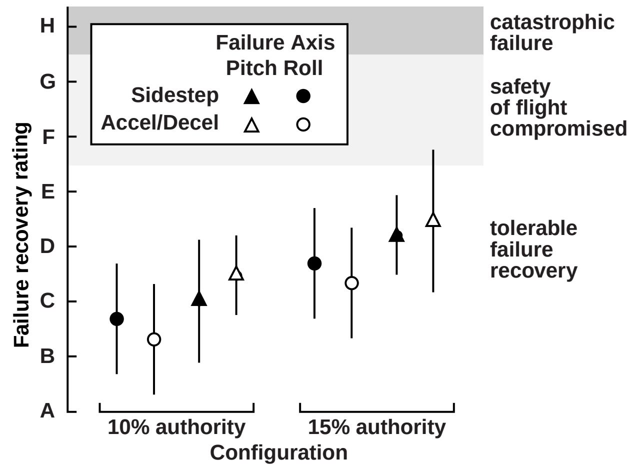

Fig. 23 Summary of failure recovery ratings (Ref. 9) for 10 and 15 percent authority series servo hardover failures.

Influence of Control Law Configuration on Series Servo Activity

Significant differences were seen in series servo behavior between the performance-optimized and frequency-matched configurations both in terms of saturation and dynamic behavior with the impact going beyond handling qualities.

As expected from the earlier design analysis, the performance-optimized configuration was seen to be more dynamic then the frequency-matched configuration in terms of control activity. This difference is illustrated in Fig. 24 which shows the series servo time history for the initial portion of the precision hover task (with no saturation).

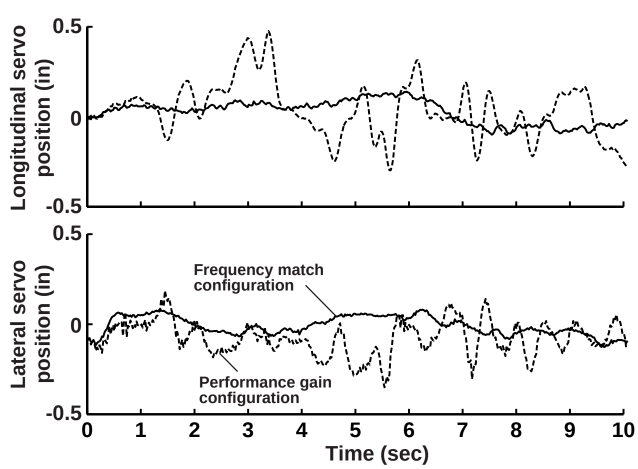

Fig. 24 Series servo time history during hover task.

The series servo activity can also be expressed in terms of the cutoff frequency. Cutoff frequency is derived from the power spectral density (PSD) function and represents the frequency at which 70 percent of the energy (area under the PSD) has been accounted for. It is analogous to the 3 dB crossover frequency for servomechanisms.[10] The lateral and longitudinal series servo cutoff frequencies are shown in Figs. 25 and 26. The data shown are mean values for all of the runs.

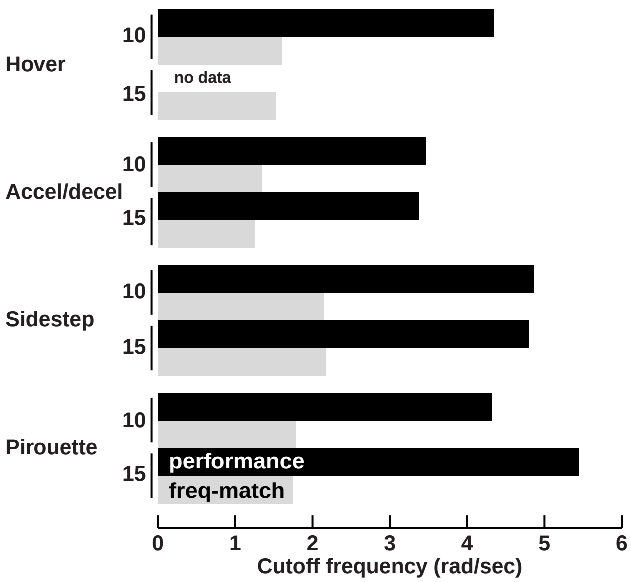

Fig. 25 Longitudinal series servo cutoff frequency.

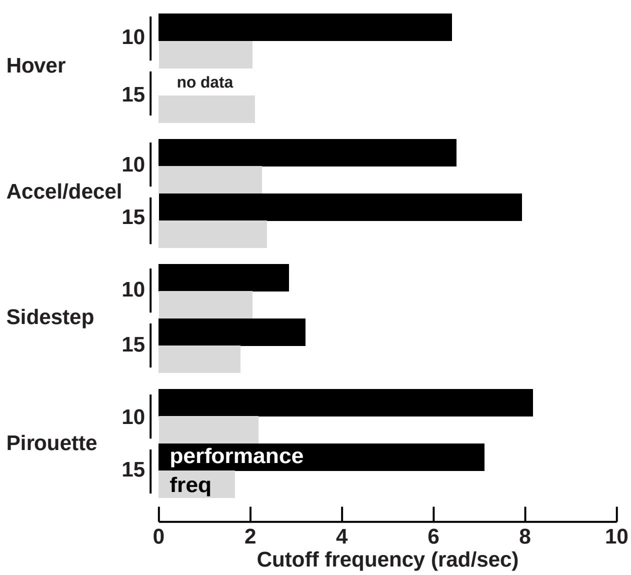

Fig. 26 Lateral series servo cutoff frequency.

The cutoff frequencies show that the performance configurations had more high-frequency activity than the frequency-matched configurations. In general, the cutoff frequency for the performance-optimized configurations was three times higher than for the frequency-matched configurations; i.e., a 300 percent increase in control energy injected to the rotor system was required to achieve a 50 percent increase in attitude bandwidth. This high-frequency behavior can have substantial negative impact on rotor system structural fatigue as described previously.

Conclusions

A ground-based piloted simulation study of a PAFCA concept for the UH-60 Black Hawk helicopter was performed to investigate the impact of series servo saturation on handling qualities in moderate aggression hover/low-speed maneuvers in a DVE. The simulated DVE was judged representative of night operation using NVGs and was assessed overall as UCE = 2.

The following major points were noted:

- The ACAH response type provided by the PAFCA control law was preferred to the response type of the standard UH-60 Black Hawk SAS for the tasks evaluated.

- Saturation of the series servos occurred in all maneuvers with the exception of the precision hover. Frequency matching of the partial authority ACAH control law reduced high-frequency series servo activity, delayed onset of series servo saturation, and improved control predictability when saturation did occur.

- Desired task performance was achieved (HQR ≤ 4) with the frequency-matched ACAH control law using only 10 percent series servo authority. Inability to perceive and precisely control longitudinal drift was cited most often as the limiting factor in achieving Level 1 handling qualities.

- Increasing series servo authority to 15 percent improved handling qualities by approximately one HQR.

- The 15 percent authority series servo hardovers were rated one failure rating point worse for the 10 percent authority hardovers, but all failures were recoverable and tolerable.

It is further concluded that the accumulated knowledge will assist in developing requirements for potential UH-60 Black Hawk upgrades and also provide guidance on optimization of PAFCA systems. Improved mission effectiveness of in-service aircraft could be achieved through relatively low cost upgrades encompassing the synergistic integration of the AFCS with the force-feel system, feedback sensors, series and parallel servos, and task tailored control laws.

In-flight test of PAFCA concepts based on the frequency-matching control law design principle is planned for 1999.

Acknowledgment

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