Flying Quality Analysis and Flight Evaluation of a Highly Augmented Combat Rotorcraft

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This paper discusses implications of digital flight control system design for rotorcraft and illustrates the analysis of the resulting handling qualities obtained with the Advanced Digital Optical Control System demonstrator in the context of the proposed new handling-qualities specification for rotorcraft. Topics covered are digital flight control design and analysis methods, flight testing techniques, handling-qualities evaluation results, and correlation of flight test results with analytical models and the proposed handling-qualities specification. The evaluation of the demonstrator system indicates desirable response characteristics based on equivalent damping and frequency, but undesirably large effective time delays (exceeding 240 ms in all axes). Piloted handling qualities are found to be desirable or adequate for all low, medium, and high pilot gain tasks, but handling qualities are inadequate for ultrahigh gain tasks such as slope and running landings. Correlation of these results with the proposed handling-qualities specification indicates good agreement for the bandwidth boundaries, but suggests the need for more stringent limits on allowable phase delay. Analytical models based on emulation (*s*-plane) techniques compare favorably with flight-extracted frequency-domain characteristics of the overall (end-to-end) system responses.

Introduction

ADVANCED combat (scout/attack) rotorcraft must exhibit good handling qualities over a diverse spectrum of operational missions. Precision flight-path and attitude control and inherent tight attitude stability are needed for nap-of-the-Earth (NOE) and hovering flight, especially in degraded visibility and/or single pilot operations, whereas, for air-to-air combat, not only agility but high maneuverability are required. To meet these requirements, advanced combat rotorcraft will require multimode, high-bandwidth digital flight-control systems. Pilot inputs may be provided through multiaxis, side-stick controllers electronically or optically linked only to a flight-control computer. A number of research aircraft[1-3] have been developed to examine technologies needed to achieve these requirements. Unfortunately, the gap between demonstrated rotorcraft flight-control technology and the handling-qualities requirements for advanced combat rotorcraft in high pilot-gain tasks[4] is still a considerable one. One largely elusive goal of advanced control system technology, as applied to modern rotorcraft, is to achieve high bandwidth and low time delay response characteristics for good overall handling qualities. Achieving this goal will require significant methodology improvements to the flight-control system at all stages of its design, implementation, and testing.

Key concepts in the analysis and design of high-bandwidth digital flight-control systems for advanced combat rotorcraft were presented and illustrated in a comprehensive analytical study by Tischler.[5] Flight testing methods have been developed especially for characterizing the response dynamics of highly augmented rotorcraft. These advanced flight-control system methods have been applied in a comprehensive evaluation of the Advanced Digital Optical Control System (ADOCS) demonstrator. This demonstrator is a UH-60A helicopter highly modified with redundant processors, instrumentation, and side-stick controllers.[1] The overall program objective of the ADOCS was to provide the technology base for the engineering development of an advanced battlefield-compatible flight-control system that 1) enhances aircraft mission capability, 2) improves handling qualities, and 3) decreases pilot workload. The ADOCS program has provided an extensive base of experience on the design, testing, and analysis of a full flight-envelope advanced combat rotorcraft. Researchers at NASA Ames Research Center (ARC) have supported the ADOCS project with piloted simulation studies,[6,7] flight-control analyses,[5,8] and flight test evaluations.

The purpose of this paper is to illustrate the application of these advanced flight-control system methodologies in a comprehensive evaluation of the ADOCS demonstrator, with the primary objectives being to describe the knowledge gained concerning the implications of digital flight-control design for rotorcraft, and to illustrate the analysis of the resulting handling qualities in the context of the new handling-qualities specification. Accordingly, a general review of the ADOCS flight-control system is given initially, with particular emphasis on the elements that are important to the design of such a digital control system for rotorcraft relative to the handling qualities. Flight test results are then reviewed, first in terms of the observed handling qualities and then in terms of closed-loop aircraft characteristics determined using system identification procedures. On this basis, the identified characteristics are matched against the new handling-qualities specifications, and the predicted handling qualities thus obtained are compared with the flight results. Additional analytical and flight test results that address digital system characteristics are presented in the original version of this paper.[9]

Advanced Flight-Control System Design and Analysis Based on the ADOCS Concept

This section presents an overview of the ADOCS concept and an analysis of the pitch channel using flight values of the control system parameters.

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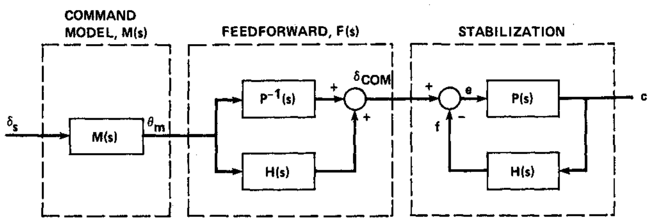

Fig. 1 ADOCS generic model-following concept.

ADOCS Concept

The ADOCS model-following concept is shown generically in Fig. 1. This architecture uses feed-forward and inverse plant dynamics to cancel the inherent rotorcraft dynamics and replace them with the desired command responses. A key advantage of this explicit model-following approach is the capability to independently set the command and stabilization response characteristics, thus providing multimode handling qualities as is required for the scout/attack (SCAT) mission. For example, an attitude command response may be desired for low-speed flight in degraded visibility conditions, whereas a rate command system may be desirable for flight in unrestricted visibility conditions. In both environments, a high degree of attitude stabilization is desirable. In the actual ADOCS implementation, the block diagram of Fig. 1 is rearranged somewhat to separate the system into two digital paths. One path, the primary flight-control system (PFCS), contains only feed-forward elements and serves as a high-reliability backup system. The other path, the automatic flight-control system (AFCS), contains both feed-forward and feedback elements. In the fully operational state, both paths are active and the response characteristics simplify to those of Fig. 1. Therefore, the distinction between the PFCS and AFCS is not important to this study.

Reference 5 presents a comprehensive case study of an advanced hover/low-speed flight-control system for the UH-60 based on the ADOCS concept using design values for the important parameters. Analog methods are used to illustrate the degradation in control system performance resulting from the various practical implementation aspects discussed earlier. Analog and direct digital methods were used to evaluate control system performance for a nominal 30-Hz operational system and a backup 15-Hz design. The following discussion presents updated results of the analysis of the 30-Hz pitch channel based on the actual flight test values of the control system parameters. Analytical and flight test results are compared later in this paper.

Pitch Axis Characteristics Using *s*-Plane Analysis Techniques

Analysis techniques based on analog (*s*-plane) control theory are very useful in evaluating the overall end-to-end performance of a moderate sample rate control system, such as the ADOCS. A block diagram of the flight test configuration pitch axis channel for hover is shown in Fig. 2. (Once again the distinction between the PFCS path and AFCS path is not important for analyzing the fully functioning system.) The feedback gains for the flight test configuration are given in the column titled Current Flight Value of Table 1. Pilot command

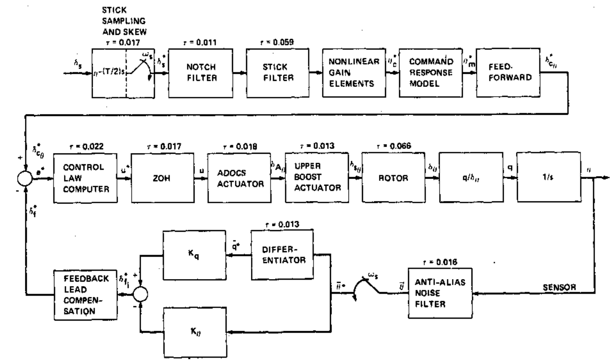

Fig. 2 Simplified schematic of ADOCS pitch channel in hover; effective time delay for high-frequency dynamics are indicated in figure.

inputs from a multiaxis, side-stick controller δ_s are sampled and then passed to the digital flight computer. Notch filter and low pass filter compensation is also required in the command path to eliminate undesirable biodynamic interference, which has been a recurring problem associated with side-stick controllers in rotorcraft[2,10] and fixed-wing aircraft.[5] The command path also contains selectable response shaping modes (e.g., attitude command or rate command) and feed-forward dynamics to improve control-response bandwidth. The command model for the pitch channel in hover is a second-order, 2-rad/s, attitude response with a 5-s trim rate follow-up to alleviate steady trim-force requirements (Table 2). The command loop contains several nonlinear elements (dead zone, nonlinear stick sensitivity function, derivative rate limiter) that are ignored in the present analysis.

The digital feedback signals are obtained from onboard sensors, which are filtered to prevent aliasing of high-frequency noise, and are then sampled and shaped through digital feedback compensation. Forward-loop compensation provides the desired open-loop response characteristic δ_f/e and crossover frequency ω_c. The digital computer is coupled to the control surface actuators through a digital-to-analog converter (a zero-order hold), which introduces delays and high-frequency actuator ripple. Finally, the rotor and actuators dominate the high-frequency dynamics in rotorcraft flight-control systems. In hovering flight, the effective rotor system bandwidth is about 15 rad/s (Ref. 9); this frequency may only be three or four times greater than the closed-loop bandwidth and will, thus, have a significant impact on the achievable response characteristics. Each of the block diagram elements is represented by high-order transfer function models that are given in Ref. 5. For illustration, the equivalent time delay of each of these elements is indicated in the figure.

A root locus plot varying stabilization loop gain is presented in Fig. 3 using the higher-order transfer functions for all system elements. The open-loop, rigid-body modes are seen to be well suppressed, even for this fairly moderate design crossover frequency. The location of the dominant closed-loop mode at 2 rad/s is determined almost entirely by the location of the compensation zero at 1.54 rad/s, associated with the ratio of pitch attitude and pitch rate gains. As can also be seen in the figure, the bandwidth is limited by the destabilization of the regressing flapping mode.

Table 1 ADOCS AFCS feedback gains in hover

Feedback signal	Initial simulation	Final simulation/ initial flight value	% Change during design	Current flight value	% Change during flight test
Pitch rate, in./rad/s	16.0	6.4	−40	6.8	+6
Pitch attitude, in./rad	34.0	13.6	−40	10.4	−24
Roll rate, in./rad/s	6.0	2.4	−40	1.3	−46
Roll attitude, in./rad	20.0	8.0	−40	8.4	5
Yaw rate, in./rad/s	7.2	3.2	−44	4.0	25
Heading, in./rad	7.7	7.6	−1	7.6	0
Average			−34		−6

Table 2 Summary of command models for angular responses

Axis	Hover	$V > 40$ kt
Pitch, θ_m/θ_c	$\dfrac{4(s+0.2)}{s(s+2)(s+2)}$	Same as hover
Roll, ϕ_m/ϕ_c	$\dfrac{6.25(s+0.33)}{s(s+2.5)(s+2.5)}$	$\dfrac{5.08}{s(s+5.08)}$
Yaw, Ψ_m/Ψ_c	$\dfrac{2}{s(s+2)}$	Same as hover

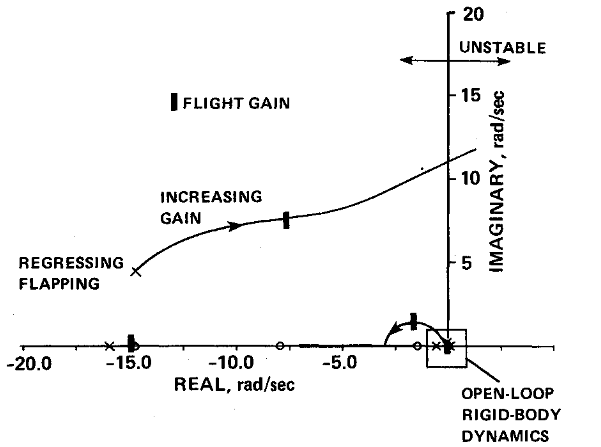

Fig. 3 Pitch channel root locus for stabilization loop vs loop gain.

The first two columns of Table 1 compare the feedback gains used in the original ADOCS simulation with the final design gains used in the first flight tests. The original simulation values[11] were based on design models that did not include many of the practical system implementation elements. The final preflight design model included these important implementation elements, as well as simulation updates based on component bench testing, and a more accurate representation of the coupled fuselage/rotor dynamics. The average gain reduction of 34% for the preflight design as compared to the original values emphasizes the importance of a high-fidelity model, especially in the representation of the high-frequency dynamic elements.[5] Once the high-fidelity design model was adopted, the flight gains were determined to within 6% of their final configuration values. This close prediction of flight gains emphasizes the need for high-fidelity math models in the control system design process, as was also demonstrated in Chen and Hindson.[12]

The frequency response of the normalized end-to-end transfer function θ/δ_s is coplotted with the response of the command model alone θ_m/θ_c in Fig. 4. The match between these responses is a good measure of the model-following performance of the system. Acceptable magnitude response following is maintained out to about 10 rad/s. At higher frequencies, following degrades because the rotor dynamics are not included in the inverse model P^{-1}.[5] Phase response following degrades at a much lower frequency because the time delays in the control system are not included in the command model.

The pitch attitude response to a step input in hover continues to increase monotonically during (and beyond) the first 4 s of the response, due to the trim rate follow-up (5-s time constant as indicated in θ_m/θ_c of Table 2). Therefore, despite having an attitude command model, the ADOCS is characterized by the handling qualities specification as a rate response type.[4] As such, the bandwidth frequency is defined the lesser of the 45-deg phase margin frequency or the 6-dB gain margin frequency. From Fig. 4, the system is gain-margin limited with a bandwidth of $\omega_{BW_\theta} = 2.48$ rad/s. The associated phase delay obtained from the figure is $\tau_{p_\theta} = 0.179$ s. Reference to the pitch response specifications of Ref. 4 indicates that the

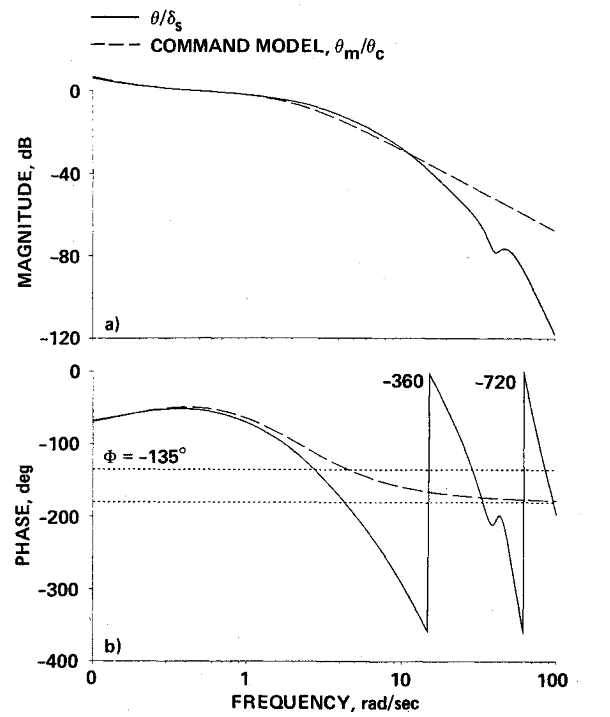

Fig. 4 Overall frequency response of the pitch system θ/δ_s compared with the command model θ_m/θ_c.

ADOCS should achieve level 1 handling qualities in all but the most severe tasks.

The end-to-end frequency response of Fig. 4 is well characterized by a second-order equivalent system model fit in the frequency range of 0.1–10.0 rad/s:

$$\frac{\theta}{\delta_s} = \frac{5.26(s+0.2)e^{-0.244s}}{s[0.964, 2.35]} \tag{1}$$

(Shorthand notation: $[\zeta, \omega]$ implies $s^2 + 2\zeta\omega s + \omega^2$.) Comparison of the equivalent system model of Eq. (1) with the handling-qualities data of Refs. 13 and 14 is shown in Figs. 5. The results of Fig. 5a indicate desirable command response characteristics based on damping ratio and natural frequency. However, reference to Fig. 5b suggests that the equivalent time delay of 244 ms will result in marginal level 2/level 3 handling qualities (HQR 6-7) for high stress pitch tasks. The breakdown of contributions by the various forward-loop elements to the total equivalent system time delay is summarized in Table 3. [The difference between the equivalent delay of Eq. (2) and the total of Table 3 is due to fit mismatch.] Clearly, the rotor, actuators, and filter dynamics are dominating the large time delay, as discussed earlier. The stick skewing and zero-order hold delays are a small fraction of the total value. Notice that the sensor filter is not included in Table 3 since elements in the feedback path do not substantially contribute to the command response time delay.

This completes the overview of the ADOCS pitch channel. Additional analytical results are presented in Refs. 5, 8, and 9.

Flight Testing Techniques

The ambitious, multiroled mission of the advanced combat rotorcraft has resulted in a significant rise in system complexity and has demanded a complete rethinking of the approach to handling-qualities evaluation and helicopter flight testing. Considerable emphasis must be placed on pilot familiarization to achieve the necessary level of training with new devices such as multiaxis sidestick controllers, advanced augmentation systems, automatic and manual mode switching, and subtle digital transient problems. Many of the classical handling-qualities tests such as stick-free stability and stick position vs speed may be meaningless because of isometric controllers, rate command response types, and high levels of feedback stability. Quantitative time-domain testing techniques based on steps and pulses are not sufficiently sensitive to equivalent time delays to expose potentially serious latent pilot-induced oscillation (PIO) tendencies and do not provide accurate measurement of bandwidth.[5,15] Therefore, a comprehensive frequency-domain-based technique using frequency sweeps and advanced system identification procedures has been developed and incorporated in the new specification.[16]

The ADOCS program has provided an excellent opportunity to evaluate advanced flight-control design and flight test techniques on a state-of-the-art combat rotorcraft. The primary objectives of the evaluation that is summarized here were to 1) evaluate the basic ADOCS handling-qualities characteristics for the AFCS in hover, low speed, and cruise flight; 2) quantify the end-to-end performance of the AFCS; 3) correlate handling-quality ratings and comments with quantitative response characteristics to provide guidance for future control system development; and 4) correlate findings with the new handling-qualities specifications.

This paper presents the results of a two-week Aeroflightdynamics Directorate (AFDD) evaluation of the 3 + 1 (collective) control configuration with a newly implemented displacement collective.

Prior to commencement of the flight evaluation, a set of frequency sweeps in each control axis was conducted on the ground with rotors stationary to familiarize the Boeing pilots with the desired input technique. As with the in-flight frequency sweeps that followed, the real-time control input data were transmitted to the ground data station for evaluation of amplitude and frequency content by the test engineer.[16]

The final phase handling-qualities evaluation was structured for one AFDD evaluation pilot flying maneuvers from the same basic test card of hover, low-speed, and up-and-away tasks on sequential flights. The assessment was structured to

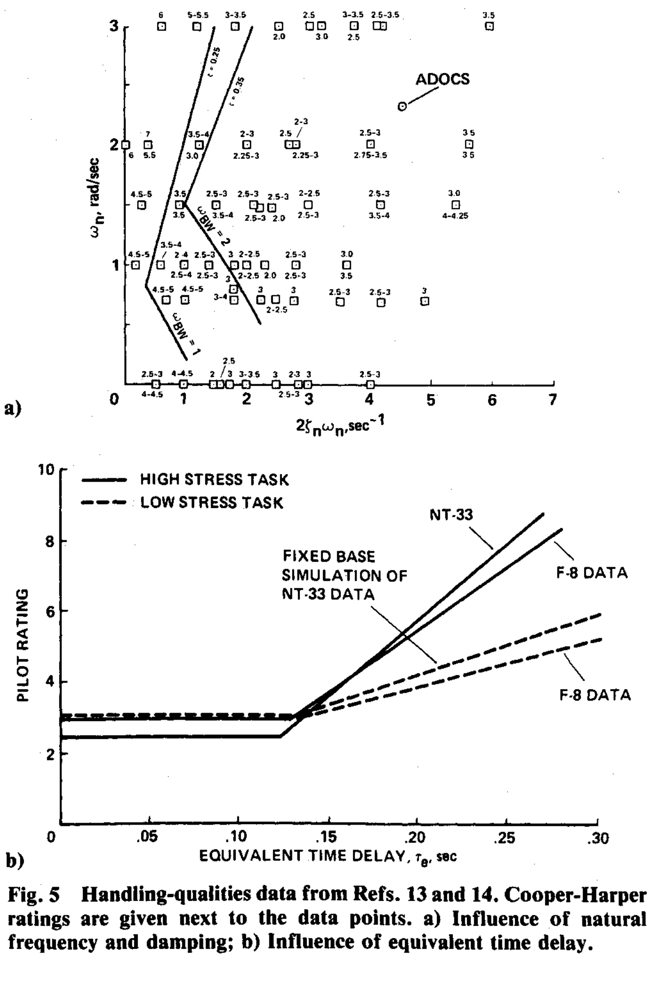

Fig. 5 Handling-qualities data from Refs. 13 and 14. Cooper-Harper ratings are given next to the data points. a) Influence of natural frequency and damping; b) Influence of equivalent time delay.

progress from primarily single-axis tasks to those requiring simultaneous control of four axes to provide a measure of the pilot learning curve on the sidearm controllers while obtaining the necessary pilot ratings. NOE, air-to-air, and PFCS-only tasks evaluated during the previous evaluations were not repeated here. Winds for all tasks were steady at speeds ranging from calm to 12 kt (variable at 6–8 kt for the most part). After a substantial number of repeat runs (3–10) (see Ref. 9), handling qualities ratings (HQR) were assigned to the tasks according to the methods and definitions contained in Ref. 17.

The primary AFCS configuration for both frequency sweep testing and the handling-qualities evaluation was the core AFCS with heading hold engaged (Fig. 6). The additional capabilities provided by the hover hold, velocity stabilization, and radar and barometric altitude hold modes were used selectively in the handling-qualities evaluation when considered appropriate for the task.

Handling-Qualities Evaluation

Side-stick controller implementations have generally demonstrated a degradation in HQRs as the pilot gain required to accomplish a task has increased. Increasing pilot gain, as used here, is indicated when the required precision of the task, as perceived by the pilot, forces an increase in control input frequency. The discussion of results obtained from the current experiment is therefore presented with respect to the low, medium, high, and ultrahigh gain nature of the individual tasks.

Low Gain Tasks

This category of task is characterized by attitude and velocity stability that produces a hands-off (or near hands-off capability) or low pilot workload in the primary control axis. The present configuration of the ADOCS appears optimized for the hover and low-speed environment where the aircraft flies best with a minimum of pilot input. Handling quality ratings were level 1 for all tasks.

Cruise Flight

In up-and-away cruise flight, the aircraft was well stabilized for constant attitude and airspeed. Direct control of collective pitch though the displacement collective resulted in good control of vertical rates. Steady-state roll rate was quite reason-

Table 3 Summary of equivalent time delays in ADOCS flight configuration pitch channel

Element	Delay, ms	% of total
Rotor	66	30
Actuators	31	14
Zero-order hold	17	8
Computations	22	10
Notch filter	11	5
Stick filter	59	26
Stick sampling skew	17	8
Total delay	223	

AFCS mode	Control axis	Less than 40 knots	Greater than 40 knots
Core	Longitudinal	Attitude/Attitude	Attitude/Airspeed Hold
	Lateral	Attitude/Attitude If $p < 1°$/sec and $\phi < 3°$	Rate/Attitude If $p < 1°$/sec
	Vertical	Direct control of collective pitch angle	
	Directional	Acceleration/Rate	Turn Coordination on lateral stick > 50 knots
Core + heading hold	Directional inflight	Rate/Attitude Full time Head Hold < 40 knots Synchronized heading on lateral stick > 40 knots	Rate/Attitude Turn Coordination on lateral stick > 50 knots
		Heading remains synchronized regardless of airspeed if lateral or directional stick out of detent or $p > 3°$/sec or $\phi > 3°$ or $r > 1°$/sec	
	Directional ground taxi	Rate/Heading Hold	

Fig. 6 ADOCS command/stabilization modes displacement collective.

able, with rollout accuracies of 2–3 deg at near maximum rates. Maintenance of roll attitude in constant bank angle turns greater than 2–3 deg was excellent, as was the directional trim. When returned to a near wings level attitude of <3 deg, the aircraft rolled to a steady-state 2–3 deg bank angle in either direction, with the ball approximately one-half out in the opposite direction.

Precision Hover

At hover in steady winds up to 12 kt, the aircraft was very stable in attitude with little resulting tendency to drift at altitudes from barely above touchdown to out-of-ground effect. Pilot workload was largely unaffected by wind azimuth at these velocities. Turns of 360 deg at 20–25 deg/s were executed with relative ease. Use of hover mode, velocity stabilization, and radar altitude hold modes generally improved the HQRs by one rating for most hover tasks. Heading control for large amplitude turns at aggressive rates was a bit jerky with heading hold engaged and a bit imprecise when stopping without heading hold selected. Hover performance was evaluated over concentric circles of 10, 54, and 108 ft in diameter painted on a taxiway.

Medium Gain Tasks

Medium gain tasks are characterized by significant pilot effort in a minimum of two control axes accompanied by an increase in the pilot attention dedicated to assessment of maneuver precision. Roll and yaw coordination account for the major portion of the workload in the tasks discussed here. Handling qualities ratings were borderline level 1/level 2.

Lateral-Directional Tasks

The hover circle is primarily a lateral-directional task in which the aircraft translates in sideward flight at a constant altitude around a circle, painted on the ground, equal in diameter to the main rotor while continuously keeping the nose pointed at circle center. Workload in the vertical and lateral axes was low, which accentuated the added effort required to continuously and smoothly yaw the aircraft against the heading hold. Deselecting the heading hold caused the yaw axis to revert from rate command/heading hold to acceleration command with rate stabilization, resulting in increased ease of input in the yaw axis and a jump in the HQR from 4 to 2.5. This improvement in handling-qualities with an acceleration command/rate stabilized system seemed to be common to tasks where the required heading was constantly changing and/or the yaw axis was being flown in a quasiopen loop fashion, without an exacting flight-path criteria [e.g., slalom tasks, directional tasks (see next section), lateral escape, and aggressive hover turns].

The 15-kt slalom task further increases the lateral-directional coordination required while increasing the effort required in the longitudinal axis for control of air/groundspeed. The task required that the pilot fly to and around lights that were spaced 300 ft apart longitudinally on alternate sides of a runway 200 ft wide. The elevated pilot workload in the yaw axis was moderated by deselecting heading hold. This produced a smoother, less jerky maneuver at the expense of reduced directional stability.

Pilot workload in sideward flight was predominantly in the roll axis with some smaller amount of effort required in yaw. Accuracy of roll attitude control near maximum roll rate was slightly less than desired due to the pilot's inability to predict the size and timing of the input for large amplitude, high-frequency tasks. Constant heading, within 2–3 deg, was maintained during lateral translations to 30 kt with heading hold selected regardless of the level of the aggressiveness.

Directional Tasks

A target switch-off task was executed from the hover between targets 30 deg apart with radar altitude hold selected in addition to core AFCS plus heading hold. Yaw rates of 20–25 deg/s were generated with overshoots not exceeding 2 deg followed by a rapid return to target (HQR 3). With heading hold deselected, the ease of maneuver entry was increased only slightly at the expense of significantly degraded target acquisition.

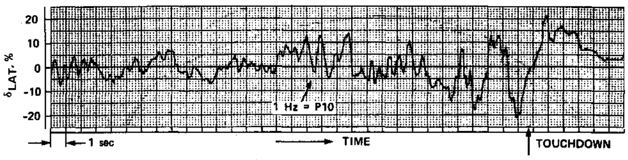

Fig. 7 Flight record of vertical landing; note persistent 1-Hz oscillations.

Vertical Tasks

The bob-up task, consisting of an aggressive climb from 20 to 75 ft above ground level (AGL), followed by a return to 20 ft, after a pause of 2–3 s, was accomplished with good vertical rates and satisfactory heave damping (HQR 2.5). Longitudinal and lateral hover positions were maintained within the 10-ft hover circle painted on the ground.

180-Deg Return to Target

This maneuver consists of an aggressive turn entry to 45 deg of bank from level flight at 80 KIAS. After 180 deg of turn, the wings are aggressively leveled and the nose rapidly fixed and held on a target 15 deg below the horizon. The nose is held on target for 3 s before being returned to level flight. Roll in and out was smoothly and accurately accomplished, on speed with the ball held centered throughout the turn. The nose was very easy to hold on the target and could have been held considerably longer (HQR 3).

High Gain Tasks

High gain tasks require significant control activity in three or four of the control axes simultaneously, or in a lesser number of axes near the maximum capacity of the pilot. These tasks received HQRs consistently in the level 2 region.

Lateral Escape

The lateral escape maneuver requires the pilot to translate laterally to an estimated 20 kt of ground speed before simultaneously rotating and lowering the nose to accelerate into forward flight at a 90-deg angle to the initial heading. The climb and acceleration at 80–90% power are continued until reaching 80 kt followed by a 180-deg turn at 40–50 deg of bank in the direction of the initial lateral translation. This maneuver was reasonably straightforward with good lateral and longitudinal control of acceleration. However, with heading hold engaged, the aircraft was excessively stiff directionally requiring considerable effort to get the aircraft yawed 90 deg at low speed (HQR 6). With heading hold deselected, the new heading was achieved with much less effort (HQR 4) with no noticeable degradation in other aspects of the overall task.

Normal Vertical Landing from Hover

In spite of the general simplicity of the maneuver, the basic landing task demonstrated the characteristics of a high gain task. The workload during the descent from hover was very low, exhibiting excellent level 1 characteristics. However, just prior to virtually all touchdowns, a persistent 1-Hz lateral PIO (Fig. 7) was observed on the telemetry data, but was not necessarily apparent to the pilot. The presence of this PIO before touchdown (more than 15 s in Fig. 7) emphasizes that the underlying cause was present in the flight configuration and was not associated with either weight-on-wheels transients or ground mode control laws. Generally, the lateral oscillation subsided in the process of getting all of the gear on the ground.

For those situations where the landing was accomplished without a DOCS monitor trip, the HQRs varied between 4 and 5. The liftoff to a hover was generally one HQR worse than the landing due to the inability to precisely modulate roll attitude during the period when the aircraft is becoming light on the landing gear.

Dash/Quickstop

The level acceleration to 50–60 kt was generally accomplished with some slight sluggishness in pitch and a small amplitude roll oscillation in the 30–40 kt airspeed range, but still within level 1. Typically, the flare produced a yaw slice to the right with several cycles of lateral 1-Hz PIO before the nose attitude was again level at a hover (HQR 4–6).

30-Knot Slalom

The handling-qualities difficulties were very similar to those during the 15-kt slalom but elevated by a perceived increase in overall control activity of 50%, a more jerky response when coordinating yaw requirements (heading hold selected), and the characteristic sluggishness longitudinally (HQR 4.5–5). With heading hold deselected, the lateral-directional task workload was reduced slightly.

Ground Taxi

Longitudinal cyclic control via direct input from the controller or the beeper trim switch was difficult to modulate with precision. Tip-path plane response to the beeper seemed slow and without sufficient visual feedback to readily control taxi speed. Precision of directional control was generally satisfactory for small heading changes but inadequate for modulating large changes or rapid heading reversals. HQRs varied from 3 to 9, increasing with complexity and required precision of the maneuver.

Ultrahigh Gain Tasks

Although not normally thought of as high or ultrahigh gain tasks, the slope and running landing tasks, as flown, required control input at, or beyond, the maximum capacity of the pilot in terms of frequency and precision of control input in at least one axis. Although some portions of these landing tasks could be accomplished successfully open loop, the goal during this evaluation was to demonstrate precise closed-loop control of aircraft attitude from maneuver start to completion. The resulting HQRs for these tasks were level 2/level 3.

Slope Landings

Slope landings were attempted both left- and right-wheel upslope, at ground angles of 3–8 deg. The 8-deg slope task was accomplished in a box painted on the ground measuring 13 × 32 ft. Left-wheel upslope landings were consistently accomplished with low work load through touchdown of the tail and left main gear in spite of the presence of the same lateral 1 Hz seen in normal vertical landings from a hover. Further lowering of the right main gear to the ground produced occasional overcontrolling in yaw and an occasional divergence of the lateral 1 Hz (HQR 4–5). Liftoffs from the slope landings were characteristically 1 HQR worse than the landing due to the pilot's inability to smoothly modulate the changing lateral control requirements from full weight on the gear to liftoff. Right-wheel-upslope landings to the 8-deg slope were never successful beyond touchdown of the right main gear. All attempts to complete the landing from this point resulted in some combination of a divergent lateral oscillation, a yaw oscillation, or an unintentional yaw pulse input (Fig. 8), which either tripped the DOCS monitor or required a safety pilot abort.

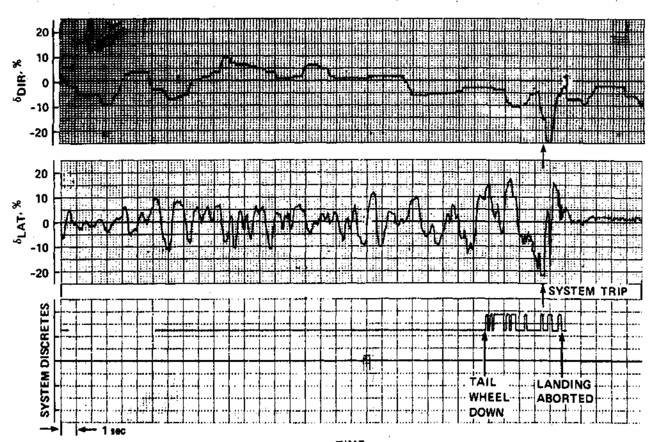

Fig. 8 Flight record of aborted slope landing with right wheel upslope.

Running Landings

The evaluation pilot was unable to complete a running landing, tail wheel first, without a DOCS monitor trip on first-wheel contact.

Running landings either in a flat attitude, or main gear first, were successful to full ground contact without monitor trips or safety pilot aborts in approximately half of the attempts at a target touchdown speed of approximately 15 kt. An inability to achieve precise directional control at high input frequencies deprived the pilot of confidence that a crabbed attitude, which developed just prior to touchdown, could be adequately corrected without directional overcontrol. Directional inputs just prior to intended touchdown frequently became oscillatory (Figs. 9) with the pilot inadvertently coupling directional inputs into the roll axis (HQR 8).

Data Analysis Techniques

The onboard pulse code modulation (PCM) data were analyzed to allow flight response comparisons with analytical models, the proposed handling-qualities specifications, and the pilot ratings and comments. The focus of the effort was in the extraction of frequency responses and transfer-function models using the methods of Ref. 16. Spectral analysis of the pilot control and motion variable time histories for the frequency-sweep tests were performed by the frequency response identification program FRESPID to produce end-to-end frequency responses and coherence in Bode plot form. The bandwidth and phase delay parameters were then calculated directly from the attitude frequency response plots as shown in Fig. 10. The results are presented in Table 4. Transfer-function models were generated from least squares fits of the Bode plots using the program NAVFIT for comparison with analytically developed transfer-function models and are given in Table 5. The time domain response of the identified models and the flight data were compared for the same pilot inputs to provide further verification of the overall identification process as shown for the pitch axis in Figs. 11. Matching of the initial slopes and general dynamic characteristics of the curves

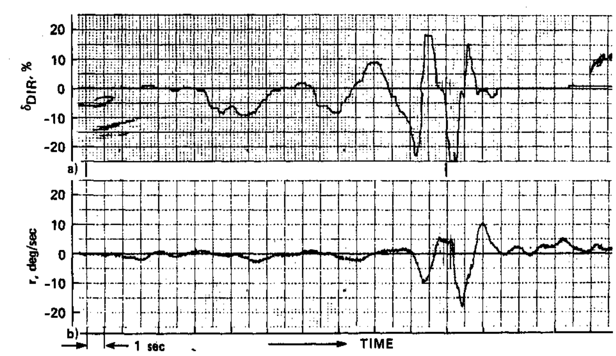

Fig. 9 Flight record of running landing: a) pilot directional input; b) yaw rate response.

is indicative of good transfer-function models that were identified. The slight mismatch in the attitude response beginning at 13 s is likely to have been caused by a disturbance input. Identification of frequency responses and transfer-function models of the bare airframe dynamics by the methodology stated earlier was also completed using swash plate deflections instead of side-stick deflections as the input time histories.

Discussion of Results

This section first compares the identified and analytical design models of the component and end-to-end system performance. Then, the handling-quality ratings and comments are correlated with the analytical models and the proposed specification requirements.

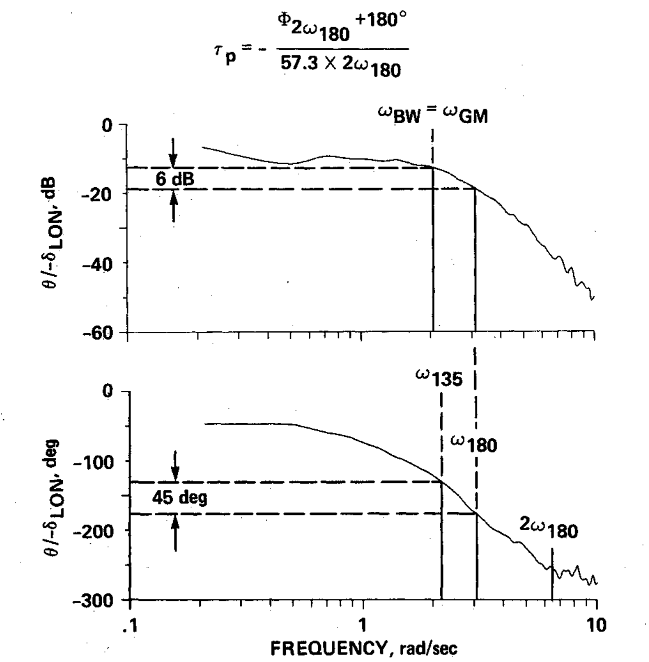

Fig. 10 Determination of bandwidth and phase delay from pitch attitude response in hover.

Table 4 Summary of identified bandwidth[a] and phase delay values

	Hover			80 kt		
Axis	ω_{BW_g}, rad/s	ω_{BW_p}, rad/s	τ_p, s	ω_{BW_g}, rad/s	ω_{BW_p}, rad/s	τ_p, s
Pitch	2.10	2.27	0.202	1.84	2.40	0.181
Roll	2.33	2.38	0.181	0.94	1.53	0.175
Yaw (pedals) (heading hold)	1.70	1.33	0.138	1.68	1.77	0.206

[a]Bandwidth frequency, ω_{BW} = lesser of ω_{BW_g} and ω_{BW_p} is underlined.

Comparison of Identified and Analytical Models

An identification of the basic (unaugmented) UH-60 in hover was completed using the measured ADOCS actuator signal as the input and the aircraft pitch rate as the output. Therefore, the resulting frequency response reflects the open-loop dynamics of the UH-60 airframe, rotor, and upper-boost actuator. A model was identified using an equivalent system fit of the flight data (1–7 rad/s):

$$\frac{q}{\delta_{A_\theta}} = \frac{0.283\, e^{-0.0877s}}{(s + 0.610)} \text{ rad/s/in.} \tag{2}$$

The identified equivalent delay of 88 ms matches the rotor and upper-boost delay shown in Fig. 2, thereby validating these models. Also, the effective bare-airframe pitch damping ($M_q = -0.61$) and pitch sensitivity $M_{\delta_\theta} = 0.283$ correspond well to known ADOCS Blackhawk characteristics.[9,11]

The comparison of the closed-loop analytical and identified equivalent system models [Eq. (1) and Table 5, respectively] is seen to be good (recall that the gain of the analytical model has been normalized). The excellent agreement in overall time

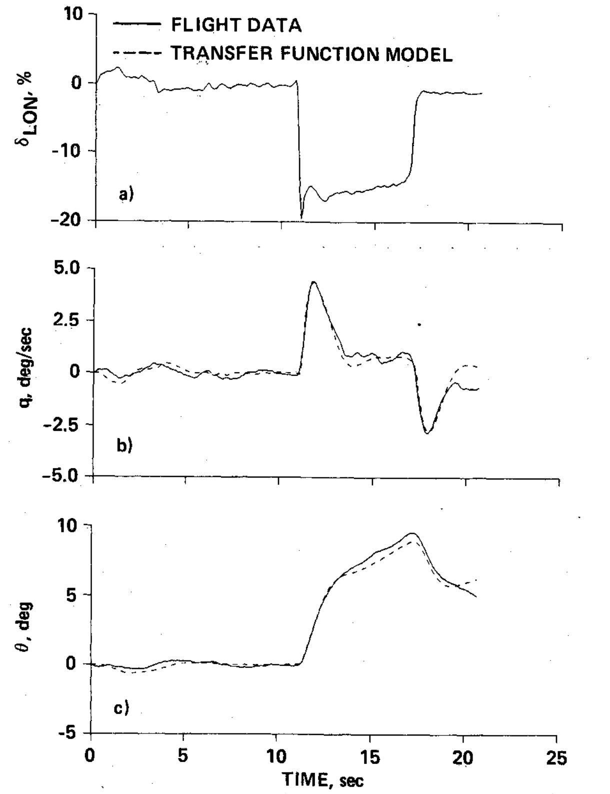

Fig. 11 Verification of identified pitch response transfer-function model: a) pilot input; b) pitch rate; c) pitch attitude.

Table 5 Summary of identified transfer-function models

Hover: Model[a,b]	Hover: Frequency range, rad/s	80 kt: Model[a,b]	80 kt: Frequency range, rad/s
$\frac{\theta}{\delta_{LON}} = \frac{-0.876(s+0.229)e^{-0.238s}}{s[0.539, 1.82]}$	0.209 – 6.75	$\frac{\theta}{\delta_{LON}} = \frac{-0.894(s+0.131)e^{-0.254s}}{s[1.09, 1.63]}$	0.209 – 8.0
$\frac{\phi}{\delta_{LAT}} = \frac{3.10(s+0.234)e^{-0.260s}}{s[1.39, 2.28]}$	0.209 – 9.03	$\frac{\phi}{\delta_{LAT}} = \frac{1.17e^{-0.239s}}{s(s+2.65)}$	0.209 – 12.0
$\frac{\Psi}{\delta_{PED}} = \frac{1.15e^{-0.224s}}{s(s+2.76)}$ (heading hold)	0.209 – 6.00	$\frac{\Psi}{\delta_{PED}} = \frac{0.715e^{-0.327s}}{s(s+5.12)}$ (heading hold)	0.8 – 6.00

[a]θ, ϕ, Ψ in deg. [b]δ_{LON}, δ_{LAT}, δ_{PED} in %.

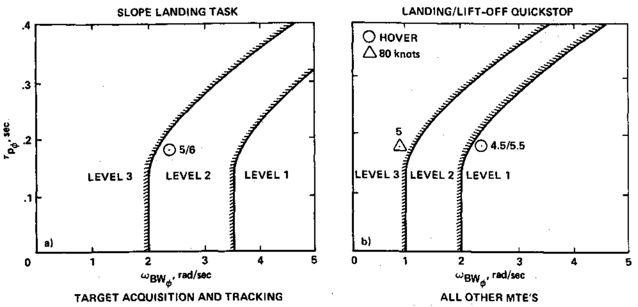

Fig. 12 Handling-qualities correlation (average ratings) of ADOCS small amplitude roll response: a) ultrahigh gain task; b) high gain tasks.

delay, along with the open-loop UH-60 agreement, validates the contribution from the remaining digital elements and the ADOCS actuator. The analytical model has a slightly higher natural frequency and damping ratio compared to the flight data, which is largely due to an open-loop pitch sensitivity error in the design model compared to the flight vehicle.[9] Reduction of the loop gain in the analytical model by the 13% discrepancy improves the agreement. The comparison of the bandwidth and phase delay of the analytical model (Fig. 4) and the identification result (Table 5) is also quite good.

Correlation of Pilot Evaluation and Identification Results with Proposed Handling Qualities Specification

This section correlates pilot evaluation and control response documentation of the ADOCS demonstrator with the proposed military handling-qualities specification. The discussion will concentrate on the attitude response characteristics because control response documentation data for the vertical axis is not currently available.

As discussed earlier, the ADOCS evaluation tasks were limited to moderate amplitude maneuvers (less than about 45 deg in roll and 25 deg in pitch) because of safety-of-flight restrictions and in-line monitoring constraints. Since the evaluation was conducted under conditions of unrestricted visibility and without secondary tasks, the applicable paragraphs of the specification are those that refer to the best usable cue environment (UCE = 1) and fully attended operation. Small amplitude specifications given in terms of required minimum bandwidth and phase delay are the same for hover/low speed and forward flight. Similarly, moderate amplitude specifications given in terms of peak angular rate per attitude change are also the same for hover/low speed and forward flight.

The small amplitude boundaries for bandwidth and phase delay applicable to ultrahigh gain tasks (target acquisition and tracking) are shown in Fig. 12a along with the identified ADOCS roll response characteristics for hover. As discussed earlier, slope landings are considered to be ultrahigh gain tasks in roll attitude regulation. The identified ADOCS response is seen to plot on the level 2/level 3 specification boundary, which is consistent with the numerical handling-qualities ratings for slope landings. However, the following discussion will argue that the pilot comments explaining the overriding cause of the poor ratings (namely the 1-Hz PIO tendency) indicates that the response should be against a more restrictive phase-delay boundary and not only against the bandwidth boundary as indicated in Fig. 12a. The roll response identification displays a phase lag of -120 deg at the 1-Hz pilot crossover frequency noted in the flight records near touchdown. Assuming a pilot neuromuscular lag of 150 ms (typical value), and using the frequency-response identification results, a pilot lead of 140 deg is necessary to achieve an overall phase margin of 45 deg. This implies a requirement for two units of pilot lead (since one unit of pilot lead provides a maximum of 90 deg). As discussed in Ref. 18, two required units of pilot phase lead can be expected to cause severe handling-qualities degradations, thereby leading to the PIO tendencies displayed in the

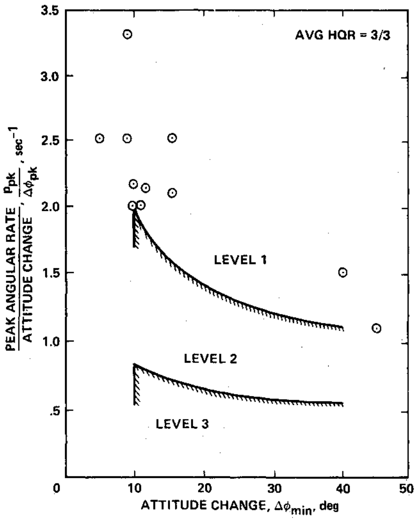

Fig. 13 Handling-qualities correlation of ADOCS moderate amplitude roll response at 80 kt: average ratings are shown for 180-deg return-to-target/level roll reversals.

roll axis. The roll axis equivalent system identification results of Table 5 further support the conclusion that command response characteristics based on natural frequency and damping are acceptable (Fig. 5a), whereas the equivalent time delay ($\tau_e = 260$ ms) will lead to Level 3 handling qualities in high stress tasks (Fig. 5b). Time-delay related handling-quality problems were reported for the Bell ARTI helicopter,[2] which also exhibited equivalent delays exceeding 240 ms. Flight experiments conducted by Houston and Horton[19] using a variable stability PUMA aircraft suggested the need for a phase-delay cap of $\tau_p = 200$ ms independent of bandwidth for ultrahigh gain tasks. Such a cap would cause the ADOCS response (shown in Fig. 12a) to be against a phase-delay boundary, which is consistent with the source of the handling-quality problems in slope landings.

Figure 12b is used for all of the roll axis tasks except for the slope landings. All low and medium gain roll axis tasks in both hover and forward flight received solid level 1 handling-qualities ratings. The normal landing, considered a high gain roll task, received solid level 2 ratings as a result of 1-Hz PIO problems. Once again, the question of a maximum time-delay cap is raised based on the hover correlation with the specification as shown in Fig. 12b.

The significant reduction in roll bandwidth for the 80-kt flight condition shown in Table 4 is due to gain margin limiting resulting from the change from an attitude command to a rate command model along with large time delays. This command model change occurs automatically as the flight speed increases above 40 kt. The considerable roll and yaw PIO problems in the 60-kt quick stop may be attributable to the (gain-margin limited) bandwidth as indicated in Fig. 12b.

Achievable roll response for moderate amplitude maneuvering are shown in Fig. 13 to be well within the level 1 requirements, which is consistent with handling-quality ratings for roll maneuvers such as the return-to-target and level roll reversals.

Running landings are considered to be an ultrahigh gain yaw task for the ADOCS aircraft. The correlation shown in Fig. 14a is consistent with the level 3 pilot ratings. Further, the associated pilot comments that directional control precision is marginal are consistent with the indication of low bandwidth. As in the roll axis, the low and medium gain yaw axis tasks receive level 1 pilot ratings, whereas high gain tasks such as the lateral escape, 30-kt slalom, and 60-kt quick stop (a high gain yaw task because of coupling) received solid level 2 ratings. These results are consistent with the correlation of ADOCS response and the specification as shown in Fig. 14b.

Ultrahigh gain pitch tasks such as air refueling or aggressive air-to-air tracking in the vertical plane were not completed

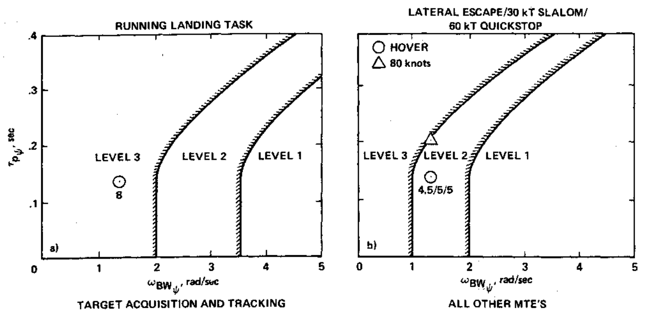

Fig. 14 Handling-qualities correlations (average ratings) of ADOCS small amplitude yaw response: a) ultrahigh gain task; b) high gain yaw tasks.

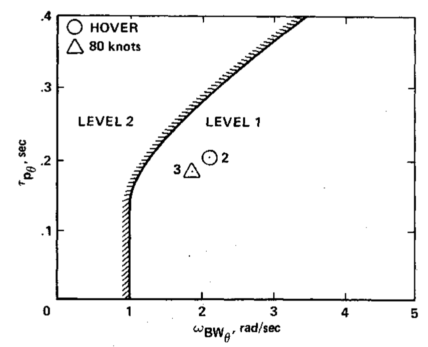

Fig. 15 Handling-qualities correlation of ADOCS small amplitude pitch response in hover and 80 kt: average ratings are shown only for low and moderate gain pitch tasks. (Hover: translations, 80 kt: 180-deg return-to-target.)

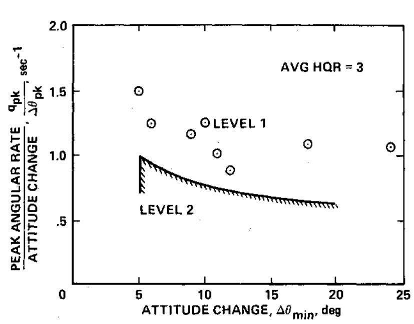

Fig. 16 Handling-qualities correlation of ADOCS moderate amplitude pitch response in hover: average rating is for initiation of dash.

during the ADOCS evaluation. Therefore, no correlation with the proposed ultrahigh gain pitch boundary is possible. High gain pure pitch tasks such as low-level contour flying were not completed in the displacement collective evaluation reported in this paper. Low and medium gain pitch tasks, as with the roll and yaw axes, received consistent level 1 ratings. These pitch ratings are consistent with the proposed small amplitude specification (Fig. 15). However, pilot comments concerning longitudinal control sluggishness during the 30-kt slalom (high gain predominantly roll/yaw task) suggest that the pitch bandwidth boundary should perhaps be raised. Correlation of pitch characteristics for moderate amplitude maneuvering is shown in Fig. 16. The correlation is consistent with level 1 handling qualities for moderate amplitude pitch tasks such as the initiation of the dash.

Summarizing the correlation of the ADOCS handling qualities results for the displacement collective with the proposed handling-qualities specification indicates 1) bandwidth specifications for ultrahigh and high gain tasks are consistent with the pilot evaluation, and 2) phase delay restrictions are too lenient. A phase delay cap of 200 ms proposed by previous researchers is supported by the ADOCS flight experiments.

Conclusions

An analytical study indicates that desirable control response characteristics based on equivalent damping and frequency are achievable with the ADOCS explicit model-following structure. Excessive equivalent time delays (exceeding 240 ms in all axes) in the ADOCS are mostly due to the rotor, stick filter, and actuator dynamics.

Piloted evaluation of the ADOCS 3 + 1 (displacement collective) AFCS configuration indicates handling qualities that are desirable (level 1) or marginally desirable (borderline level 1/level 2) for low and moderate gain tasks. Handling qualities are adequate (level 2) for high gain tasks and are inadequate (level 3) for ultrahigh gain tasks such as slope and running landings. The primary cause of ADOCS handling-qualities deficiencies is considered to be excessive equivalent time delays.

Analytical models compare favorably with flight-extracted frequency-domain characteristics of the overall (end-to-end) ADOCS responses.

Correlation of the piloted evaluation results with the proposed handling-qualities specification indicates generally good agreement for the bandwidth boundaries, but suggests the need for more stringent limits on allowable phase delay.

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