Paper for 65th AHS Forum Handling Qualities Session

An Investigation of Rotorcraft Stability-Phase Margin Requirements in Hover

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Abstract

A cooperative study was performed to investigate the handling quality effects from reduced flight control system stability margins, and the trade-offs with higher disturbance rejection bandwidth (DRB). The piloted simulation study, perform on the NASA-Ames Vertical Motion Simulator, included three classes of rotorcraft in four configurations: a utility-class helicopter; a medium-lift helicopter evaluated with and without an external slung load; and a large (heavy-lift) civil tiltrotor aircraft. This large aircraft also allowed an initial assessment of ADS-33 handling quality requirements for an aircraft of this size. Ten experimental test pilots representing the U.S. Army, Marine Corps, NASA, rotorcraft industry, and the German Aerospace Center (DLR), evaluated the four aircraft configurations, for a range of flight control stability-margins and turbulence levels, while primarily performing the ADS-33 Hover and Lateral Reposition MTEs. Pilot comments and aircraft-task performance data were analyzed. The preliminary stability margin results suggest higher DRB and less phase margin cases are preferred as the aircraft increases in size. Extra care will need to be taken to assess the influence of variability when nominal flight control gains start with reduced margins. Phase margins as low as 20-23 degrees resulted in low disturbance-response damping ratios, objectionable oscillations, PIO tendencies, and a perception of an incipient handling qualities cliff. Pilot comments on the disturbance response of the aircraft correlated well to the DRB guidelines provided in the ADS-33 Test Guide. The ADS-33 mid-term response-to-control damping ratio metrics can be measured and applied to the disturbance-response damping ratio. An initial assessment of LCTR yaw bandwidth shows the current Level 1 boundary needs to be relaxed to help account for a large pilot off-set from the c.g. Future efforts should continue to investigate the applicability/refinement of the current ADS-33 requirements to large vehicles, like an LCTR.

Introduction

Handling quality requirements embodied in the U.S. Army's Aeronautical Design Standard–33 (ADS-33) [1] are the basis for military rotorcraft flight control design in the U.S., such as most recently on the fly-by-wire UH-60MU [2], and internationally on the NH-90 [3]. ADS-33 also serves as design guidance for civil rotorcraft. Key among the quantitative requirements are minimum values of metrics associated with response to piloted stick inputs, such as: bandwidth and phase delay, short-term response damping, and attitude quickness. The same requirements often translate to design guidelines for civilian aircraft as well, such as documented for the S-92 [4].

In addition to providing satisfactory response to piloted inputs as defined in ADS-33, the feedback system must also reject aircraft response due to disturbances and provide for an inherently stable platform with satisfactory margins to address both expected variations in flight conditions and dynamic response uncertainties. There is very little guidance in ADS-33 on disturbance rejection requirements and no explicit requirements on closed-loop stability margin. The U.S. Army's Aeroflightdyanmics Directorate (AFDD) has developed and flight-test validated a disturbance rejection bandwidth (DRB) metric that is directly analogous to the piloted bandwidth metric, but for disturbance inputs. Increased DRB associated with higher feedback levels, is desirable for flight operations in degraded weather and visibility, but is accompanied by reduced stability margins and increased actuator activity [5]. This metric has been found to be well suited to flight control design and flight testing, and proposed criteria values for inclusion in ADS-33 have been published [6].

While ADS-33 has no direct requirements on stability margin, the minimum mid-term control response damping ratio requirement of $\zeta \geq 0.35$ (for modes below the bandwidth frequency) can be interpreted as a 35-degree phase margin requirement for an equivalent second-order system [7]. Refinements to the U.S. Department of Defense (DoD) specification for air vehicle flight control systems [8] recently incorporated into SAE 94900 [9] require a phase/gain margin of not less than 45 deg/6dB for the worst case flight condition and at least half these margin levels in the presence of uncertainties of up to 20% in the dominant stability and control derivatives. Adequate margins are needed to help ensure that: the flight control system is robust to expected variations in flight condition that are not gain-scheduled (e.g., c.g., weight, turn rate, etc.) and has some margin against modeling uncertainties; there are opportunities for future expansion in the flight envelope; and there are no detrimental effects due to flight control hardware degradation over the life of the aircraft. Also, ensuring adequate stability margins keep potentially adverse dynamics associated with rotor/body coupling and coupled structural/flight control response outside of pilot's frequency range, thus preventing a key potential trigger for pilot-induced oscillations [10].

The current minimum stability margin requirements of SAE 94900 are not well supported with published data, but rather are generally based on historical rules-of-thumb, and can be considered to be conservative. Lower margins might be acceptable and allow for tighter disturbance rejection, but the handling-quality implications are not well understood. In the CH-47F Digital Automatic Flight Control System (DAFCS) development program [11], good handling qualities were obtained for roll-axis disturbance rejection even though this resulted in reduced stability margins (about 30-deg) as compared to 94900. A waiver for reduced stability margin has also been granted for flight control design of the CH-53K when carrying external loads in order to achieve acceptable feedback loop performance [12]. It is expected that this fundamental trade-off between satisfactory disturbance rejection performance and stability margin will become more acute as rotorcraft increase in size and associated control power becomes more limited (e.g., joint heavy lift).

In order to address these considerations and fill in the link between achievable disturbance rejection, associated stability margin, and handling qualities, a collaborative seven-week ground-based piloted simulation was performed on the NASA-Ames Vertical Motion Simulator (VMS). Principal investigators were from the Aeroflightdynamics Directorate's (AFDD) Flight Control and Cockpit Integration Division, NASA-Ames Aeromechanics Branch, and from the German Aerospace Center's (DLR) Institute for Flight Systems. This collaborative work was performed under Memorandums of Understanding (MoU). The following sections describe the objectives, the simulation model and the conduct of the test, the results, and some concluding remarks.

Objectives

While considering the rotorcraft handling quality requirements of ADS-33, the objectives of this collaborative effort were to determine the handling quality implications of reduced flight control stability margins, i.e., below the 94900 recommendations, and the trade-offs with higher disturbance rejection bandwidth (DRB). This provides a database for handling quality boundaries on a proposed DRB specification and for exploring design trade space between DRB, stability margins, and actuator usage. An additional objective included investigating the effects of aircraft size, providing not only reduced stability margin – DRB trade-off data, but also allowed an initial assessment of the ADS-33 handling quality requirements using a large tiltrotor aircraft.

Approach

The overall approach was to collect performance and pilot opinion data while flying ADS-33 hover and low-speed Mission Task Elements (MTEs) on the NASA-Ames VMS. Four rotorcraft configurations were assessed: a UH-60-sized aircraft; a medium-lift CH-53K-sized aircraft, with and without an external slung load; and a large civil tiltrotor aircraft, with rotors fixed at the hover angle. Within each MTE – aircraft combination, the pilot's evaluated different levels of flight control stability margins and disturbance rejection bandwidth in the presence of external turbulence. The aircraft models were relatively simple stability-derivative type models with sufficient complexity to capture the key physics of each aircraft, including key nonlinearities such as actuator position and rate limiting. The *Control Designer's Unified Interface* (CONDUIT®) software tool [13] was used with these aircraft models and a model-following flight control architecture to establish a family of optimized cases with varying DRB and stability margins, all the while trying to meet the Level 1 quantitative requirements in ADS-33. The following section describes the simulation models in greater detail.

Simulation Model

A real-time piloted simulation model concept was needed to accommodate a broad range of control system performance/stability trade-offs for three very different rotorcraft classes: (1) a utility class UH-60 sized aircraft – hereto referred to as H-60; (2) a medium-lift cargo class CH-53K sized aircraft, with and without an external slung load – hereto referred to as H-53; and (3) a heavy-lift large civil tiltrotor sized aircraft – hereto referred to as LCTR. The bare-airframe models for the three aircraft studied needed to be simple enough to allow easy setup of different control system designs, while retaining the key physics of coupled rotor-body response for a representative trade-off between disturbance rejection, stability margin, and closed-loop modal damping. This was necessary to ensure, for example, that a given disturbance rejection bandwidth (DRB) for the H-60, was achieved with a representative feedback gain and actuator usage, and associated stability margin and damping ratio. Linearized (25-state) bare-airframe models were obtained from high-fidelity blade-element simulation models of the three aircraft. These models retained the key rotor-body coupling, but dropped the off-axis response, thereby allowing a smooth and independent variation in feedback characteristics in a single axis. The final reduced-order, decoupled 11-state model was then validated against the original 25-state model by comparing the modes and frequency responses of the two models. The H-53 model with the external slung load included two additional states associated with the relative motions in pitch and roll.

A generic control system block diagram was needed that allowed easy adjustment of the feedback characteristics while retaining a constant Level 1 response to piloted inputs. An excellent choice for this requirement was the explicit-model following architecture, shown in Figure 1, where the response to piloted inputs is determined by the command model transfer function, while the regulator can be

independently designed to set the disturbance rejection bandwidth and associated stability characteristics. This was crucial to the conduct of this experiment, as variations in the feedback path could be examined without impacting the piloted bandwidth of the aircraft.
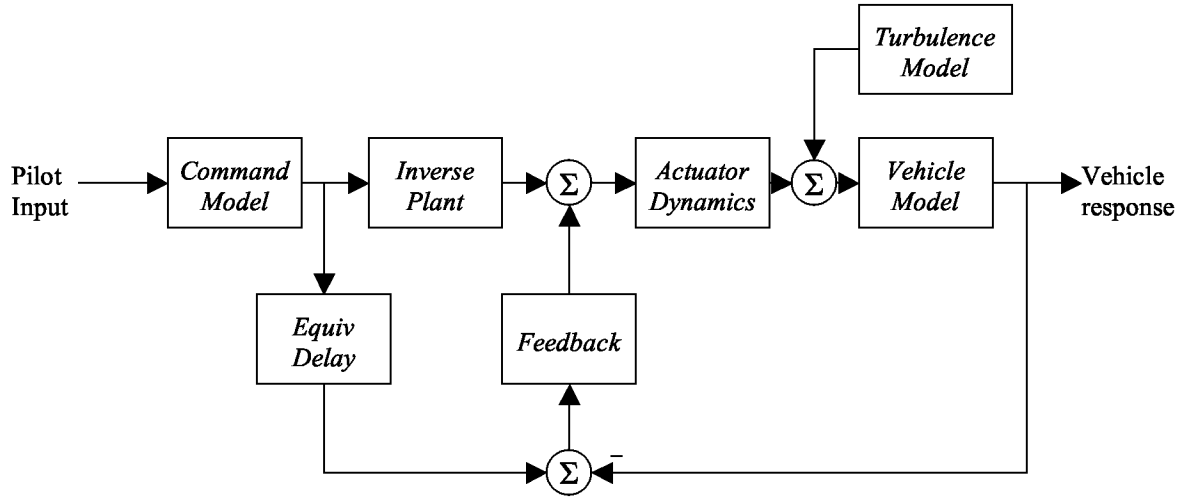

Figure 1. Overview of the model following architecture

The command models, shown in equations (1), were designed to meet ADS-33 Level 1 bandwidth requirements. A second-order command model was used in the pitch and roll axes to achieve an attitude command response type, and a first-order command model was used in the yaw axis to achieve a rate command response type. The pitch and roll command model dynamics were independently set.

$$\frac{\phi_{cmd}}{\delta_{lat}}, \frac{\theta_{cmd}}{\delta_{lon}} = \frac{K\omega_n^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2}, \quad \frac{r_{cmd}}{\delta_{ped}} = \frac{K}{\tau s + 1} \tag{1}$$

For the H-53 configuration, the command model parameters were initially set to meet the Level 1 bandwidths in ADS-33 (for *All other MTEs*). After actuator rate limiting was observed, the command model parameters were reduced (Level 2 bandwidth) to minimize the negative impact of actuator rate limiting. The vertical response for the H-60 and H-53 configurations was unaugmented (which is a Level 1 vertical rate response). In the case of LCTR, to compensate for the very low vertical damping, a first-order command model was needed in the vertical channel.

The inverse plant model inverts the short-term aircraft response dynamics, ignoring the higher-order dynamics of the rotor and actuators. First-order inverse models were generated for each channel based on simple equivalent-system fits of on-axis angular-rate responses of the 11-state bare-airframe model. For example:

$$\frac{p}{\delta_{lat}} = \frac{L_{\delta_{lat}} e^{-\tau s}}{s - L_p} \tag{2}$$

Since the aircraft response is known, there is a nearly perfect match between the inverse and aircraft dynamics in the frequency range of interest. This, however, is seldom the case in real aircraft, and so

30% uncertainties were introduced into the parameters of the inverse model to simulate mismatch between the expected and actual inversion behavior. This degrades the otherwise perfect inversion and has the desired effect of exciting the feedback path as would occur in reality, thereby bringing out the differences between the different feedback cases of each design configuration.

The equivalent time delay block is included to avoid overdriving higher-order dynamics (rotor and actuator) that are not included in the lower-order pseudo-inverse. The values are determined using an equivalent system match of the forward path response to the command model response.

Model Following Performance for Pilot Input

Model following accuracy is a measure of how well the vehicle responses match the responses generated by the command model, and is calculated by a mismatch cost function between the closed-loop response and the delayed command model response. Model following cost values less than 100 indicate reasonable agreement, and values under 50 indicate nearly perfect agreement. An overlay of the commanded roll attitude response, the closed-loop roll attitude response with no uncertainty in the inverse model, and the closed-loop roll attitude response with uncertainty in the inverse model, for the nominal H-60 configuration, is shown in Figure 2. As expected, with no uncertainty in the inverse model, there is a very good match between 0.1 to 8 rad/sec frequencies, where the inverse model matches the bare-airframe responses well, while at higher frequencies (above 10 rad/sec), the mismatch is greater because of the additional modes present in the bare-airframe response. The model following cost in this Case is 30. The introduction of uncertainty to the inverse model degrades model following performance, increasing to model following cost to above 200, and allows the rotor-body coupling to come through more.
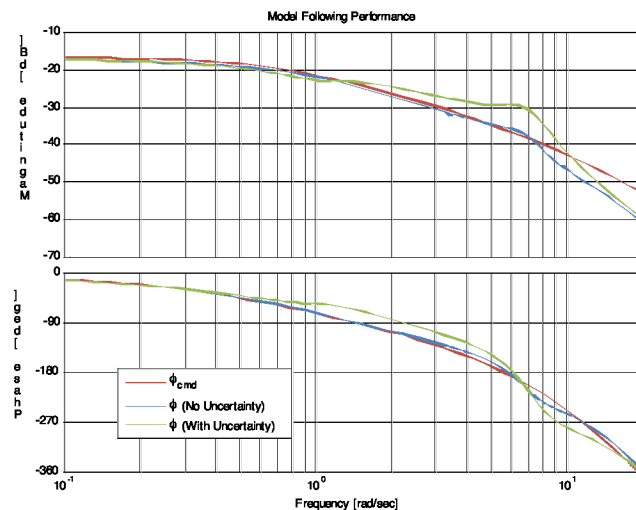

Figure 2. Model-following performance in the roll axis for the nominal H-60 configuration with and without uncertainty in the inverse model.

Turbulence Input Model

The AFDD Control Equivalent Turbulence Input (CETI) model [14] was included in each airframe to provide realistic gust inputs (added to the airframe control inputs) and allow an evaluation of the handling quality impact of the disturbance rejection levels and related stability margins. The CETI model is a hover/low-speed turbulence model that simulates the effects of atmospheric turbulence on a conventional rotorcraft. The inputs to the CETI model are physical parameters of the aircraft and atmospheric parameters. The aircraft parameters, such as main rotor diameter, are used to scale the CETI model between different rotorcraft. The atmospheric parameters are the mean wind speed and the wind speed

standard deviation in the lateral and vertical directions. The outputs of the CETI model are *disturbances* injected into the control system of an aircraft operating in calm atmospheric conditions to cause the aircraft to respond as if it were operating in a prescribed level of atmospheric turbulence.

Design Trade-offs for H-60

CONDUIT® [13] was used to design families of control law configurations of varying DRB/stability-margin combinations for each airframe model. Starting from the baseline Level 1 control system, design margin optimization [5] was used to generate a family of cases of increasing disturbance rejection bandwidth (DRB) and associated reduced stability margin (and damping ratio). A constant crossover frequency was set to provide adequate model following and performance robustness to uncertainty. In the case of the H-60 configuration, the baseline design was matched to the UH-60M Upgrade [2].

Figure 3 shows the DRB and resulting stability margin in the lateral axis, for the family of cases generated for the H-60. Similar families were generated for the other aircraft evaluated. Note, for the H-53 configuration with the external slung load, the "no-load" control laws were re-optimized to account for normal degradations associated with the addition of the slung load. The cross-over frequency was held approximately constant for all four cases. Figure 4 shows the associated roll-axis attitude and rate feedback gains, for the H-60 family of cases. Increased DRB requires a significant increase in attitude gain accompanied by a slight decrease in rate gain. Figure 5 shows the responses of the different cases to a pilot lateral stick input and a disturbance pulse input, and demonstrates that as the DRB of the aircraft is increased, the response to disturbance is faster. However, due to the decrease in phase margin, the response is more oscillatory as well. This is also seen as an increase in the magnitude peaks in Figure 3(a) for the higher DRB configurations and the oscillatory response leads to increased actuator usage – leading to the possibility of actuator rate saturation especially in the pitch axis. Figure 6 shows the actuator activity associated with the disturbance input shown in Figure 5(b).

(a)   (b)
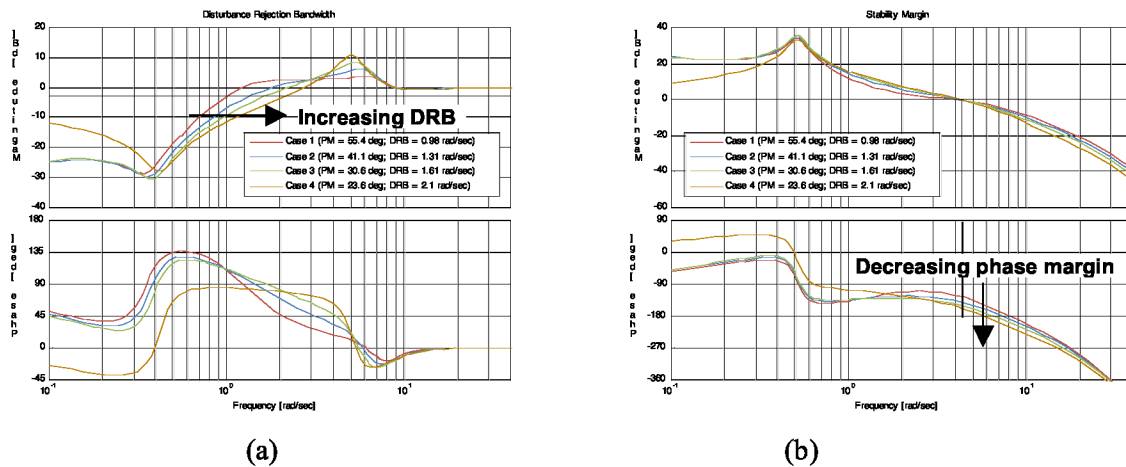
Figure 3. (a) Disturbance rejection and (b) stability margin in the Lateral axis for the H-60 family of cases. An increase in DRB [arrow on (a)] is accompanied by a decrease in phase margin [arrow on (b)].
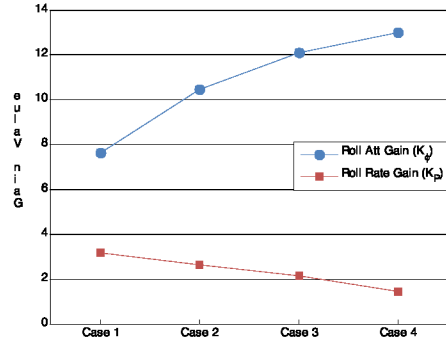
Figure 4. Variations in the roll axis feedback attitude and rate gains for the H-60 family of cases.

(a)   (b)
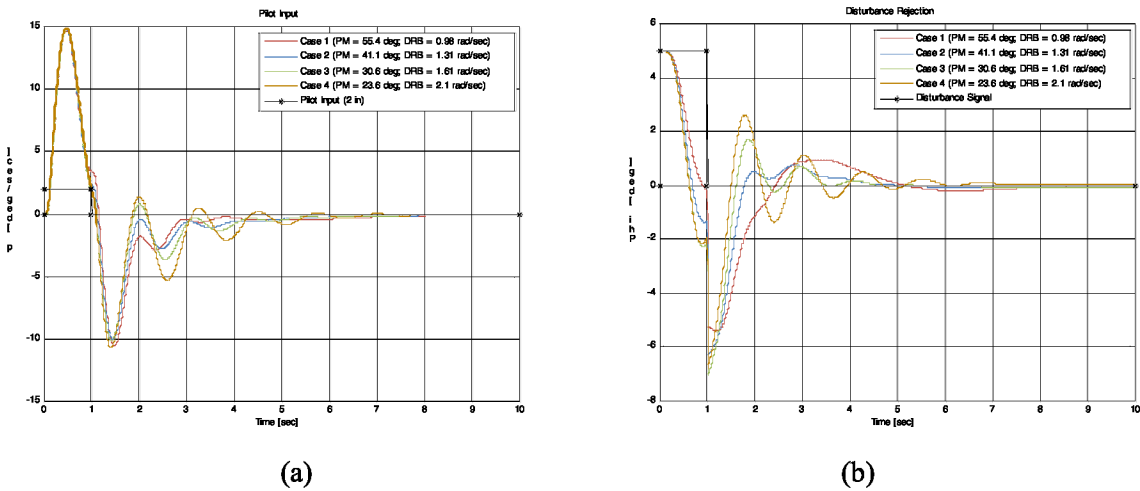
Figure 5. Time histories of (a) a lateral cyclic stick pulse and (b) a disturbance pulse in phi for the H-60 family of cases.
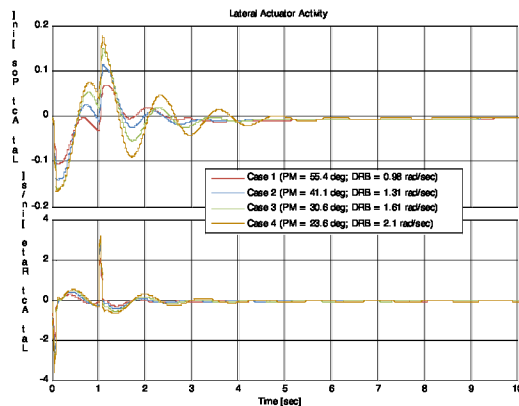

Figure 6. Lateral actuator activity for a 5-degree disturbance pulse input into phi for the H-60 family of cases. Actuator position and rate limits are ±2.5 in and ±5 in/sec, respectively.

Conduct of Test

This section describes the vehicle configurations, the flight control and turbulence configurations, the facility where the simulation was performed, and the evaluation and test procedures.

Vehicle Configurations
Three rotorcraft sizes were investigated in this experiment. Table 1 shows the weights and rotor diameters of the different configurations. Figure 7 shows the four aircraft configurations flown.

Table 1. Aircraft Configurations.

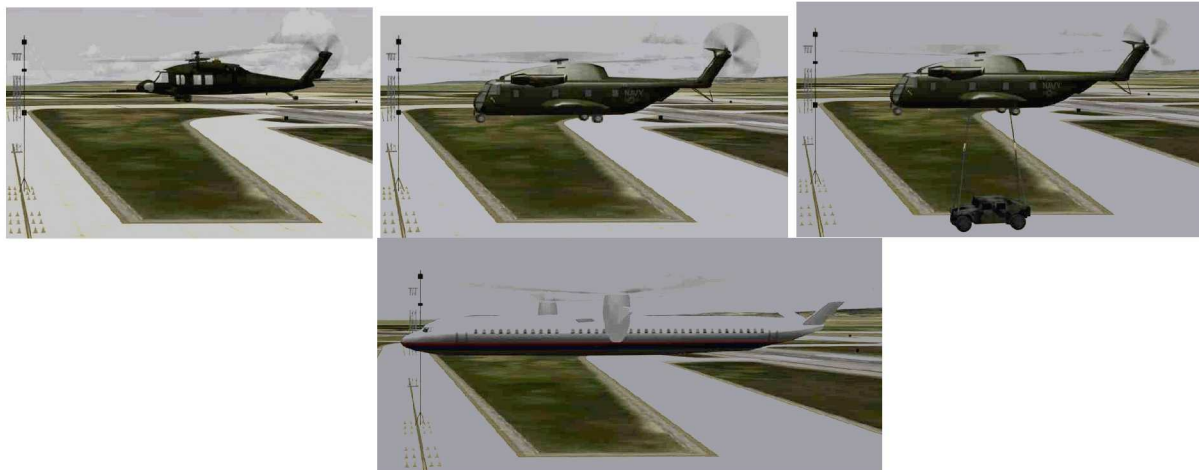| Aircraft	Weight (lbs)	Rotor Diameter (ft)
H-60	16,000	53.6
H-53	46,000	79
H-53 with slung load	46,000+29,500 (ext load)	79
LCTR	120,000	65 (x2)

Figure 7. The four aircraft configurations.

Each of the four aircraft configurations had a family of four control laws designed for evaluation. These ranged from high phase margin/low DRB (Case 1), to low phase margin/high DRB (Case 4). As mentioned in the Simulation Model section, the piloted bandwidths and crossover frequencies of the different cases remained constant. For the different aircraft configurations, Figure 8 shows the trade-off between phase margin and Figure 9 shows the variation in damping ratio as the DRB increases for (a) the roll and (b) the pitch axes. Here, the damping ratio was calculated using the overshoot method for a step put into the disturbance input in each channel. Table 2 presents for the four aircraft configurations and flight control cases, a summary of pitch and roll axes stability margins, disturbance rejection bandwidth, damping ratio to disturbance and control inputs, and the control response bandwidths. Furthermore, each case was tested in multiple levels of turbulence, ranging from ambient to light to moderate, using the CETI model parameters shown in Table 3, where U_o represents the mean wind speed, and σ_v and σ_w represent the standard deviation of lateral and vertical wind speeds. The parameters for a moderate level of turbulence in Table 3 are based on values used for the in-flight simulation study conducted on the RASCAL helicopter [14]. The moderate values of U_o and σ_v were increased slightly for this study so that

the project pilot flying the H-60 in the VMS rated the turbulence as "moderate." The parameters for the light level of turbulence were set to one half the moderate values. The ambient parameters were selected to provide a very low level of disturbance.
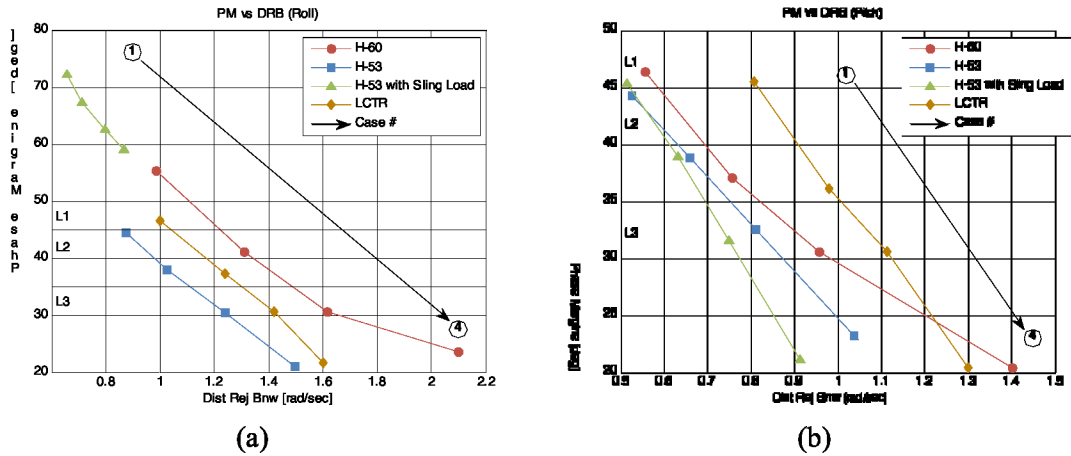

(a) (b)

Figure 8. Stability Margin vs. Disturbance Rejection Bandwidth of the different aircraft configurations.
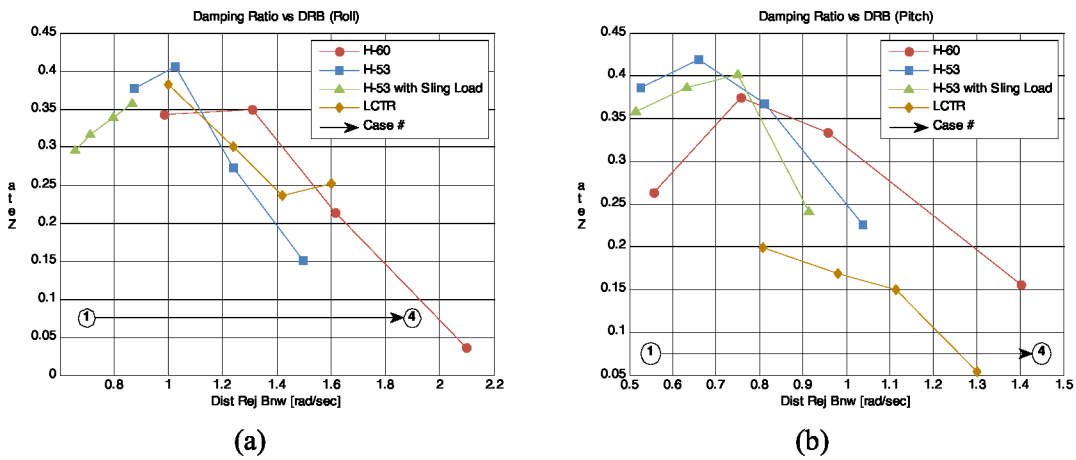

(a) (b)

Figure 9. Damping ratio vs. Disturbance Rejection Bandwidth of the different aircraft configurations.

Table 2. Aircraft configurations and flight control system characteristics.

Aircraft Config	Case	Phase Margin, Gain Margin [deg], [dB]		DRB [rad/sec]		Damping Ratio Disturbance input		Control input		Bandwidth [r/s] Control input	
		Lat	Lon	Lat	Lon	Lat	Lon	Lat	Lon	Lat	Lon
H-60	1	55.4, 5.9	46.4, 9.0	0.98	0.56	0.34	0.26	1.00	1.00	4.72	3.84
↓	2	41.2, 5.5	37.1, 8.6	1.31	0.76	0.35	0.37	1.00	1.00	4.85	3.82
	3	30.6, 4.9	30.6, 8.3	1.62	0.96	0.21	0.33	1.00	1.00	4.86	3.78
	4	23.6, 3.9	20.4, 7.5	2.10	1.40	0.04	0.16	0.62	0.63	4.78	3.64
H-53	1	44.4, 7.0	44.3, 10.4	0.88	0.53	0.38	0.39	1.00	1.00	2.15	2.17
↓	2	37.9, 6.6	38.8, 10.1	1.03	0.66	0.41	0.42	1.00	1.00	2.25	2.27
	3	30.4, 5.9	32.5, 9.7	1.24	0.81	0.27	0.37	1.00	1.00	2.39	2.41
	4	20.9, 4.7	23.2, 9.0	1.50	1.04	0.15	0.23	1.00	1.00	2.89	2.62
H-53 w/ext slung load	1	72.2, 11.4	45.3, 11.7	0.66	0.52	0.29	0.36	0.57	1.00	4.06	2.52
	2	67.2, 10.8	38.9, 11.3	0.71	0.63	0.32	0.39	0.65	1.00	4.18	2.59
	3	62.5, 9.9	31.5, 10.9	0.80	0.75	0.34	0.40	0.73	1.00	4.31	2.67
	4	59.0, 8.7	21.1, 9.5	0.87	0.91	0.36	0.24	0.78	1.00	4.41	2.78
LCTR	1	46.6, 9.1	45.5, 10.7	1.00	0.81	0.38	0.20	1.00	0.77	2.09	2.19
↓	2	37.3, 9.4	36.1, 10.6	1.24	0.98	0.30	0.17	1.00	1.00	2.22	2.14
	3	30.6, 8.9	30.6, 9.9	1.42	1.12	0.24	0.15	1.00	1.00	2.27	2.18
	4	21.7, 9.2	20.4, 10.0	1.60	1.30	0.25	0.05	1.00	1.00	2.79	2.19

Table 3. CETI turbulence model parameters.

Turbulence level	CETI model inputs		
	U_o (ft/sec)	σ_v (ft/sec)	σ_w (ft/sec)
moderate	60.0	8.5	6.5
light	30.0	4.3	3.3
ambient	13.3	1.9	1.5

Facility

The experiment was conducted in the NASA Ames Vertical Motion Simulator VMS [15], seen in Figure 10. The Transport Cab was used for its large horizontal field-of-view, as seen in Figure 11. Traditional helicopter pilot-control inceptors, i.e., center stick, collective, and pedals were provided for the right cockpit seat, as seen in Figure 12. The primary flight display and horizontal situation (hover) display, replicating the Army's Common Avionics Architecture System (CAAS) displays, were provided on the instrument panel.

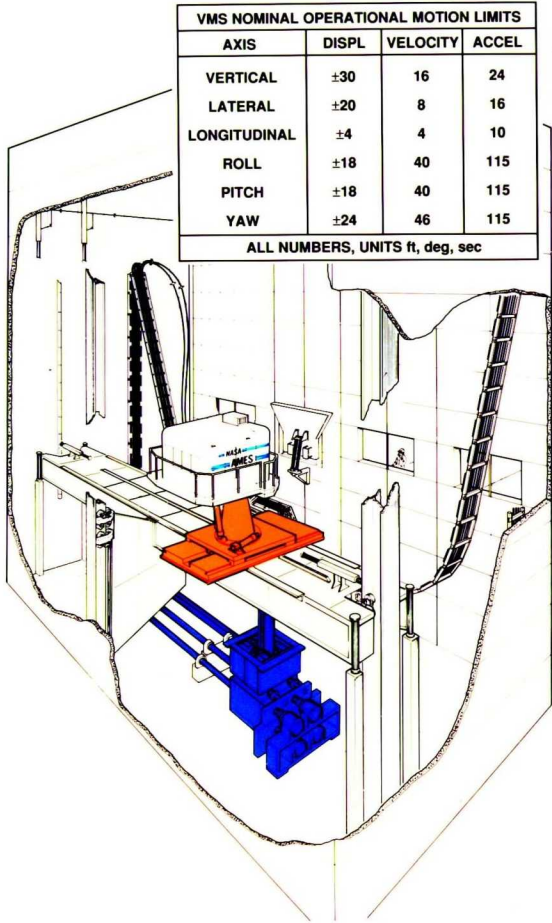| VMS NOMINAL OPERATIONAL MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±30	16	24
LATERAL	±20	8	16
LONGITUDINAL	±4	4	10
ROLL	±18	40	115
PITCH	±18	40	115
YAW	±24	46	115
ALL NUMBERS, UNITS ft, deg, sec			

Figure 10. Vertical Motion Simulator.

Figure 11. VMS two-seat Transport Cab overview.

Figure 12. Pilot's view at precision hover station-keeping point.

Evaluation tasks

The evaluation tasks included hover and low-speed MTEs from ADS-33. Specifically, these included the Hover MTE, the Lateral Reposition MTE, the Pirouette MTE, and the Depart/Abort MTE. However, the majority of the data were collected for the Hover and Lateral Reposition MTEs. From early training and initial evaluations, it was found that these two maneuvers, especially the Hover MTE, best-exposed potential differences in the configurations. The ADS-33 cargo/utility maneuver performance standards were used. For the H-53 external slung load configuration, the ADS-33 external load maneuver performance standards were used. For LCTR, some refinements to the Hover MTE performance standards were necessary. It was found during the initial phase of the simulation that the cargo/utility maneuver performance standards were too "small" and aggressive for this large of an aircraft. The iterations towards more acceptable and appropriate standards for this large aircraft are discussed in the results section below. However, the cargo/utility performance standards for the Lateral Reposition MTE were found acceptable for the LCTR configuration.

Evaluation Procedure

Ten pilots provided evaluations during this experiment. Most flew and evaluated a subset of the four aircraft configurations and weather conditions. All pilots were experienced experimental test pilots with significant rotorcraft experience. Three had tiltrotor flight experience. Pilots represented the Army, Marine Corps, NASA, the US rotorcraft industry, and a German military pilot from Wehrtechnische Dienststelle 61 (WTD-61) representing the DLR. All pilots were familiar with the Cooper-Harper Handling Quality Rating (HQR) scale [16] and with the ADS-33 evaluation tasks.

Pilots completed at least two simulation sessions for training in the overall experiment objectives, methodology, and familiarization with the aircraft configurations prior to the start of formal evaluations. Task performance displays in the VMS lab presented pilot-vehicle task performance in terms the *desired* and *adequate* standards for each MTE. This information was read back to the pilot after each maneuver was completed. In the formal evaluation sessions, pilots first flew the MTE-aircraft-turbulence configuration until consistent performance was achieved and then at least three formal data runs were accomplished and recorded. If the pilot felt one of these formal data runs was out-of-the-ordinary compared to the others, additional data runs were included to resolve the inconsistency. In general, a pilot could complete an aircraft configuration and weather condition evaluation set with four control system

variations in one evaluation session. Data collected and recorded include the aircraft control inputs and state data, task performance data, and pilot comments. A formal questionnaire was used to illicit pilot comments about task aggressiveness/performance, aircraft characteristics, and pilot workload. The pilots used the HQR scale to provide a qualitative evaluation of the configuration.

Results

The results from this study are presented in terms of observations, qualitative comments, and quantitative data. The following sections cover the main results, i.e., the stability margin and damping ratio results, and the disturbance rejection bandwidth (DRB) results. Additional results are presented for LCTR-specific items and for a flight control design criterion that considers actuator rate limiting.

Stability Margin / Damping Ratio Results
Results of this experiment were composed of objective task measures for the ADS-33 evaluation tasks and pilot evaluations using a questionnaire that led to the assignment of a Cooper Harper Handling Qualities Rating (HQR) [16]. Results are discussed in terms of HQRs and time history data analysis, and then in terms of pilot comments on aircraft/task characteristics.

HQRs. For the Hover MTE, the averaged HQRs are shown in Figure 13 for the four aircraft configurations as functions of the control system phase margin cases. The bars represent the 90% confidence bands for the data available. The task required the pilot to actively work with the control system through all three phases of the task: the 6-10 knot translation, deceleration, and 30-second station-keeping phase. The task required significant longitudinal, lateral and heave control activity, while the yaw axis could be largely ignored.

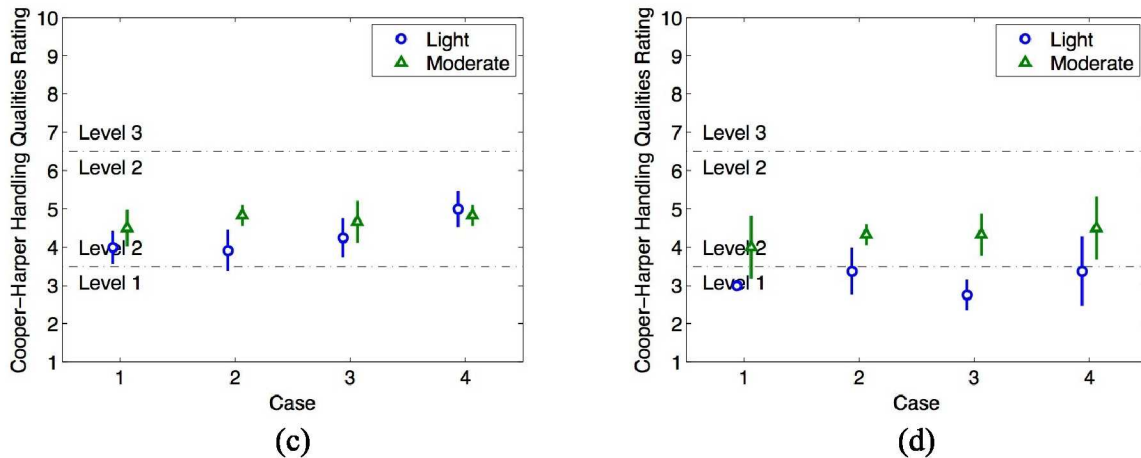(a)   (b)
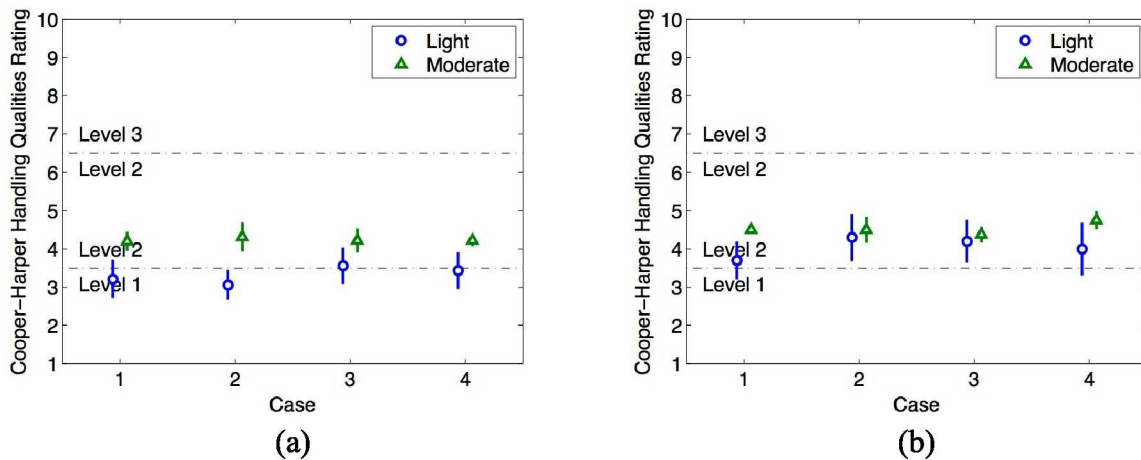
Figure 13. HQRs for Hover MTE: a) H-60, b) H-53, c) H-53 with slung load, and d) LCTR.

The Hover MTE proved a Level 1 task in light turbulence that degraded to Level 2 in moderate turbulence for the H-60 and the LCTR aircraft. As expected, after the response bandwidth reduction for the H-53 to minimize actuator rate limiting, this configuration was rated as Level 2 in both turbulence levels. The average HQRs do not vary much over control system configuration for a given aircraft and turbulence level. A preliminary look at task performance did not reveal any significant differences either.

For the Lateral Reposition MTE, the averaged HQRs are shown in Figure 14 for the four aircraft configurations as functions of the control system phase margin cases. Average values of the HQRs for the Lateral Reposition MTE tended to be particularly flat, even more so than those for the Hover MTE. The Lateral Reposition task required a large initial step-like input to initiate the maneuver and build up speed, but otherwise demanded smooth, low frequency stick commands. This input activity was not sufficient, and not at the right frequency, to raise the gains enough to bring the aircraft close to PIO for Case 4 the same way it did in the Hover MTE.

In general, all the aircraft configurations tended to straddle the boundary between Level 1 and Level 2 handling qualities independent of turbulence. In nearly all cases the average HQR differences between the light and moderate amounts of turbulence were small, except for two configurations: the H-60 for phase margin Cases 3 and 4; and the H-53 with an external slung load for Cases 1 and 2. These Cases were degraded into the Level 2 region with an increase in turbulence to moderate amounts.

Interesting were the comparisons of H-53 configuration with and without the external slung load. The H-53 with an external slung load was rated better in *every* Case / level of turbulence combination (except Case 2 for moderate turbulence) compared to the H-53 without an external slung load. A contributing factor for this is the "relaxed" time-to-complete the maneuver with an external slung load compared to without. The amplitude and frequency of the inputs commanded by the pilots are such that they do not force or excite the response of the slung load dynamics, even with the low stability margin cases.
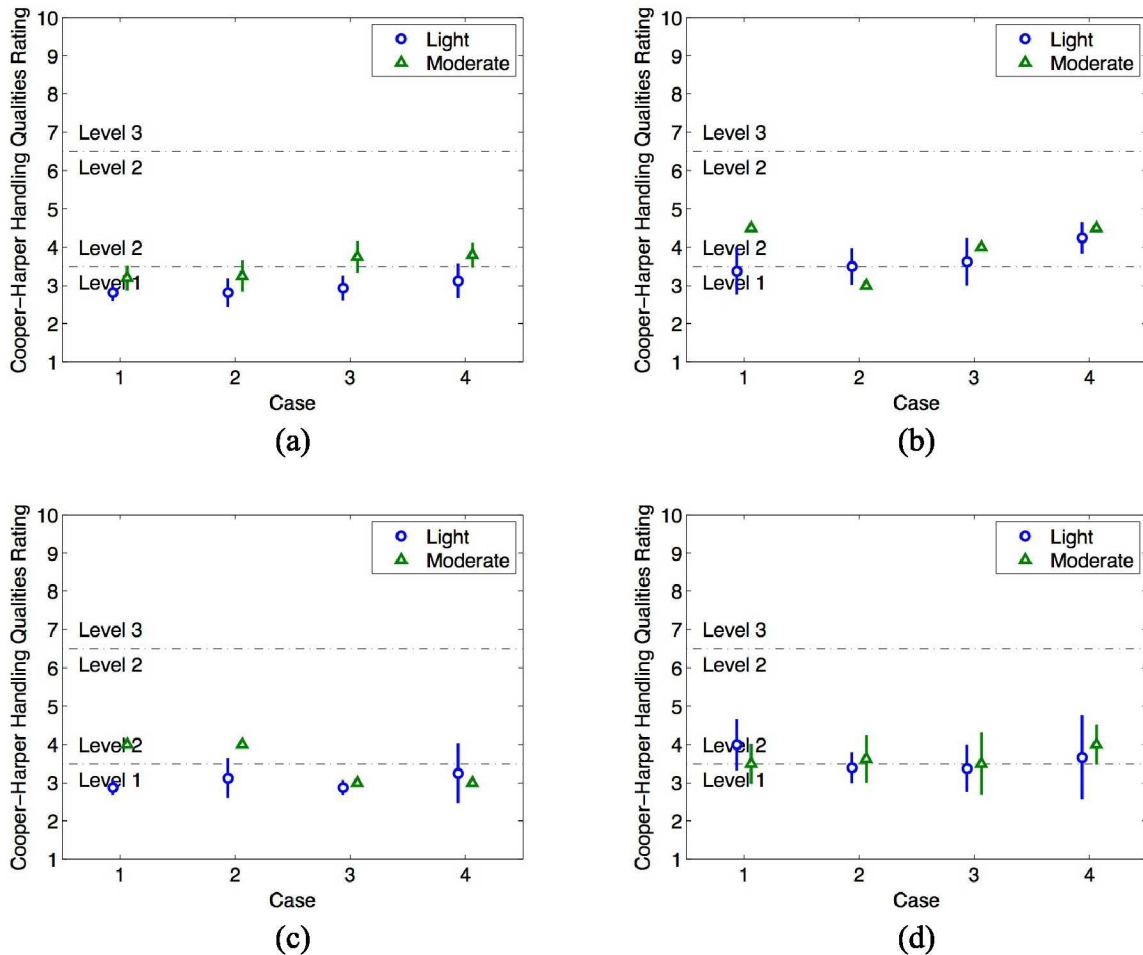
Figure 14. HQRs for Lateral Reposition MTE: a) H-60, b) H-53, c) H-53 with slung load, and d) LCTR.

Pilot comments on aircraft/task characteristics. Pilots were asked to qualify different characteristics of the aircraft, as part of the standard conduct of the experiment, before proceeding to rate it according to the Cooper-Harper handling qualities scale. Two of the fundamental aircraft characteristics considered were the oscillatory behavior, and the predictability of the initial aircraft response. In the absence of any major differences in the HQRs, it was necessary to qualify the different control system configurations on the basis of these aircraft characteristics. It should be noted that pilot commentary was complex and rich with detail. In order to extract any potential trends out of it, it was found useful to break the commentary down into more generic categories.

Pilot comments on aircraft oscillations were broken down and lumped into three discrete categories: annoying or slight, objectionable or unacceptable, and PIO propensity. Results were plotted in terms of the number of pilots who described a specific configuration as possessing any one of these characteristics, or, alternatively, the number of times a specific configuration was characterized as such by the pilots. It should be noted that pilot judgment represents a measure of the overall oscillatory motion of the aircraft. Pilots often found it difficult to distinguish oscillation of the aircraft induced from its response to external gusts or from oscillation resulting from pilot input. These are naturally coupled, since the pilot needs to

Figure 14. HQRs for Lateral Reposition MTE: a) H-60, b) H-53, c) H-53 with slung load, and d) LCTR.

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be in the loop to compensate for the aircraft response to gusts. There is a fundamental trade-off between disturbance rejection bandwidth and stability phase margins, and thus pilot perception is a good, overall indicator of this trade-off. ADS-33 requirements for mid-term response to control inputs may need to be expanded to account for gust response metrics in conjunction with pilot input response damping ratio.

Pilot commentary regarding the predictability of the initial response tended to be graded between two distinct extremes, with pilots describing the initial aircraft response as "predictable" on one end, and "unpredictable" in the other. Situations that did not clearly fit within these two extreme descriptions were lumped into a third, and intermediate, category. Consequently, cases described as slightly unpredictable, or less predictable (relative to the most predictable of the control system configurations), e.g., were assigned within this category. These results are presented for the Moderate Turbulence levels.

Figure 15 presents a summary of the pilot comments on aircraft oscillations for the H-60 configurations while performing the Hover MTE. Overall, ten pilots evaluated Case 1, nine pilots evaluated Cases 3 and 4, and eight pilots evaluated Case 2. Case 1 did not have any objectionable oscillation or PIO comments. Aircraft oscillatory behavior, for the lower stability phase margin cases, was found to be objectionable. Case 4 was determined to be highly objectionable by the pilots, pointing to an impending handling-qualities cliff, despite the damping ratio of the closed-loop attitude response to pilot input for this case being above 0.6 (Table 2).
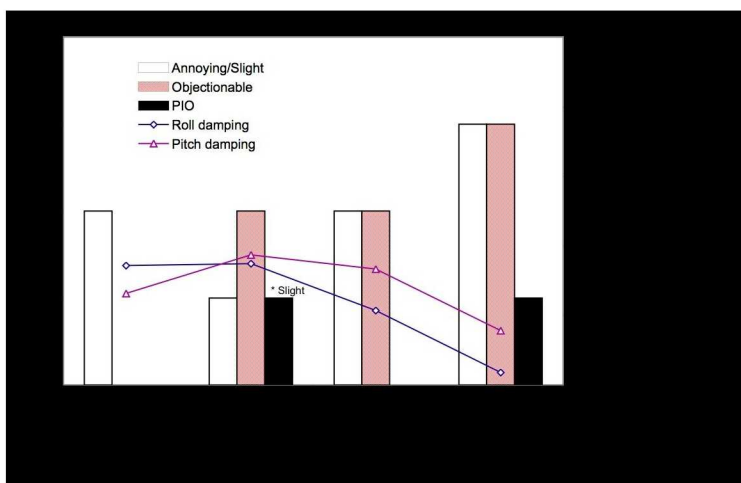

Figure 15. Pilot commentary on aircraft oscillations and damping ratio of system response due to disturbances, H-60 in moderate turbulence.

Also shown in Figure 15 is the damping ratio of the attitude response due to disturbances for both the pitch and roll axes. For Cases 1, 2, and 3, the disturbance response damping ratios were above 0.2. For the "highly-objectionable" Case 4, both pitch and roll disturbance response damping ratios dropped below 0.2, distinctly separating this configuration from the rest. Additional data, including flight data, is needed to help to support and anchor a mid-term gust response damping ratio criteria.

Pilot reports correlated very well with the quantitative attitude and rate measurements taken during the 30-second stabilized hover portion of the Hover MTE. Figure 16 shows the roll rate rms values for the H-60 helicopter for both turbulence levels. For the moderate turbulence level, there is an increase in roll rate rms values as the stability margins decrease, supporting pilot perception of objectionable oscillations and impending PIO.
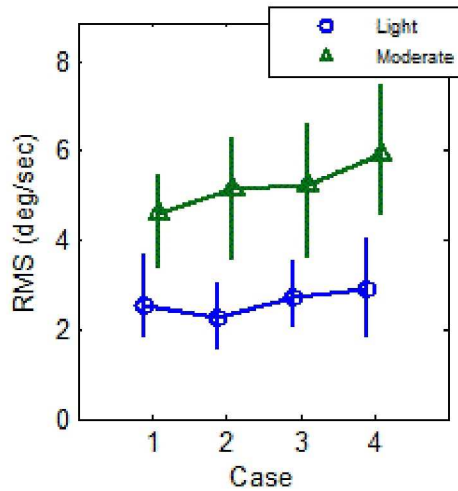
Figure 16. H-60 roll rate rms during 30-second stabilized hover.

Pilot perception of the predictability of the initial response of the H-60 helicopter in moderate turbulence is summarized in Figure 17. Although Case 2 had only *Predictable* comments, i.e., no negative comments, Case 1 received more favorable comments. The two *Unpredictable* comments were from the same pilot, who employed a high gain approach and was consistently more aggressive in controlling the aircraft. Cases labeled as unpredictable were also reported to possess *crisp* or *good* response types. A strong argument could be made, based on the overall assessment of oscillation and predictability of the H-60 configuration, that the nominal stability phase margins (Case 1) rendered desired characteristics, i.e., the best trade-off between disturbance rejection bandwidth and stability, while Case 4 was found to be unacceptable on the basis of its objectionable oscillation and PIO propensity. The latter may indicate an incipient handling qualities cliff for Case 4.
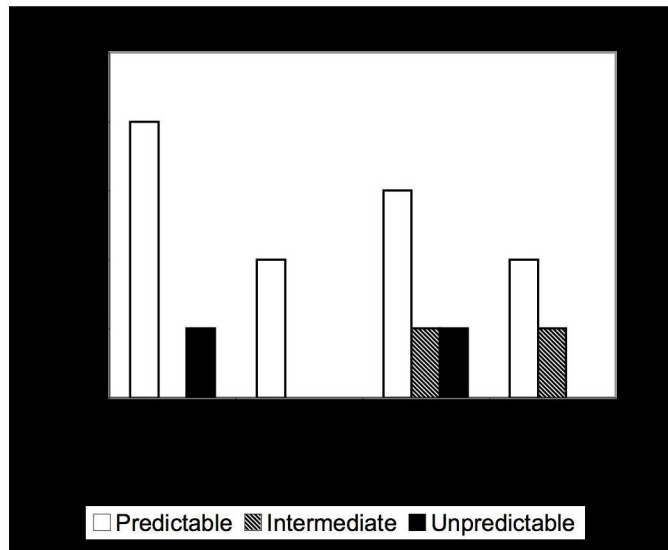
Figure 17. Pilot commentary on predictability of initial aircraft response, H-60 in moderate turbulence.

Figure 18 summarizes pilot appraisal of the oscillatory behavior of a H-53 class helicopter in moderate turbulence while performing the Hover MTE. Four pilots in total rated this configuration. The bar graph shows Case 1 was flagged as objectionably oscillatory by one pilot, while Case 2 elicited no

"objectionable" comments. Additionally, one pilot reported for Case 1 to have excited slight oscillations of the aircraft by attempting very tight hover position control. These were classified as "pilot induced oscillations", but it should be noted that they were not objectionable, nor was the aircraft particularly prone to PIO in a precision task such as this one. Figure 19 shows Case 2 was consistently chosen as the preferred configuration, in terms of the predictability of the initial response, while Case 4 was the worst. Together, these two elements make a strong argument that from the cases evaluated, Case 2 and the higher DRB, has a preference over Case 1 for this class of aircraft. However, similarly to the H-60 configuration, phase-margin for Case 4 was determined to be too low, resulting in the incipient handling-qualities cliff indicated by the objectionable oscillatory characteristics and PIO propensity, as well as the unfavorable assessment of predictability. Roll rate rms shown in Figure 20 supports pilot comments for Case 4, but Cases 1–3 were found to exhibit comparable oscillation rates and thus did not fully support pilot perception. If anything, Case 1 was the least oscillatory (slightly) of the four Cases, even less than Case 2 and Case 3.
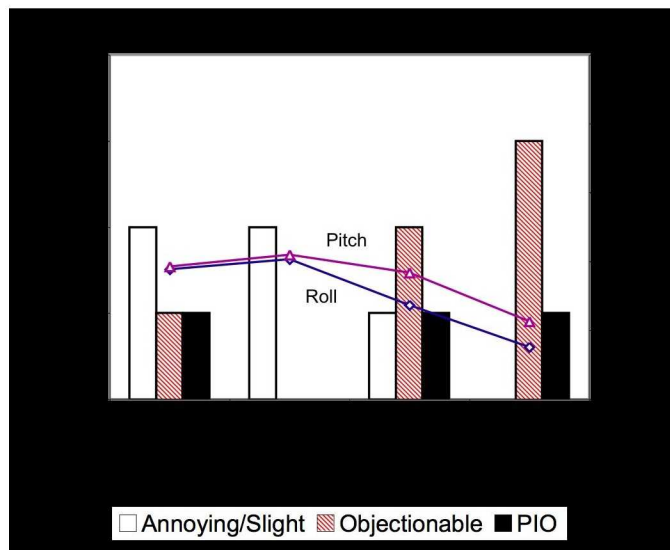

Figure 18. Pilot commentary on aircraft oscillations and damping ratio of system response due to disturbances, H-53 in moderate turbulence.
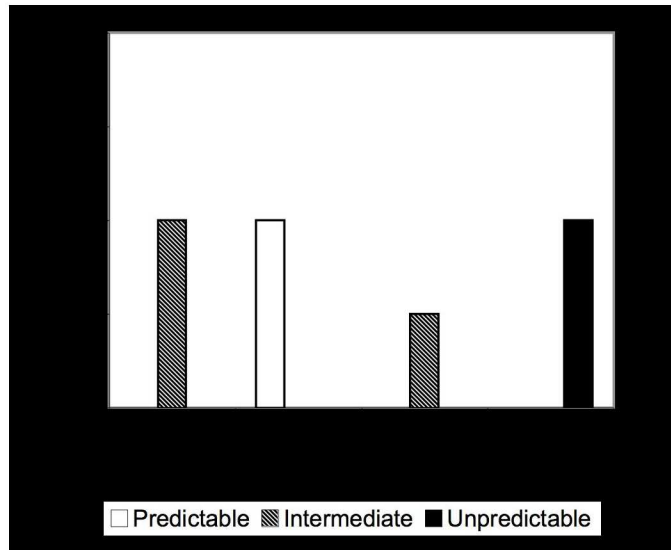
Figure 19. Pilot commentary on predictability of initial aircraft response, H-53 in moderate turbulence.
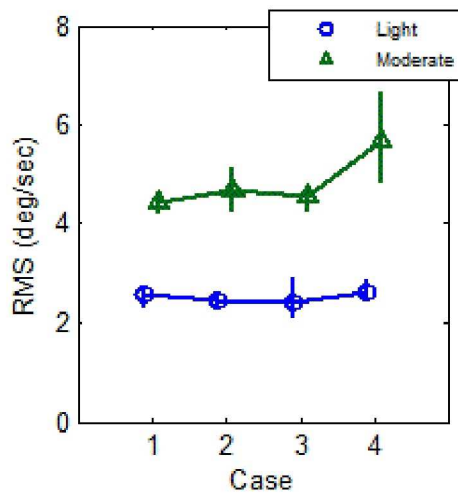

Figure 20. H-53 roll rate rms during 30-second stabilized hover.

The damping ratio of the attitude response to gust disturbances is also shown in Figure 18. For the H-53 configuration, these results show that when the damping ratio of the lateral response (to gust disturbances, in this case) dropped below 0.3–0.35, the resulting oscillations of the aircraft were deemed by the pilots to be worse, or objectionable, compared to the other cases. This result is consistent with ADS-33 mid-term response to control input requirements.

Station Keeping Performance with Increasing Turbulence

The rms of the aircraft position error (i.e., the distance between the pilot station and the hover reference point in feet) for the stable hover portion of the Hover MTE with light and moderate turbulence is shown for the H-60 in Figure 21 and for the H-53 in Figure 22. The average value for each case and turbulence level is shown as a marker, and the vertical bars represent the maximum and minimum values. As the level of turbulence increases from light to moderate, the H-60 lateral and longitudinal data show an

increasing trend in the mean rms position error for all cases. For the H-53, this trend is only slightly apparent in the lateral position error data. The trends in these data correlate well with the handling qualities ratings shown in Figure 13, where as the turbulence level increased, the H-60 showed a degradation in handling qualities of about one full rating for all cases, while the H-53 ratings remained about the same for both levels of turbulence.
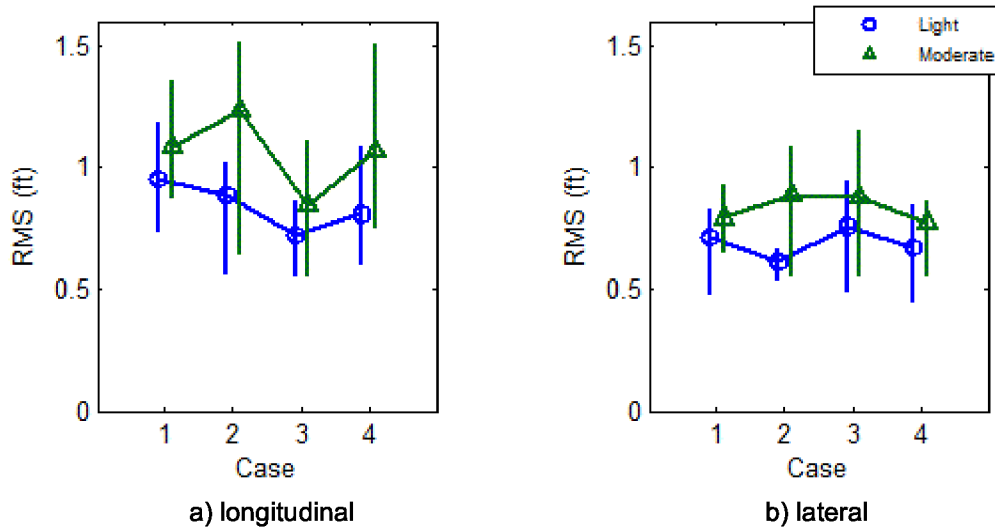
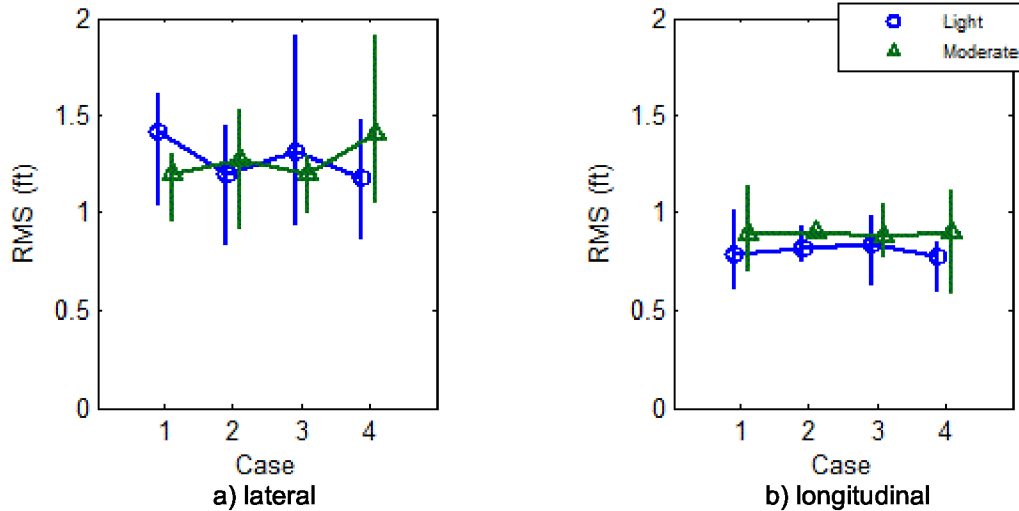Figure 21. H-60 lateral and longitudinal position error rms during 30-second stabilized Hover.

Figure 22. H-53 lateral and longitudinal position error rms during 30-second stabilized Hover.

For the moderate level of turbulence, the highest level tested, the data does not show a decreasing trend in the rms position error as the disturbance rejection bandwidth increases. In fact, Figures 21 and 22 show that the position error for Case 1 (lowest disturbance rejection bandwidth) was approximately the same or less than the position error for Case 4 (highest disturbance rejection bandwidth). In addition, Figures 16 and 20 show that the highest aircraft roll rates were associated with Case 4 in moderate turbulence, and pilot comments indicated that this combination was unacceptable on the basis of objectionable aircraft

oscillation and PIO propensity. While a minimum disturbance rejection bandwidth is required to reject atmospheric turbulence, these results show that there may also be an upper limit, beyond which increasing the DRB does not improve station keeping performance, and can result in unacceptable oscillations when the aircraft is subjected to atmospheric turbulence.

DRB Limits

The experiment featured varying levels of disturbance rejection bandwidth (DRB). This information was used to validate the disturbance rejection bandwidth table given in the ADS-33 Test Guide [6] and provide more data towards proposing Level 1 boundaries. Since the effect of the disturbance rejection bandwidth is most strong in turbulent conditions, where there is a need for disturbances to be rejected; only the data sets from moderate turbulence were considered. The low and ambient turbulence settings were too calm for the pilots to discern a difference in the ability of the control system to reject disturbances.

Disturbance rejection bandwidth is a measure of the speed at which the control system can reject disturbances. This should be directly related to the standard deviation of the attitude excursions during a stabilized hover in turbulence if the pilot was out of the loop. However, since the pilot was in the loop, he provided additional disturbance rejection to minimize attitude excursions (at an increased work-load), even when the control laws exhibited low disturbance rejection bandwidth. Therefore, it was important to consider a combination of the attitude rms data during the Hover maneuver (30-second stable portion), as well as piloted comments. These data were used to support ADS-33 Test Guide values for satisfactory pitch and roll disturbance rejection bandwidth. The results are shown in Figures 23 and 24.
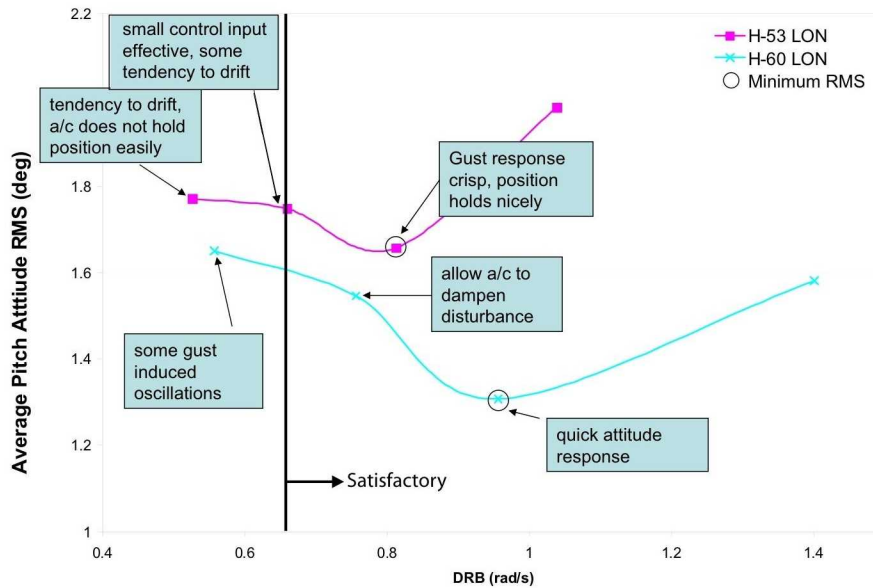

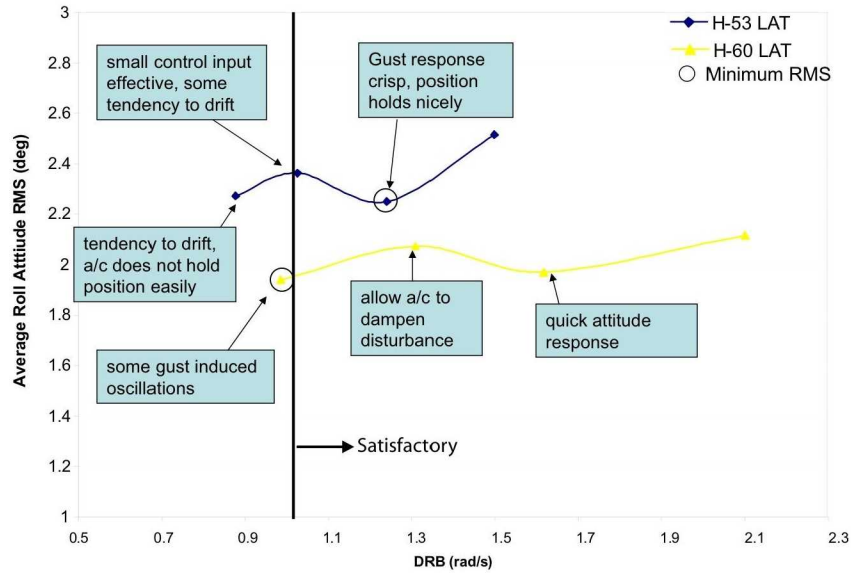Figure 23. Proposed Boundary for Pitch Attitude DRB.

Figure 24. Proposed Boundary for Roll Attitude DRB.

There was better correlation between the pitch rms and the comments than the roll rms and the comments. This may be because the cueing is better for the roll axis where the hover board is directly in front of the pilot. Therefore, the pilot was more aware of attitude excursions and was in the loop making corrections. In pitch, the pilot has to look out the side window for cueing, which is less convenient. Thus, the pilot relied more on the control system to reject the longitudinal disturbances since he could not constantly monitor this axis easily. The highest DRB cases showed an increase in attitude rms, not from the increased DRB, but because of the low stability margin and effective damping.

The proposed boundaries of Figure 24 correlate well to the "typical" disturbance rejection bandwidths given in the ADS-33 Test Guide, as shown in Table 4. The results from the VMS show a slightly higher minimum frequency for the boundary in the pitch axis, but close to the ADS-33 Test Guide.

Table 4. Comparison of Proposed Disturbance Rejection Bandwidth Boundaries.

Satisfactory DRB	ADS-33 Test Guide	VMS
Roll Attitude	1 (rad/sec)	1 (rad/sec)
Pitch Attitude	0.5 (rad/sec)	0.65 (rad/sec)

Large Tiltrotor–specific Results
Four pilots evaluated the large tiltrotor configuration. Three of these pilots had tiltrotor flight experience. The large aircraft size, resulting in a long moment arm between the aircraft center of gravity and the cockpit produced the most significant result differences between this aircraft configuration and the other, more conventional, single main rotor helicopters of this investigation. This large aircraft had a prop-rotor tip-to-tip clearance on the order of 150 feet, prompting evaluation task altitude changes to ensure appropriate safety margins for ground clearance. Both the Hover and Lateral Reposition MTEs were raised to 50 feet with consequent reduction in visual cues both in field-of-view impacts and reduced texture noted by pilots.

Another impact of the LCTR was a sense by the evaluation pilots that the ADS-33 cargo/utility Hover MTE performance standards were "too small" for this large aircraft. Specifically, once in the stable hover, the tolerances for lateral-longitudinal position deviations (±3 ft) and altitude deviations (±2 ft) were considered too tight. The pilot's outside visual task cues (shown in Figure 13) and the task performance displays in the VMS were made digitally scalable to easily address this issue. Using the baseline LCTR (Case 1), several pilots evaluated a range of standards: lateral-longitudinal positions deviations included ±3, ±4, ±5, and ±10 ft. Altitude deviations were varied in like-aspect ratio and included ±2, ±3, ±4, ±6 ft. The ±10 ft was considered too large. The ±5 ft was also considered a little larger than necessary. The pilot's agreed the ±4 ft lateral-longitudinal position deviation and ±3 ft altitude deviation were appropriate for the limits of *desired* performance. *Adequate* position and altitude performance limits were set at double the *desired* limits, i.e., ±8 ft and ±6 ft., respectively. All other cargo-utility Hover MTE standards remain unchanged for the LCTR configuration.

Another consequence of aircraft size was the impact of the long moment arm to the cockpit. This was immediately seen as heave reactions at the cockpit due to aircraft pitch attitude changes and abrupt side-force due to yaw. The yaw-axis impact was dealt with by a small study and tuning provided by one pilot with results reported below. These results provided the selected yaw-bandwidth configuration for the rest of the evaluations, which had a reduced yaw control bandwidth compared to the original design. A more complete study is warranted but was beyond the scope of this effort. The heave with pitch response led to altered pilot control techniques attempting to minimize the impact. In general, pilots sought to minimize their use of pitch attitude for longitudinal position control, relying on the aircraft stabilization to do most of the longitudinal station keeping of both evaluation tasks. The precision hover task required pitch movement to initiate and terminate the inbound translation to the station keeping point. Pilots compensated by using thrust control simultaneous with the pitch control, keeping the cockpit at a constant height above ground.

In common with the helicopter configurations investigated, formal HQRs for Hover and Lateral Reposition MTEs with the LCTR were relatively insensitive to the primary control system characteristic variations, as seen in Figures 13c and 14c. While the numerical ratings assigned by pilots to each case show little variation, the pilot comments supporting those choices do show differences. Table 5 lists selected pilot comments illustrative of the four control configurations for the Hover and Lateral Reposition MTE.

Table 5. Selected Pilot Comments for LCTR.

LCTR Case	Hover MTE	Lateral Reposition MTE
1	Desired performance achieved but can be inconsistent. Pilot in control loop leads to higher workload. Sluggish in longitudinal axis.	Sluggish in roll—takes a lot to get it going. No oscillation. More work in lateral.
2	Desired performance achieved (one pilot). On border of desired performance. Cautious control strategy used (another pilot). Moderate pilot compensation—heave with pitch.	Controls crisp. Could be aggressive with aircraft because aircraft responded as desired. Predictable. Could be fairly precise.
3	Adequate performance. Reasonably stable in turbulence. Easier ability to stop in (station keeping) box. Workload still high. By far, best looking configuration.	Pretty aggressive maneuver. Did not seem too oscillatory in roll (some noted, though). Must use smooth control inputs to avoid adverse modes.
4	Working hard. Oscillation apparent. Large collective reactions required. On edge (of controllability) when pilot gets into control loop.	Poor predictability. Lurking on edge of a rough ride. Wild ride with pilot in control loop. Could not get aggressiveness up to meet task standards. Could make desired performance, but a cliff awaits.

The Case 1 control responses were regarded as providing a sluggish aircraft, with the pilot having to work at getting the desired maneuver performance. Cases 2 and 3 were assessed as having crisper control response, being more predictable, and being more stable in turbulence. For this larger aircraft, the pilots preferred Cases 2 and 3 over Case 1. Again, Case 4, with low stability margins, had apparent oscillations, could be easily upset with the pilot active in the control loop, and pilots sensed an incipient cliff.

This experiment represented one of the first investigations at pilot control of a large hovering aircraft. Modifications to controls such as the yaw bandwidth selection and pilot control strategy development, often with considerable compensation (e.g., height control with pitch) indicate further investigation of control systems, control strategies and even appropriate evaluation tasks are warranted. Pilots of this experiment chose to minimize pitch control inputs to reduce the coupling to height control. The tiltrotor pilots noted they would ordinarily use nacelle movement for longitudinal acceleration and positioning, an option not available with the simple math model employed. Similarly, use of parallel lateral cyclic control was suggested for flat maneuver control of such a large aircraft.

This experiment concentrated on the ADS-33 Hover and Lateral Reposition MTEs, as they provided the most illustrative pilot commentary on differences among the control systems. The ADS-33 Pirouette MTE was looked at briefly but not selected for evaluations. Initial comments on it questioned the nominal task geometry of a 100-ft radius circle when the aircraft in use spread much further than that tip to tip.

LCTR – Yaw bandwidth results

An informal assessment of the LCTR aircraft was performed with the intention of fine-tuning the aircraft's yaw bandwidth. This was made necessary because the initial design bandwidth, based on the ADS-33 requirements, was quickly found to be extremely obtrusive to the pilot, and therefore, disruptive of the normal execution of the experiment.

It is possible, however, to glean some interesting insight, from this exercise, into the adequate measure of control authority required for this type of aircraft. There are two basic elements that define overall yaw control authority: first, the heading control power or maximum yaw rate, and second, the precision required in capturing a target heading (higher dependence on the yaw bandwidth).

The first element is not in question in this case, since it was generally possible to reach maximum yaw rates up to about 27.5 deg/sec with the yaw-rate command system implemented. This surpasses the ADS-33 Level 1 minimum achievable yaw rate for Moderate Agility. With the pilot sitting 38.85 ft ahead of the CG it became apparent that bandwidth requirements for future large rotorcraft of this type would need to be balanced from a human factors perspective. Bandwidth is intimately related to the angular yaw acceleration. At almost 39 ft ahead of the CG, the pilot was subjected to peak lateral accelerations in excess of 0.6g's. These were reported to be highly objectionable.

Current ADS-33 bandwidth requirements are minimums and are not bounded on the high side. Whether the actual aircraft is capable of generating such quick responses remains to be seen. The current exercise simply illustrates the potential necessity to curtail or modify current requirements, to account for aircraft size.

The maneuver that was performed in this yaw-bandwidth investigation loosely resembled the Hovering Turn MTE specified in ADS-33. No restrictions were placed on the aggressiveness and agility with which the maneuver was to be performed, however. The maneuver consisted of the pilot aligning the

aircraft along the runway centerline, at an arbitrary altitude, and then executing 180 or 360 degree turns in an attempt to recapture the aircraft-runway alignment.

Phase delay values for all control system configurations were around 0.15 sec. This places the ADS-33 yaw bandwidth requirements approximately at 0.5 rad/sec for the Level 2 minimum and 2.0 rad/sec for the Level 1 minimum. The original design was set at 2.0 rad/sec, with the intent being that the design point sat right on the Level 1 boundary.

In the absence of HQRs and a formal MTE evaluation process, the available pilot commentary represents the best means for qualifying the control system configurations. Future examination of the problem should include formal HQR evaluations. This should, ideally, include also several values of the phase delay, as well as the bandwidth, in order to better characterize the full bandwidth vs. phase delay map.

Figure 25 summarizes pilot commentary for the different bandwidth and phase delay design points that were tested. Those configurations that nominally fell within the ADS-33 Level 3 handling qualities region (for All Other MTEs) were, not surprisingly, found to be lacking in terms of yaw bandwidth. However, design points that should theoretically possess Level 2 properties were unexpectedly characterized as having a major deficiency. The design point at 1.5 rad/sec, in particular, was reported to have very degraded characteristics. The original design bandwidth of 2.0 rad/sec was immediately considered to be unacceptable by the pilots who tested this configuration. However, this point is not included in the Figure 25, since it was not formally included in the evaluation process.
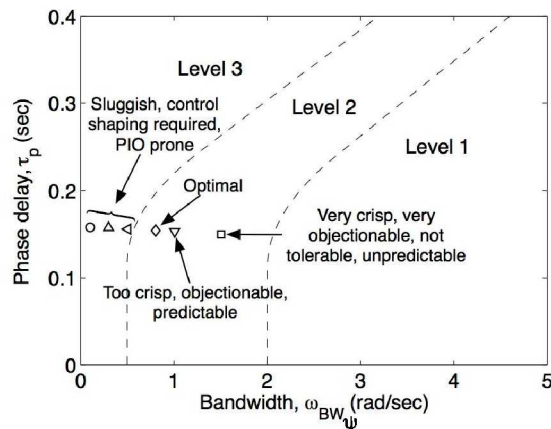

Figure 25. Pilot commentary for LCTR yaw bandwidth and phase delay design points.

Response to pedal inputs for the three control system configurations with bandwidth values under 0.5 rad/sec was described by the pilot as being too sluggish. All of these configurations required some level of pilot shaping of the pedal inputs in order to capture the desired heading accurately. In particular, the lowest bandwidth case, i.e., 0.1 rad/sec, was found to be deficient in the ability to capture a desired heading, and highly prone to PIO, as well. Additionally, larger pedal input was required in order to achieve the desired initial response (understood as yaw rate). Pilot comments for these cases would seem to support the assertion that yaw performance is not adequate enough for these cases to be considered to have Level 2 handling qualities; the 0.5 rad/sec case was considered to be a borderline situation.

The other end of the spectrum, as characterized by yaw bandwidths of 0.8, 1.0 and 1.5 rad/sec, possessed quicker response characteristics, and therefore tended, up to a point, to lead to more predictable configurations. The 0.8 rad/sec point was deemed to be the optimal setting by the test pilot. A second

pilot evaluated and confirmed this setting as providing the best tradeoff. At the higher bandwidth values (i.e., 1.0 and 1.5 rad/sec), and in particular, for 1.5 rad/sec, effects of the large distance between the pilot station and the axis of rotation manifests a sharpness of the response that was characterized as a major deficiency, with controllability even put into question. The latter assessment was considered to be particularly true for the initial design configuration at 2.0 rad/sec.

OLOP Criteria
A useful specification that considers actuator rate limiting is the open-loop onset point (OLOP) criteria [17] for category II pilot-induced oscillation (PIO). Category II PIOs are associated with the non-linear effects of rate and position limiting, which can be very dangerous and has been a factor in most recent PIO accidents. With linear analysis methods, such as Simulink's® "linmod" function, the effects of position and rate limiting are ignored. Thus it is possible to push the linear design of the system well beyond the actual capability of the aircraft, such that when implemented with the nonlinear elements there is severe limiting of rates and positions. The OLOP specification is based on frequency domain describing function concepts, but does not require the user to apply the describing function technique.

The OLOP criteria were used to determine the maximum command model bandwidth for the H-53 control laws. By changing the command model bandwidth, it is possible to tune the bandwidth of the closed-loop system in order to obtain Level 1 pitch and roll bandwidth as given by ADS-33E-PRF. In linear analysis, there is no penalty for increasing the command model bandwidth because the rate and attitude limits of the actuators are not taken into account. Initially, both the pitch and roll command model natural frequencies (ω_n) were set to 1.7 rad/sec, which allowed the pitch and roll axis bandwidths to meet the 2.0 rad/sec Level 1 requirement.

However, upon testing this set of bandwidths in the VMS, which uses non-linear actuator models, the system was reaching the rate limits of the actuators very often, and the pilots were having difficulty flying the system under such conditions. An example simulation time history is shown in Figure 26 for the 20-degree phase margin (PM) case for the H-53, with ω_n=1.7 rad/sec. As shown in Figure 26, actuator rate limiting was occurring frequently. This led to PIO and divergence at the end of the record (circled), where the piloted eventually ended the simulation as he was unable to recover from the large pitch attitude excursion. The pilot comments following this event indicated the difficulty of flying the configuration "Strong degradation of performance, HQR 8-9, Very PIO sensitive, Uncontrollable, Quick Divergence."
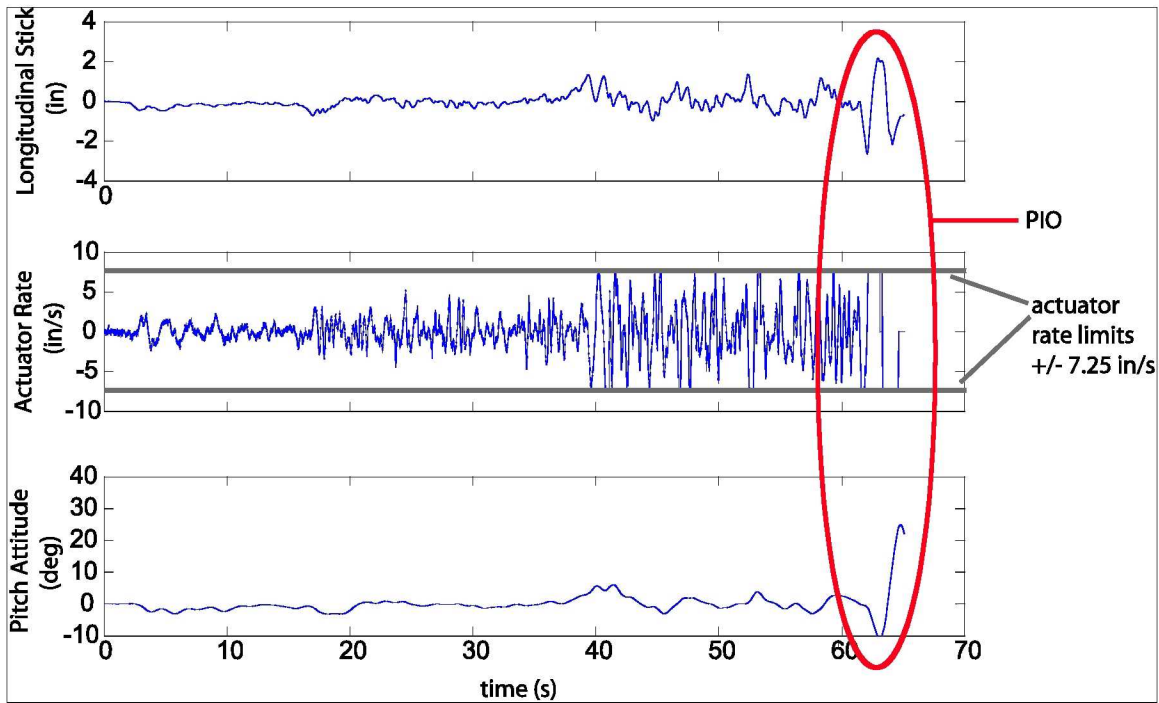
Figure 26. Longitudinal PIO due to actuator rate limiting, 20 degree PM case, ω_n=1.7 rad/sec.

This was related to the bandwidth of the system being too high for the actuators to handle. This can be clearly shown via the open loop onset point (OLOP) specification, which uses linear analysis to determine the likelihood of PIO due to actuator rate limiting [17]. As shown in Figure 27, the cases with the natural frequency of 1.7 rad/sec were all in the "PIO Likely" region. The 20-degree case was well into the PIO region, which is consistent with the time history data and PIO comments.
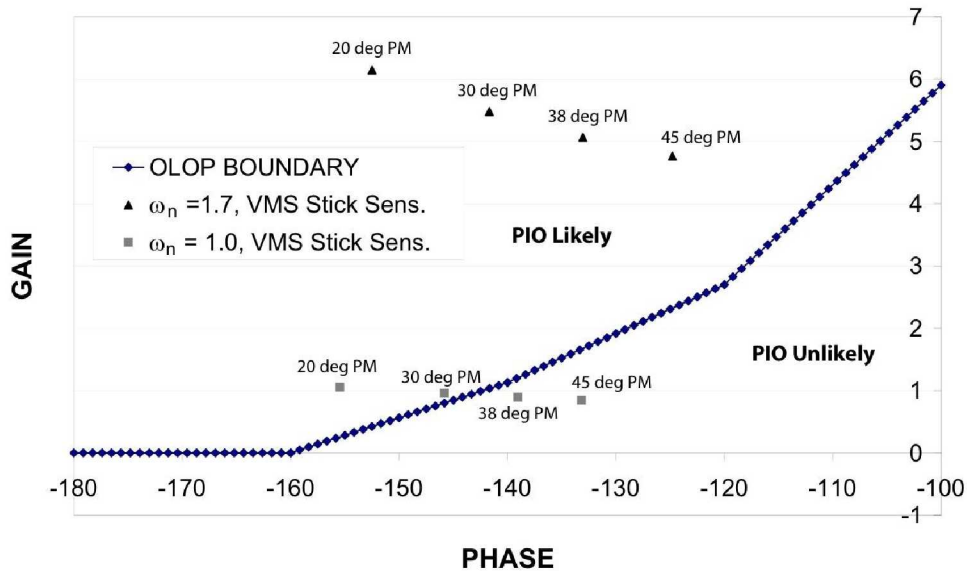

Figure 27. OLOP Criteria for H-53 Pitch Axis.

As a result of this analysis and the piloted experience in the simulation, the natural frequency of the command model was reduced to 1.0 rad/sec. For the 1.0 rad/sec case in the pitch axis, shown in Figure 27, the PIO likelihood was much reduced. Similar results were seen in the roll axis, and its natural frequency was also reduced from 1.7 rad/sec to 1.0 rad/sec. This moved the attitude bandwidth into Level 2, (see Table 2) but was considered a necessary trade-off in order to reduce PIO from actuator rate limiting.

The improvement in the OLOP specification was consistent with the results observed in the simulation for the lowered command model natural frequency. For the revised design, with $\omega_n = 1.0$, there was very little rate limiting as shown for the 20-degree PM case in Figure 28. The figure indicates that the maneuver was well controlled, with no PIO, and no rate limiting of the actuators. In general, the piloted commented less on PIO once the command model frequency was lowered, which was consistent with the OLOP specification.
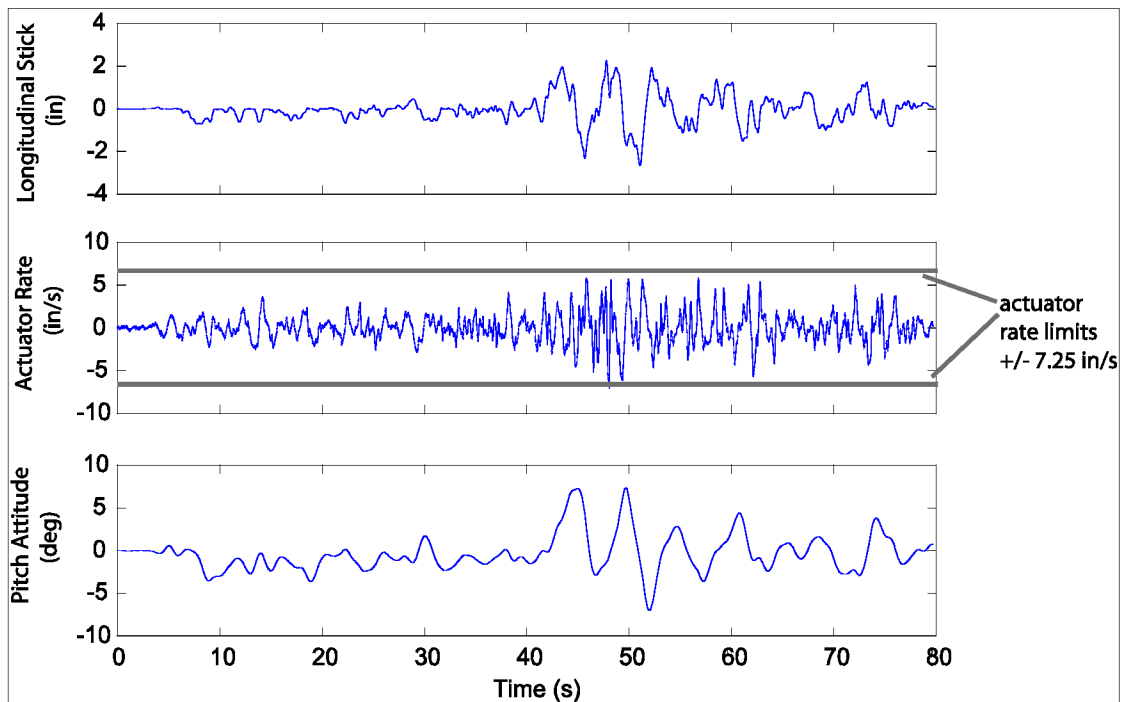

Figure 28. Longitudinal responses, 20-degree PM case, ω_n=1.0 rad/sec.

The use of the OLOP specification was useful for determining the maximum command model frequency. This was a large time saver compared to tuning the command model by hand and then checking to see if the pilots were getting into PIO from actuator rate limiting. The OLOP specification, which was developed for fixed wing applications, is a legitimate method for rotorcraft and proved very useful in this analysis.

Discussion and Implementation

Stability margin requirements

In practice, rotorcraft flight control gains are generally scheduled with airspeed based on discrete anchor points (e.g. at every 20 kts), and sometimes may include pressure altitude dependency. Unlike fixed-wing aircraft, rotorcraft gains are generally not scheduled with weight, inertia, or c.g. Further, even in the most recent applications (CH-47F [11]; UH-60MU [2]) gain scheduling is not included as a function of external load or control system mode. Therefore, the single design must accommodate degradations in stability margin, damping ratio, and disturbance rejection bandwidth that occur at off-nominal conditions as well as due to typical system wear over time.

AFDD has conducted many frequency-sweep flight tests of the UH-60 aircraft over the years. Figure 29 shows the variation of the bare airframe roll-rate response, including the primary actuators, (p/δ_{lat}) in hover from several of these frequency-sweep tests. The measurements shown were obtained over a 17-month period, and encompass a 10-kt variation in average wind speed and a 6% variation in unloaded weight. As can be seen, the measured variations generally fall within the envelope predicted by the simulation model (FORECAST) for typical variations in trim flight condition.
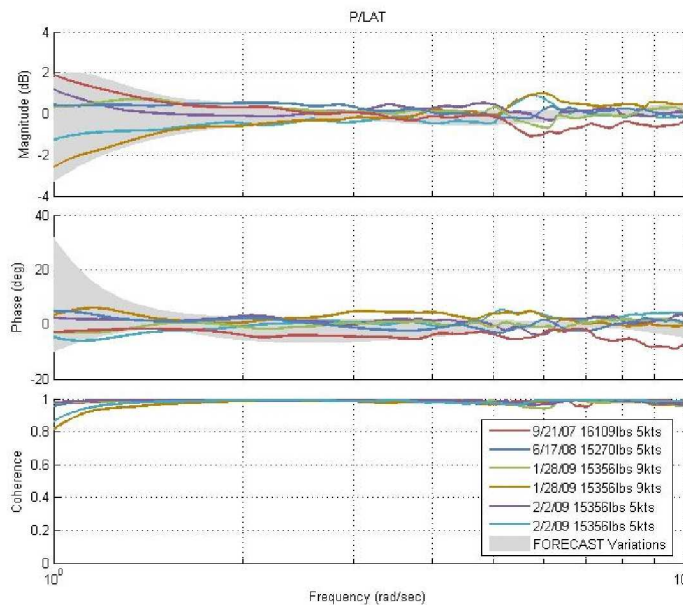

Figure 29. Variation of measured roll-rate response for hover over a 17-month period and 10 kt changes in wind speed, 6% changes in unloaded weight and c.g.

The broken-loop response (*GH*) that determines the stability margins is the product of the airframe response ($G = p/\delta_{lat}$), which has the variations shown in Figure 29, and the feedback (*H*), which is digital and can be assumed not to vary (at a given flight condition). These responses are easily determined in the frequency domain ($G(j\omega)*H(j\omega)$) and the margins plotted as be seen in Figure 30 for the flight-test gain set of Fletcher [2] (which corresponds to Case 1). The resulting scatter in stability-margin values is about 16 deg in phase margin and about 1.3 dB in gain margin. Figure 30 also shows the predicted stability margin ("analysis") for the same gain set based on a high-order linearized model from FORECAST. The nominal simulation analysis model margins are seen to be well within the Level 1 region, while the measurements are mostly in the Level 2 region – emphasizing the need to build in an allowance for modeling error.

The stability margin requirements of 94900 (e.g., 45 deg, 6 dB) are intended to be applied to the most critical configuration of the nominal system, such as the most adverse center-of-gravity location or mass distribution – not to the center of the envelope. Then considering gain and phase characteristics in the presence of uncertainties in flight condition, wear, nonlinearities, such as seen in Figures 29 and 30, the 94900 requirements allow a reduction in the margins of 50% (i.e., from 45 deg, 6 dB reduced to 27 deg, 3 dB).
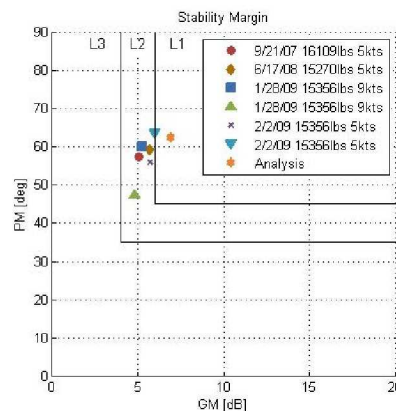

Figure 30. Stability margin calculations based on open-loop aircraft measurements. Also shown is the analysis model prediction.

For the H-60 helicopter, Case 1 with minimum margins of 46 deg, 6 dB was generally judged as the desired configuration – based on pilot comments and corresponding quantitative performance metrics. This agrees with the flight-test results for the UH-60 [18] which found the 94900 design margins were preferred to a higher DRB/reduced margin design for hover. We should interpret these requirements to be applicable to the worst-case configuration – such as most critical weight or c.g. Then, adopting the variability in the flight-test results of Figure 30 of about 16 deg or 1.4 dB would allow a degradation due to uncertainty and wear to margins of 30 deg, 4.6 dB which is consistent with the 94900 requirements. These degraded margins correspond to Case 3 for the UH-60, which was certainly less favorable, *but not at the levels of Case 4 which exhibited an incipient handling-qualities cliff.*

For the larger aircraft (H-53 class, and LCTR), the pilots favored higher DRB and lower stability. For the H-53, Case 2 was preferred as offering the best combination of disturbance rejection and stability (margins, 38 deg, 6.6 dB). For the even larger LCTR this trend continued, now including Case 2 and Case 3 (30.6 deg, 8.9 dB) as being clearly preferred. These simulation results for the larger aircraft are consistent with the flight-test findings for the CH-47F DAFCS flight control development wherein the pilots favored increased DRB in exchange for reduced stability margins [11], and supports the current requirements for the 53K that are relaxed for the external load condition to 40 deg [12]. Yet, if the same uncertainty characteristics from the UH-60 flight test data are applied to the H-53 preferred Case, this would result in a degradation to 22 deg and 5.2 dB. These degraded margins correspond to Case 4 for the H-53, which was judged as *objectionable and PIO-prone*. The same effect would be seen in the LCTR, with degradation of the phase margin to 14.6 deg, which is about a third less than Case 4 – already reported as being oscillatory and on the verge of uncontrollable. Based on these results, extra care must be taken to assess the influence of variability when nominal flight control designs for larger helicopters start with the reduced margins.

Damping ratio requirements
The simulation results of Figure 18 (H-53) generally support the current ADS-33 damping ratio requirements of at least $\zeta = 0.35$, but in this case applied to the response to a disturbance at the output, in

addition to the piloted input. In particular, the results show for the H-53 sized aircraft that when the damping ratio of the lateral response (to gust disturbances, in this case) dropped below 0.3–0.35, the resulting oscillations of the aircraft were deemed by the pilots to be worse, or objectionable, compared to the other cases. For the H-60 configurations, when the disturbance-response damping ratio dropped below 0.2, the resulting oscillations were deemed highly objectionable. This damping ratio requirement finding is supported by the UH-60 flight-test results as well, where a disturbance-response damping ratio of 0.26 was considered satisfactory [18]. An important aspect is that we have determined the effective damping ratio from the step response of the attitude overshoot (as based on the mapping for a 2nd-order system), rather than using the log-decrement method. This approach was taken since in most of the cases there were no residual oscillations below the piloted bandwidth, even though there were large overshoots observed.

Disturbance rejection bandwidth (DRB) requirements
The H-60 and H-53 results of Figures 23 and 24, respectively, support the currently proposed ADS-33 requirements for disturbance rejection bandwidth as published in the flight test guide (i.e., Table 4 [6]). These requirements are also supported by the recent UH-60 flight test results [18]. Further, the VMS simulation and the UH-60 flight-test experience [2] [18] showed that injecting an automated sweep at the output is a practical test technique to determine the DRB value safely and efficiently.

LCTR Yaw-Bandwidth requirements
This experiment was a first handling-qualities study of a large civil tiltrotor. The simulator experience showed that much more work will be needed to adjust the ADS-33 mission-task elements and associated standards for this much larger-scale vehicle. Future efforts will need to take into account the intended mission of the aircraft and the influence of the pilot location. In the present case, the large arm between the pilot station the vehicle center of gravity resulted in large and unacceptable lateral accelerations when the yaw bandwidth was set to meet the ADS-33 Level 1 requirements. Future efforts will need to focus on the other axes and the potential use of nacelle-tilt as a configuration parameter.

Open-Loop Onset Point (OLOP) Criteria
The key design requirements of piloted control-response bandwidth, disturbance rejection bandwidth, and stability margin are based on linear analysis methods. Including the OLOP analysis criteria, which was developed for fixed-wing applications, was found to be very useful in the design process to assess the potential for helicopter actuator rate limiting and resulting PIO tendency - even when the key linear requirements were satisfied. An earlier case study based on the XV-15 in hover [5] showed that this criteria was important for setting the maximum achievable crossover frequency. In the present study, the OLOP specification showed that the maximum command model frequency for the H-53 needed to be reduced to Level 2 to avoid actuator rate limiting and PIO. Though not enough rotorcraft experience has been gained to validate the exact boundary location, which is currently based on fixed-wing data, the analysis has been very useful in flagging clearly PIO-prone configurations.

Conclusions

A collaborative, piloted simulation was performed on the NASA-Ames Vertical Motion Simulator with the primary purpose of investigating the handling quality implications of reduced flight control system stability margins, and the trade-offs with higher disturbance rejection bandwidth (DRB). The study included three classes of rotorcraft, in four configurations: a utility-class helicopter, referred to as H-60; a medium-lift helicopter, referred to as H-53, evaluated with and without an external slung load; and a large (heavy-lift) civil tiltrotor aircraft, referred to as LCTR. This large aircraft also allowed an initial

assessment of the applicability of ADS-33 handling quality requirements to an aircraft of this size. Ten experimental test pilots representing the U.S. Army, Marine Corps, NASA, rotorcraft industry, and the German Aerospace Center (DLR), evaluated a range of aircraft configurations, flight control stability-margins, and turbulence levels, while primarily performing the ADS-33 Hover and Lateral Reposition MTEs. Pilot comments and aircraft-task performance data were analyzed and the results suggest the following conclusions:

• For all aircraft configurations evaluated, the low phase margin cases (20-23 degrees) were unanimously rated as oscillatory, PIO prone, and objectionable with a potential handling quality cliff awaiting. This is in spite the fact that the Cooper-Harper Handling Quality Ratings (HQRs) for the range of cases were remarkably the same, being either Level 1 or barely into the Level 2 region.

• For the utility-class helicopter, H-60, the current recommended stability margins in 94900, i.e., 45 degrees and 6 dB, were preferred by the pilots over the lower stability-margin/higher DRB cases. Maintaining these margins may allow for acceptable degradation due to uncertainty and wear and would be consistent with 94900 requirements.

• For the medium-lift helicopter, H-53, the pilots preferred a higher DRB/lower stability margin configuration (roughly 38 degrees of phase margin). Beginning with these margins and assuming the same uncertainty and wear, this stability margin configuration would degrade to the low phase margin case that had objectionable oscillations and was PIO prone, with an incipient handling qualities cliff nearby. Hence, extra care must be taken to assess the influence of variability when nominal flight control gains start with reduced margins.

• For the large (heavy-lift) civil tiltrotor aircraft, LCTR, the pilot's preference included not only the 38-degree phase margin case but also an even higher DBR/lower stability margin configuration (roughly 30 degrees). Degradations due to uncertainty and wear become even more critical due to the reduced margin starting point.

• The ADS-33 mid-term response-to-control damping ratio metrics can be applied to the disturbance-response damping ratio. Disturbance-response damping ratios less than 0.2, combined with the low phase margin cases, resulted in highly objectionable oscillations for the utility-class helicopter. However, for the medium-lift helicopter, when the lateral axis disturbance-response damping ratios dropped below 0.3–0.35, the aircraft response was deemed worse or objectionable by the pilots when compared to other cases.

• The pilot comments on the disturbance response of the aircraft correlated well to the DRB guidelines provided in the ADS-33 Test Guide. The comments indicate that the pitch DRB guidelines should be increased slightly from 0.5 rad/sec to 0.65 rad/sec, which correlates well with recent UH-60 flight tests. The roll DRB guidelines remain at 1.0 rad/sec.

• From the initial handling quality assessments using a large (heavy-lift) civil tiltrotor (LCTR) aircraft, hover control of large aircraft poses interesting challenges. The long moment arm of the cockpit ahead of the center of gravity creates significant heave coupling with pitch. Similarly, yaw axis accelerations can produce substantial side-force at the cockpit for such large configurations, mandating a reduction in the Level 1 yaw bandwidth requirements. In addition, the lateral and longitudinal position tolerances for ADS-33 Hover MTE needed to be increased to better fit the vehicle size. The Lateral Reposition MTE standards remained unchanged and were satisfactory for this large vehicle. Future efforts are needed to continue to investigate applicability/refinement of the current ADS-33 requirements to large vehicles, like an LCTR. Control system response types such as translational rate control should be investigated for precision control in hover of such aircraft.

- The open-loop onset point (OLOP) criteria, currently based on fixed-wing data, proved to be a useful and accurate tool for predicting actuator rate limiting for rotorcraft. Additional helicopter data is needed to determine a more precise rotorcraft boundary.

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