An Investigation of Large Tilt-Rotor Short-term Attitude Response Handling Qualities Requirements in Hover

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Introduction

The development of both civilian and military rotorcraft typically involves meeting certain sets of specifications and guidelines that cover all phases of design and operation, including environmental, structural and performance requirements. Within these performance standards are flight control requirements, which include handling qualities requirements in addition to flight control system requirements. Design requirements and specifications for civilian rotorcraft may include the FAA Airworthiness Standards contained in Part 27 for Normal Category Rotorcraft and in Part 29 for Transport Category Rotorcraft. For military rotorcraft, the handling qualities and flight control system requirements may include criteria from MIL-H-8501 (Ref. 1) or more recently, from the U.S. Army's Aeronautical Design Standard-33 (ADS-33) (Ref. 2) and MIL-DTL-9490E (Ref. 3). Although civilian rotorcraft are not certified to these military specifications, the standards embodied in ADS-33 represent "good" engineering practices and often translate into guidelines for use in flight control design for civilian applications.

The handling qualities requirements set forth in ADS-33 are well supported for VTOL currently flying aircraft ranging in size up to cargo class helicopters, but their direct applicability to significantly larger rotorcraft—such as Large Civil Tilt Rotor (LCTR2) (Ref. 4) and Joint Heavy Lift (JHL) configurations—has yet to be established. Of particular interest to this study are the short-term pitch, roll and yaw attitude response requirements of ADS-33 and how they relate to large tilt-rotors. This interest is driven by a previous experiment with a large tilt-rotor configuration (Ref. 5), which identified handling qualities issues resulting from large aircraft size; mainly from cockpit locations well ahead of the center of gravity (i.e., natural point of rotation) and from the impact of the reduced natural response frequencies of much greater moments of inertia. Here pilot commentary suggested that handling qualities—particularly in the yaw axis—degraded for high and low bandwidth cases, indicating that there is a limited range of acceptable bandwidths as a direct consequence of the higher inertias and pilot station offset from the center of gravity associated with this large tilt-rotor. A formal evaluation of the roll, pitch and yaw short-term response requirements—as they relate to handling qualities of LCTR2-sized tilt-rotors is found lacking.

A piloted simulation investigation was conducted using the NASA Ames Vertical Motion Simulator to study the impact of pitch, roll and yaw attitude bandwidth and phase delay on handling qualities of large tilt-rotor aircraft. Multiple bandwidth and phase delay pairs were investigated for each axis. The simulation also investigated the effect that the pilot offset from the center of gravity has on handling qualities. While pilot offset does not change the dynamics of the vehicle, it does affect the proprioceptive and visual cues and it can have an impact on handling qualities. The experiment concentrated on two primary evaluation tasks: a precision hover task and a simple hover pedal turn. Six pilots flew over 1400 data runs with evaluation comments and objective performance data recorded. The paper will describe the experiment design and methodology, discuss the results of the experiment and summarize the findings.

Sample Results

Data in the form of Cooper-Harper handling qualities ratings were collected for a wide pool of experimental pilots, painting a fairly consistent picture of the short-term pitch and roll attitude response characteristics for this class of aircraft. Level 1 handling qualities were not consistently attainable for a large aircraft of this class, i.e., with the pilot station located 40 ft ahead of the CG and an ACAH response type. Figure 1 shows optimal Handling Qualities Ratings tend to line up with the constant 1 rad/sec natural frequency line and phase delay lower than 250 milliseconds.

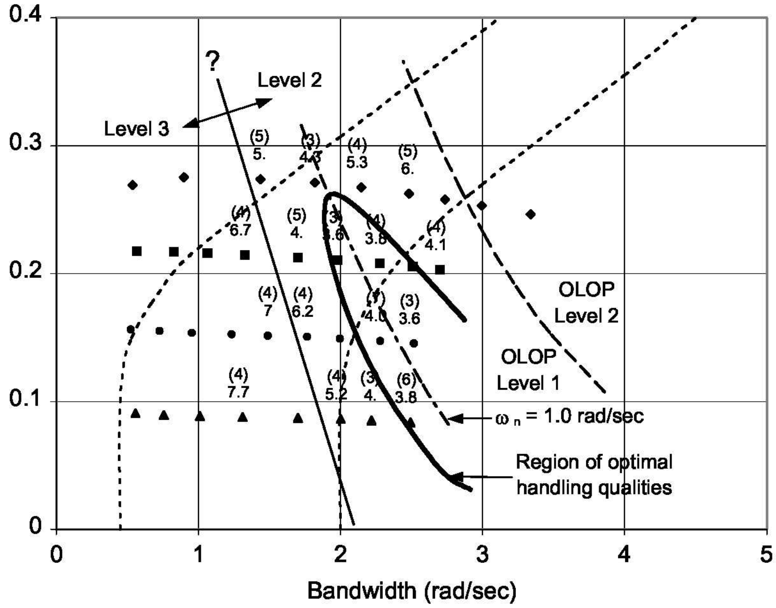

Figure 1. Short-term roll response handling qualities evaluations for a 40 ft pilot offset.

It is suspected that increasing phase delay along this line will be conducive to increasingly worsening handling qualities. Increasing HQR gradients tend to point outward, from this 1 rad/sec constant line, in a direction orthogonal to the constant frequency lines, suggesting handling qualities are primarily driven by the natural frequency of the approximate second order response. OLOP boundaries (Ref. 6), which are primarily a function of natural frequency and hence are coincident with the constant frequency lines, fundamentally impose an upper limit on acceptable bandwidths. Above these boundaries handling qualities will only degrade as a consequence of actuator rate limiting.

However detrimental to the short-term attitude response handling qualities, rate limiting is not the only factor negatively impacting the performance of the aircraft. Not shown here, aircraft size, in terms of the location of the cockpit, is found to have a notorious effect on pitch and roll handling qualities. A general one-half to one HQR reduction throughout the test configurations evidences this for the 10 ft pilot offset case, when compared to the 40 ft pilot offset case. This resulted in a shifting of the suggested Level 2 boundary to lower frequencies, and in Level 1 ratings being obtained more consistently, particularly for natural frequencies of 1 rad/sec and above. Unfortunately only one pilot flew and rated the high frequency test points for both pilot offset distances. Both of these configurations were rated at 3 with the pilot station offset set at 10 ft, and 4.5 and 6 for the 40 ft offset, however.

Based on a yaw task developed during the exercise, preliminary results in Figure 2 indicate there is a very broad operational yaw axis bandwidth range where the aircraft will prove satisfactory. Although pilots were able to push for much higher aggressiveness, this task would be considered representative of an actual mission an aircraft of this size would be required to perform. As expected from Ref. 5, pilot offset from the CG plays a significant role in the handling qualities, in particular at high bandwidths. At pilot offsets greater than 30 ft, the kinematical response of

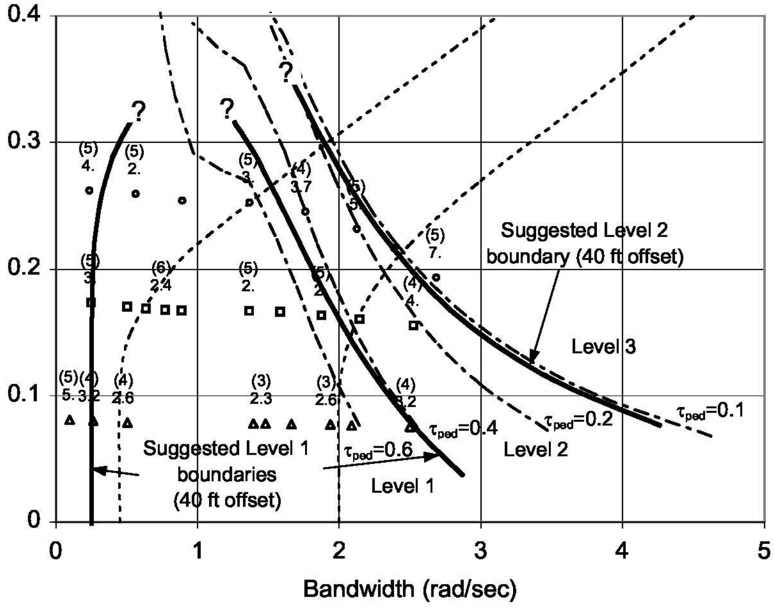

Figure 2. Short-term yaw response handling qualities evaluations for a 40 ft pilot offset.

the aircraft is amplified into high accelerations, or side-forces, which severely interfere with the ability of the pilot to control the aircraft in order to capture a precise heading. Figure 3 shows an increase of two (2) handling qualities ratings between 20 and 30 ft for the high frequency test configuration shown in Figure 3.

Preliminary Conclusions

Based on a quick view of the objective task performance data and pilot evaluation comments several preliminary conclusions and observations may be made:

1. Proprioceptive and visual cueing at cockpit locations much farther ahead of the center of gravity compared to currently flying cargo class rotorcraft (i.e., 30+ feet) have a significant negative impact on the short-term attitude response handling qualities of the aircraft in hover for both high and low bandwidths.

2. Quickness of the attitude response (primarily in the yaw axis) associated with the high frequency configurations translates into objectionable load factors (a ride qualities issue) and unpredictable aircraft response (a handling qualities issue).

3. At low frequencies there is a general lack of control authority, with sluggish aircraft response lending itself to PIO, especially as pilots attempt the aggressive control techniques required to achieve desired position control. Pilot station offset obfuscates pilot perception of position, primarily due to the coupling of pitch and heave motions of the cockpit, and therefore it mainly serves the purpose of increasing task difficulty.

4. Control system response types such as translational rate control should be investigated for precision control in hover.

5. A broad range of acceptable yaw bandwidths was identified based on the proposed heading capture MTE. Reduction of the bandwidth requirement from 2.0 to 2.5 rad/sec, approximately, should alleviate structural and rotor design requirements.

6. The ADS-33 short-term attitude response handling qualities boundaries proved to be inadequate in predicting the handling qualities, independent of the position of the cockpit. For small time delays, short-term response handling qualities appear to be driven fundamentally by the natural frequency of the commanded second-order system response. Proposed boundaries therefore tend to follow the constant natural frequency lines. Effect of larger time delays should be investigated further.

7. 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. Evidence suggests rate limiting fundamentally acts as an upper bound on all acceptable bandwidths (or natural frequencies). Additional flight data is needed to determine a more precise rotorcraft boundary.

8. Further maneuver and handling qualities task definition is needed for large hovering aircraft.

Additional results will be shown in the final version of the paper, in particular results for the pitch axis will complement those shown in the abstract. Further data analysis of the experiment results will also be performed in preparation of the paper.

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Abstract

Short-term pitch and roll attitude and heading handling quality requirements for large rotorcraft in hover were investigated. The piloted simulation study, performed on the NASA-Ames Vertical Motion Simulator, focused on a large (heavy-lift) civil tilt-rotor aircraft. Five experimental test pilots representing the U.S. Army, Marine Corps, NASA, and rotorcraft industry evaluated the aircraft configuration for a range of bandwidth and phase delay values, and pilot offsets from the center of gravity, in moderate turbulence conditions, while performing modified versions of the ADS-33 Hover and Hovering Turn MTEs. Pilot comments and aircraft-task performance data were analyzed. Level 2 and Level 3 handling qualities ratings were recorded using Attitude Command/Attitude Hold (ACAH) response type. Refinements to the Hovering Turn MTE were developed in order to make it consistent with the Limited Agility MTE category in the hover and low speed ADS-33 requirements for large-amplitude attitude changes. Evaluated against this task, yaw bandwidth shows that significant relaxation of the Level 1 boundary from 2 to .25 rad/sec is possible to help account for large pilot offset from the center of gravity.

Notation

Variables

$\vec{a}$	Acceleration vector
K	Command model sensitivity coefficients
r	Yaw rate (rad/sec or deg/sec)
s	Laplace transform complex variable
δ	Pilot control input
ζ	Command model damping ratio
θ	Pitch attitude (rad or deg)
$\vec{\rho}$	Pilot offset vector from the center of gravity (ft)
τ	Time constant or delay (sec)
ϕ	Roll attitude (rad or deg)
$\vec{\omega}$	Aircraft angular velocity vector
ω_n	Command model natural frequency (rad/sec)
ω_{BW}	Bandwidth frequency (rad/sec)

Subindices

cmd	Command model, commanded
lat	Lateral cyclic
lon	Longitudinal cyclic
p	Pilot
ped	Pedal

Abbreviations

ACAH	Attitude Command/Attitude Hold
AGL	Above Ground Level
BW	Bandwidth
CG	Center of gravity
HQR	Handling Qualities Rating
LCTR	Large Civil Tilt-Rotor
MTE	Mission Task Element
OLOP	Open-Loop Onset Point
PID	Proportional-Integral-Differential control
RC	Rate Command
TCL	Thrust Control Lever
UCE	Usable Cue Environment
VMS	Vertical Motion Simulator

Presented at the American Helicopter Society 66th Annual Forum, Phoenix, AZ, May 11-13, 2010.

Introduction

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The handling qualities requirements set forth in ADS-33 are well supported for currently flying helicopters ranging in size up to cargo class helicopters, but their direct applicability to significantly larger rotorcraft—such as Large Civil Tilt–Rotor (LCTR2) (Ref. 4) and Joint Heavy Lift (JHL) configurations—has yet to be established. Of particular interest to this study are the fundamental short-term pitch, roll and yaw attitude response requirements of ADS-33 and how they relate to large tilt-rotors. This interest is driven from a previous experiment with a large tilt-rotor configuration (Ref. 5), which identified handling qualities issues resulting from large aircraft size; mainly from cockpit locations well ahead of the center of gravity (i.e., natural point of rotation) and from the impact of the reduced natural response frequencies of much greater vehicle moments of inertia. Here pilot commentary suggested that handling qualities—particularly in the yaw axis—degraded for high and low bandwidth cases. This indicates that there is a limited range of acceptable bandwidths as a direct consequence of the higher inertias and pilot station offset from the center of gravity associated with this large tilt-rotor. A formal evaluation of the fundamental pitch, roll and yaw short-term response requirements—as they relate to handling qualities of LCTR2-sized tilt-rotors is needed.

Objectives

The objective of this effort was to investigate pitch, roll and yaw bandwidth and phase delay on piloted handling qualities for LCTR2-sized configurations. Another objective was to investigate how the pilot offset from the center of gravity affects handling qualities ratings. The hover and low speed Mission Task Elements (MTEs) from ADS-33 needed review for large tilt-rotor aircraft and, if necessary, modification to be more appropriate for the maneuvering capabilities of these larger machines.

Approach

A piloted flight simulation investigation used the NASA-Ames Vertical Motion Simulator (VMS) facility (Ref. 6). The cockpit was configured with standard inceptors and instruments. A simple stability-derivative mathematical model provided direct control of experimental variables. A carefully tailored visual scene provided task cueing. Experimental test pilots provided evaluations in the form of comments, and handling qualities ratings (HQRs) using the Cooper-Harper rating scale (Ref. 7). Evaluation tasks for the piloted handling quality assessments used the ADS-33-derived hover and low-speed flight demonstration maneuvers.

This simulation focused on a large civil tilt-rotor aircraft similar to that described in Ref. 4. The aircraft model was a relatively simple stability-derivative type model with sufficient complexity to capture the key physics of a large rotorcraft in hover, including key nonlinearities such as actuator position and rate limiting. Model-following flight control architecture was used to establish a family of bandwidth and phase delay configurations. The following section describes the simulation model in greater detail.

In addition to bandwidth and phase delay variations in each control axis, the value of the pilot fuselage station was varied to create multiple offsets from vehicle center of gravity to pilot. Changing the pilot fuselage station offset did not change the vehicle response dynamics, but did change the visual scenes and motion responses of the cab, especially the linear accelerations resulting from yaw and pitch control inputs.

Simulation Model

An 11-state, reduced-order, decoupled stability derivative bare-airframe model was employed. The model retained the key rotor-body coupling, but dropped the high frequency rotor modes and off-axis response, thereby allowing for independent variation of the feedback properties in a single axis. A turbulence model in the form of the AFDD Control Equivalent Turbulence Input (CETI) model (Ref. 8) provided realistic gust inputs. This aircraft model was updated from that used in a previous piloted flight simulation experiment (Ref. 5) with increased inertial properties and corresponding control system gains aimed at maintaining Level 1 stability margins and disturbance rejection characteristics. A detailed description and validation of the methods used to generate this model was published in Ref. 5.

The vehicle model was augmented to provide pitch and roll Attitude Command/Attitude Hold (ACAH) and yaw Rate Command (RC) control response types. A simplified block diagram view of the explicit model-following control system architecture used is shown in Figure 1. The basic bare-airframe vehicle model was augmented with turbulence and actuator dynamics models for added realism. The two main components of the control system are a feedforward path, comprised by the command and inverse plant models, and a feedback loop, consisting of a simple Proportional-Integral-Differential (PID) controller. Provided with an estimate of the control input, the objective of the feedback PID regulator is to track the commanded responses with minimal error. Some amount of time delay is introduced into the commanded responses in order to avoid overdriving higher-order dynamics (rotor and actuator) that are not included in the lower-order pseudo-inverse. As long as actuator saturation or rate limiting does not compromise control authority, tracking, or model-following, performance is independent of the command model transfer function, and depends only on the characteristics of the feedback loops. This approach allowed variations in the piloted bandwidth and phase delay of the aircraft to be examined, while keeping the inner-loop or feedback control law gains fixed at a baseline set of values such that the gain and phase margins, and the disturbance rejection characteristics of the aircraft remained constant throughout the experiment. Quickness of response is determined by the natural frequency of the pitch and roll command models or the time constant in the yaw rate command model. Time delay parameters determine the moment of the onset of the response after the pilot introduces a control input. Combined, these two parameters define a unique combination of bandwidth and phase delay of the commanded response to pilot input (Ref. 9).

An ideal second-order command model was used in the pitch and roll axes to achieve the Attitude Command response type.

$$\frac{\phi_{cmd}}{\delta_{lat}}, \frac{\theta_{cmd}}{\delta_{lon}} = \frac{K_n \omega_n^2 \cdot e^{-\tau_n s}}{s^2 + 2\zeta_n \omega_n s + \omega_n^2} \tag{1}$$

The pitch and roll command model dynamics were independently set, although care was taken to produce harmonious response characteristics. Similarly, an ideal first-order command model was used in the yaw axis to achieve a Rate Command response type.

$$\frac{r_{cmd}}{\delta_{ped}} = \frac{K e^{-\tau_{cmd} s}}{\tau_{ped} s + 1} \tag{2}$$

Pitch and roll bandwidth and phase delay values could therefore be set by varying the natural frequency, ω_n, and the pilot input to response time delay, τ_n, in the command model transfer functions defined in Eq. (1). The yaw axis was treated analogously with the time constant, τ_{ped}, and the delay, τ_{cmd}, in Eq. (2) becoming the piloted response tuning parameters.

Because the handling qualities evaluation maneuvers are primarily visual tracking tasks, extra delay (not shown in the block diagram) has been added to the closed-loop pilot input to vehicle response to account for visual delay in the image processing hardware of the simulator. The visual delay has been measured to be 47 milliseconds.

The sensitivity gains define the steady-state ratio of the commanded response to pilot input. These were left unchanged throughout the experiment, ensuring all control system configurations had identical low frequency gains, independent of the natural frequency or time constant. In the frequency domain, varying these gains would have the effect of shifting, up or down, the magnitude curve of the closed-loop attitude response to pilot input. While this has no impact on the bandwidth and phase delay values, it can play a significant role on the handling qualities of the aircraft for pilot-in-the-loop maneuvering. Sensitivity gains were set at: .2 rad/inch for pitch and roll, and .15 rad/sec/inch for yaw.

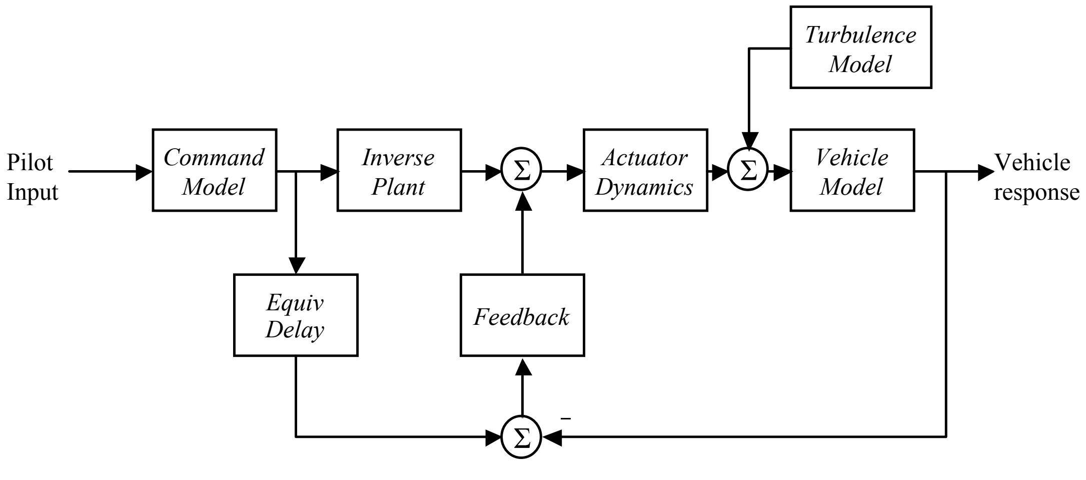


Figure 1. Overview of the model-following control system architecture.

Model following performance

Model following performance is a measure of how well the actual vehicle response matches the commanded response generated by the command model. A detailed analysis of the model following performance as a function of uncertainty in the inverse model was presented in Ref. 5. The optimized regulator was shown to provide reasonable tracking performance over the frequency range of interest. While the introduction of uncertainty to the inverse model allowed the rotor-body coupling to somewhat degrade the model following performance, the effect on the closed-loop bandwidth and phase delay was not significant.

Previously, model following cost had been calculated by a mismatch cost function between the linearized closed-loop response and the linearized delayed command model response. Model following cost values less than 100 indicate reasonable agreement, and values under 50 indicate nearly perfect agreement. For low bandwidth cases, where non-linearities such as actuator rate limiting are not an issue, this linear method provided an accurate value for the model following performance of the system. However, for the higher bandwidth cases, this tended to over-estimate the model following performance of the system. Therefore, the cost was calculated by sweeping the system, using several different frequency sweep signals of varying amplitudes, and analyzing the commanded responses and actual responses. This generated a model following cost that accounts for the non-linearities in the system, as a function of sweep amplitude.

Overlaid in Figure 2 is the model following cost for the yaw axis (r/δ_{ped}) as a function of amplitude of the harmonic test signal, in percent of pedal input, for three different levels of quickness of response (τ_{ped} = .42 sec, τ_{ped} = .22 sec and τ_{ped} = .05). Time delays of the commanded response for these three cases ensure bandwidth remained approximately constant within 2.5–2.7 rad/sec. Based on a linear system analysis, the mismatch cost between the closed-loop frequency response and the delayed command model response remained constant at 96. The discrepancies with increasing amplitude of the input are directly associated with actuator rate limiting, and are an indication that quick responding command model dynamics will degrade the model-following performance. The maximum throw of the pedal inceptor is ±2.69 in, indicating that it takes very little control inputs (about a quarter of an inch) to excite these nonlinearities for the extreme command model configuration defined by τ_{ped} = .05 sec.

During optimization of the system feedback gains and command model parameters, model following performance, bandwidth and phase delay values were computed from a linear system analysis, and these would not capture the effects of non-linear phenomena such as rate limiting. The open-loop onset point (OLOP) criteria (Ref. 17) were employed to account for the effect of actuator rate limiting on the predicted handling qualities. The OLOP criteria, based primarily on fixed-wing data, proved in Ref. 5 to be a useful tool for predicting actuator rate limiting for rotorcraft.

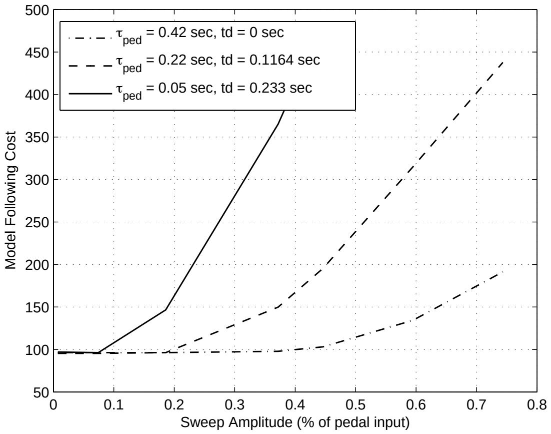


Figure 2. Quantification of model following performance for three commanded yaw rate response time constants.

Pilot offset

Given the kinematic response of the aircraft, the acceleration at the pilot station in the simulator is computed by solving the general motion equations with respect to the center of gravity for any arbitrary pilot to center of gravity offset.

$$\vec{a}_p = \vec{a}_{CG} + \dot{\vec{\omega}} \times \vec{\rho} + \omega \times \left(\omega \times \vec{\rho}\right) \qquad (3)$$

The VMS lab motion system then exercises the appropriate combination of translation and rotation to generate the accelerations expected at the pilot station. The generated visual scene is updated accordingly. The attitude dynamics of the aircraft are independent of pilot offset, allowing for independent evaluation of the effects of vestibular and visual cueing variations on the handling qualities.

Conduct of Test

Facility

The experiment was conducted in the NASA Ames Vertical Motion Simulator VMS, described in detail in Ref. 6. The Transport Cab was used for its large horizontal field-of-view, as seen in Figure 3 and Figure 4. Traditional helicopter pilot-control inceptors, i.e., center stick and pedals, were provided for the right cockpit seat. A tilt-rotor-specific vertical Thrust Control Lever (TCL) replaced the collective control used in the previous experiment (Ref. 5). Pilots could manually adjust the friction coefficient on the TCL to their preference. Primary flight display and horizontal situation (hover) display, replicating the Army's Common Avionics Architecture System (CAAS) displays, were provided.

Figure 3. VMS two-seat transport cab overview.

(a)

(b)

Figure 4. Pilot's view at precision hover station-keeping point. (a) Standard ADS-33 test course (b) Modified test course at increased altitude

Evaluation tasks

The evaluation tasks included a modified precision Hover MTE from ADS-33, and a hover pedal turn maneuver that was developed specifically for this simulation experiment. Refinements to the Hover MTE performance standards for an LCTR-type aircraft documented in Ref. 5 were adopted. The precision hover station-keeping box was ±4 ft and located at 55 ft AGL. These modifications were made necessary because cargo/utility maneuver performance standards were considered too "tight" and aggressive for this large of an aircraft. The increased altitude, and the associated degradation of the visual cues are contrasted in Figure 4 for the utility class position in (a) and the large tilt-rotor one in (b). The Hover MTE was used primarily for the evaluation of the pitch and roll handling qualities. Definition of an appropriate task to evaluate yaw short-term attitude response handling qualities was necessary. The task utilized for evaluation was based on a simple 90-degree turn about the aircraft center of gravity. The iterations towards more appropriate standards for this large aircraft are discussed in the results section of this paper.

Evaluations were performed in a realistic turbulent environment designed to perturb the aircraft and force the pilots to increase their control activity to compensate for the ensuing drift. The level of turbulence used in all evaluations corresponded to the "moderate" turbulence exercised in Ref. 5.

Matrix of Configurations

A single combination of stability margins and disturbance rejection bandwidths, about 38 deg and 12 dB in all axes, was used for the entire experiment, which fixed the control law gains of the attitude inner-loops. While these values do not meet the MIL-DTL-9490E requirements, they were considered acceptable based on the trade-off analysis findings in Ref. 5. The corresponding disturbance rejection bandwidths associated with these gains were approximately 1.0 rad/sec in the lateral axis, .8 rad/sec in the longitudinal, and .7 rad/sec in yaw.

The bandwidth and phase delay for the pitch, roll and yaw axes were varied through changes to the command model parameters while keeping the inner-loop feedback gains constant. All bandwidth and phase delay test point pairs are shown in Figures 5–7, overlaid onto the hover and low speed ADS-33 requirements for All Other MTEs and Usable Cue Environment (UCE) greater than 1. Boundaries separating the different handling qualities regions are shown. The bandwidth and phase delay include an additional 47 milliseconds to account for stick-to-visual delay. It should be noted that a small amount of extra delay is produced due to the mismatch in the closed-loop and commanded responses introduced by model uncertainty. Therefore, even if zero delay is commanded, there will be a minimum value of phase delay present.

Stark differences in the on– and off–axis responses of an aircraft in forward flight makes them more naturally distinguishable to a typical human pilot. The same is not true in hover, where pilots desire from the aircraft similar response characteristics in both axes. Consequently, large differences in the attitude bandwidth or phase delay metrics between the roll and pitch axes resulted in objectionable disharmony of control. A direct implication of this is that the roll and pitch attitude short-term response characteristics could not be evaluated independently of each other, and therefore, every point in Figure 5 is paired to another in Figure 6 (and vice versa). While there are discrepancies between the pitch and the roll bandwidth and phase delay values for each pitch-roll pairing, each configuration was tested for harmony of control before formal evaluations were performed.

OLOP boundaries are shown for reference purposes. It is noted that precise rotorcraft boundaries have not been determined due to lack of data. Although developed primarily based on fixed-wing data, these criteria proved to be useful in a previous experiment (Ref. 5) and were therefore applied to this experiment.

The pilot offset from the center of gravity was varied with the pilot locations of 10, 20, 30, 40, and 50 feet forward of the center of gravity. The 10-foot configuration was chosen to provide comparable results with existing utility class helicopters.

Evaluation Procedure

Five pilots provided evaluations during this experiment. All pilots were experienced experimental test pilots with significant rotorcraft experience. Pilots were from the U.S. Army, Marine Corps, NASA, and the rotorcraft industry. Two pilots had extensive tilt-rotor flight experience. More importantly, considering the very fundamental distinction between transport and utility-sized rotorcraft at the core of this experiment, four had significant experience with large rotorcraft. All pilots were familiar with the Cooper-Harper Handling Quality Rating (HQR) scale (Ref. 7) and with the ADS-33 evaluation tasks. All flew and evaluated a subset of the bandwidth and phase delay combinations and pilot to center of gravity offsets.

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 of the *desired* and *adequate* standards for each MTE. This information was read back to the pilot after each maneuver was completed, both during training and formal evaluation.

During formal evaluation sessions, pilots first flew the MTE-bandwidth/phase delay 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 anomalous compared to the others, additional data runs were included to resolve the inconsistency. Only in rare cases, when it was evident the aircraft configuration exhibited major control deficiencies, as would be the case with an HQR 9 or 10, or offered an extremely uncomfortable ride quality were the formal evaluations suspended short of the three required runs. Data collected and recorded include the aircraft control inputs and state data, task performance data, and pilot comments. A formal questionnaire was used to elicit pilot opinion about task aggressiveness/performance, aircraft characteristics, and pilot workload. The pilots used the HQR scale to provide a qualitative evaluation of the configuration.

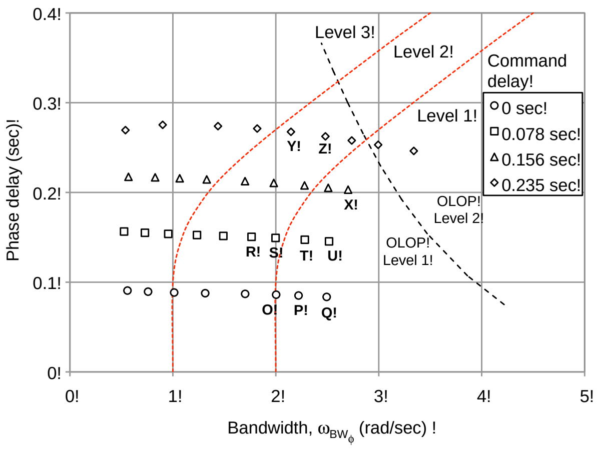


Figure 5. Roll bandwidth and phase delay test points

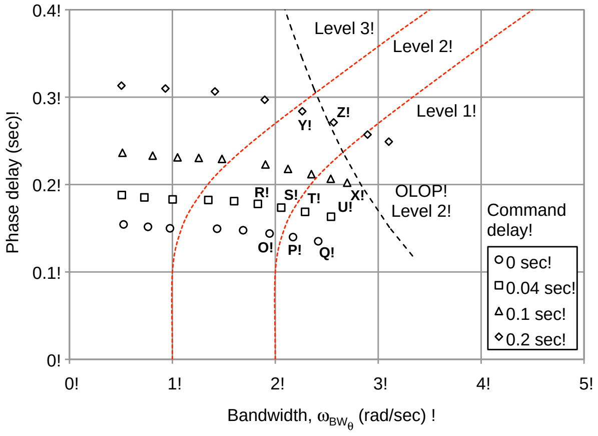


Figure 6. Pitch bandwidth and phase delay test points

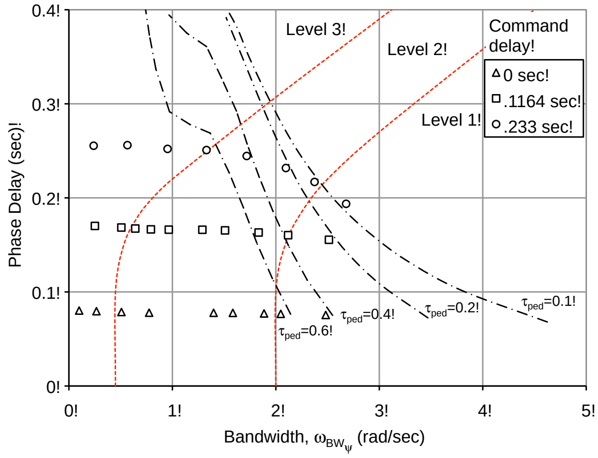


Figure 7. Yaw bandwidth and phase delay test points

Results

Results for pitch and roll short-term attitude response requirements will be presented first, followed by those for yaw. Data in the form of Cooper-Harper handling qualities ratings will be presented for both cases. Pilot evaluation commentary will be included within the overall discussion highlighting specific handling qualities or ride qualities issues. A quantitative assessment of pilot control techniques will complete the analysis. A brief discussion of the evaluation task that was developed specifically for the yaw case is included, also. For pitch and roll, a comparison between the 40 ft and 10 ft offsets will be made. Discussion of yaw results for varying offset will focus largely on the high bandwidth configurations.

Pitch and roll requirements

HQRs and Pilot evaluation for 40 foot offset. The Cooper-Harper handling qualities ratings painted a fairly consistent picture of the short-term pitch and roll attitude response characteristics for this class of aircraft. Average ratings for a subset of the matrix of configurations are shown in Figure 8. Shown in Figure 8 are the current ADS-33 Level 1, Level 2 and Level 3 regions. Boundaries separating the three regions are included. Level 1 handling qualities were not consistently attainable for a large aircraft of this class, i.e., with the pilot station located 40 ft ahead of the center of gravity and an ACAH response type, in moderate turbulence. Figure 8 shows that better Handling Qualities Ratings tend to line up with the constant 1 rad/sec natural frequency contour for a given amount of phase delay. It is suspected that increasing delay along this line will result in increasingly worse handling qualities, in a manner that is qualitatively consistent with the current specifications. Increasing HQR gradients tend to point outward from this 1 rad/sec constant line, towards both higher and lower frequencies, in directions roughly orthogonal to the constant frequency lines. This result suggests there is a strong correlation between the handling qualities and the natural frequency of the approximate second order attitude response of the aircraft to pilot input.

These same trends were observed in Figure 9 for the pitch bandwidth and phase delay values investigated; mainly the clustering of the better configurations around the 1 rad/sec line and below 250 milliseconds of phase delay into a characteristic “thumbprint” pattern, plus the overall inability to achieve Level 1 handling qualities.

The preponderant influence of the natural frequency on the ratings is further evidenced by the approximate loci of the Level 2–Level 3 boundary lines suggested by the data. Boundary lines separating the Level 2 and Level 3 ratings in the low frequency region for the particular test correspond roughly to natural frequencies of about .6 rad/sec for roll, and in between .4–.5 rad/sec for pitch. At lower frequencies, configurations were deemed too sluggish in response to pilot input, consistently resulting in intolerable workloads and adequate performance not being achieved. Additional data is required to better qualify boundaries for higher values of phase delay

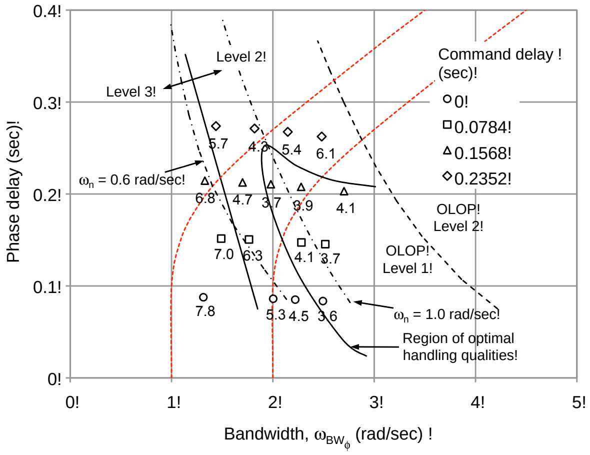


Figure 8. Short-term roll response handling qualities evaluations for a 40 ft pilot offset.

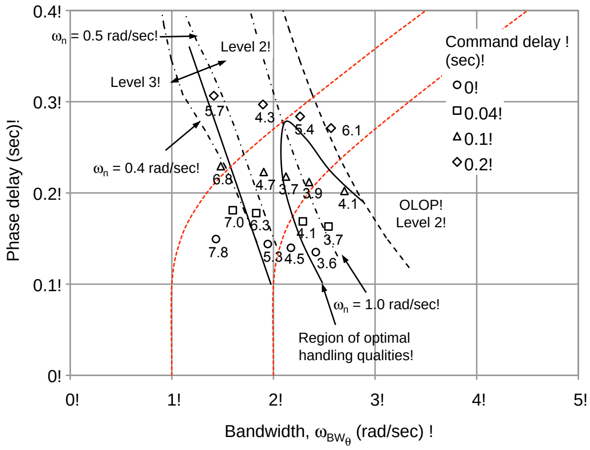


Figure 9. Short-term pitch response handling qualities evaluations for a 40 ft pilot offset.

Figure 10 shows the correlation between the natural frequency and the average Cooper-Harper handling qualities ratings for the large aircraft configuration (40 ft pilot offset). Plotting results in this fashion obfuscates the effect of delay in the response. Differences in the average handling qualities rating for configurations with similar natural frequencies are caused by the different values of delay in the response. For example, configuration X (Figures 5 and 6) sits around 200 milliseconds of phase delay, while cases Y and Z possess about 262–284 milliseconds. Configurations with roll and pitch attitude natural frequencies below .6 rad/sec and .4 rad/sec, respectively, were all found to possess Level 3 qualities. Better handling qualities ratings were found to be between .8 and 1.2 rad/sec, but Level 1 handling qualities were not attainable and the average rating scores tended to rise with increasing natural frequency.

It should be pointed out that these maneuvers were carried out in moderate turbulence conditions. These results are not surprising, necessarily, considering the pilot is required to decelerate what is essentially a very large aircraft into a relatively tight hover box (±4 ft) with ACAH response type and no Position Hold.

The severe unexpected degradation of ride and handling qualities for high frequency is contrary to the experience with current utility type rotorcraft. Pilots clearly encountered, in cases X, Y and Z, an aircraft that was highly intolerant of pilot control aggressiveness, particularly in the longitudinal axis. This was due to both an objectionable sensitivity to control (characterized by a disproportionate amplitude and quickness of the response to pilot input), and a high propensity to rate limiting of the actuators. Combined, these characteristics yielded an unpredictable aircraft response, both in its initial and its mid-term response. In practice these qualities translated into increased difficulty to cancel out aircraft position drift and a heightened visual cue pattern scan frequency necessary to ascertain the hover position. As such, both of the "measurable" handling qualities elements, performance and workload were directly impacted. Only by substantially decreasing their control gains were some of the pilots able to effect the precise maneuvering necessary to achieve desired task performance. This situation would not be representative of an average pilot using normal control technique. Compounding the handling qualities issues discussed above, pilots complained in general about an uncomfortable roughness of ride and this oftentimes factored decisively in the rating process.

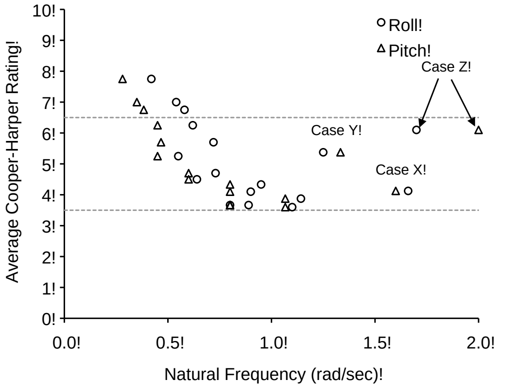


Figure 10. Correlation of natural frequency of the commanded second order response with average Cooper-Harper handling qualities ratings for 40 ft pilot offset

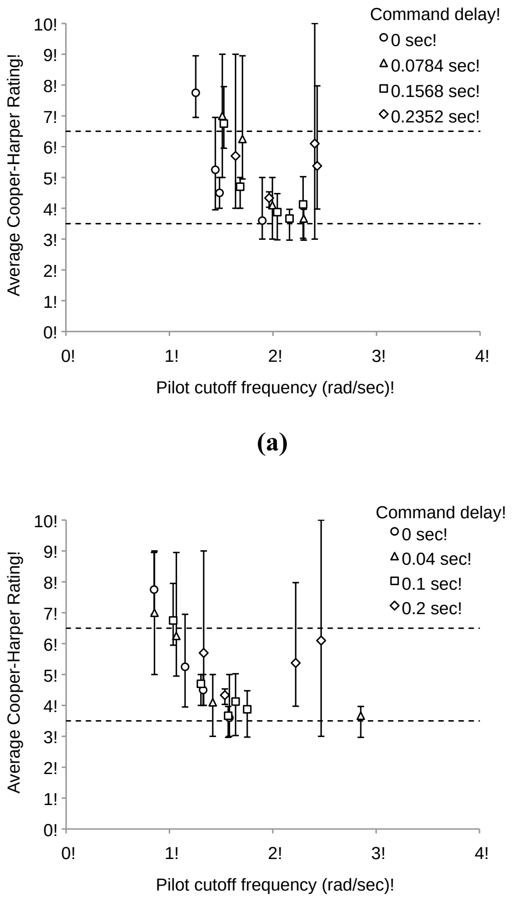
The effect of delay on these configurations can be implied from the subtleties in pilot evaluation. Case X elicited similar general comments from pilots as Y and Z did. The main differences were in degree of severity, with task performance not compromised as strongly in the lower phase delay case.

Deficiencies in the handling qualities were noted primarily in the longitudinal axis, with the ability to compensate for longitudinal drift through control of pitch attitude deteriorating due to an objectionable heave coupling. This pitch-heave coupling has been shown to be an issue closely associated with the location of the cockpit relative to the center of gravity of the aircraft and it is hence a clear indicator of the potential impact of aircraft size on the handling qualities.

The second issue impacting the ability of the pilots to maintain longitudinal position was rate limiting of the actuators. Case Z is a Level 2 OLOP specification in pitch, which explains the actuator rate limiting frequently experienced by the pilots who flew it. Rate limiting was experienced in all three high frequency configurations, however. The usefulness of OLOP specifications to predict actuator rate limiting for utility size aircraft was observed in Ref. 5. The preponderance of rate limiting for cases X and Y may be a further indicator of increased pilot activity resulting from variations in control technique required for the 40 ft offset.

Pilot cutoff frequencies. Pilot cutoff frequency, determined from the spectral analysis of the inceptor position time histories—during the 30 second precision hover hold subtask—is a measure of pilot operating frequency, and considered a good estimate of pilot crossover frequency for pilot-in-the-loop tasks (Refs. 11–13). The concentration of good handling qualities ratings around 2.1 rad/sec in Figure 11(a) indicate pilots consistently preferred the vehicle roll dynamics that allowed them to operate at this frequency. Pilots appeared to be more tentative in pitch, with the mean longitudinal control cutoff frequency for these optimal control system configurations dropping to about 1.6 rad/sec (Figure 11(b)). In general, operating at higher frequencies excited objectionable deficiencies in the aircraft response qualities.

One particular case stands out in Figure 11(b) as an exception where pilots, on average, used a higher crossover frequency of about 2.85 rad/sec, yet rated this configuration to have borderline Level 1–Level 2 handling qualities. However, large standard deviation of .89 rad/sec in the longitudinal control cutoff frequency, along with a 1.72 rad/sec minimum and 4.27 rad/sec maximum, indicate significant variability in the control techniques. Reviewing pilot comments, it is evident that ride quality, though described as "very rough", was not weighed into the HQR score for this particular configuration. Pilots indicated they could operate the aircraft with continuous, but small amplitude, control inputs. This is consistent with the quantitative cutoff frequency measurements. While pilots disliked the ride qualities of the aircraft, they liked the fact that the control system allowed them, under the appropriate control technique, to achieve reasonable accuracy in task performance.



(a)

(b)

Figure 11. Correlation of Handling Qualities Rating with pilot cutoff frequency, (a) lateral axis, and (b) longitudinal axis

Pilot operating points defined by the average input cutoff frequencies are overlaid onto the attitude frequency response curves shown in Figure 12 and Figure 13. Results indicate pilots tended, on average, to operate at a frequency near the roll bandwidth, so that the mean roll response phase is approximately –131 degrees, and thus effectively creating 49 degrees of phase margin for the pilot-in-the-loop closure. In pitch control, pilots appeared to decrease their input frequency and back away from the bandwidth, operating at a phase margin of about 61.4 degrees. However, results indicate that pilot operating frequency for the ACAH response type was, in general, primarily driven by the bandwidth.

The average magnitude of the roll and pitch frequency response for the set of preferred configurations is .054 (-25.4 dB) and .037 (-28.6 dB). More importantly, the magnitude of the frequency responses for the different pilot operating points shows a monotonically increasing trend, such that forcing the aircraft response at higher frequencies resulted in higher amplitude attitude oscillation per unit of stick displacement. This larger attitude response magnitude, combined with higher frequencies is the likely contributing factor to the objectionable response characteristics reported by pilots for the 40 ft cockpit position offset. It was found during the experiment that pilots adjusted to these configurations by reducing to a minimum their control inputs. Similarly, at lower frequencies the magnitude of response is too small, requiring the pilots to adjust control technique by increasing the amplitude of their control inputs. This characteristic, combined with the overall sluggishness of response is the principal cause for the handling qualities deficiencies experienced at low frequency.

It should be noted that stick sensitivity, inasmuch as it causes the magnitude curve to shift up or down, could be varied in an attempt to correct for these deficiencies. Care should still be taken not to increase the low frequency gain excessively, since doing so tends to increase the pilot stick forces beyond acceptable levels.

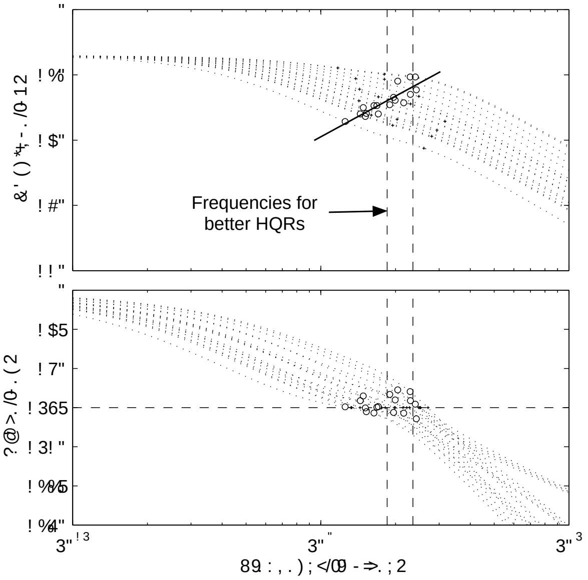


Figure 12. Average roll attitude frequency responses for 40 foot offset

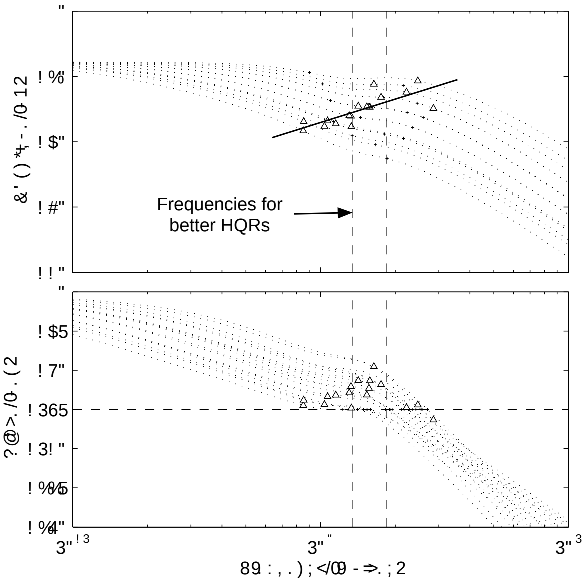


Figure 13. Average pitch attitude frequency responses for 40 foot offset

HQRs and pilot evaluation for 10 foot pilot offset. The 10 ft cockpit offset corresponds to existing utility class helicopters upon which much of the current testing for ADS-33 requirements is based. HQR results for 10 ft cockpit offsets are shown in Figure 14 (roll axis) and Figure 15 (pitch axis). Also shown are the boundaries suggested for the 40 ft offset. Aircraft size, in terms of the location of the cockpit, was found to have a noticeable effect on pitch and roll handling qualities. A general one-half to one HQR improvement throughout the test configurations for the 10 ft pilot offset case, when compared to the 40 ft pilot offset case is evidence of this. This is shown as a shifting of Level 3 configurations to lower frequencies, and in Level 1 ratings being reported more routinely, in particular for natural frequencies of .8 rad/sec and above. The main implication stemming from this shift in the Level 2–3 boundary is that the 10 ft offset aircraft configuration can possess more sluggish attitude response characteristics before performance is compromised or pilot workload becomes intolerable. More importantly, it points to a fundamental difference in the nature of the control technique required from the pilots.

Control configurations with roll natural frequency between .45–.55 rad/sec and pitch natural frequency between .3–.35 rad/sec, for phase delay below 175–200 milliseconds, were nominally rated with an HQR 6 or 6.5. Pilots consistently indicated the aircraft possessed such objectionable handling characteristics that extensive compensation was required just to achieve adequate performance. Issues were due mainly to sluggishness in the response and overall lack of controllability. Corresponding bandwidths were within 1.23–1.7 rad/sec for both pitch and roll. Reducing natural frequency further (and consequently the bandwidth too) caused significant degradation of the response, resulting in major control deficiencies. In the extreme case, pitch and roll natural frequencies of .22 rad/sec and .31 rad/sec, respectively, produced a marginally uncontrollable aircraft. Pilots required maximum control authority, defined by inceptor displacement, just to maintain control of the aircraft much less to adequately perform the task. Data are insufficient to formulate complete Level 2–3 boundaries dividing these two regions with any certainty. A high phase delay configuration with an HQR 7 and a low phase delay one with an HQR 8 were evaluated by only one pilot, such that Level 2–3 boundaries established would not be representative of a wide population of pilots.

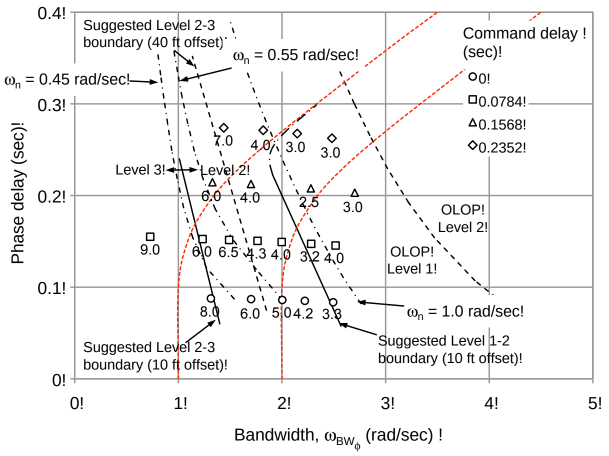


Figure 14. Short-term roll response handling qualities evaluations for a 10 ft pilot offset.

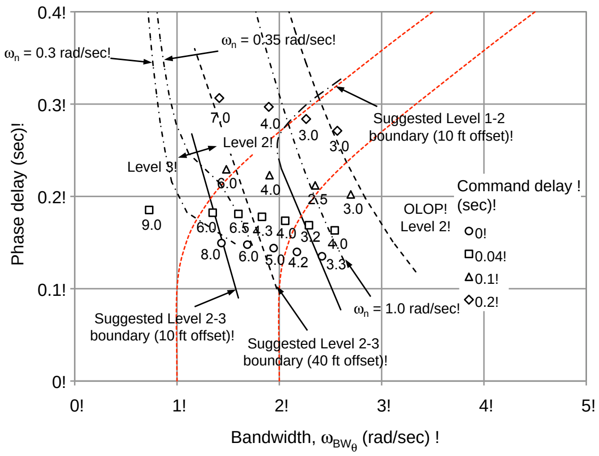


Figure 15. Short-term pitch response handling qualities evaluations for a 10 ft pilot offset.

Approximate Level 1–2 boundaries suggested are roughly based on the average Cooper-Harper handling qualities ratings gradient, and in this sense are traced to represent constant 3.5 ratings. Unfortunately, data collected around the fringes of the test configuration matrix were too sparse to establish any sweeping conclusions. These configurations comprise all high bandwidth and phase delay regions.

Certainly, available data was deemed insufficient to establish accurate and representative Level 1 boundaries for phase delay above 250 milliseconds. The available data do appear to suggest a curving of the boundary line in a manner consistent with the current ADS-33 specifications.

Configurations indicated by points O, P, R and S in Figures 5 and 6 appear to be Level 2 based purely on the average Cooper-Harper HQRs, whereas points Q and T are more suggestive of Level 1 aircraft. Table 1 summarizes the number of pilots who rated these configurations, as well as maximum and minimum ratings obtained, for the specific subset of bandwidth and phase delay points identified by letters O through T. Point O is the only configuration that can be confidently categorized as Level 2. Bandwidth and phase delay values for this configuration would place it right on the ADS-33 Level 1–2 roll boundary, but squarely in the Level 2 region for pitch, and hence, consistent with the assigned rating. Statistical variation for points P through T suggests that these command model configurations could be rated Level 1 or Level 2 with a similar probability. Points R and S should, theoretically, be solidly Level 2 configurations according to ADS-33, yet pilot opinion for these configurations was divided. Similarly, point P should be solidly Level 1, but a significant sub-set of the experimental pilots who tested this configuration found it to be unsatisfactory. While possessing higher bandwidth and lower phase delay than R and S, respectively, points O and P appeared to the pilots to be in general more sluggish and unpredictable than the former two configurations.

These findings reinforce the observation that a stronger dependency on natural frequency of the response, rather that bandwidth, tended to drive the handling qualities of the aircraft, and indeed pilot ratings for the 10 ft offset show very good correlation in Figure 16 with results from earlier handling qualities investigations (Ref. 14) that evaluated the effect of ideal second order system responses. Configurations with average pilot ratings between 3.5 and 4.5 straddled the Level 1 boundary, which is not an unreasonable expectation considering these dividing lines separate the ratings into Level 2 configurations that ensure desired task performance was not compromised.

Table 1. Cooper-Harper ratings for specific high bandwidth and low phase delay cases

Test case	Bandwidth (rad/sec)		Natural frequency (rad/sec)		No. of ratings	Cooper-Harper Rating		
	Pitch	Roll	Pitch	Roll		Avg	Min	Max
O	1.94	2.00	0.45	0.55	4	5.00	4.0	7.0
P	2.17	2.22	0.6	0.64	3	4.17	3.0	5.0
Q	2.42	2.49	0.8	0.8	4	3.25	3.0	4.0
R	1.83	1.76	0.45	0.62	4	4.25	3.0	5.0
S	2.06	2.00	0.6	0.72	3	4.00	3.0	5.0
T	2.29	2.28	0.8	0.9	5	3.20	2.0	4.0

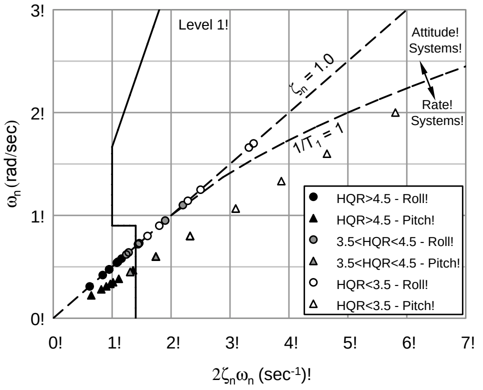


Figure 16. Correlation of average HQRs with second order system response characteristics

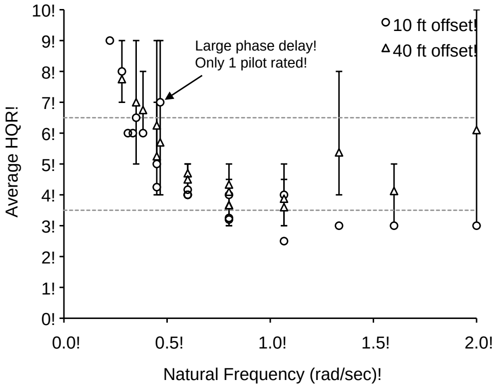


Figure 17. Correlation of natural frequency of the commanded second order response with average Cooper-Harper handling qualities ratings (pitch axis)

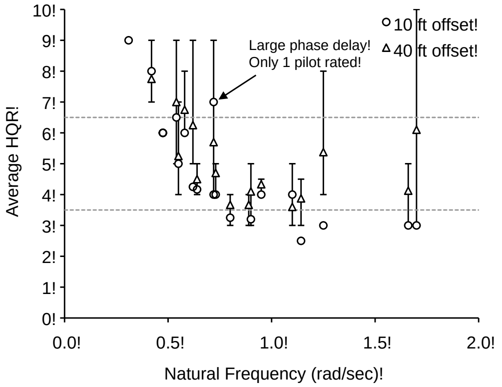


Figure 18. Correlation of natural frequency of the commanded second order response with average Cooper-Harper handling qualities ratings (roll axis)

Correlations, shown in Figure 17 and Figure 18, of the average Cooper-Harper ratings with the natural frequency of the commanded second order response for pilot offsets of 10 and 40 ft reveal a sharp divergence of the handling qualities ratings for the 40 ft cockpit location for natural frequencies over .7 rad/sec, compared to the 10 ft configuration, which achieves Level 1 in a manner consistent with existing utility class helicopters.

Pilot cutoff frequencies. An increase, in both axes, of the pilot cutoff frequencies for this shorter fuselage configuration, shown in Figure 19 and Figure 20, indicate that pilots felt comfortable driving the 10 ft offset configuration at higher frequencies even though both configurations had identical attitude frequency responses. Maximum average cutoff frequencies increased from 2.43 rad/sec to 2.96 rad/sec, in the lateral axis, and from 2.85 rad/sec to 3.37 rad/sec in the longitudinal. These increments imply that pilots generally opted to operate at smaller stability margins compared to those with the 40 ft offset: 45 degrees in roll and 55 degrees in pitch on average.

Predicted vertical (heave) acceleration response magnitudes of the cockpit at the pilot cutoff frequencies for both pilot station offsets are shown in Figure 21. Pilots operated at these high frequencies for the 10 ft offset, essentially doubling the attitude frequency response magnitude, with respect to the better cases for the 40 ft configuration. This was achieved without inducing the objectionable ride and control characteristics associated with the 40 ft cockpit location as evidenced by the kinematic response of the cockpit in Figure 21.

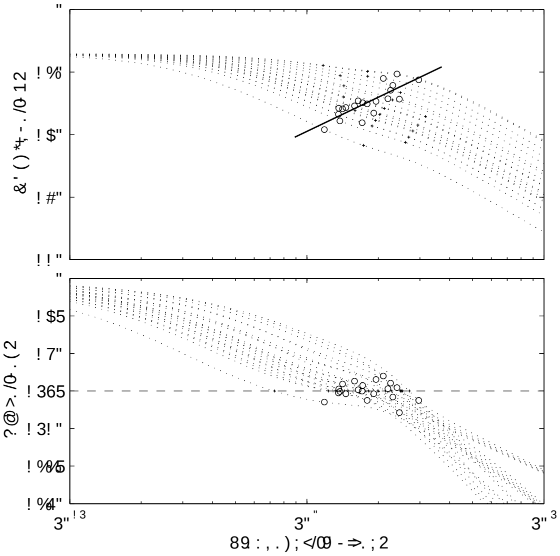


Figure 19. Roll attitude frequency responses for 10 foot offset

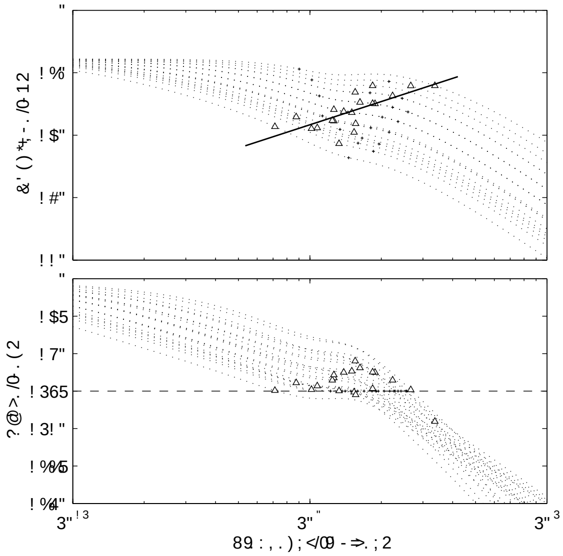


Figure 20. Pitch attitude frequency responses for 10 foot offset

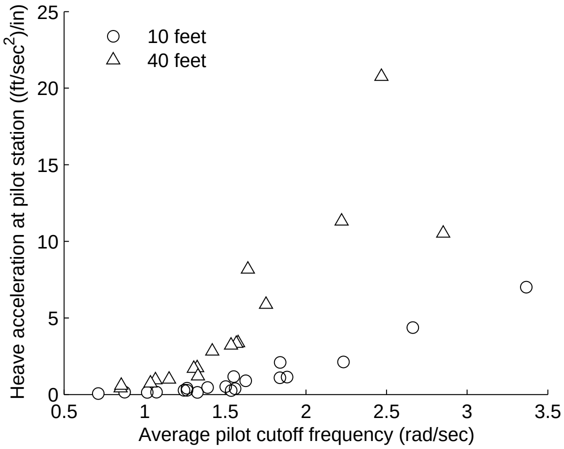


Figure 21. Predicted heave acceleration response magnitude for pilot cutoff frequencies

Yaw requirements

Task development. The previous experiment (Ref. 5) pointed to the need for a formal evaluation of yaw response characteristics for large hovering aircraft. A project pilot using a series of 180-degree pedal turns evaluated the yaw axis response for that experiment. For the formal evaluations of the current experiment, an early effort was the development of a formal yaw evaluation task (MTE definition). The initial yaw evaluation task proposed required a complete, 360-degree, turn about the pilot station. This task was dismissed quickly due to lack of appropriate visual cues. Pilots found the workload in the lateral and longitudinal channels to be extreme, masking the yaw characteristics.

A simple pedal hover turn was developed to independently evaluate the yaw axis response dynamics. The Hovering Turn MTE in ADS-33 for Cargo/Utility class was modified to better suit the very large aircraft being evaluated. A 90-degree turn was performed with pedal input alone, in turbulence but without steady wind. The lack of wind compensated for the lack of a hover position hold system that likely would be provided for the large aircraft size. The 90 degree heading change was sufficient for the evaluation and well supported by available visual cues. Task standards retained the time standards of the Cargo/Utility MTE: 15 sec for desired, and 20 sec for adequate performance. This effectively halved the desired maximum yaw rate to the order of 9.5 deg/sec. This rate was consistent with the Limited Agility MTE category in the hover and low speed ADS 33 requirements for large-amplitude attitude changes. Although pilots were able to fly the aircraft more aggressively than this rate, this maneuver was considered to be more appropriate to an aircraft of this size, in terms of the agility required. Final heading capture tolerances were set at ±3 deg, which forced enough aggressiveness and precision from the pilots to evaluate the different issues at hand.

Pilot evaluations. Based on the yaw task developed for this investigation, average HQR scores shown in Figure 22 indicate there is a very broad operational yaw axis bandwidth range where the aircraft will prove satisfactory. Although pilots were able to push for much higher aggressiveness, this task would be considered representative of an actual mission an aircraft of this size would be required to perform.

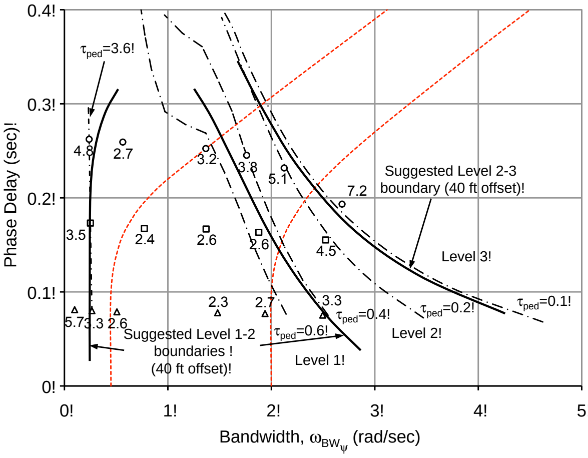


Figure 22. Short-term yaw response handling qualities evaluations for a 40 ft pilot offset

A minimum bandwidth of .25 rad/sec was required to generate satisfactory yaw control for precise heading capture maneuvers. Anything below this frequency produced enough sluggishness in the yaw response that control characteristics became unsatisfactory for precision capture of the desired heading.

For the minimum delay case this .25 rad/sec bandwidth is associated with a time constant (τ_{ped}) of 3.6 seconds. At these time scales, handling qualities are largely insensitive to phase delay. Additional 116–233 milliseconds of delay in the response do not result in substantial degradation of the handling qualities. It is expected that yaw control will eventually be lost in the limit when bandwidth approaches zero, as the time to build up desired rates would become excessive and meeting the performance metrics impossible. It is noted that while the current ADS-33 short-term yaw response boundaries are not supported for the yaw task defined for this experiment, for low bandwidths the same trends are observed, mainly that increasing yaw bandwidth result in improving handling qualities.

The size of this class of vehicle presents unexpected kinematic issues for high yaw bandwidth configurations, which have not been anticipated in current specifications. Degradation, into Level 2, of the short-term response handling qualities was observed for bandwidth and phase delay pairs beyond a line defined by rate response time constants in the order of .45–.5 seconds. Increasing the quickness of response even further, and hence, indirectly, the bandwidth, down to response time constants of .1 sec, or less, resulted in major control deficiencies that put the aircraft, with the 40 ft pilot offset, squarely in Level 3 handling qualities. It should be noted that the quickness commanded at these levels far exceeded the ability of the control system to track aggressive pilot commanded responses due to rate limiting of the actuators. In this sense, actuator rate limiting played a significant role in the degradation of the handling qualities. Figure 23 shows the direct impact the ideal, or commanded, second order system response parameters play on the handling qualities.

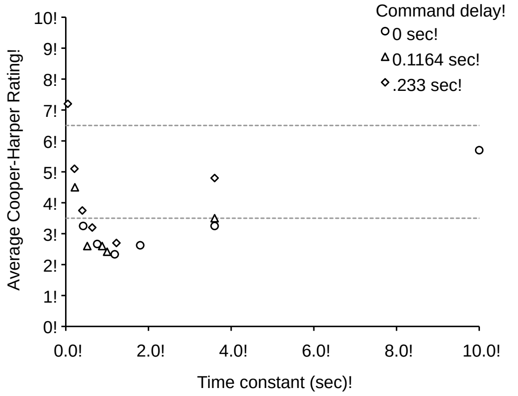


Figure 23. Correlation of average Cooper-Harper handling qualities ratings with natural time constants of the commanded first order rate response for 40 foot offset

Delay in the response had a more significant impact on the handling qualities at bandwidths over 1.5 rad/sec. All three configurations, e.g., with bandwidth between 2.5 and 2.7 rad/sec, jumped one full handling qualities Level for every 116 milliseconds of time delay added to the commanded response dynamics. Pilots consistently described the extreme (i.e., Level 3) case as having an unpredictable initial response to input. This is not an unexpected result considering the strong susceptibility to actuator-rate limiting for the high quickness required of the commanded response ($\tau_{ped} = .05$ sec). This situation was unavoidable with the current actuator design (rate limits), considering the magnitude of the time scales associated with the commanded response dynamics. In order to achieve a desired commanded response bandwidth it is necessary to progressively reduce the time constant of the response in order to compensate for increasing response delay in the loop. In the extreme case this creates a distorted response where the delay in the response, to a step input, e.g., can be several orders of magnitude greater than the rise time, i.e., the time to reach 63.2% of the steady state rate.

The yaw kinematic response of the aircraft for pilot offsets of 30 ft and greater is amplified into large lateral accelerations, or side-forces, at the pilot station, which severely interfered with the ability of the pilot to capture a precise heading. Figure 24 shows, e.g., an increase of two (2) full handling qualities ratings between 20 and 30 ft for the high frequency test configuration defined by 2.68 rad/sec bandwidth and .193 sec of phase delay (time constant 50 milliseconds and 233 milliseconds of delay).

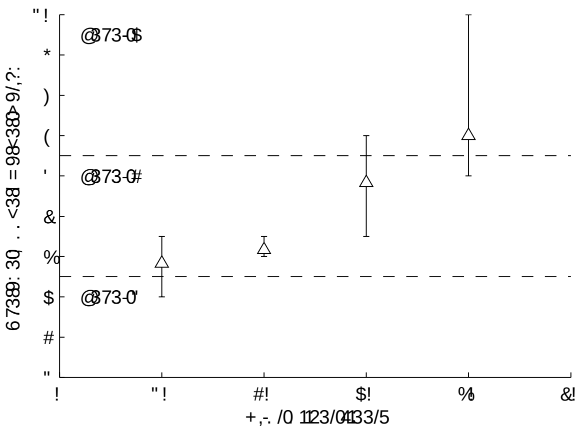


Figure 24. Effect of cockpit position on HQR scores for high bandwidth response

Time histories. Figure 25 illustrates different control strategies employed as pilots adapted to different bandwidths for the 40 ft pilot offset. Pure time delay for all cases was .233 second. The prolonged rate buildup typical of low bandwidth can be observed for the 0.24 rad/sec case ($\tau_{ped} = 3.6$ sec), as the pilot commands a full pedal step input and the commanded rate takes 5–6 seconds to develop. This lack of response forces him to do full pedal reversal to try to get the aircraft to stop. This type of control shaping was considered undesirable for the rate command system modeled. These characteristics drove this control configuration into Level 2, considering the pilot was still able to achieve the desired performance. With 1.37 rad/sec of bandwidth ($\tau_{ped} = 0.64$ sec) pilots can now generate the desired rates in a more responsive manner. The improved controllability brings the aircraft into Level 1. While pilots could generate rates quickly in the 2.12 rad/sec ($\tau_{ped} = 0.21$ sec) case, lateral kinematic issues start showing up and pilots tended to slow down the maneuver by reducing the maximum rates generated and consequently the overall task performance is compromised. These characteristics become even more exaggerated, for the given delay, as bandwidth increases to 2.68 rad/sec ($\tau_{ped} = 0.05$ sec) and higher.

Inasmuch as the offset distance amplifies the lateral pilot station accelerations, or more precisely their time rate of change, Figure 26 shows that pilots undergo similar adjustments of their control technique for increasing pilot offsets. The jerk felt in response to a pedal input relates more to the rate of change of the acceleration, rather than the magnitude of the acceleration itself. It is noted that all four configurations, having the same bandwidth, exhibited similar high frequency jerks in the response when pilots attempted the heading capture maneuver. The reduction in amplitude makes the maneuver more tolerable to the pilots.

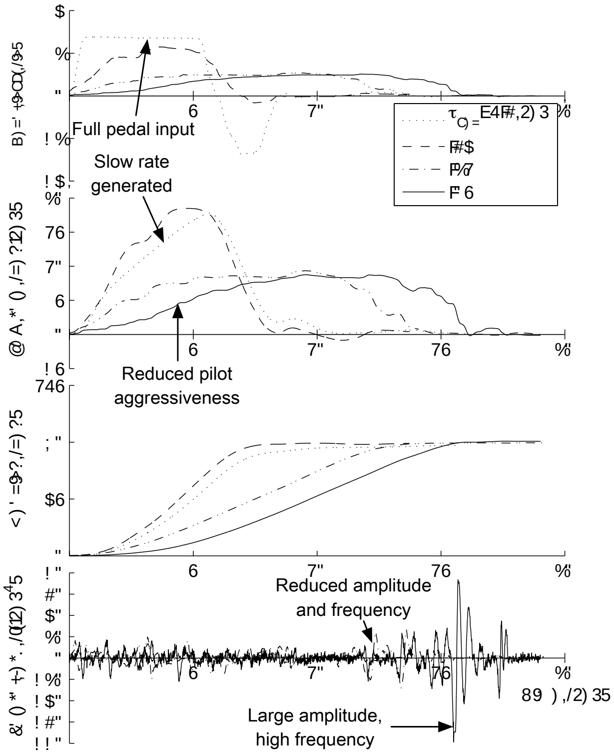


Figure 25. Effects of bandwidth on hover turn maneuvers (40 foot offset).

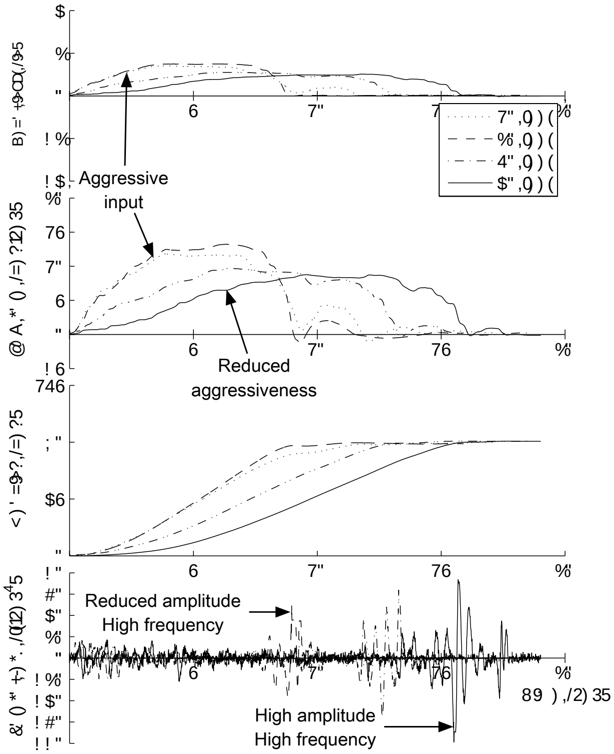


Figure 26. Effect of pilot offset for high bandwidth response on hover turn maneuvers.

Conclusions

A piloted flight simulation was performed on the NASA-Ames Vertical Motion Simulator (VMS) to investigate the applicability and potential refinements of the current ADS-33 short-term attitude and heading handling quality requirements to large (heavy-lift) tilt-rotor aircraft. Five experimental test pilots representing the U.S. Army, Marine Corps, NASA, and rotorcraft industry evaluated the Large Civil Tilt-Rotor (LCTR2) configuration for a range of bandwidth and phase delay values, and pilot offsets from the center of gravity, in moderate turbulence conditions, while primarily performing revised versions of the ADS-33 Hover and Hovering Turn MTEs. Analysis of objective aircraft-task performance data and pilot evaluation comments suggests the following conclusions and observations:

1. Attitude Command/Attitude Hold response type was investigated for hover control of an aircraft with a large (i.e., 40 ft) pilot offset from the center of gravity in moderate turbulence environmental conditions. Level 1 handling qualities, given these experimental constraints was not achievable.
2. Quickness of the attitude response (in all axes, but primarily in the yaw axis) associated with the higher frequency cases (over 1.2 rad/sec pitch and roll commanded response natural frequencies and under .5 sec yaw rate commanded response time constants) translated into objectionable impulsive load factor rates (a ride qualities issue) and unpredictable aircraft response (a handling qualities issue).
3. Actuator rate limiting acted as a fundamental upper bound on acceptable bandwidths in all axes.
4. For low response frequencies there was a general lack of control authority in all axes, with sluggish aircraft response lending itself to excessive workload, especially as pilots attempt the high amplitude aggressive control techniques required to achieve desired position control. Pilot station offset obfuscates pilot perception of position in the hover task, primarily due to the coupling of pitch and heave motions of the cockpit, and therefore it mainly serves the purpose of increasing task difficulty.
5. Pilot cutoff frequency for ACAH response type was naturally constrained to the phase bandwidth, plus or minus a margin of error. Higher bandwidths led

pilots to operate at control frequencies that excited high amplitude and frequency oscillation.

6. The ADS-33 short-term pitch and roll attitude response handling qualities boundaries did not support the assigned handling qualities for this vehicle, independent of the position of the cockpit. For small time delays, short-term response handling qualities appear to be driven fundamentally by the natural frequency of the commanded second-order system response. Proposed boundaries therefore tend to follow the constant natural frequency lines.
7. A broad range of acceptable yaw bandwidths was identified based on the proposed heading capture evaluation maneuver. Relaxation of the Level 1 yaw bandwidth requirement from 2.0 rad/sec to .25 rad/sec was possible to help account for the large pilot offset from the center of gravity.

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