An Investigation of Large Tilt-Rotor Hover and Low Speed Handling Qualities

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Abstract

A piloted simulation experiment conducted on the NASA-Ames Vertical Motion Simulator evaluated the hover and low speed handling qualities of a large tilt-rotor concept, with particular emphasis on longitudinal and lateral position control. Ten experimental test pilots evaluated different combinations of Attitude Command-Attitude Hold (ACAH) and Translational Rate Command (TRC) response types, nacelle conversion actuator authority limits and inceptor choices. Pilots performed evaluations in revised versions of the ADS-33 Hover, Lateral Reposition and Depart/Abort MTEs and moderate turbulence conditions. Level 2 handling qualities ratings were primarily recorded using ACAH response type in all three of the evaluation maneuvers. The baseline TRC conferred Level 1 handling qualities in the Hover MTE, but there was a tendency to enter into a PIO associated with nacelle actuator rate limiting when employing large, aggressive control inputs. Interestingly, increasing rate limits also led to a reduction in the handling qualities ratings. This led to the identification of a nacelle rate to rotor longitudinal flapping coupling effect that induced undesired, pitching motions proportional to the allowable amount of nacelle rate. A modification that counteracted this effect significantly improved the handling qualities. Evaluation of the different response type variants showed that inclusion of TRC response could provide Level 1 handling qualities in the Lateral Reposition maneuver by reducing coupled pitch and heave off axis responses that otherwise manifest with ACAH. Finally, evaluations in the Depart/Abort maneuver showed that uncertainty about commanded nacelle position and ensuing aircraft response, when manually controlling the nacelle, demanded high levels of attention from the pilot. Additional requirements to maintain pitch attitude within ±5 deg compounded the necessary workload.

Introduction

As part of the continuing research of advanced flight control system technologies that will enable next generation rotorcraft and civilian air travel, the current simulation experiment evaluated the hover and low speed handling qualities of a notional large tilt-rotor aircraft, with particular emphasis on longitudinal and lateral position control. It has long been recognized that higher levels of control augmentation are required for conventional rotorcraft to achieve acceptable handling qualities for nap-of-the-earth hover and low speed precision tasks and operations in degraded visual environments. In particular, advantages of Translational Rate Command (TRC) over Rate Command (RC) and Attitude Command-Attitude Hold (ACAH) response types for handling qualities improvements in degraded visual conditions are reported in Ref. 1. More recently, advanced control modes with response types other than RC and ACAH have been extensively investigated for heavy-lift utility class helicopters such as the CH–47F (Refs. 2 and 3) and CH–53K (Ref. 4). These have resulted in improved handling qualities and reduced pilot workload without sacrificing the purported agility of RC. An early piloted simulation study of TRC for a tilt-rotor aircraft (Ref. 5), conducted in the now-retired NASA-Ames Flight Simulator for Advanced Aircraft (FSAA) motion platform, investigated actuator authority requirements for the XV-15 stability and control augmentation system (SCAS). The study was the first to exploit the tilt-rotor ability to effect longitudinal and lateral thrust vectoring via the nacelles and parallel lateral cyclic tilting of the rotors. Reduction of large attitude excursions made possible by maneuvering using vectored thrust was a major factor in the handling qualities ratings improvements.

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The current line of research of the handling qualities requirements for large rotorcraft in hover began in 2008 with piloted simulation experiments conducted on the NASA Ames Research Center Vertical Motion Simulator (VMS). This first experiment (Ref. 6) explored the control system dynamic response requirements for stability margin and disturbance rejection bandwidth for a range of rotorcraft sizes, from a utility helicopter to a large heavy-lift tilt-rotor (greater than 100,000 pounds gross weight). The experiment exposed fundamental issues related to large aircraft size, especially the large distance between the pilot station and the center of gravity.

A second simulation experiment in 2009 (Ref. 7), also conducted on the VMS, investigated short-term angular response requirements to controls in hover for the NASA Large Civil Tilt-Rotor 2 (LCTR2) shown in Figure 1, and described in Ref. 8. Results of this second experiment confirmed some of the previous observations and determined yaw bandwidth requirements that were considerably lower than those suggested by ADS-33 (Ref. 9) metrics, which were defined for much smaller aircraft. Pitch and roll responses were also investigated, with a primary finding that Level 1 handling qualities could not be achieved via an attitude command control system. A major deficiency was an objectionable pitch induced heave motion at the pilot station, a direct consequence of the long fuselage of this tilt-rotor design. This outcome led to the key hypothesis of the current investigation: mainly that TRC, or a mix of TRC and attitude command control, could achieve Level 1 handling qualities by allowing maneuvering without inducing large attitude changes.

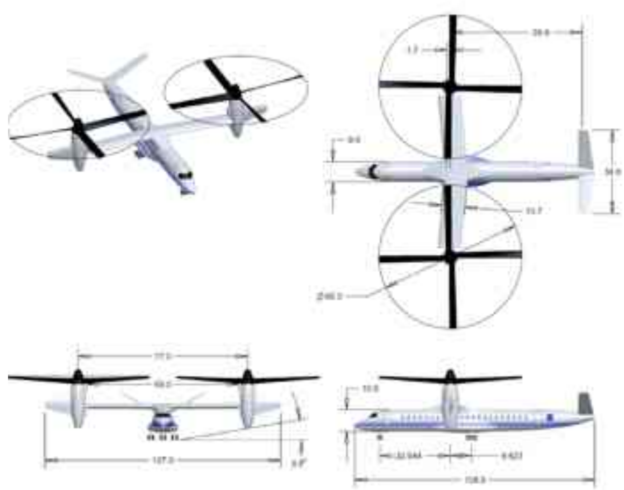


Figure 1. NASA Large Civil Tilt-Rotor (LCTR2)

Objectives

The main objective of this study was to investigate the efficacy of Translational Rate Command (TRC) on piloted handling qualities for large-sized tilt-rotors, in particular the handling qualities impact of various TRC design parameters, such as, inceptor type and control response requirements (i.e. sensitivities), and nacelle conversion actuator position and rate limits. A secondary objective of the simulation was to evaluate the handling qualities of the aircraft beyond hover, into the low speed flight regime, by assessing direct pilot control of nacelles and Attitude Command-Attitude Hold (ACAH) control.

Approach

A piloted handling qualities simulation of a large tilt-rotor was conducted in the NASA-Ames Vertical Motion Simulator to address these questions. An implementation of Translational Rate Command (TRC) in which control of the nacelles was performed automatically by the flight control system was compared to a conventional Attitude Command-Attitude Hold (ACAH) control. The mathematical model of the aircraft, detailed in Ref. 10, consisted of a Linear Parametric Varying (LPV) system constructed by “stitching” together various stability derivative-based linear models and thus allowing experimentation with a linear model valid for a nacelle angle envelope, between 95 and 60 deg, and airspeed from hover to 60 kts. The flight control system was designed to allow investigation of ACAH and TRC fundamental response types, as well as a “Hybrid” response type in which attitude and translational rate were commanded simultaneously. Independent control of roll and lateral translation was achieved by combining anti-symmetric (differential) collective and anti-symmetric (parallel) lateral cyclic rotor inputs, respectively. A proportional controller mounted on the Thrust Control Lever (TCL) grip, under the pilot’s left thumb, was configured for control of TRC implementations and compared to center stick control during the experiment. This inceptor was included in the experiment as it was hypothesized that being accustomed to control of attitude through the center stick, pilots might find it counter-intuitive to control translational rate through the same control. Separation of control action between left and right hands and the different nature of the controllers were considered desirable as a possible solution to overcome this center stick to attitude control paradigm. Implementation variations used in the experiment included multiple combinations of nacelle conversion angle and rate limits, as well as center stick sensitivities and control mode mixings. Finally, manual pilot control of nacelles was done via a discrete-step and a proportional nacelle rate thumb inceptor. The first offered repeatable execution, while the second allowed for higher rate of nacelle conversion to be commanded.

The experiment relied on three primary evaluation tasks: a precision hover task, a lateral reposition task, and an aborted departure maneuver, all of which were modeled after revised versions of standard ADS-33 Mission Task Elements. TRC was evaluated only in the hover and lateral reposition tasks. Evaluation of discrete-step and proportional nacelle rate thumb controllers was carried out in the Depart/Abort maneuver, with the primary response type being ACAH. Experimental pilots tested the different control variants, with evaluation comments and objective task performance data recorded. The following section describes the experiment design and methodology in more detail, including the simulation model and experimental procedures.

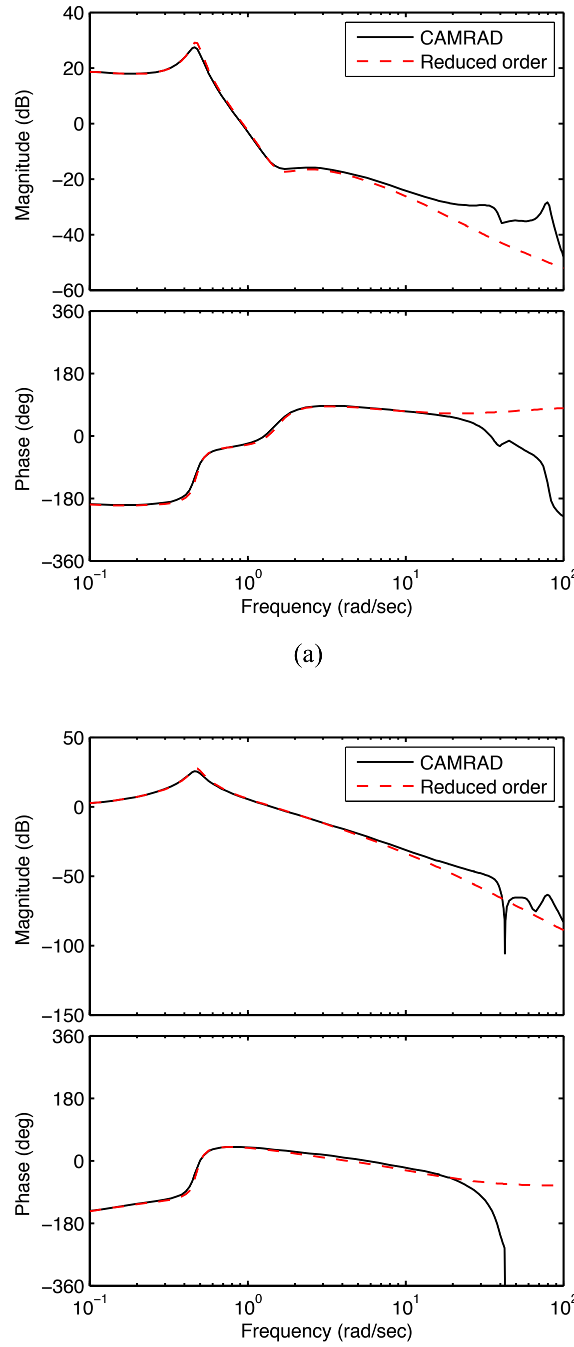
Simulation Model

Aircraft Model

A real-time piloted simulation model was needed to accommodate the range of design trade-offs. The bare-airframe model needed to be flexible enough to allow easy setup of different control system designs, but yet accurate enough to ensure that adequate aircraft response was achieved with a representative amount of actuator usage. The mathematical model of the aircraft was significantly updated from that used in previous piloted flight simulation experiments (Refs. 6 and 7). A 13-state, reduced-order, fully-coupled Linear Parametric Varying model was used to simulate the bare-airframe dynamics of the aircraft for airspeed and mast conversion angle between hover to 60 kts and 60 to 95 degrees, respectively. This model was composed of linear stability-derivative models obtained for trimmed flight conditions in the speed and nacelle angle range of interest. A detailed description and validation of the methods used to generate this model was reported in Ref. 10.

The comprehensive aeromechanical rotorcraft analysis code, CAMRAD II (Refs. 11 and 12), was used to generate the high-order linearized systems for each nacelle angle and airspeed datum combination. The order of these linear systems was unnecessarily large for handling qualities and simple feedback control design, and therefore reduced order models were created. The reduced-order models retained the key rotor-body couplings, including both the lateral and longitudinal rotor blade flapping dynamics for each rotor, but dropped the high frequency rotor modes. It is shown in Figure 2 that these adequately represent bare-airframe dynamics over the frequency of interest for pilot control (i.e., 1–10 rad/s). Figure 2 shows the main on-axis bare-airframe aircraft frequency responses for anti-symmetric lateral cyclic swashplate input. Lateral flapping was a key addition to the model, providing the necessary degree of freedom for control of lateral translation. In previous iterations (Refs. 6 and 7), where lateral translation was achieved through changes in the roll attitude, control had been limited to the differential (or anti-symmetric) collective rotor pitch.

The modeling tool FLIGHTLAB (Ref. 13) was used separately to generate values for the control derivatives corresponding to nacelle conversion angle, rate and acceleration perturbations of the reduced-order model. Figure 3 shows that the FLIGHTLAB-generated derivatives compare well to analytical predictions based on first principles, providing confidence in the modeling approach. Enhancements to the first principles analytical modeling, compared to the simplified approach reported in Ref. 10, improved the comparisons to the FLIGHTLAB–generated derivatives, especially in the phase curve.



(a)

(b)

Figure 2. Comparison of frequency responses to anti-symmetric lateral cyclic for the high-order (CAMRAD II) and reduced-order models: (a) lateral velocity and (b) roll attitude

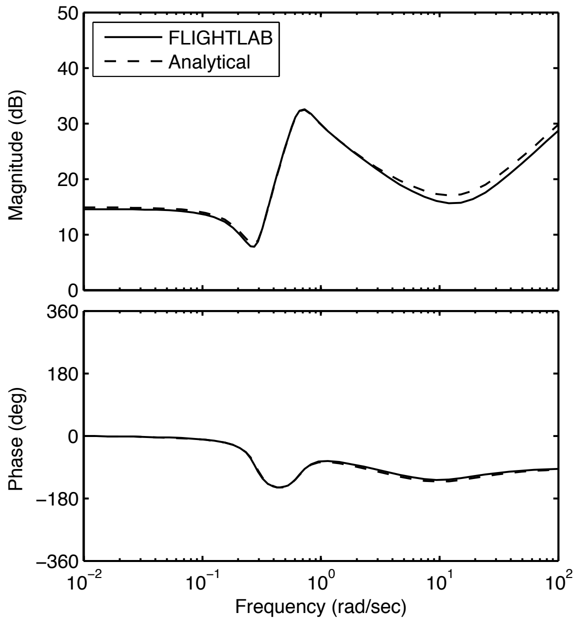


Figure 3. Comparison of frequency responses of aircraft *u* velocity to nacelle angle using FLIGHTLAB and Analytical derivations. Note, the convention followed here is that the nacelle conversion angle is positive for a forward rotation from the hover position.

In generating the bare-airframe nacelle/rotor model, inertia of the nacelle component was neglected initially, such that total mass of the nacelle/rotor system corresponded to that of the rotor only and the center of mass was located at the rotor hub. Inertial properties of the rotor blade mass distribution were accounted for via the multibody dynamics formulation used in FLIGHTLAB. This is not necessarily the most realistic assumption, but in the absence of more tangible design data, it represented a reasonably adequate starting point for flight control system design, and handling qualities evaluation. As long as nacelle to airframe moment of inertia ratio remains small, the assumption can be considered reasonable. Conservative estimates indicate that nacelle pitching moment of inertia could account for 5–6% of the airframe pitching moment in addition to the current 2.8% ratio.

It is noted in particular, that this assumption lent itself to an unbalanced nacelle system, that is, one in which the aircraft center of gravity moves with the mast conversion angle. However, this was not considered to have a noticeable effect on the handling qualities for small ranges of motion. Below 10 rad/s, the primary effect on the rigid body dynamics of the airframe from the tilting rotor/nacelle is predominantly an effect of the quasi-steady reorientation of the rotor thrust vectors. Estimates show that inertial effects of angular nacelle acceleration only begin to dominate the *X*–force component (i.e., force component along the body x axis) for nacelle frequencies over 10 rad/s, which is well beyond the normal frequency range of control of the pilot.

Flight Control System

Control architecture. The flight control system design utilized the same generic explicit model-following architecture used in the previous experiments and shown in Figure 4. This architecture was ideal for this series of experiments because it allowed easy and independent variation of the vehicle response to piloted inputs in each axis without affecting the feedback characteristics. The existing Attitude Command-Attitude Hold control system was augmented to enable longitudinal and lateral Translational Rate response to piloted inputs by introducing velocity feedback and command paths. In addition to the primary experimental TRC and ACAH response types, the control system provided yaw Rate Command and vertical (heave) Rate Command control response types.

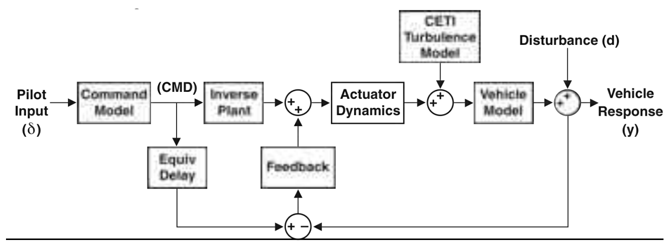


Figure 4. Overview of the generic model-following control system architecture.

The implementation of TRC employed primarily lateral parallel cyclic for lateral translational rate control, and nacelle tilt angle for longitudinal control. Lateral and longitudinal velocities are compared to the desired vehicle response determined by the command model, and the error is fed back through a simple Proportional-Integral-Differential (PID) Single-Input/Single-Output (SISO) regulator that makes the necessary corrections to the control inputs being estimated by the inverse plant model.

With TRC, the ACAH control loops were still active but in order to ensure deck level flight conditions, zero pitch and roll attitude regulation was achieved by maintaining the command model inputs at zero. Automatic regulation of the longitudinal cyclic and differential collective counteracted the natural tendency to pitch and roll in response to nacelle and lateral parallel cyclic inputs, respectively. Thus, the velocity and attitude loops were closed in parallel, with neither one possessing hierarchical superiority over the other (i.e., there was no inner/outer loop structure). Consequently, the two sets of regulators complemented each other by acting on the independent control mechanisms. This was made possible by the additional degrees of control afforded in a tilt-rotor aircraft.

The TRC command models were designed to meet the first order qualitative character (i.e., absence of objectionable pith and roll oscillations, zero velocity for zero stick displacement, and no noticeable overshoots in the response of translational rate to control inputs) and the equivalent rise time specifications defined in ADS-33. Additionally, the command models provided experimental control over the variation in translational rate with control deflection. A first-order command model was used in the lateral and longitudinal axes to achieve desired translational rate command response types.

$$\frac{u_{cmd}}{\delta_{lon}}, \frac{v_{cmd}}{\delta_{lat}} = \frac{Ke^{-\tau_{cmd}s}}{\tau s+1}$$

Here δ_{lon} and δ_{lat} refer to the pilot inputs, either through the center stick or the thumb stick, and v_{cmd} and u_{cmd} are the commanded body axes velocities. Time constants τ_{cmd} and τ define the commanded response delay and equivalent rise times, respectively. The sensitivity gain K specifies the control response requirements.

For the ACAH control laws, second-order command models were used in the pitch and roll axes. Command model dynamics in all axes were set independently. This command model structure offered a convenient way of implementing "Hybrid" response types in which attitude and translational rate were commanded simultaneously, allowing for the investigation of such response types, as well as the ACAH and TRC fundamental response types. Issues of interest for investigating hybrid response types included: (a) effect of control system implementation on rotor flapping demands, and (b) mechanics for transitioning between angular and translational response types.

After notable pitch perturbations associated with the longitudinal flapping response of the rotors were observed, in response to high nacelle conversion rates, crossfeed signals between nacelle conversion rate and longitudinal cyclic were introduced to minimize the negative impact of the rotor delay. These gains effectively introduced a feed-forward lead component that eliminated a significant amount of the delay.

Design specifications. Quickness specifications, defined by an equivalent rise time constant, were set at 5 s for both the lateral and longitudinal rate response types. The baseline ACAH command model gains were selected based on the results from Ref. 7. Accordingly, pitch and roll command model featured 1.0 rad/s natural frequencies, and 1.45 and 1.0 damping ratios defined the input-output dynamics. The project pilot systematically checked this configuration against various natural frequency command model configurations and found it to be the best behaved. This was later verified by a sub-set of the evaluation pilots. A control optimization, using CONDUIT (Ref. 14), was performed to determine a set of feedback gains that would ensure 38 deg stability phase margins in the pitch and roll axes, per the findings of Ref. 6. TRC gains were set to achieve the more conventional 45 deg stability margins. This optimization solution sets the values of disturbance rejection bandwidth. Table 1 summarizes the fundamental augmentation regulator characteristics and system bandwidth for the baseline configurations.

Actuators. Models of actuator dynamics were necessary so that the control system design could correctly account for nonlinearities such as position and rate limits, and time delays. Simplified nacelle servo-actuator dynamic models were assumed to be second order. Bandwidth and damping characteristics were selected to avoid low frequency cut-off of pilot input, and to avoid natural oscillatory behavior. With this in mind, 1.0 damping ratio and 8 rad/s natural frequency characterized the nacelle conversion actuator angular rate response dynamics. This fixed-point design was therefore driven by the handling qualities and flight control requirements while disregarding any potential structural constraints at this stage. Nacelle conversion actuator, in the baseline TRC configuration, was allowed to rotate 9 deg forwards and backwards, from the 86 deg hover position (77–95 deg range) at a peak rate of 7.5 deg/s. These rate limits were based on typical maximum rates of actual tilt-rotors.

Table 1. Control augmentation characteristics for baseline configurations

	Disturbance Rejection Bandwidth[a] (rad/s)		Gain/Phase Stability Margins (dB)/(deg)		Input/Output Bandwidth[b] (rad/s)/(ms)	
	lat	lon	lat	lon	lat	lon
ACAH	1.32	1.02	8.3/38.1	10.5/38.1	1.58/148	1.66/151
TRC[c]	1.24	0.31	21.0/45.3	9.1/45.9	4.85/52	1.38/115
TRC[d]	1.24	0.31	21.0/45.3	11.7/53.7	4.84/49	1.84/108

[a] Defined in ADS-33 Test Guide (Ref. 15)
[b] Based on linear analysis. ACAH values refer to the attitude response to piloted input (bandwidth taken as phase bandwidth). TRC values refer to the translational rate response to piloted input (bandwidth taken as the lesser of the gain bandwidth and phase bandwidth).
[c] Baseline configuration without nacelle rate to longitudinal cyclic crossfeed.
[d] Improved configuration with nacelle rate to longitudinal cyclic crossfeed.

Turbulence model

Aircraft response to atmospheric gust disturbances was simulated by means of the Control Equivalent Turbulence Input (CETI) model developed by the AFDD, and described in Ref. 16. Conceptually, the CETI model is a hover/low-speed turbulence model that simulates the effects of atmospheric turbulence on a *conventional* rotorcraft. The CETI model was designed to provide realistic gust inputs through the bare-airframe control inputs, i.e., the symmetric and anti-symmetric collective and longitudinal cyclic swashplate inputs, in this case. Consequently, primary responses to turbulence are in the heave, roll, pitch and yaw degrees of freedom. Longitudinal and lateral vehicle perturbations due to turbulence are of a secondary nature and are represented as a consequence of attitude changes. Validity of this model for use in tilt-rotor aircraft has not yet been verified. This approach was, however, adjudged by the experimental test pilots to provide a reasonable representation of aircraft motion in a turbulent flow field and was therefore adopted for use in this investigation.

Conduct of Test

This section describes the control system configurations adopted for this experiment, the simulation facility where the experiment was performed (including pilot controls and situational displays), and the evaluation tasks and test procedures.

Control system configurations

Response types. Two fundamental control modes were investigated in this experiment: ACAH and TRC control. The ACAH control mode provided a baseline reference to compare the new model with the findings of the previous investigations. A third, ACAH/TRC hybrid control mode in the lateral axis, was configured such that center stick displacements greater than one inch from center would command roll attitude at reduced sensitivity (0.3 of the baseline ACAH command model) in addition to the normal translational lateral rate commanded. TRC control variants included different inceptor types and control sensitivities (i.e., control response requirements defined by the variation in steady state translational rates with inceptor deflection), and nacelle actuator rate and position limits.

TRC variants. Two different types of TRC pilot inceptor were evaluated in this study. The primary approach used the conventional center stick controller. All of the control variants configured for center stick evaluation are summarized in Table 2. An alternate thumb stick inceptor on the Thrust Control Lever (TCL) grip was also configured for control of vehicle translational rates.

Table 2. TRC center stick control experimental parameters

Control sensitivity (ft/s/in)	Nacelle rate limits (deg/s)	Nacelle range (deg)
10.0 14.0 15.0 16.0 17.0	±7.5	77–95
15.0	±2.5 ±5.0 ±10.0 ±12.5 ±15.0	
	±5.0 ±7.5	81.5–91.5

Center stick inceptor gradient and break-out force-feel characteristics were configured for ACAH at 0.9 lb/in and 1.0 lb in the longitudinal direction and 0.7 lb/in and 0.6 lb in the lateral direction. Given these force-feel characteristics, center stick TRC control sensitivities were adjusted to provide the best-expected task performance with acceptable forces for the required inceptor displacements. Evaluation maneuver constraints for the center stick implementation required that 25 ft/s be achieved as a minimum. Only directly proportional variations in translational rate with control deflection were investigated (i.e, constant sensitivity gains). Early exploration runs appeared to indicate a relationship between stick sensitivity and a tendency to PIO. It was consequently decided to expand the test matrix in and around the baseline sensitivity design point. Thumb stick sensitivity was set at 0.9 ft/s/deg (i.e., 0.9 ft/s would be commanded for every degree of stick displacement). The thumb stick had a ±25 deg range, so a 22.5 ft/s maximum speed could be commanded.

OLOP. The Open-Loop Onset Point (OLOP) design criteria (Ref. 17), often used in fixed wing flight control system design and tested for use in rotorcraft in Ref. 6, was used in this case to predict the potential handling qualities impact associated with rate limiting of the nacelle conversion actuator. Figure 5 illustrates the effect of pilot input amplitude on the OLOP criteria. Center stick maximum displacement range was ±5 in, allowing the handling qualities impact of piloted input frequency and amplitude to be freely evaluated. For comparison, Figure 6 shows the effect of the experimental nacelle rate limits on the OLOP phase and amplitude criteria assuming a 1 in maximum amplitude control input. The extra margins offered by the larger rate limits are clearly illustrated. Thumb stick incepted TRC phase and amplitude at the onset frequency for maximum inceptor displacement were -134.6 deg and 1.9 dB, respectively, effectively meeting Level 1 OLOP specifications.

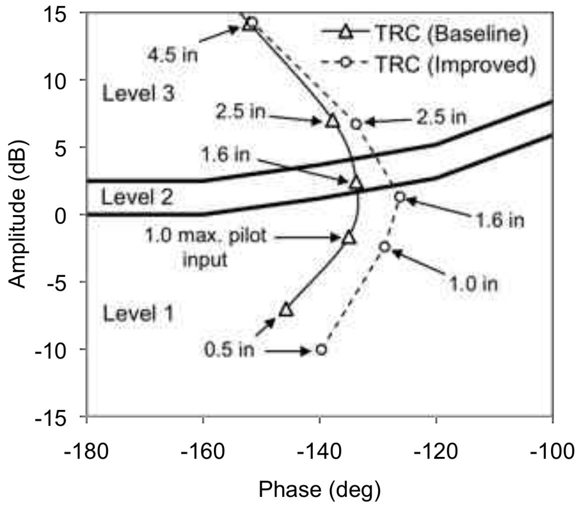


Figure 5. OLOP specifications for baseline and improved TRC configurations (15 ft/s/in control sensitivity and ±7.5 deg/s rate limits)

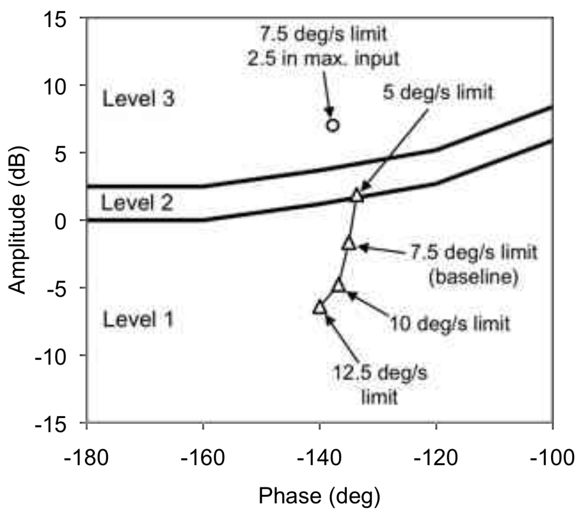


Figure 6. OLOP specifications for varying nacelle rate limits (15 ft/s/in sensitivity, 1.0 in maximum pilot input)

Nacelle inceptors. When the control system was set to ACAH, the fore/aft axis of the thumb stick commanded nacelle rate proportional to the displacement, up to a 7.5 deg/s maximum rate. An alternative method employed a rocker switch, which would discretely advance the nacelle to the next stop within a sequence of predetermined angular positions summarized in Table 3. Nacelle rotation was commanded at a constant 2 deg/s angular rate between each step.

Table 3. Discrete nacelle conversion angle stops

Conversion direction	Discrete nacelle stops (deg)				
Forward	95	86	–	75	60
Rearward	60	–	80	86	95

Facility

As with the preceding studies, this experiment was conducted in the NASA-Ames Vertical Motion Simulator (VMS), described in Ref. 18 (Figure 7). The Transport Cab (T-Cab) was employed for its large field of view as seen in Figure 8. Traditional helicopter center stick and pedal pilot control inceptors were installed for the right cockpit seat, the evaluation pilot position. The experimental tilt-rotor specific vertical Thrust Control Lever (TCL) mentioned above is shown in Figure 9. It was provided instead of the standard helicopter collective stick. Pilots could manually adjust the friction coefficient on the TCL to their preference. Figure 9 also shows the experimental thumb stick inceptor configured in place of the more conventional thumb wheel commonly used for control of the nacelle position. The thumb stick fundamentally functioned as a miniature, spring-loaded, linear, dual-axis joystick. After displacement of the inceptor it returns back to center. The spring constant was fixed.

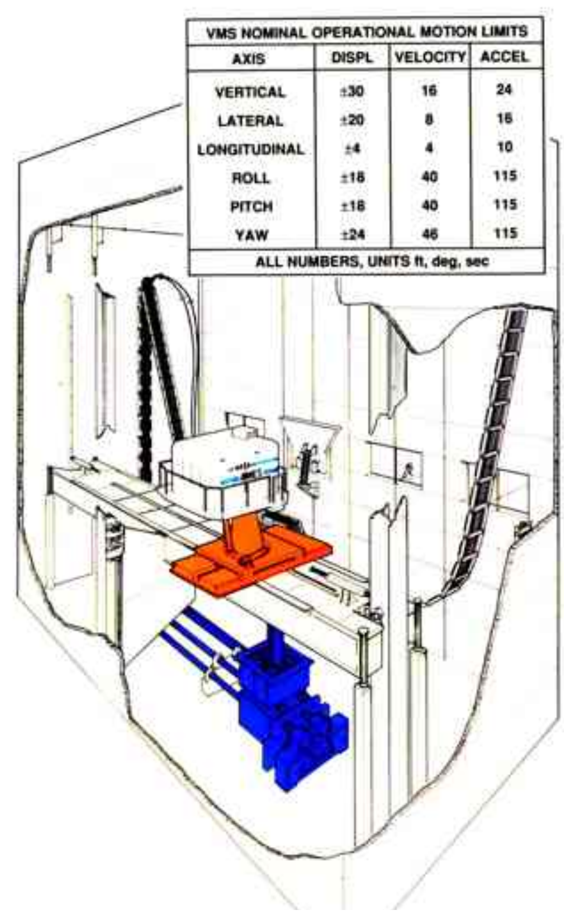


Figure 7. NASA-Ames Vertical Motion Simulator (VMS).

The primary flight display and the horizontal situation (hover) display, replicating the Army's Common Avionics Architecture System (CAAS) displays, were provided on the instrument panel. A nacelle position indicator showing current position and direction of motion, and discrete position stops was added to these displays (Figure 10).

Figure 8. VMS two-seat transport cab overview.

Figure 9. Thrust Control Lever Grip. Center rocker switch controls discrete nacelle movement. The thumb stick is a two-axis proportional controller. Used with TRC the stick provides an alternative to center stick inputs for longitudinal and lateral speed control. In ACAH, the thumb stick controls fore and aft nacelle rate, proportional to control displacement, up to a maximum of 7.5 deg/s.

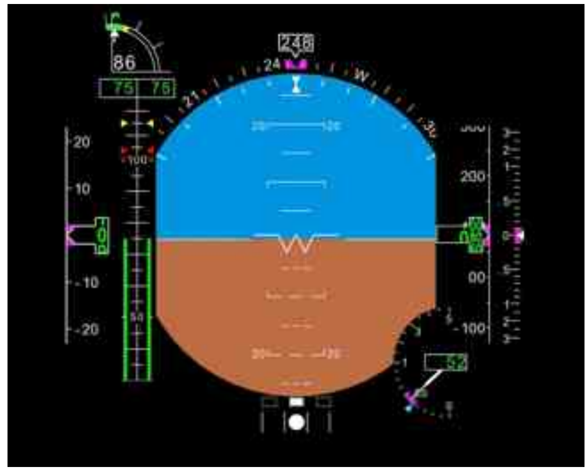


Figure 10. CAAS display with nacelle position indicator (top left)

Evaluation tasks and procedures

As introduced already, test configurations were evaluated by the pilots in revised versions of the ADS-33 Hover, Lateral Reposition and Depart/Abort MTE maneuvers. TRC was evaluated only in the hover and lateral repositioning tasks. The Depart/Abort maneuver was employed only for the evaluation of discrete-step and proportional nacelle rate thumb inceptors, in ACAH. Refinements to the ADS-33 Hover MTE position performance standards (Ref. 6) were necessary because cargo/utility maneuver performance metrics were found to be too "tight" and aggressive for an aircraft of this size. It was found that ±4 ft lateral-longitudinal position deviation and ±3 ft altitude deviation were more appropriate for the limits of *desired* task performance. *Adequate* position and altitude performance limits were set at double the desired limits, i.e., ±8 ft and ±6 ft., respectively. All maneuvers were defined around a pilot eye-point altitude of 55 ft AGL. Lateral Reposition MTE revisions were aimed at reducing the speed requirement from 35+ knots to 15+ knots groundspeed. Accordingly, completion times were redefined at 25 s for *desired* performance and 30 s for *adequate*. Revisions of the Depart/Abort MTE included a course length extension to 1200 ft. Additionally, performance standards were modified to constrain pitch attitude within ±5 deg for *desired* performance and ±7 deg for *adequate*. *Desired* and *adequate* maneuver completion times were respectively modified to 40 and 45 s.

Ten pilots, including the project pilot, provided evaluations during this experiment. All pilots had extensive rotorcraft experience ranging from light utility single main rotor helicopters to medium and heavy lift tandem helicopters. Two of the pilots were highly experienced tilt-rotor pilots. Importantly also, five pilots of the group had participated in the previous experiments and were therefore familiar with the aircraft and some of the issues associated with it. This provided continuity between the series of experiments. This diverse breadth of backgrounds and control techniques provided a widely representative sampling group. All pilots were experienced test pilots and were familiar with the use of the Cooper-Harper Handling Quality Rating scale (Ref. 19).

Pilots were required to complete initial training sessions to familiarize themselves with the experiment objectives, methodology, the Hover and Lateral Reposition MTEs and baseline control configurations prior to the start of formal evaluations. Evaluation of the Depart/Abort required that pilots, who did not possess formal tilt-rotor training, be fully briefed beforehand on basic tilt-rotor operations. An additional training session, focusing on familiarization of manual nacelle control, was performed for this purpose under project pilot instruction and supervision.

Data recorded included the aircraft control inputs and state data, task performance data, and pilot comments. A formal questionnaire was used to elicit structured pilot opinion about task aggressiveness versus performance, aircraft characteristics, and pilot workload. The pilots used the Cooper-Harper HQR scale to provide a qualitative evaluation of the configuration. Pilots flew each test configuration for familiarization purposes, as many times as required until they felt consistent performance was achieved. A minimum of three formal evaluation runs was performed, prior to collection of pilot comments and ratings. If pilots felt a run of the three was anomalous they were free to execute additional runs to resolve the inconsistency. Task performance displays in the VMS control room 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.

Evaluation in the Lateral Reposition and the Depart/Abort required different orientations of the cab, with the cab oriented with the longitudinal axis across the beam for evaluation in the Lateral Reposition, and along the beam for the Depart/Abort. Although evaluation in the Hover MTE could be performed in either orientation, this was restricted to the crossbeam orientation for consistency with previous experiments. The orientation of a particular axis along the beam was selected to provide a greater range of motion allowing higher and more sustained accelerations to be imparted along the primary direction of the maneuver. Consequently, motion cues along this axis may be potentially more compelling, thus offering increased simulation fidelity.

Results

The results of the piloted evaluations, including HQR scores and evaluation comments, will be presented in this section. Complementing these results will be the objective task performance measurements and piloted control traces.

The results for the Hover MTE evaluations embody the majority of the results that are presented. These are presented first and are divided into several sub-sections. The first part shows the results for the baseline configurations. The next part shows the results for the improved version, with the nacelle rate to longitudinal cyclic crossfeed included. Rounding up the results for the Hover MTE evaluations is a brief presentation of the results for the thumb TRC inceptor. The final two parts of the results section show the results for the evaluations of the ACAH, TRC and Hybrid response types in the Lateral Reposition MTE, and the evaluations of the manual nacelle position inceptors in the Depart/Abort MTE.

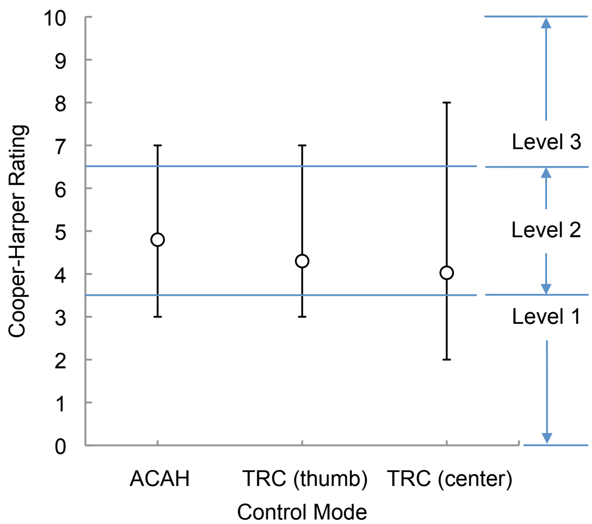
Precision hover performance

Ratings for the ACAH and TRC configurations in the Hover MTE are shown in Figure 11. Figure 11(a) shows slight improvements in the average ratings for the three configurations (4.8 for ACAH, 4.3 for the thumb stick incepted TRC, and 4.0 for the center stick incepted TRC). Center stick configurations in Figure 11 encompass all control sensitivity and nacelle position and rate limit variants, without the nacelle rate to longitudinal cyclic crossfeed improvement. Furthermore, the minimum and maximum ratings for the thumb stick incepted TRC were identical to the ACAH range. The center stick incepted TRC conferred an even wider range of ratings. The average improvement, however, would suggest an increased weighting of the HQRs towards Level 1.

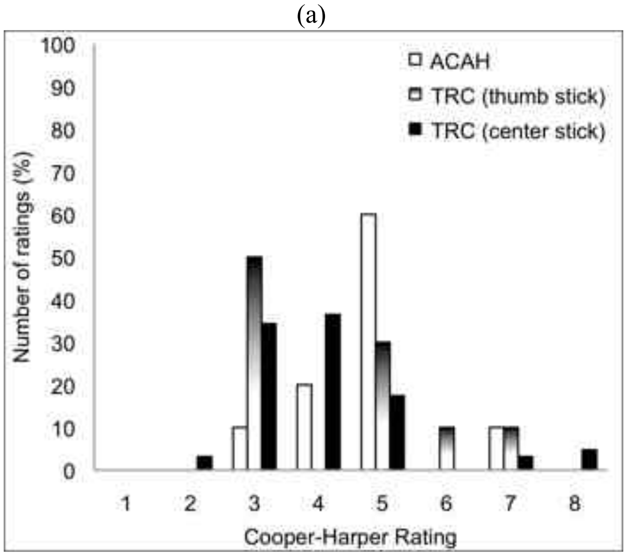
Figure 11(b) shows a more detailed description of the HQR allocation for the ACAH and TRC configurations in the Hover MTE. The data indicate the number of times (in percentage) that the different configurations were assigned a given rating. Percentage values represent a normalization technique, as a different number of evaluations may have been conducted for the each configuration, rather than an attempt to establish any significant statistical comparison. Therefore, ACAH, e.g., was rated HQR 5 about 60% of the time. Results indicate that improvements in the handling qualities were possible with the TRC configurations, with Level 1 handling qualities more frequently achieved, but that a handling qualities cliff was exposed. This is evidenced by the fact that a comparable number of pilots rated the handling qualities with TRC to be either worse or equal to those with ACAH control mode. Evaluations of the thumb stick incepted TRC configuration, for example, were assigned HQR 5–7 scores by about 50% of the pilots. Center stick incepted configurations, whilst heavily rated in the HQR 3–4 range, also received HQR 5–8 scores.

It is noted that upon closure of the velocity feedback loops there was a notable reduction in the turbulence-generated motion of the aircraft. Once pilots had stabilized in the hover, workload ceased being a factor, as in opinion of the pilots the aircraft appeared to reject turbulence very effectively. The critical sub-phase of the maneuver, then, was consistently observed to be the deceleration into the hover, which appeared in some occasions to drive the aggressive pilot compensation and thus expose the handling qualities cliff.

Clearly, deficiencies in the TRC control system meant that it did not confer *consistent* Level 1 handling qualities with either inceptor type. Also, specific deficiencies in the mechanical characteristics of the thumb controller were found to prevent some pilots from modulating their input as desired. Moreover, TRC control was found to be very sensitive to pilot aggressiveness, especially when incepted through the center stick. These issues are discussed in more detail in the following sections.



(a)



(b)

Figure 11. Handling qualities ratings for the three primary response type control configurations in the Hover MTE

Effect of control sensitivity. The baseline 15 (ft/s)/in gain marked the upper control sensitivity limit for the given nacelle actuator position and rate limits. Despite the apparently small difference between the gains, the higher sensitivity gain, 16 ft/s/in, displayed a higher preponderance of HQR 4 ratings in Figure 12, whereas the lower sensitivities, including the baseline, were rated HQR 3, and 2, more frequently. This trend is emulated by a clear shift in the minimum and maximum HQR scores attained. Additionally, a slightly higher propensity for actuator rate limiting was observed. Pilots reported, in general, that they could not be very aggressive with any of the configurations, but this was more obvious with the higher sensitivity case.

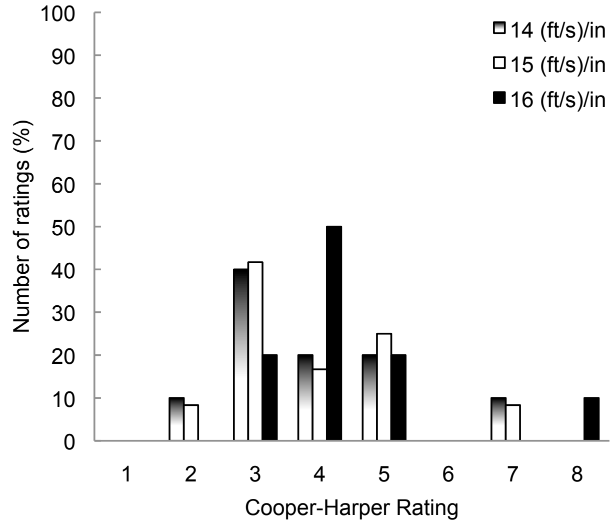


Figure 12. Handling qualities ratings for varying control sensitivity configurations in the Hover MTE

Effect of nacelle rate limit. HQRs for evaluations in the Hover MTE of four nacelle conversion actuator rate limits for the baseline sensitivity gain are shown in Figure 13. Error bars indicate the maximum and minimum values. Results suggest that 10 deg/s was found consistently to be the least objectionable of the nacelle actuator rate limit configurations. Lower rate limits (5 and 7.5 deg/s) were found to be too restrictive of pilot input and resulted in PIO more frequently. The 5 deg/s rate limit in particular, was rated at least one HQR higher than the others. The 7.5 deg/s rate limit did confer the lowest rating, however. Interestingly, the 12.5 deg/s rate limit, while expected to be less restrictive, was sometimes found to display sufficiently unsatisfactory deficiencies in the form of obtrusive pitch perturbations that Level 3 ratings were awarded.

Looking at this configuration more closely, the control system was observed to command nacelle rates, near or at the 12.5 deg/s limits, but frequently without rate limiting. Pilot comments for this configuration consistently mentioned the presence of a notable pitch oscillation accompanied by what was described as an unsettling heaving motion. While this oscillation was described as annoying, or bothersome, it did not appear to compromise the ability to meet the desired performance standards. A few evaluation comments hinted to a quick pitch reversal in response to rapid input, and more interestingly, indicated that this pitch motion could be cueing them on to a false sense of aircraft response because the pitch response was opposite to the expected response pilot control input (e.g., nose up pitch for a forward stick displacement). It was purported that this opposite pitch response to pilot input may have been falsely cueing the pilots into overcorrecting after an initial input. Additionally, this pitch oscillation appeared to affect the altitude maintenance due to the presence of an obvious heave perception.

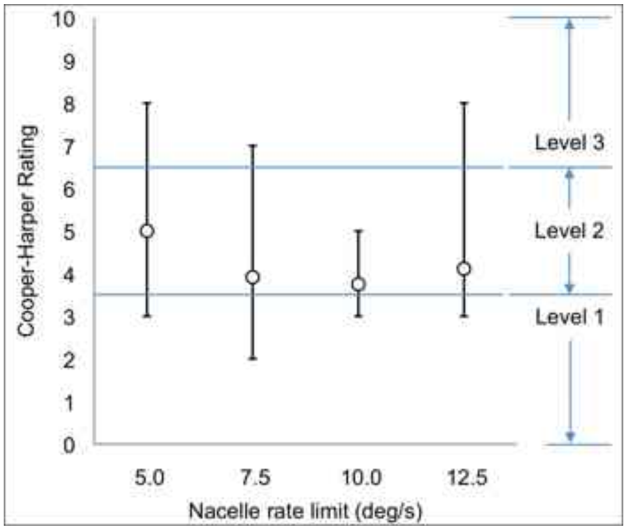
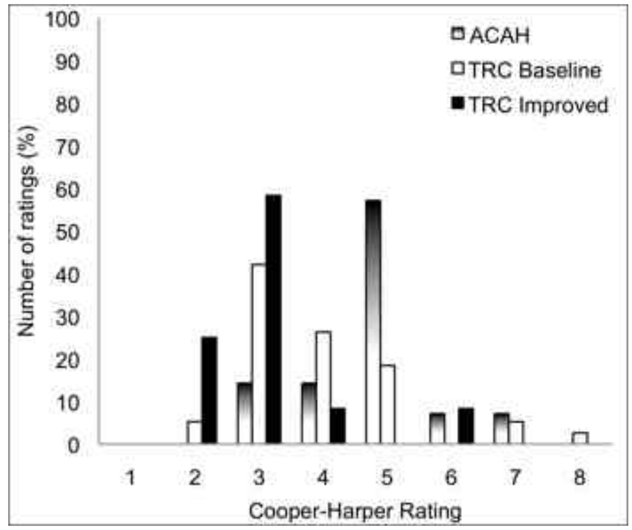


Figure 13. Minimum and maximum handling qualities ratings for varying nacelle actuator rate limits (baseline sensitivity and position limits) in the Hover MTE

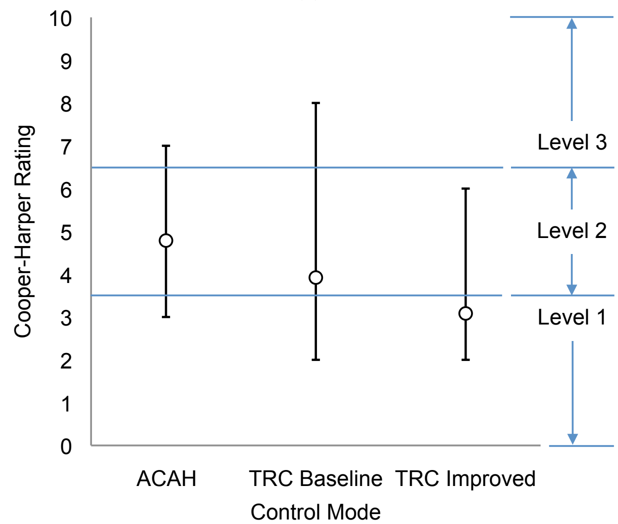
Effect of crossfeed. The control system was modified in order to minimize the pitching response associated with nacelle conversion rate. This consisted of a cross-feed gain between nacelle angular rate and longitudinal cyclic pitch input. This modified control law was evaluated by a subset of the experiment test pilots.

Results for several stick sensitivities (steady state velocity commanded) using the 7.5 deg/s rate limit for the TRC are shown in Figure 14, highlighting improvement of the handling qualities to Level 1 conferred by the crossfeed. Thse improvements were found to confer a reduced sensitivity to pilot aggression level and varying technique, virtually eliminating the PIO tendency

Lawrence et al. in Ref. 20 present an in-depth analysis of the flight dynamics aspects of these control system and actuator configurations from the experiment. The influence of rotor longitudinal flapping dynamics, nacelle actuator limits and piloted input amplitude on the system bandwidth of the longitudinal translational rate response were thoroughly analyzed. The analysis clearly showed that the improved TRC (with nacelle rate to longitudinal cyclic crossfeed) not only reduced the pitching response to almost zero, but also significantly improved longitudinal velocity bandwidth characteristics. It was found that the key effect of this crossfeed gain was to reduce the tendency for the rotor flapping to lag behind the nacelle rotations. The net effect was that by keeping the rotor tip-path-planes perpendicular to the shaft axes, the lagging or retarding effect on the velocity response caused by both the rotor flap back, and subsequent pitching motions, were minimized.



(a)



(b)

Figure 14. Comparison of the handling qualities ratings for the Improved TRC configuration, relative to the Baseline and the ACAH modes in the Hover MTE

Pilot cutoff frequency, determined from the spectral analysis of the inceptor position time histories—during the 30 second precision hover hold subtask—is an approximate measure of pilot operating frequency, and considered a good estimate of the pilot crossover frequency for pilot-in-the-loop tasks (Ref. 21). Additionally, the root mean square (RMS) of the piloted inputs is a statistical measure of the magnitude in the maneuver. A strong correlation between the handling qualities and piloted input frequency and magnitude data can be seen in the contour plot of Figure 15, where the Cooper-Harper ratings are seen to increase dramatically with the amplitude of pilot control inputs, as indicated by the RMS of the longitudinal control input time histories. Increasing pilot input amplitude with the baseline control law caused greater nacelle rate and position limiting and a reduction in the bandwidth of the longitudinal velocity response to stick input, and thus caused a worsening situation and increased PIO tendency. Without the crossfeed, longitudinal inputs with an RMS greater than 1.0 in, especially for higher cut-off frequencies, were correlated with ratings in the HQR 5–8 range. When the crossfeed is included, there is a noticeable reduction in the range of cut-off frequencies and RMS amplitudes employed by the pilots, along with the ensuing reduction in the HQRs. This suggests that aggressive pilot control compensation was not required to achieve the desired task performance.

Overall, results need to be tempered somewhat by the fact that the improved TRC control law was evaluted mostly with the cab oriented along the beam, rather than across the beam, which was the nominal configuration for the Hover MTE evaluations. Longitudinal motion cues were significantly higher in this alternate orientation, due to the larger range of motion available. Insufficient data was recorded in the two cab orientations, making it impossible to discern if handling qualities improvements were due entirely as a consequence of the control system modification, or merely by the fact that motion cues in the longitudinal axis were more compelling in this orientation.

Thumb stick inceptor evaluation

Precise hover performance of TRC control with the TCL-mounted thumb stick showed mixed results, as evidenced by the spread in the HQRs previously shown in Figure 11. The handling qualities ratings ranged from 3 through 7, with the average value at 4.2. About 50% of the pilots rated the aircraft control configuration at Level 1 handling qualities (HQR 3). The remaining 50%, however, rated it very poorly (HQR 5–7). The implication from the latter is that only half the pilots were able to achieve adequate performance standards. Overall, about half of the pilots described the controller was *intuitive*; the remainder felt it was *abnormal*, and the handling qualities ratings effectively reflected this divided opinion.

Some of the difficulties with the thumb stick control were related to the inherent dynamics of the nacelle-controlled longitudinal response that affected the center stick configurations. Many of the same issues with longitudinal axis over-control were manifest throughout the experiment. However, the major contributing factor to the Level 3 ratings was related to the stick mechanics. One frequent observation by the evaluation pilots was that the location of the controller, on the TCL, could complicate the task of simultaneously controlling altitude and translational rates. This in itself did not render the control system unsatisfactory, as large TCL adjustments were not needed. Consequently, some of the pilots rated it as Level 1 despite this deficiency. It appears most likely, based on pilot reports, that the very different mechanical "feel" characteristics and scale of input size of the inceptor made it difficult for the pilots to precisely and harmonically modulate their inputs.

Due to the first order nature of the TRC response type definitions and the command model implementation, if the pilot inceptor is returned to center from a non-zero position, commanded rates undergo an exponential decay. Some amount of opposite input was required in order to arrest the translational rate more aggressively.

Pilots unanimously felt that the critical sub-phase of the maneuver driving the ratings was the deceleration into the hover area. Pilots who were able to find a control technique that allowed them to achieve the desired times and precision readily rated the aircraft as Level 1. The key to this was the ability to successfully cancel out the run in lateral and longitudinal rates simultaneously with one single diagonal opposite input.

Careful modulation of the input was essential for desired performance to be achieved. However, uncertainty in the amount of input required to smoothly decelerate the aircraft within parameters affected the performance times.

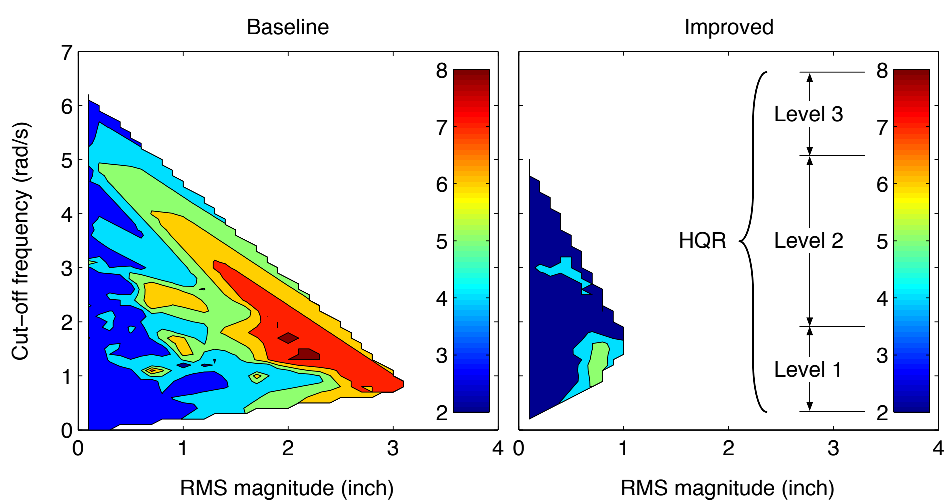


Figure 15 Contour plot of handling quality ratings for varying pilot longitudinal stick input cut-off frequency and RMS amplitude for stabilized hover phase of Hover MTE – comparison of baseline and improved TRC

Difficulty in modulating input with the thumb stick led a majority of pilots to employ it as a beep type controller—making corrections by introducing rapid pulse-type inputs in the desired, orthogonal, directions—especially during the deceleration and hover position maintenance phases of the maneuver. Evidence of this is reflected in the relatively high cut-off frequencies and the low RMS amplitudes of the control input time history traces for most pilots. This control technique led to a strategy where, in the words of an evaluation pilot, the pilot was almost "assisting" the aircraft, not "controlling" it.

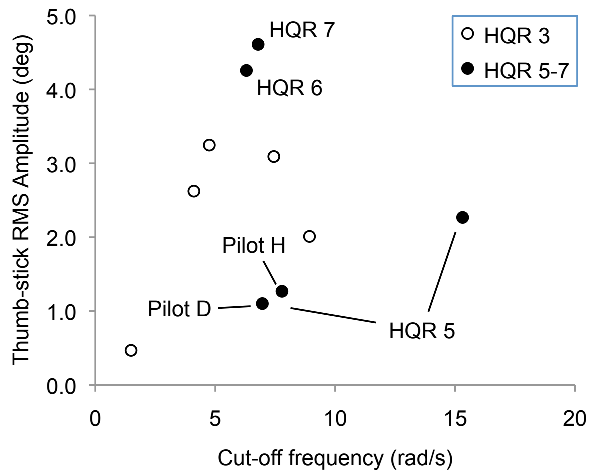


Figure 16. Correlation between handling qualities ratings and average piloted longitudinal thumb-stick control RMS amplitudes and cut-off frequencies.

Figure 16 provides, in conjunction with the pilot reports, a correlation between pilot control input activity and handling qualities. Generally, higher control amplitudes and cut-off frequencies with the thumb stick correlated with the worse handling qualities ratings. Pilots H and D were the exceptions as they both reported they had purposely stayed out of the loop and accepted only adequate performance in order to avoid exciting any objectionable dynamics in the aircraft. This is reflected in the reduced longitudinal stick input RMS and cut-off frequencies. Also, the HQR 5 scores substantiate the inability to achieve desired performance.

High speed lateral maneuvering

The baseline TRC configuration with 15 ft/s/in sensitivity and 7.5 deg/s nacelle rate limit was evaluated and compared against the ACAH and hybrid configurations in the Lateral Reposition MTE. As shown in Figure 17, this configuration was consistently rated HQR 2–3. In contrast, ACAH was mostly rated HQR 4 (with a few HQR 3 and one HQR 6). Finally, the Hybrid mode clearly fell in between the pure TRC and the ACAH response types in terms of their handling qualities (most configurations were rated HQR 3).

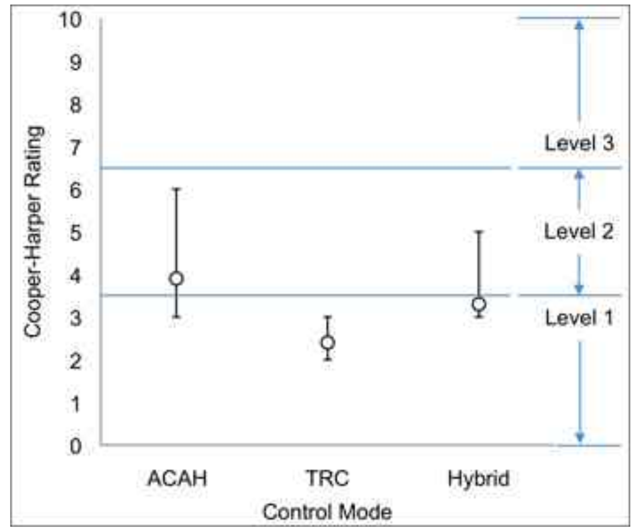


Figure 17. Comparison of the handling qualities ratings for the ACAH, TRC and Hybrid response type control configurations in the Lateral Reposition.

Experimental observations suggested that the high bank angles associated with the ACAH were a major cause of performance degradation. The maneuver required high amplitude attitudes, which appeared to cause a sequence of events that significantly increased the pilot workload. Figure 18 illustrates the typical differences in performance and compensation between the three configurations for one pilot. In all three cases the pilot was able to achieve the required 25 ft/s speed, but, as shown, differences in the bank angle attained were quite significant. ACAH typically required about 7–10 deg to sustain the lateral velocity. The Hybrid mode required only about 4 deg angles. Moreover, in ACAH a 20–25 deg bank angle reversal was required to arrest the lateral velocities and return to a hover. TRC, on the other hand, conferred the desired lateral velocity with minimal roll attitude generated. Desired performance in terms of the times, altitude and longitudinal position were achieved in all three control configurations, but with varying levels of workload. ACAH and Hybrid configurations displayed, however, a tendency to drift aft, while the TRC conferred the ability to translate laterally with minimal longitudinal and altitude deviations. Also shown in Figure 18 is a notable difference in the TCL stick control input activity between the three configurations, an indicator of differences in the workload in the heave axis. Less significant, is the larger size of lateral input required with the TRC and Hybrid configurations, compared to ACAH. Pilots often mentioned that stick forces generated with these configurations were a little high.

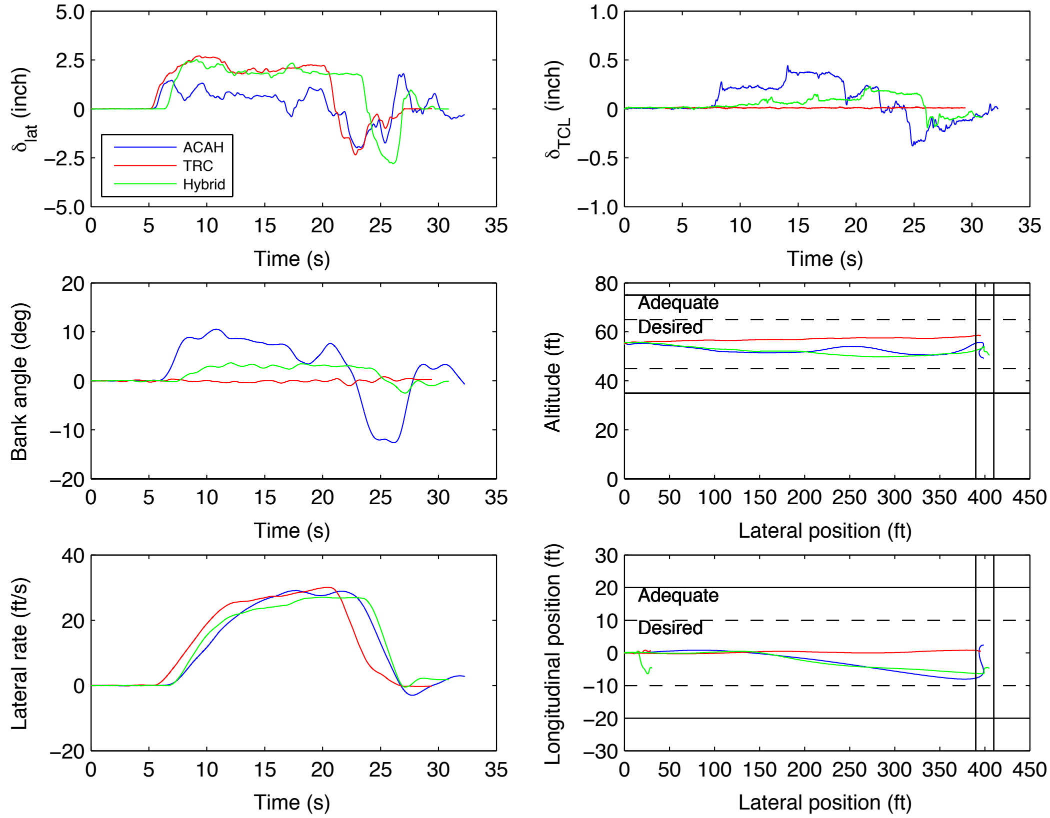


Figure 18. Time histories from VMS piloted simulations comparing Lateral Reposition MTE flown with ACAH, TRC and Hybrid control laws.

ACAH. A survey of the pilot evaluation comments indicated that high workload in the longitudinal axis and altitude maintenance, both of which were not in the main axis of interest, were contributing reasons for the elevated handling qualities ratings assigned to the ACAH mode. The simultaneous workload increase in these two axes was not surprising considering the perceived coupling between heave and pitch associated with the large offset between pilot station and aircraft CG. Also, a frequent observation pointed to a lack of usable visual cues when executing the maneuver, especially during the deceleration, since pilots tended to lose sight of the longitudinal position cuing when commanding the large bank angles required to arrest the lateral rates at the hover point. Additionally, a tendency to pitch up could cause the pilots to lose the lateral position cue.

Evaluation pilots identified two specific issues with ACAH control: a) a tendency to "balloon", or gain altitude easily, during the deceleration phase of the maneuver, and b) significant control activity in the longitudinal axis to maintain position within the desired parameters. Figure 19 illustrates some of these issues for two different pilots. Not evident in the time histories is the fact that the pilots have reached the final position by about 25 s. Deceleration takes place between 20 and 25 s. This is when the highest control activity takes place.

This ballooning can be explained through the way the heave control axis was implemented. When decelerating aggressively the control system would see the sudden change in the body z-axis velocity component as an un-commanded sink rate. Differences in the commanded and actual rates, if not adjusted quickly by the pilot would result in the control system increasing power rather suddenly. This, in conjunction with the sudden change in aerodynamic angle of attack naturally caused the aircraft to climb.

Pilots consistently indicated in their evaluations, that the major source of workload in ACAH was motivated by the degree of compensation in the longitudinal axis necessary to regulate fore and aft drift. A slight tendency for the aircraft to pitch up and drift aft during the sustained banking was observed in a number of runs. It should be noted that the heave and longitudinal axes are naturally coupled, with thrust increments producing a slight nose down pitch response. While it may be possible, due to the natural cross-couplings of the aircraft, that slowly developing drift could be generated in response to the large and sustained bank angles being commanded, these were in themselves not considered sufficient to degrade position performance out of the desired parameters. It is not even clearly understood if pilots could, or did, cue on to these mid- to long-term responses, especially in light of the reported deficiencies in the visual cueing. These issues were only mentioned by two of the ten evaluation pilots.

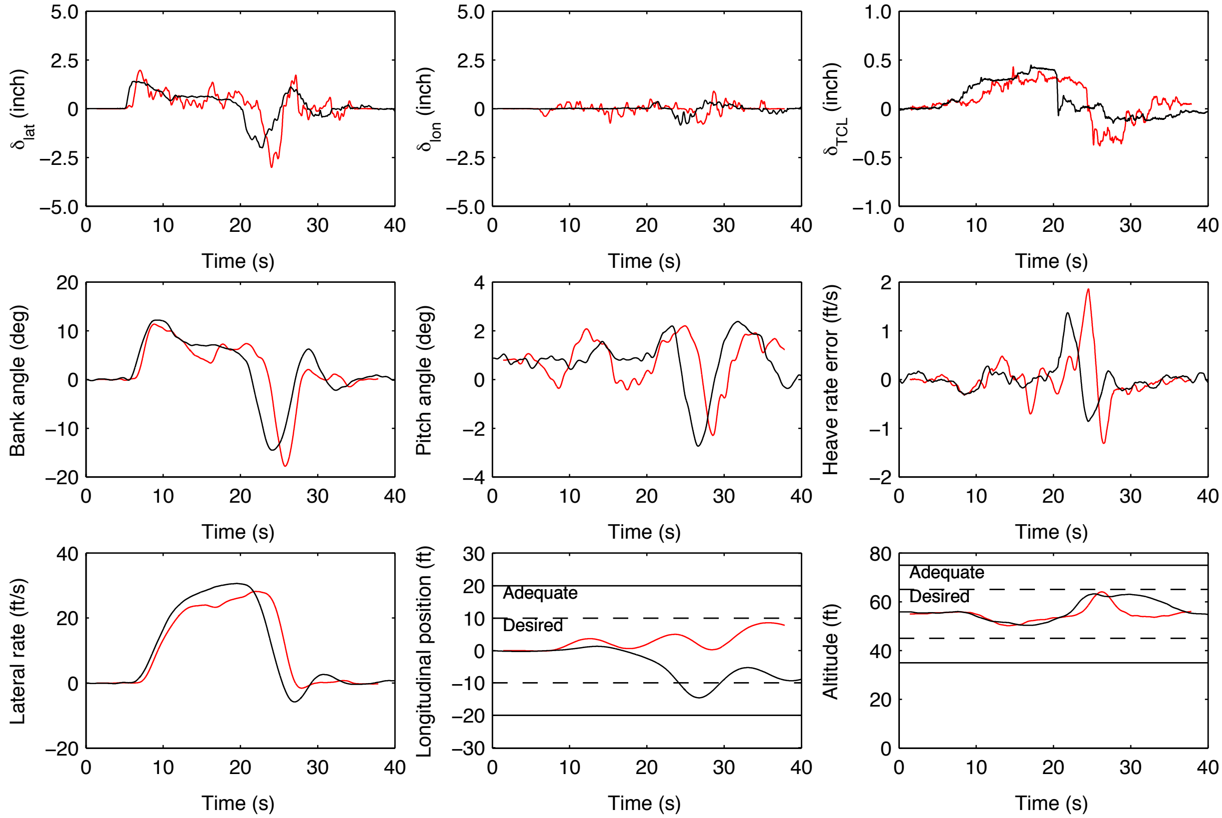


Figure 19. Time histories from VMS piloted simulations comparing Lateral Reposition MTE flown by two different pilots with ACAH control laws.

Careful examination of the lateral reposition maneuver time histories did not uncover any conclusive evidence of significant pitch being induced by any off-axis aircraft coupling/response. Rather, longitudinal position excursions generally appeared to be pilot created. Whether intentional or not, piloted inputs were frequently introduced at the same time as lateral inputs were commanded. Once disturbed, it generally required significant compensation by the pilot to stay within the desired task parameters due to the ensuing longitudinal fore or aft motion. This issue was exacerbated during the deceleration because pilots would typically lose sight of the runway as soon as the high opposite bank angle was commanded. At this precise moment pilots were also more prone to introducing longitudinal inputs while simultaneously ballooning. Also complicating matters would be the well-documented pitch/heave perception coupling produced by the long offset between the cockpit and the aircraft center of gravity. All of these events happening simultaneously combined to quickly drive the workload to considerable levels.

TRC. Translational Rate Command reduced the task workload by almost making this a pure one-axis task. Pilots were able to accomplish the maneuver with a lateral input to initiate and a carefully modulated opposite input to capture the final hover spot, with minimal compensation required. As long as longitudinal motions were not inadvertently introduced, the aircraft was able to translate along the desired trajectory with great ease. Any unintended excitations of the longitudinal axis would sometimes result in the already documented issues related to the nacelle dynamics, especially in the final hover position capture. TRC typically made a significant difference by eliminating the bank angle from the equation. Without the large bank angles pilots did not lose sight of the runway. Also the aircraft did not experience significant changes in altitude, such that power/altitude maintenance did not require attention. Elimination of pitch also minimized the compelling pitch/heave perception issues associated with cockpit to CG offset. Pilots did describe the lack of bank as *odd*, but agreed it was possibly the right way to fly this type of aircraft, and the HQRs confirmed their preference and better performance

Hybrid. Not surprisingly, by introducing some amount of banking through the Hybrid control mode some of the objections already discussed reappear, but in a more toned down form. The Hybrid mode was not without its own faults however, as issues with the phasing in and out of the bank angle felt somewhat unpredictable to two of the evaluation pilots. Longitudinal position control in the Hybrid mode was, however, achieved primarily by actuation of the nacelles, as with the TRC mode. Therefore the ability of the pilot to control the longitudinal axis would be reduced by the deficiencies associated with nacelle actuation, which has been documented above.

Evaluation of manual nacelle control

The Cooper-Harper handling qualities ratings for the Depart/Abort evaluations with the revised MTE parameters are presented in Figure 20. The majority of ratings for both configurations were Level 2, reflecting that, in general, the majority of evaluation pilots had difficulty achieving the desired performance. The key objection was a general unpredictability of the aircraft response to nacelle input. One aspect of this was the slowness of response to piloted input. Position control with the discrete nacelle switch allowed, in the opinion of evaluation pilots, for a slight reduction in workload, which is reflected in the higher percentage of Level 1 ratings (33% compared to only 11%). Comments from the evaluation pilots indicated that the proportional controller generally did not allow easy recovery of an adequate nacelle position for hover, within the allotted distance parameters. In general, the discrete controller offered better awareness, but could also result in erroneous commands. It is noted that the 2 deg/s conversion rate allowed by the discrete-step switch was too slow for the general execution of the maneuver, and was employed only for the final capture of the hover configuration.

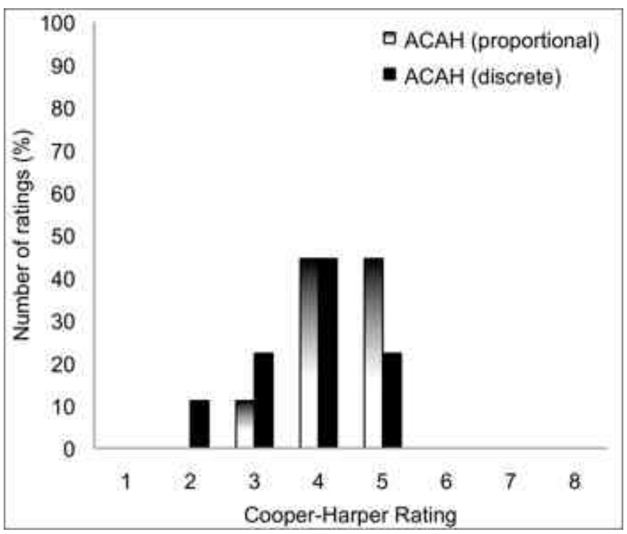


Figure 20. Pilot handling qualities ratings in the Depart/Abort MTE.

Figure 21 shows typical time histories of the Depart/Abort MTE maneuver for the nacelle discrete-step and proportional rate inceptors. Results show that performance with both inceptors was very similar. The one subtle difference is illustrated by the final nacelle conversion angle, β_m, after about 33 seconds. Here the discrete-step switch allowed reconfiguration back to hover with one command of the switch, whereas the pilot had to "hunt" around with the proportional rate inceptor. This resulted in the aircraft pitching up briefly into the adequate performance region. The data also show ho the highest control activity in the pitch axis occurs at the very end of the maneuver when trying to precisely capture the final hover point.

One aspect universally preferred by the pilots was the deceleration rate afforded by the rotors in full aft position, and the ability to move the nacelles quickly to that position with the maximum rate attainable with the proportional controller (i.e., 7.5 deg/s). Pilots were able to arrest the required speed (67.5 ft/s) within 600 ft in about 15 seconds.

In order to achieve desired performance within the pitch attitude constraints, pilots were forced to simultaneously coordinate nacelle position and longitudinal cyclic. This multi-axis control strategy resulted in a high mental workload environment, with pilots having difficulty judging when to make the correct actions due to a general unpredictability of the nacelle position control. Whether due to the primary experience-base being in helicopters, or not, pilots confirmed that interpreting the response of the aircraft to a given nacelle position was not intuitive, or natural. Uncertainty in the nacelle position led to breakdowns in the scan patterns in order to check the head down indicator display (Figure 10). Pitch control through the cyclic, on the other hand, felt very natural. Furthermore, it was easy, while focusing on the longitudinal axis, to inadvertently introduce lateral cyclic inputs, which would degrade the ability to perform within the desired standards. The added attention required for control of the lateral position forced, in the opinion of some evaluation pilots, the workload to be considerable.

Summary and Discussion

A piloted simulation conducted on the NASA-Ames Vertical Motion Simulator (VMS) investigated hover and low speed handling qualities of a large tilt-rotor aircraft, with a particular emphasis on longitudinal and lateral position control with minimal attitude change. A closed-loop flight control system design implementing Translational Rate Command (TRC) with minimal attitude change on a large (heavy-lift) tilt-rotor by exploiting its thrust vectoring capabilities was demonstrated. Independent control of attitude and velocity was achieved by directly controlling the nacelles for longitudinal control, and by combining anti-symmetric (or parallel) lateral rotor cyclic and anti-symmetric (or differential) rotor collective between the two rotors. Ten experimental test pilots evaluated on average fourteen different flight control system configurations while flying three different revised versions of the ADS-33 Mission Task Element (MTE) maneuvers (Hover, Lateral Reposition and Depart/Abort) throughout the experiment. Alternative implementations of TRC (sensitivities, nacelle angular rate and position limits, and rotor flapping lag delays) and how it is incepted (center stick vs. thumb control) were investigated.

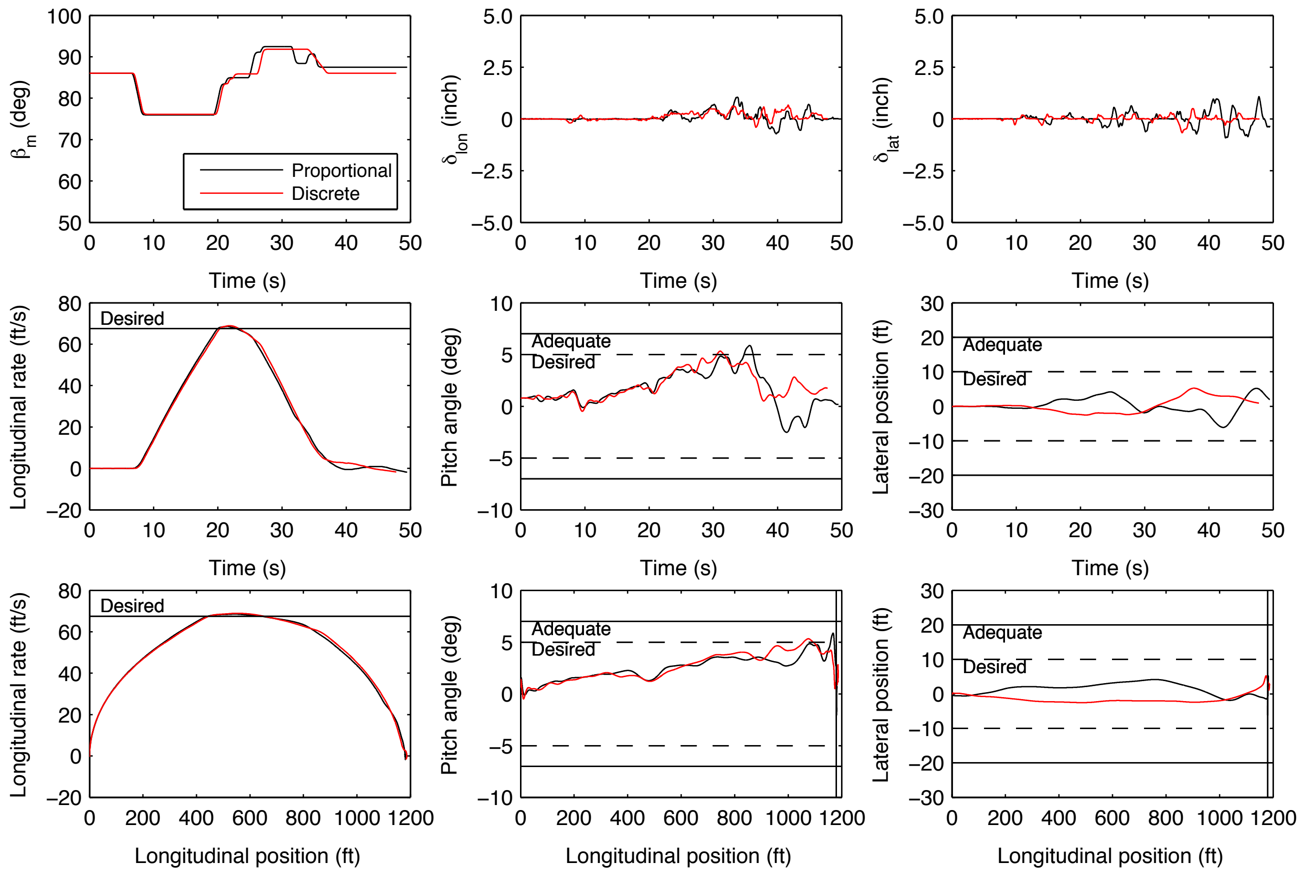


Figure 21. Time histories from VMS piloted simulations comparing Depart/Abort MTE flown with nacelle discrete-step and proportional rate inceptor

Hover and low speed control without attitude change, as with this TRC design, was found to be very effective at removing objectionable pitch to heave coupling of large, long tilt-rotor aircraft designs, and resulted in Level 1 handling qualities.

Rotor tendency to flap back in response to nacelle rate induced a noticeable opposite pitch response, which some pilots perceived to be counterintuitive. Aircraft hover handling qualities were improved by minimization of the longitudinal flapping in response to nacelle motion through the use of a crossfeed gain between nacelle rate and longitudinal cyclic. With this improvement, the TRC architecture using automatic nacelle angle deflections with rate limits of ±7.5 deg/s was shown to be a viable method of providing precise longitudinal and lateral position control in hover and low speed whilst minimizing attitude changes.

Without this crossfeed, hover handling qualities ratings with the baseline control law were extremely susceptible to pilot control technique, which is indicative of a handling qualities cliff. Aggressive longitudinal position control with this particular implementation of a closed-loop TRC control system demanded high rate nacelle rotations, with 7.5–12.5 deg/s, or higher, typically required to achieve desired precision. This nacelle activity resulted in rate limiting of the modeled actuators, and an ensuing PIO in the longitudinal control axis.

The critical sub-phase of the Hover MTE maneuver was found to be the deceleration segment. Deceleration times were the only task performance parameters of the Hover MTE left unrevised. Based on the observed sensitivity that aggressive decelerations could have on the HQRs, i.e. if the pilots decelerated rapidly or they approached at a slightly quicker speed before decelerating (Ref. 20), the respective Cargo/Utility class *desired* and *adequate* task performance deceleration time requirements of 5 and 8 seconds may have been too "tight". Based on this, future investigations warrant further consideration of this aspect to determine whether the current Cargo/Utility deceleration times of the Hover MTE are appropriate to LCTR-sized classes of rotorcraft and their anticipated role.

Pilots were readily, and easily, able to adapt to a control response type outside of the normal paradigm of rotorcraft flight control, which assumes attitude as the primary response to center stick input. Although pilot comments indicated that lack of attitude response felt "unnatural", control performance in TRC was not compromised by use of the center stick. Furthermore, while the thumb stick controller proved to be adequate for the tasks at hand, position control through the center stick was generally preferable.

Translational Rate Command was very effective at allowing lateral translations to be conducted with minimal off-axis departures, effectively reducing the execution of the Lateral Reposition maneuver to a single axis task. This improvement provided the necessary reduction in workload warranting the Level 1 handling qualities ratings conferred.

Attitude Command-Attitude Hold aircraft response type, in conjunction with two pilot nacelle position controllers, was evaluated for control of a large tilt-rotor aircraft in an aborted departure. Difficulty in re-establishing trimmed hover within desired task parameters resulted in Level 2 handling qualities ratings. Compared to a nacelle proportional thumb controller alone, a discrete nacelle position controller was demonstrated to be a useful workload reducer. This was achieved by assisting the pilot in setting the nacelles back to the trim hover position. However, it was also found to be susceptible to occasional, inadvertent input by the pilot leading to conversion into a non-hover nacelle position.

Conclusions

Based on a thorough review of the pilot evaluation comments and objective task performance data, and in light of the discussion presented above, several conclusions are established:

- TRC using a form of longitudinal and lateral thrust vectoring using nacelle tilt and parallel lateral cyclic was shown to be a viable method of providing precise position control in hover and low speed, as evaluated in revised Hover and Lateral Reposition MTEs.
- The baseline TRC control law provided handling qualities improvements compared to ACAH, but encountered a tendency to PIO in the longitudinal axis in some circumstances.
- An improved TRC with nacelle rate to longitudinal cyclic crossfeed conferred Level 1 handling qualities by reducing the pitching response to almost zero and improving the longitudinal rate system bandwidth.
- Mechanisms for manual nacelle control were shown to be adequate, with Level 2 handling qualities attained in the Depart/Abort MTE.

Acknowledgements

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