

Handling Qualities of a Large Civil Tiltrotor in Hover using Translational Rate Command

Carlos A. Malpica
carlos.a.malpica@nasa.gov
Colin R. Theodore
colin.theodore@nasa.gov
NASA Ames Research Center
Moffett Field, CA

Ben Lawrence
ben.lawrence@nasa.gov
San Jose State University
Research Foundation
Ames Research Center
Moffett Field, CA

James Lindsey
james.e.lindsey@nasa.gov
Monterey Technologies
Monterey, CA

Chris L. Blanken
chris.l.blanken@us.army.mil
Aeroflightdynamics Directorate
(AMRDEC)
U.S. Army RDECOM
Moffett Field, CA

Abstract

A Translational Rate Command (TRC) control law has been developed to enable low speed maneuvering of a large civil tiltrotor with minimal pitch changes by means of automatic nacelle angle deflections for longitudinal velocity control. The nacelle actuator bandwidth required to achieve Level 1 handling qualities in hover and the feasibility of additional longitudinal cyclic control to augment low bandwidth nacelle actuation were investigated. A frequency-domain handling qualities criterion characterizing TRC response in terms of bandwidth and phase delay was proposed and validated against a piloted simulation conducted on the NASA-Ames Vertical Motion Simulator. Seven experimental test pilots completed evaluations in the ADS-33E-PRF Hover Mission Task Element (MTE) for a matrix of nacelle actuator bandwidths, equivalent rise times and control response sensitivities, and longitudinal cyclic control allocations. Evaluated against this task, longitudinal phase delay shows the Level 1 boundary is around 0.4-0.5 s. Accordingly, Level 1 handling qualities were achieved either with a nacelle actuator bandwidth greater than 4 rad/s, or by employing longitudinal cyclic control to augment low bandwidth nacelle actuation.

Introduction

Background

A series of piloted simulation experiments have been conducted on the NASA Ames Research Center Vertical Motion Simulator (VMS) in recent years (Refs. [1], [2] & [3]) to systematically study the fundamental flight control and handling qualities issues associated with the characteristics of large rotorcraft, including tiltrotors, in hover.

LCTR2

The particular interest for tiltrotors stems from studies [4] which show that large, advanced technology tiltrotors consistently outpace other rotorcraft configurations in the ability to meet the proposed civil mission of operating short-haul regional routes carrying approximately 90 passengers over a range of at least

1000nm at a cruise speed of 300 knots. NASA has developed the 'Large Civil Tiltrotor' concept as a notional design with the best potential to meet these projected requirements. The design has evolved to the LCTR2 (Large Civil Tiltrotor, 2nd generation) configuration which weighs around 100,000lbs, has a 107ft wingspan, and two tilting nacelles supporting 65ft diameter rotors [5]. Its payload, range and speed requirements determine it to be a large vehicle - much larger than any previous tiltrotor, and this brings a variety of issues to the flight control and handling qualities domain in hover.

LCTR2 handling qualities research

The results from experiments conducted in 2008-2010 (Refs. [1], [2] & [3]) have highlighted a likely requirement for advanced control modes in order to achieve satisfactory handling qualities.

The first two experiments (Refs. [1] and [2]) concluded that Level 1 handling qualities could not be achieved via an attitude command control system. A fundamental issue, related to the large aircraft size, was an objectionable pitch-induced heave motion at

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the pilot station, a direct consequence of the long fuselage of this tiltrotor design, which was shown to severely impact the pilot control strategy.

Consequently for the third experiment [3] a Translational Rate Command (TRC) control law was developed that used nacelle angle deflections for longitudinal velocity control and lateral cyclic for lateral control in hover and low speed maneuvering. This approach allowed maneuvering in translation with minimal pitch and roll attitude responses as the attitude control loops were engaged in parallel with the TRC, and maintained the trim attitudes. In this experiment, the nacelle actuators featured relatively high bandwidth and damping characteristics of 8 rad/s and 1.0 damping ratio to avoid low frequency cut-off of pilot input, and to avoid natural oscillatory behavior in the TRC control law. The primary experimental parameters were the nacelle actuator rate and angular position limits and their impact on the piloted handling qualities. The influence of actuator bandwidth for this form of TRC control system remained unaddressed.

The TRC control law of Ref. [3] conferred Level 1 handling qualities in the Hover MTE, but with a tendency to enter a PIO associated with nacelle actuator rate limiting when employing large aggressive control inputs. The experiment also identified a nacelle rate to longitudinal rotor flapping coupling effect that induced undesired, pitching motions proportional to the nacelle rate. A modification using a crossfeed control of longitudinal cyclic proportional to nacelle rate counteracted this effect significantly and improved the handling qualities, including the tendency to PIO [6]. A key conclusion of the experiment was that the TRC response type was capable of providing Level 1 handling qualities for the LCTR2 configuration in hover and low speed maneuvering.

ADS-33 TRC requirements

The TRC control law was designed to the criteria specified in ADS-33E, and although there is no requirement to apply the military-focused ADS-33 specifications to the civilian LCTR2, it is considered the de-facto design standard for rotorcraft handling qualities and therefore a good basis for the control law design. The ADS-33 TRC design criterion is limited to 2 quantitative parameters that consist of an 'equivalent rise time' and steady state stick to control response sensitivity and certain characteristics for the translational response that 'should have a qualitative first-order response' in conjunction with the following requirements [7]:

- a) The pitch and roll attitudes shall not exhibit objectionable overshoots in response to a step cockpit controller input.
- b) Zero cockpit control force and deflection shall correspond to zero translational rate with respect to fixed objects, or to the landing point on a moving ship.

- c) There shall be no noticeable overshoots in the response of translational rate to control inputs. The gradient of translational rate with control input shall be smooth and continuous.

The ADS-33E criteria encompass a significant amount of research in their foundation, and it is useful to review this body of work to understand how they were established and also to compare the earlier analysis to results in this paper.

ADS-33 criteria definition

The ADS-33E design criteria is built upon data from a variety of sources, including some of the important work described in Refs. [8], [9] & [10] that contributed largely to the criteria selection. In particular, this work led to the respective minimum and maximum rise times of 2.5 and 5 seconds that were recommended for the desired first-order translational response. The reason for a maximum limit is intuitive, in that if the rise time is too long, the aircraft response will be too sluggish for precise maneuvering. The cause for the minimum rise time is less obvious, but it is fundamentally linked to the implementation of TRC where an inner attitude loop is enclosed by an outer loop where the translational motion is caused by changing the attitude of the aircraft. A minimum rise time is a compromise between achieving a quick enough translational response while mitigating the abrupt attitude changes.

The other key TRC requirement in ADS-33 is the 'Control Response' which is the steady state translational velocity response per unit stick. Again, Ref. [8] was the key source for establishing the boundaries. They consist of an upper and lower limit for a non-linear control shaping of the sensitivity in ft/sec/in. The non-linear shaping confers reduced control sensitivity between 3 and 6 ft/s/in for speeds of up to ~10 knots.

The references drawn on by ADS-33E feature a number of experimental analyses of TRC conducted in flight test, motion-base and fixed-based simulation on a variety of platforms including the X-22A ducted fan V/STOL aircraft (Refs. [10], [11] & [12]), the AV-8B jet aircraft [13], the XV-15 tiltrotor (Refs. [14], [15]), as well as other generic types. References [10] and [11] report an in-flight simulation experiment using the X-22A variable stability aircraft. Highlights included the use of an inner/outer loop style TRC control law using attitude changes. The experiment examined equivalent translational response rise times in the range of 1.5 s to 4 s, and variation of the control response sensitivity in the range of 3 to 12 ft/s/in. Much the same conclusions to that of Ref. [8] were arrived at, in that pilots did not like the attitude changes that came with this form of TRC.

Reference [10] described how different pilots reacted to the attitude changes in TRC. The results from their experiment were used to create a TRC handling qualities criterion which was reappraised in an analysis

in Ref. [12]. This follow up study was aimed at validating the use of fixed-base simulation for the prediction of the X-22A in-flight simulation TRC handling qualities. A key premise of the paper was that TRC criteria based on correlating the regions of cross-plots of the equivalent rise time and the control/response sensitivity parameter (linear constant) were found to be inconsistent in predicting the piloted handling qualities.

The alternate criteria in Ref. [12] used a frequency domain approach of regions on a Bode plot of the translational velocity response to stick input of predicted Level 1 and Level 2 handling qualities. The envelopes were applied to both the magnitude and phase plots of the frequency response and the different regions of the plot were annotated to indicate what the likely HQ problems might be if a system frequency response curve had dynamics that entered that region.

Reference [12] showed that this frequency domain approach was superior in predicting the handling qualities especially when used in conjunction with a secondary criterion which included a measure of the magnitude and abruptness of the attitude response. The paper reported that this attitude sensitivity aspect was raised as an area of 'critical concern' by pilots.

This secondary criterion was based on a similar sensitivity criterion from a study in Ref. [14] that investigated TRC using a XV-15 simulation. In this work, the TRC system sensitivity, stiffness, and damping were varied parametrically using simplified linear models. Here, the stiffness is akin to the rise-time parameter as it effectively determines the quickness of the response, and as it was an attitude-based TRC, it also consequently governed the magnitude and abruptness of the attitude response. Again, optimum values for the translational response sensitivity and stiffness featured a tradeoff between attaining adequate translational response in gross maneuvering and fine control as well as between having low enough time constants to provide precise, responsive control but without large or abrupt attitude changes. The pilots preferred a TRC that was more first-order in nature with less oscillations and overshoots in the velocity response.

The importance of this first-order characteristic is highlighted by Ref. [9] where the use of Lower-Order Equivalent System models (LOES) to characterize the TRC response is described. They highlighted that where the aircraft translational response fitted well to a first-order form such as in equation (1), better handling qualities were reported. In equation (1) \dot{X} represents the translational rate, δ_{pilot} is the pilot stick input, and $K_{\dot{X}}$ and $T_{\dot{X}}$ are the control response sensitivity and equivalent rise time, respectively. When a third-order form was required to capture the aircraft response characteristics, i.e., the attitude dynamics were significantly affecting the TRC response, the handling qualities were worse - reinforcing the observation that

these configurations are unacceptable due to the excessive attitude responses.

$$\frac{\dot{X}}{\delta_{pilot}} = \frac{K_{\dot{X}}}{T_{\dot{X}}s + 1} \quad (1)$$

Reference [9] also assesses the equivalent rise time and steady state velocity response sensitivity of the TRC control laws. Their analysis (based on results from Ref. [15]) is in alignment with the others reported in that they identified an optimum rise time for handling qualities in the 2.5 s to 5 s range. For the sensitivity characteristics there was general complaint that the maximum speed attainable (~24 knots) in TRC was too low. However, one interesting observation made is that a trend that higher control sensitivity for attitude based TRC can be accepted when the rise time increased, i.e., when more sluggish. The hypothesis derived from this observation was that the pilot HQ ratings somewhat align with curves of constant attitude per unit stick in TRC (this ratio being a function of both the rise time and sensitivity).

The underpinning aspect of all of this previous evidence was that attitude-based TRC approach was used, and that there are some characteristics of that approach that bring limitations, a point not completely disregarded in the literature. References [9] and [13] both discuss the possibilities of TRC using Direct Force Control (DFC) through forms of thrust vectoring. Reference [16] also presents an analysis of DFC based response types, taking it to the extent of comparing both acceleration and translational rate response types using both DFC and attitude-based approaches. Reference [13] reports on a fixed-based simulation study based on the AV-8B aircraft, the paper highlights how DFC decouples the attitude response from the translational response and on how the experiment compared TRC based on attitude changes, DFC, and a combination of the two. A key result was that the pilots liked the attitude-only TRC systems the least and unanimously preferred the DFC systems. The handling qualities ratings recorded in the experiment were plotted against the criteria from both the previous Calspan X-22A [10] and the System Technology Inc (STI) XV-15 [9] based studies. The ratings for the attitude TRC did not match well with either the Calspan or STI criteria, predominantly because the ratings were mostly connected with the attitude changing aspect, something that the rise-time vs. steady-state velocity sensitivity criteria do not explicitly cover. When the DFC ratings were compared, much better correlation was achieved, particularly with the Calspan boundaries.

Another important experimental result achieved using the DFC based TRC was that it was shown that increasingly better HQRs were obtained with increasingly quicker (shorter) rise-times. Rise times down to 0.7 seconds were examined which conferred Level 1 (HQR<3) ratings. This is an important result as

the 2.5 s minimum acceptable level reported in a number of the attitude based TRC studies (and ADS-33) were no longer appropriate due to the fact that attitude changes were no longer a factor.

This conclusion of the superiority of DFC TRC response type is not however universal. Reference [9] also briefly discusses DFC vs. attitude TRC and states: "There is some evidence that complete decoupling between attitude and horizontal translation is not necessarily superior". They go on to refer to the study in Ref. [16] and another using the X-14A V/STOL aircraft. Reference [16] reported that the prime reason that the DFC based TRC was rated worse was because of negative ride quality effects caused by the generation of 'non-gravitational' reaction forces acting on the pilot when maneuvering. It is important to note that Ref. [16] study featured motion cueing as opposed to that in Ref. [13] which was a fixed-base simulation. Another study of TRC using DFC is a simulation experiment in the NASA VMS of an Advanced V/STOL (ASTOVL) aircraft in Refs. [17] & [18]. This study has a number of useful parallels with the current research in this paper in that it is a motion base study in the NASA VMS, and features an analysis of a hovering vehicle using a DFC form of TRC (in the longitudinal axis). The discussion of the performance of the TRC control law focused much more on frequency domain parameters such as bandwidth and phase delay.

For longitudinal control, the results showed that bandwidths (based on the -45 deg phase margin frequency from the translational velocity to stick input frequency response) of between 0.4 and 0.9 rad/sec conferred consistently satisfactory handling qualities, whereas values below 0.22 rad/s and above 1.1 rad/s were only adequate. The authors refer to the ADS-33 rise-time criteria of 2.5 s and 5 s and compute that for an equivalent first-order response, these equate to bandwidths of 0.4 and 0.2 rad/s respectively. The authors note that the 0.2 rad/s value agrees well with their results while at the other end of the range their results indicate an ability to accept much quicker (higher bandwidth/short rise time) TRC response with acceptable handling qualities. This discrepancy is attributed to 'differences in implementation of the longitudinal velocity command systems', which alludes to the previously discussed issues connected with attitude based TRC. Another insight brought to the fore was through the use of the phase delay parameter, where it was highlighted that delays as high as 0.78 s could be tolerated before the handling qualities degraded to adequate. It was reported that the pilots could sense the delay but were able to compensate without too much effort until the delays became extreme. The authors suggested the Level 1-2 boundary based on phase delay is in the region of 0.4-0.6 s.

Some of the TRC research literature presented has included tiltrotors which are of particular relevance to

the current research. However, the tiltrotor research has not reported any experimentation with the DFC form of TRC using nacelle tilt to vector the thrust (for longitudinal translation). The only mention of such an approach was a consideration by Ref. [15] to implement a 'mast-angle controller' for the XV-15 simulation. This proposed development was abandoned when it became apparent that as a consequence of the limited performance of the nacelle actuators the system would possess very low u/δ_{lon} bandwidth of around 0.7 rad/s, although it is not apparent which measure of bandwidth is used.

In summary, the key issues of how the ADS-33 TRC criteria were established have been discussed, as well as the implementation-specific aspects that underpin them. It has been shown that there are a number of useful similarities in the body of work in the literature to the current LCTR2 research. However, there are a number of aspects of the LCTR2 control architecture that are unaddressed in the current body of work that require new research. A key aspect is the influence of nacelle actuation bandwidth on this form of nacelle-based TRC and its impact on large tiltrotor handling qualities.

Objectives

The global objective of this study was to investigate the fundamental handling qualities of a large tiltrotor in hover and low speed flight using TRC. In particular, the study was aimed at:

1. Investigating the nacelle actuator bandwidth required to achieve Level 1 handling qualities in hover with a form of TRC using nacelle tilt to achieve thrust vectoring
2. Exploring various TRC architectures to improve handling qualities at low nacelle actuator bandwidth values

Approach

A pilot-in-the-loop handling qualities simulation of the current LCTR2 design was conducted in the NASA-Ames Vertical Motion Simulator (VMS) to address these objectives. The aircraft model was configured with a flight control system implementing a TRC response by using automatic nacelle tilt for longitudinal control. This baseline control system was designed to meet the first-order qualitative character and the equivalent rise time specifications defined in ADS-33 for Level 1 handling qualities. Nacelle actuator bandwidth, and TRC control/response sensitivity and equivalent rise time parameters were varied systematically to isolate their effect on the handling qualities, as characterized by a closed-loop longitudinal position (X) response bandwidth and phase delay criteria which are adopted herein. Also, a control system was developed for comparison where longitudinal cyclic was used to supplement nacelle actuation and compared to the baseline. The

experiment relied exclusively on a precision hover task, which was modeled after a revised version of the standard ADS-33 Hover Mission Task Element (MTE). Experimental test pilots evaluated the different control law 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 test procedures.

Description of the Tests

Aircraft Model and FCS Architecture

The LCTR2 simulation model used a qLPV (quasi-Linear Parameter Varying) or ‘stitched’ [19] modeling approach that combined multiple linear stability derivative-based state-space models to provide varying model dynamics and trim characteristics for changing flight speed and nacelle angle [20]. The envelope of the model was valid from hover up to medium speeds (0-140 knots) and for nacelle angles between 60 and 95 degrees. This model is able to represent ‘quasi non-linear’ effects through the trim datum and state space coefficients being a lookup table function of speed and nacelle angle. The reader is directed to Ref. [20] for a full explanation of the theory.

The comprehensive rotorcraft aeromechanics analysis code, CAMRAD II, (Refs. [21] and [22]) 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 control design purposes, and therefore reduced-order models were created. The reduced-order models retained the key rigid-body rotor-body couplings, including both the lateral and longitudinal rotor blade flapping dynamics for each rotor, but dropped the high frequency rotor modes. This reduced model consisted of the nine body states, $[u, v, w, p, q, r, \phi, \theta, \psi]$, and the four low frequency rotor flap states, $[\beta_{1s_1}, \beta_{1s_2}, \beta_{1c_1}, \beta_{1c_2}]$. Control derivatives for symmetric and anti-symmetric rotor combinations of longitudinal and lateral cyclic and collective on the left and right rotors were also included in the reduced-order model. It is shown in Ref. [3] that these adequately represent bare-airframe dynamics over the frequencies of interest for piloted control (i.e., 1-10 rad/s).

Improvements to the nacelle modeling in CAMRAD II were made with an inclusion of an estimation of the nacelle mass and inertia (due to engine, drive train, airframe contributions, etc) not present in the earlier models. It is noted in Ref. [3] that the model therein featured an ‘unbalanced’ nacelle system, that is, one in which the total nacelle center of gravity (including the rotor mass) is offset from the point of rotation such that the overall aircraft c.g. moves fore-aft with the nacelle angle. However, this was not considered to have a noticeable effect on the handling qualities for small

ranges of motion. The new additional mass was located at the nacelle hinge, assumed to be the nacelle-only (i.e. minus the rotor) center of gravity. As such, this additional nacelle mass has no additional contribution to the aircraft c.g. motion when the nacelle is rotated. However, the additional nacelle mass was modeled as a distributed mass with a moment of inertia about the hinge which did confer an additional effect when the nacelles were moved, the most significant difference being an increased value of the control derivative with respect to angular acceleration of the nacelle, $M_{\ddot{\beta}_m}$.

Models of the actuator dynamics were necessary to correctly account for the fundamental time delays associated with actuator response bandwidth. For the nacelle actuator modeling, a second-order servo-actuator dynamic model (Eq. (2)) was assumed for a nacelle angular command:

$$\frac{\beta_m}{\beta_{mc}} = \frac{k_{nac}\omega_{nac}^2}{s^2 + 2\zeta_{nac}\omega_{nac}s + \omega_{nac}^2} \quad (2)$$

Here, β_m refers to the mast angle, which is used equivalently to the nacelle angle, and ω_{nac} is the natural frequency, or bandwidth, of the nacelle tilting actuator, which was one of the parameters being varied during the experiment. Nacelle conversion position and rate limits were also modeled to ensure their effect is accounted for. Rotor swashplate servo-actuator models were also included and assumed to possess simplified second-order dynamic response characteristics, but featured rate limits only.

The actuator and bare-airframe qLPV models were integrated into an explicit model-following architecture, as depicted in Figure 1. These model-following TRC control laws employed parallel velocity feedback and feedforward command paths to enable longitudinal translational rate response to piloted inputs by means of simultaneous nacelle and longitudinal rotor cyclic actuation. This was implemented to provide additional longitudinal control to augment the nacelle-actuated TRC response.

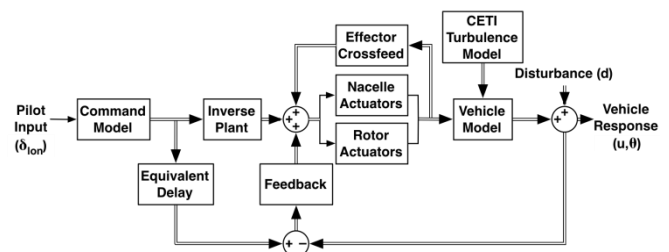


Figure 1. Model-following architecture for longitudinal TRC

In the baseline configuration, the TRC control laws actuated the nacelles to effect direct control of longitudinal force by tilting the thrust vector, while the pitch attitude control loop independently performed automatic regulation of pitch around a steady (i.e., trim)

reference by means of simultaneous symmetric (i.e., parallel) longitudinal cyclic actuation of both rotors. The lateral response axes of the TRC control laws employ an analogous structure, except that lateral force is effected by means of parallel lateral cyclic and the roll moments are countered through differential collective. In addition to lateral and longitudinal TRC, the control system provided yaw Rate Command and vertical (heave) Rate Command response types. Alternatively, pitch and roll Attitude Command-Attitude Hold (ACAH) response types could also be configured simply by opening the TRC loops.

The TRC command models were designed to provide the first-order qualitative character (Eq. (3)) and equivalent rise time specifications as defined in ADS-33. Additionally, the command models provided convenient experimental control over the variation in translational rate response sensitivity to control deflection and the equivalent rise time to achieve desired translational rate command response characteristics.

$$\frac{u_{cmd}}{\delta_{lon}} = \frac{v_{cmd}}{\delta_{lat}} = \frac{Ke^{-\tau_{cmd}s}}{T_{eq}s + 1} \quad (3)$$

Here δ_{lon} and δ_{lat} are the longitudinal and lateral pilot inputs, through the center stick, and u_{cmd} and v_{cmd} are the commanded body axes velocities. Time constants τ_{cmd} and T_{eq} define the commanded response delay and equivalent rise times, respectively. Coefficient K defines the response/control sensitivity gain in (ft/s)/in, where the maximum stick deflection was ± 5 inches. When in TRC mode, an ACAH command model is still active but receiving zero input. The ACAH loops thus maintain regulation of pitch and roll attitude at the datum values.

The feedback loops act on the velocity error between the desired vehicle response determined by the command model and the actual (or sensed) vehicle response. A simple Proportional-Integral-Differential (PID) Single-Input/Single-Output (SISO) regulator makes the necessary corrections to the feedforward nacelle commands being estimated by the inverse plant model. Proportional-Differential (PD) control was used to regulate the loops feeding back velocity error to longitudinal rotor cyclic for the augmented TRC control laws.

A key feature shown in Figure 1 are the crossfeeds, these include a nacelle rate to longitudinal cyclic crossfeed which the experiment in Ref. [3] showed was critical to obtaining good handling qualities by improving longitudinal TRC response bandwidth and minimizing coupled pitching motions associated with longitudinal flap back of the rotors caused by the nacelle motions. The fundamental benefit of this crossfeed is to reduce a 'lag effect' on the translational response caused by the opposing tilting of the rotor thrust vector when there is no crossfeed [6].

The aircraft response to atmospheric disturbances was simulated by means of a Control Equivalent Turbulence Input (CETI) model based on that described in Ref. [23]. Originally developed to meet the needs of simulating the effects of atmospheric turbulence on conventional single main rotor helicopters in hover and low speed, the CETI model adopted for use in this investigation was extended for use with tiltrotor aircraft.

The CETI model operates on the fundamental assumption that the dominant response to atmospheric turbulence of a helicopter in roll, pitch and heave is due to the rotor (moment and thrust) response to a vertical velocity gust field. Yaw response is driven by the tail rotor thrust response to a lateral velocity field. Equivalent control inputs are generated to reproduce this response, and are introduced between the actuators and the bare-airframe.

In the previous LCTR handling qualities work, the CETI model was adapted to a tiltrotor by applying gust inputs to the bare-airframe control inputs, i.e., the symmetric and anti-symmetric collective and longitudinal cyclic swashplate inputs, because these were the primary mechanisms for heave, roll, pitch and yaw control. The governing equations, however, remained fundamentally the same as for the single main rotor configuration. Although this approach was adjudged by experimental test pilots to provide a reasonable representation of aircraft motion in a turbulent flow field, its validity for use in tiltrotor aircraft has not yet been verified, nor tested. This approach arguably provides an accurate characterization of pitch and heave, but the lateral/directional response is fundamentally incongruent because the effect of lateral cyclic response to turbulence is omitted.

The extension of the CETI model adopted herein was restructured to be more appropriate to a two rotor aircraft, and relies on two sets of three equations (4), one for each rotor, governing the equivalent non-rotating frame blade pitch inputs (i.e., lateral, longitudinal and collective blade pitch angles) required to generate the simulated aircraft response to atmospheric turbulence.

$$\begin{aligned} \frac{\theta_{1c}}{W_n} &= K_a \sigma^x \sqrt{\frac{U_0}{\pi L}} \cdot \frac{1}{s + \frac{U_0}{L}} \cdot f_2(s) \\ \frac{\theta_{1s}}{W_n} &= K_a \sigma^x \sqrt{\frac{U_0}{\pi L}} \cdot \frac{1}{s + \frac{U_0}{L}} \cdot f_2(s) \\ \frac{\theta_0}{W_n} &= K_a \sigma^x \sqrt{\frac{3U_0}{\pi L}} \cdot \frac{s + 20 \frac{U_0}{L}}{(s + .63 \frac{U_0}{L})(s + 5 \frac{U_0}{L})} \cdot f_2(s) \end{aligned} \quad (4)$$

Here U_0 represents the mean wind speed at the main rotor altitude, L is a characteristic scaling length parameter taken to be the rotor radius, σ is the wind RMS in the vertical direction, and K_a and x are an

atmospheric scaling coefficient and exponent, respectively. Extensive tuning of these parameters was performed with the project pilot, until satisfied the turbulence response felt realistic and comparable to the earlier CETI models, whilst providing a more representative approach.

Test Configurations

The primary experimental parameter being varied during the tests was the nacelle actuator bandwidth, characterized by the natural frequency of the second-order actuator dynamics. Four values of natural frequency were chosen, as summarized in Table 1. The selection of these values was driven by the experimental handling qualities and flight control requirements assuming a rigid wing structure, thus disregarding any potential structural implications at this stage. A preliminary assessment in simulations with the project experimental pilot suggested that a 3 rad/s bandwidth represented the lowest practicable value for the baseline TRC control system design used in this research. Lower bandwidths led to severe controllability issues.

The baseline damping ratio of 1.0 was carried forward from previous work. This value was chosen to ensure the quickest nacelle response for a given bandwidth, but without displaying any natural oscillatory behavior. The angular displacement limits of the nacelle conversion actuator, in the baseline TRC configuration, were rotations of 9 deg forwards and backwards from the 86 deg hover datum position conferring a 77-95 deg range (0 being horizontal, airplane mode).

Listed in Table 2, various control system gain sets to include varying control/response sensitivity gradients, nominal equivalent rise times, nacelle rate to longitudinal cyclic crossfeeds, and cyclic-augmented configurations were also evaluated during the experiment. The baseline TRC control system was represented by gain set 1, consisting of 10 (ft/s)/in control/response sensitivity, a 5.0 s equivalent rise time, and a 0.0735 in/(deg/s) nacelle rate to longitudinal cyclic crossfeed, with no longitudinal cyclic TRC augmentation. Control system gain sets 0-5 basically enforce variations in the control/response parameter and the equivalent rise time. Gains sets A-D represent control laws aimed at augmenting the actuator response bandwidth, with C and D employing velocity feedback to longitudinal rotor cyclic.

Table 1: Nacelle actuator configurations

Bandwidth (rad/s)	Rate Limits (deg/s)
3	5.0
4	5.0
8	7.5
16	7.5

Table 2: Control law cases

Gain set	Control sensitivity ((ft/s)/in)	Nominal rise time (s)	Effector crossfeed (in/(deg/s))	Specific actuator
0	15	5.0	0.0735	N/A
1*	10	5.0	0.0735	N/A
2	5	5.0	0.0735	N/A
3	15	2.5	0.0735	N/A
4	10	2.5	0.0735	N/A
5	5	2.5	0.0735	N/A
A	10	5.0	0.1000	N/A
B	10	5.0	0.1250	N/A
C	10	5.0	0.0735	4 rad/s
D	10	5.0	0.0735	3 rad/s

* Baseline

Control implications of actuator phase roll-off

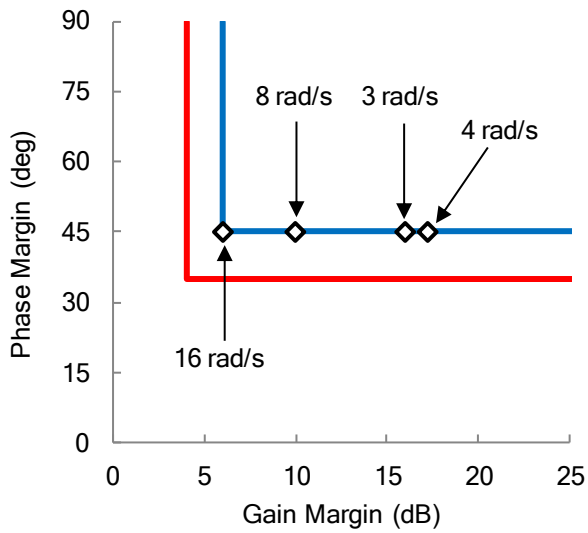
Since nacelle dynamics are contained in the main feedback loop, their phase roll-off will necessarily have a direct impact on the stability margin characteristics, as well as the closed-loop end-to-end response phase delay.

With all else being equal, an increase in actuator bandwidth will provide an increase in the stability margins, primarily the phase margin. A control system optimization, using CONDUIT (Ref. [24]), was performed for each set of actuators to determine a set of feedback gains that would ensure 45 deg stability phase margins in the lateral and longitudinal translational axes, and 38 deg stability phase margins in the pitch and roll axes, as per the findings of Ref. [1]. The optimization strategy was to maximize the disturbance rejection bandwidth (DRB) [25] in the longitudinal translational axis for a given set of actuator dynamics, while minimizing the margins to the allowable extent (the values of which are shown in Figure 2).

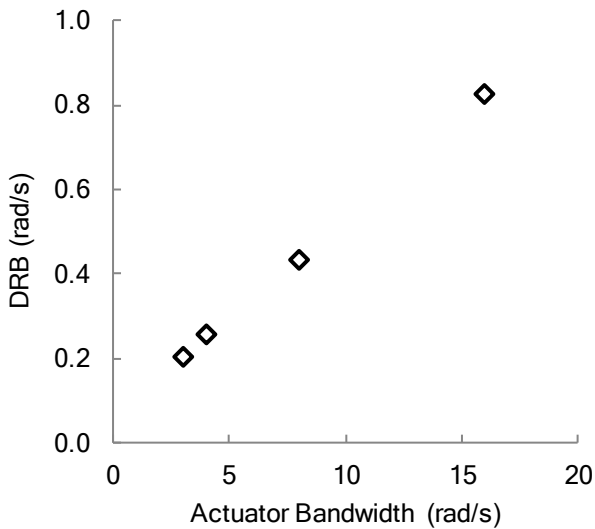
Phase roll-off of the actuator dynamics also has a direct impact on the phase characteristics of the closed-loop end-to-end translational response as illustrated by the longitudinal position response X/δ_{lon} bode plot in Figure 3 for the four baseline actuator configurations.

The effect of actuator phase roll-off may be potentially characterized either by the u/δ_{lon} phase bandwidth or the X/δ_{lon} phase delay, per an extension of the definitions employed in ADS-33 for attitude responses. Whilst u/δ_{lon} may be a more natural representation of the aircraft TRC response, neither the gain or phase bandwidth definitions are representative of pilot in the loop operating frequencies for position regulation tasks. Herein the X/δ_{lon} frequency response was chosen to characterize the TRC response as it was deemed to be a more suitable characterization for pilot

in the loop position control tasks, paralleling the approach by Franklin et al. [18].



(a)



(b)

Figure 2. Longitudinal velocity feedback characteristics for varying actuator bandwidths, (a) stability margins, and (b) disturbance rejection bandwidth

The case employing the 16 rad/s actuator configuration is shown in Figure 3 to have a mild resonance peak near 7 rad/s, after which the phase drops suddenly. This is partly a natural consequence of the low phase roll-off of the actuator in superposition with the bare-airframe response of the aircraft and partly a construct of the control system optimization. By attempting to increase disturbance rejection bandwidth the solution has pushed the broken loop crossover frequency up to 2.4 rad/s and, importantly, too close to the 180 deg phase crossover frequency (7.7 rad/s). Phase margins within this frequency range are insufficient to prevent magnification of the closed-loop response. Within this

frequency range the closed-loop response also manifests a marked phase recovery.

It is noted that the X/δ_{lon} -180 deg phase curve crossover is between 0.74 and 1.1 rad/s, with values monotonically increasing as a function of actuator bandwidth, except for the 16 rad/s actuator case displaying a crossover at 0.8 rad/s. These, in conjunction with the phase delay values are an indication of the potentially limiting control margins available to the pilots, should they be required to operate beyond the installed bandwidth, particularly for the low actuator bandwidth cases. Operating at these frequencies would undoubtedly lead the pilot to be out of phase with the desired position response, and consequently at risk of entering PIO.

Figure 4 shows the varying closed-loop TRC response phase bandwidth and delay values for the experimental equivalent rise times of 2.5 and 5.0 s (baseline) and various nacelle actuator natural frequencies. Also shown are the phase bandwidth and delay of cyclic-augmented control law gain set, D, and the 3 rad/s actuator bandwidth it was associated with.

Equivalent rise time is shown to have a fundamental effect on the bandwidth, as defined from the X/δ_{lon} transfer function, but a much lesser effect on the phase delay for each actuator bandwidth configuration. The baseline cases, with equivalent rise time of 5.0 s all had a phase bandwidth of around 0.2 rad/s. Similarly, the 2.5 s equivalent rise time conferred a phase bandwidth closer to 0.36 rad/s. Actuator bandwidth, conversely, is seen to have a fundamental influence on the phase delay, only. The 3 rad/s actuator, for example, is seen to confer a phase delay in the order of 650 ms. A progressive reduction in the phase delay is shown for increasing actuator bandwidths, down to about 200 ms for the 8 and 16 rad/s actuator bandwidths. Finally, it is noted that the augmented configuration conferred a 200 ms phase delay reduction over the baseline configuration with the 3 rad/s actuator. Phase bandwidth was still driven by the equivalent rise time and was accordingly close to 0.2 rad/s for this configuration.

Nonlinearities

In handling qualities and flight control analyses, it is typical to characterize the aircraft response using linear systems theory. This can entail the derivation of linear models and their analysis or directly analyzing the response of the actual aircraft or nonlinear model through the use of frequency sweeps. Another important assumption behind the use of these techniques is that the dynamics of interest remain linear within the envelope of likely piloted activity, i.e., small angles, no actuator rate limiting or saturation and no discontinuous dynamic behavior. This is usually sufficient and also correlates with what is required for satisfactory handling qualities.

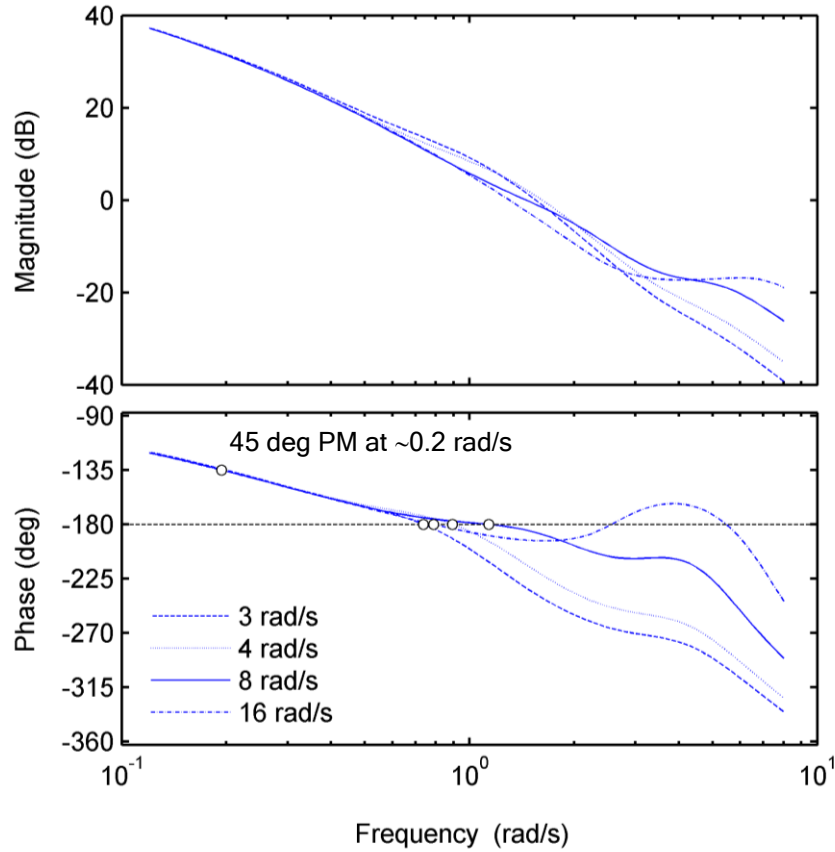


Figure 3. Closed-loop X/δ_{lon} frequency response for varying actuator bandwidths (baseline)

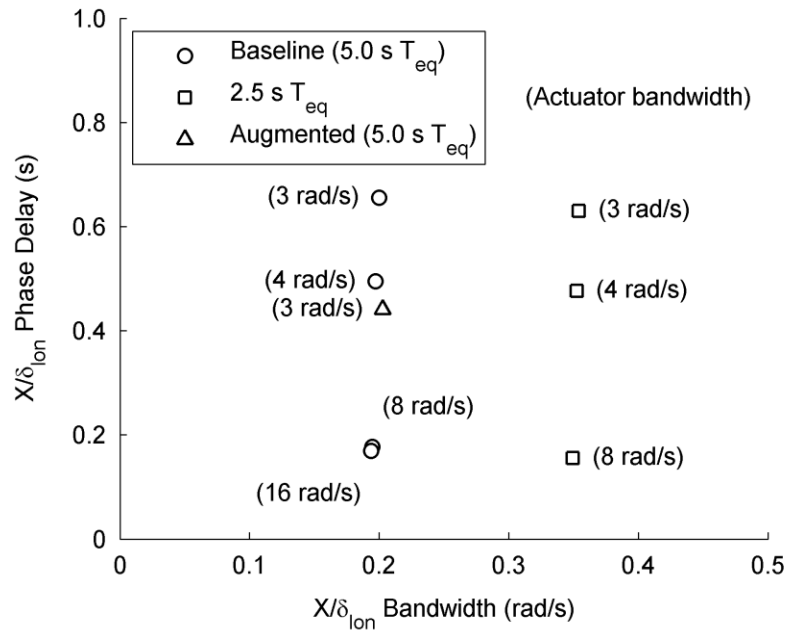


Figure 4. Closed-loop X/δ_{lon} bandwidth and phase delay for a subset of experimental configurations

With the investigation of the nacelle-actuation based form of longitudinal TRC on the LCTR2 [6], it was discovered that the longitudinal aircraft response characteristics varied quite significantly with the amplitude of the pilot input due to actuator limiting. From a handling qualities perspective, this in itself was not necessarily a problem as many of the configurations with these nonlinear characteristics were perfectly able to be flown. However, it constituted some difficulty when trying to categorize the performance of the particular configuration. A purely linear model of the system does not exhibit this behavior and therefore comparing different configurations is difficult as the linear dynamics may not be entirely representative of the model when flown in piloted simulation.

These nonlinearities are a direct consequence of modeling representative actuator characteristics for the piloted real-time simulation model. Therefore it was necessary to better identify their effect on the handling qualities in order to separate them from the primary experimental effects of actuator bandwidth during the

data analysis. The following analysis attempts to characterize the changing aircraft response characteristics using linear systems analysis as a function of pilot control amplitude.

The analysis that follows identified the effects of independently sweeping over a range of either nacelle actuator bandwidth or rate limit on the dynamic response parameters, X/δ_{lon} bandwidth, ω_{BW_X} , and phase delay, τ_{pX} . These were all computed using frequency sweeps of the qLPV LCTR2 model at four different input amplitudes of the longitudinal stick input, δ_{lon} . The sweeps were performed on the baseline configuration (8 rad/s bandwidth, 7.5 deg/s rate limit) with one of the two parameters held constant at these values while the other was varied. On each of the figures the 3, 4 and 8 rad/s configurations from the piloted experiment are also plotted for comparison - the key difference between these cases and the sweep results is that their control law gains have been optimized for a specific combination of actuator bandwidth and rate limit point designs.

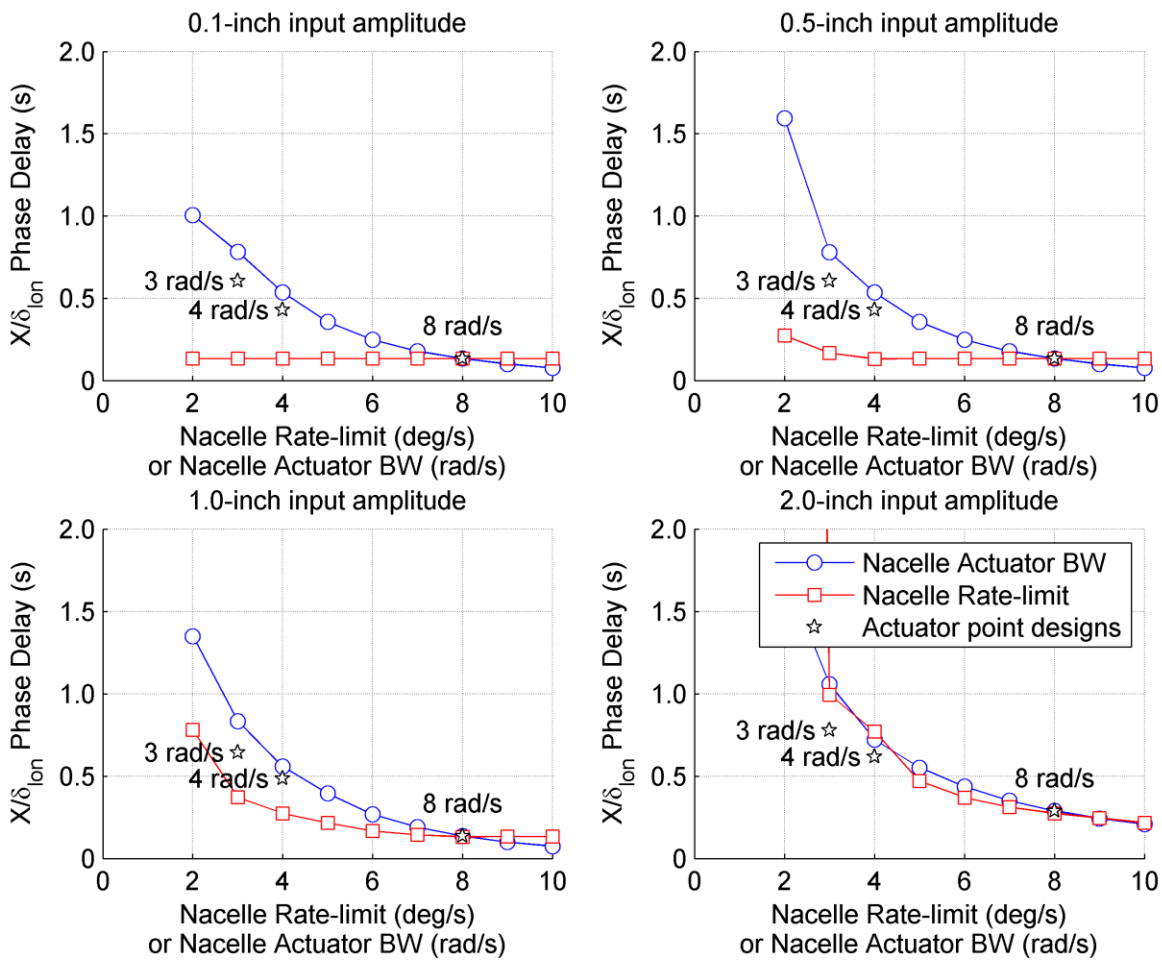


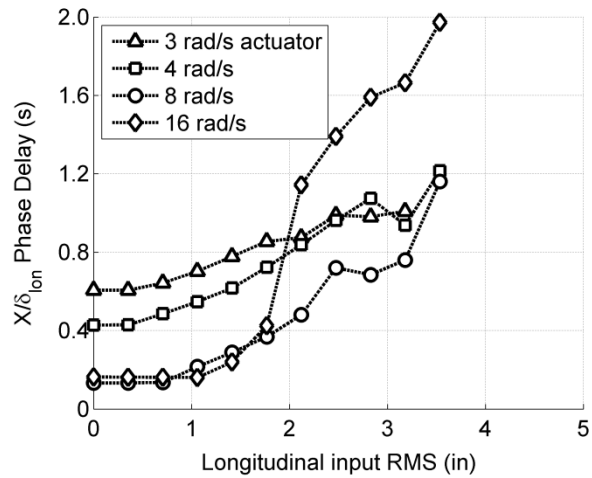
Figure 5. Closed-loop X/δ_{lon} phase delay from varying amplitude frequency sweeps for varying nacelle actuator rate limits and bandwidths

Not shown, the effect on the longitudinal position response bandwidth ω_{BW_X} is minimal from either parameter variation except at very low actuator bandwidth or rate limit, where there are some variations. The value of ω_{BW_X} is already a very low frequency, and is essentially governed by the translational response rise-time for all the configurations which was 5 s.

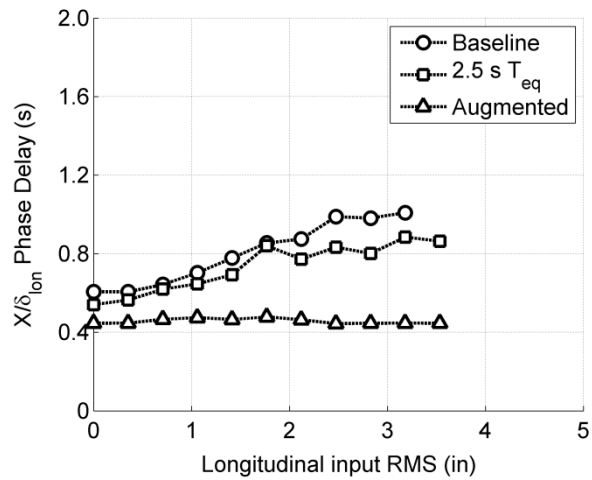
The longitudinal position response phase delay, τ_{p_X} results in Figure 5 are more informative. There are continuous trends of increasing delay with both bandwidth and rate limit, with both showing differing amounts of sensitivity to the input amplitude. At low amplitudes the rate limit does not really influence the delay until it gets very low whereas bandwidth has an effect at all amplitudes. As the amplitude increases the effect of the two variations becomes almost indistinguishable despite the rate limiting being a nonlinear discontinuity and the bandwidth being entirely a linear dynamic parameter. It is also useful to note that the experimental point designs for the 3 and 4 rad/s actuators have smaller phase delays than the sweep analysis, implying that the optimization of the TRC gains appears to bring some noticeable benefit.

The nonlinear trends with input amplitude varied from configuration to configuration. Figure 6 illustrates the variation of the longitudinal position response phase delay τ_{p_X} with longitudinal stick amplitude represented in Root Mean Square of the sinusoidal input used in the automated frequency sweeps. What can be seen is that for the lower bandwidth cases (3 and 4 rad/s), the phase delay starts at higher values at small amplitudes and increase almost immediately with increased RMS input. The higher actuator bandwidth cases (8 and 16 rad/s) have much lower minimum phase delays at low input and actually maintain that value constants up until a given input amplitude after which there is a rapid rise in the phase delay. The trend appearing to be that the breakpoint for the rising phase delay is at higher amplitudes for higher actuator bandwidth but with a more aggressive increase, i.e. the higher bandwidth able to rate limit more aggressively when reached. Also for comparison is a 3 rad/s actuator bandwidth but with a faster equivalent rise time in the command model of 2.5 s. Comparing with the baseline (5.0 s) 3 rad/s actuator case, this confers a small decrease in the overall phase delay as well as a small decrease in the rate of growth of the delay with amplitude.

Finally, the longitudinal cyclic augmented TRC case, also with the lowest 3 rad/s bandwidth nacelle actuator (but with a 5s rise time) shows further improvements. The overall phase delay is lower than both un-augmented cases, and notably, the rise in delay with amplitude is eliminated. Effectively the vehicle appears much more 'linear' with no changes in response characteristics with changing pilot input amplitude - a significantly improved handling qualities characteristic.



(a)



(b)

Figure 6. X/δ_{lon} phase delay for varying frequency sweep amplitude, (a) baseline and (b) 3 rad/s actuator

Quickness Criteria

The Quickness parameter is a handling qualities metric that is appropriate to gauging the response of an aircraft to intermediate or moderate amplitude and frequency inputs. It is a time domain parameter, and in ADS-33E it is solely arranged for quantifying the attitude response quickness of rotorcraft, and has been applied to both rate and attitude response types. However, there is no usage in ADS-33 of a quickness type parameter for TRC response types. Figure 7 is an attempt to characterize the longitudinal TRC quickness by assuming longitudinal velocity is analogous to attitude and the acceleration is analogous to the angular rate. It shows the quickness formulated by $\dot{u}_{pk}/\Delta u$ for the four key nacelle bandwidth configurations, (3, 4, 8 and 16 rad/s). The input shape was an overdriven step type input where the input magnitude was overdriven a moderate amount before dropping to the steady state value. This approach is analogous to attitude quickness testing with an attitude command response type, [25], as opposed to utilizing a

pulse input for an attitude rate response type. The plots indicate consistent trends with the highest bandwidth actuator conferring the highest longitudinal ‘velocity quickness’. This trend is distinct up to a certain magnitude of longitudinal velocity where all the lines collapse together. The reason for this effect is due to the nacelle reaching its angular position limit and thus limiting the longitudinal acceleration that can be generated. This is clearly shown in Figure 8 by the quickness calculations performed for a configuration where the maximum forward angle limit for the nacelle was parametrically varied (the default is 77 degrees). As the limit was moved forwards (0 deg being horizontal) the quickness curve is maintained at a higher level out to larger velocity perturbations.

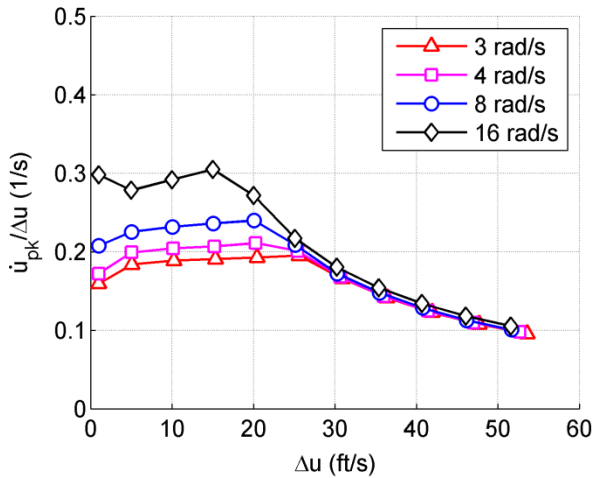


Figure 7. TRC quickness criterion for varying nacelle actuator bandwidths (baseline)

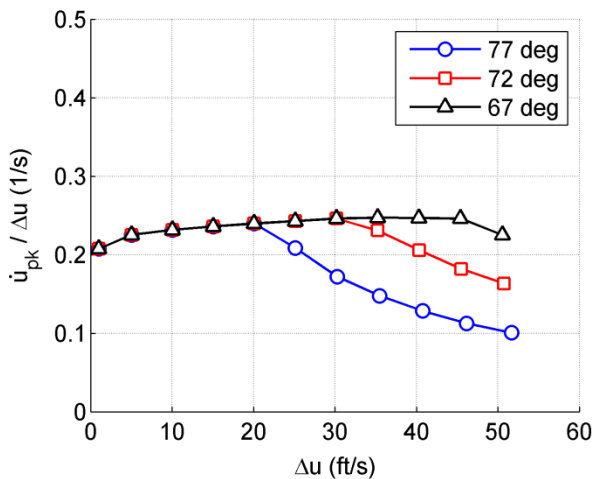


Figure 8. TRC quickness criterion for varying actuator position limits

Task & Conduct of Test

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

Facility

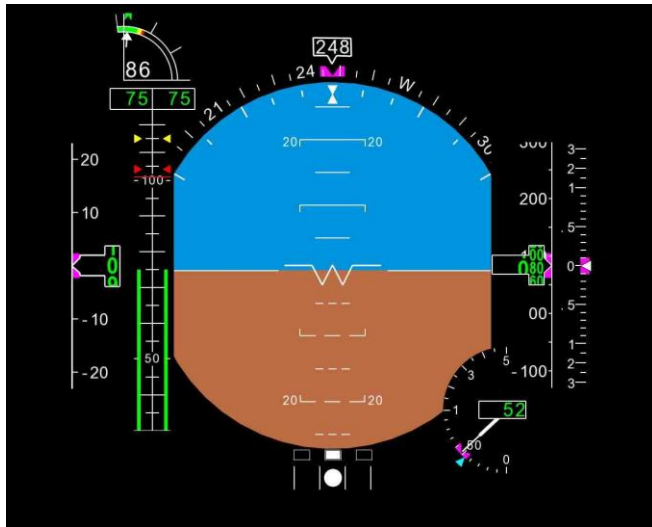
As with the preceding studies, this experiment was conducted in the NASA-Ames Vertical Motion Simulator (VMS), described in Ref. [27]. The Transport Cab (T-Cab) was employed for its large field of view. Traditional helicopter center stick and pedal pilot control inceptors were installed for the right cockpit seat, the evaluation pilot position. An experimental tiltrotor specific vertical Thrust Control Lever (TCL) was provided instead of the standard helicopter collective stick. Pilots could manually adjust the friction coefficient on the TCL to their preference.

The primary flight display and the horizontal situation (hover) display (Figure 9), replicating the Army’s Common Avionics Architecture System (CAAS) displays, were provided on the instrument panel. Slight modifications were done to include a nacelle position indicator in upper left corner, and a magenta commanded velocity vector when in TRC.

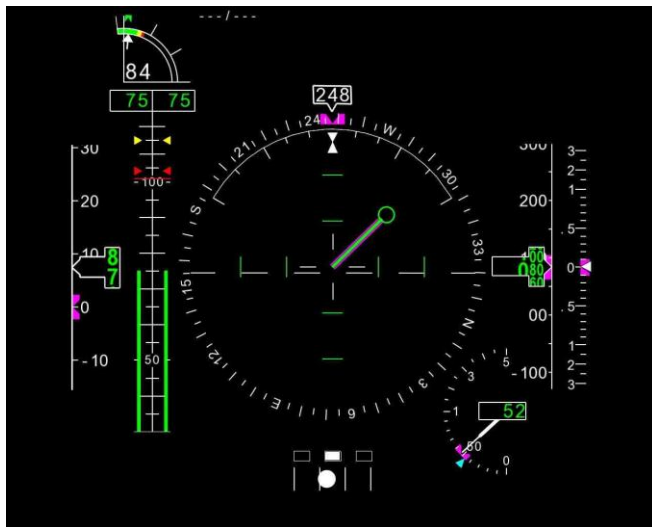
Evaluation tasks and procedures

Evaluation of the experimental test configurations was performed by the pilots in a revised version of the ADS-33 Hover MTE maneuver, only. Refinements to the ADS-33 Hover MTE position performance standards were necessary because cargo/utility maneuver performance metrics were considered 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 [1]. *Adequate* position and altitude performance limits were set at double the desired limits, i.e., ± 8 ft and ± 6 ft., respectively. The maneuver was defined around a pilot eye-point altitude of 55 ft AGL.

Seven 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. Four of the pilots were highly experienced tiltrotor test 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. [28]). Pilots were required to complete initial training sessions to familiarize themselves with the experiment objectives, methodology, and the Hover MTE task and baseline control configurations prior to the start of formal evaluations.



(a)



(b)

Figure 9. CAAS displays, (a) primary flight display, (b) horizontal situation display

Data recorded included the aircraft control inputs and state data, task performance data, and pilot comments. A 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.

The Hover MTE maneuvers were executed with the VMS cab oriented with the longitudinal aircraft axis

along the beam. This orientation was selected to provide a greater range of longitudinal motion, allowing higher and more sustained accelerations to be imparted along this, the primary axis of interest as identified in an earlier VMS experiment [3].

Task bandwidth

Figure 10 illustrates what would be considered to be the *ideal* longitudinal control input required with TRC to complete a deceleration into a stable hover over the designated position. Starting from a steady control stick displacement, the pilot would ideally like to, in one action, return the stick back to center and have the aircraft stop at the desired position. In reality, because the TRC equivalent rise times may not allow this within the time constraints of the task, it is expected the pilot will have to overdrive the input somewhat and introduce opposite input to arrest the aircraft translational rate before bringing the control back to center to complete the stable hover capture. Additional shaping may be required if the aircraft stops short, or overshoots, but this is arguably a reasonable idealization of the deceleration maneuver control input strategy.

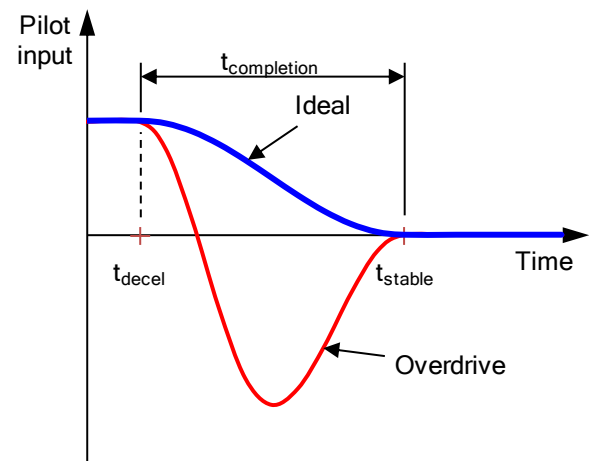


Figure 10. Idealized control input shaping for deceleration maneuver

The key is that the resulting control shapes can be approximated by sinusoidal or 'pseudo-sinusoidal' signals. In the ideal scenario, the maneuver is fundamentally completed with one-half control input cycle, whereas in the more actual scenario, one full cycle is employed. Assuming the control strategies described, the time constraint enforced by the Hover MTE deceleration performance requirements of 5 s for *desired* and 8 s for *adequate* performance, fundamentally specifies a task bandwidth between 0.4 and 1.2 rad/s, depending on how much the pilot had to overdrive the system. For example, if a pilot is required to significantly overdrive his control input employing a full 'pseudo-sinusoidal' input cycle in order to complete the maneuver successfully in 5 s, then the operating frequency could be up to 1.2 rad/s. Clearly the resulting

pilot operating frequency is predicated on the aircraft being able to provide the required response. Consequently there is a direct relationship between pilot input frequency and rise time (or equivalently an inverse relationship with the installed bandwidth).

The previous analysis suggests that a configuration with insufficient installed bandwidth (as defined by the rise time) will force the pilot to increase his control activity, and consequently operate at a higher frequency, in order to complete the deceleration maneuver within the required performance standards, or have to accept performance degradation. In fact this is not a new idea. The same precept is suggested by the classical crossover model of pilot-in-the-loop control.

This consideration is highly significant in light of the X/δ_{lon} frequency response phase curves in Figure 3 which indicate the -180 deg phase crossover points are within the 0.7-1.1 rad/s range. The deceleration portion of the Hover MTE may potentially require pilot operating frequencies of 1.2 rad/s, and clearly at risk of operating out of phase with the position response.

Results & Discussion

This section presents the results of the piloted evaluations, including Cooper-Harper Ratings and evaluation comments. Complementing these results, and presented last, will be the objective task performance and pilot control activity measurements and analysis, focusing primarily on pilot longitudinal stick control activity

Piloted Evaluations

The first set of results discussed is for the baseline configurations with varying nacelle actuator bandwidth. The second shows the results for a 2.5 s equivalent rise time and for a redundant control configuration, with the 3 rad/s nacelle actuator bandwidth, compared to the baseline. Rounding out the results for the piloted evaluations is a brief presentation of the results for the varying control sensitivity and equivalent rise time cases and the 8 rad/s bandwidth actuator.

Baseline

The handling qualities ratings shown in Figure 11 for the baseline TRC implementation indicate that with nacelle-only actuation Level 1 handling qualities are possible with actuator bandwidths greater than 4 rad/s. As was shown in Figure 4, phase delay for these four configurations ranged from 650 ms for the 3 rad/s case to 200 ms for the 8 and 16 rad/s cases. Phase delay for the 4 rad/s case was in the order of 480-500 ms. With this in consideration, the results in Figure 11 also indicate there is a good correlation with X/δ_{lon} phase delay, with 480-500 ms (of the 4 rad/s actuator configuration) conferring borderline Level 1-2 handling qualities, on average, for a TRC phase bandwidth of 0.2 rad/s. These results are consistent with those of

Jacklin et al. [18], which proposed a Level 1-2 boundary at 0.4-0.6 s for a similar type of TRC implementation.

It should be noted that although the 3 and 4 rad/s actuators had lower rate-limits than the 8 and 16 rad/s actuator configurations, rate-limiting was carefully monitored throughout the experiment and was judged to not have been a major factor in the results. As suggested by Figure 6 these lower bandwidth configurations would have only experienced gradual degradation of the effective phase delay for control amplitudes (in terms of RMS) up to 1 inch. Rate-limiting certainly compounded the problems encountered when very large control inputs were required by the pilot, but it was never the precipitator of the initial handling qualities problem, which was a phase response delay due to the low actuator bandwidth.

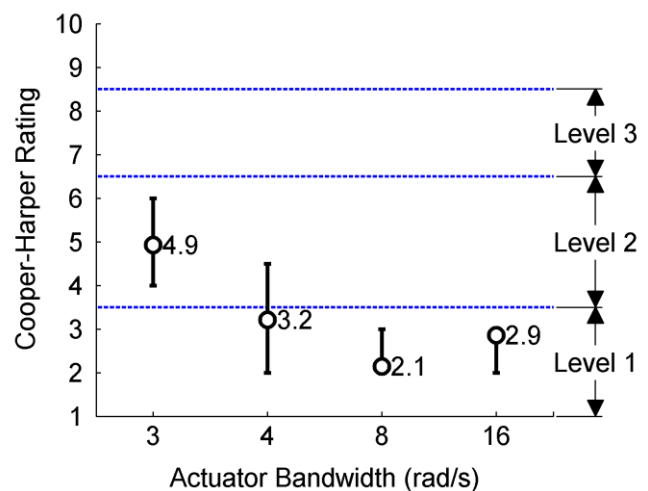


Figure 11. HQRs for varying actuator bandwidth configurations

The response lag in the longitudinal axis associated with the actuator bandwidth of 3 rad/s was consistently deemed by the evaluation pilots to be excessive and PIO conducive. Phase delay was in the order of 650 ms (Figure 4). This configuration was convincingly rated Level 2 by all evaluating pilots. Handling qualities improved significantly with the 4 rad/s actuator, with the perceived response lag being less objectionable, but still problematic with aggressive control. Comments generally pointed to mid-term or residual oscillations, particularly after an aggressive deceleration, which implies that pilots could not relax after achieving a stable hover. Initial response was not crisp, but still predictable. All of this amounted to an inability to be aggressive with the aircraft, but which easily allowed for desired performance to be achieved if employing a low gain control technique. Consistent with these comments, HQR score indicate borderline Level 1-2 handling qualities were conferred with this configuration.

High bandwidth actuators (8 and 16 rad/s) conferring low phase delay values (under 200 ms for both)

consistently led to “very predictable” and “crisp” responding qualities, offering “very good speed control” with “precise and low workload hover stabilization”. Only passing mentions of a slight tendency to oscillate longitudinally from aggressive deceleration attempts were made by one pilot. Most pilots indicated that these configurations were quite insensitive to aggressiveness.

Although rated as conferring Level 1 handling qualities, the 16 rad/s actuator unexpectedly conferred slightly degraded handling qualities compared to the 8 rad/s actuator. Not shown, inspection of the q/δ_{lon} Bode diagram indicates the pitch rate response is roughly 3.5 dB higher for frequencies below 1 rad/s. This would be consistent with pilot evaluations, which suggested there were noticeable perceived heave accelerations due to pitch, which were affecting the compensation required. Other issues reported in the piloted evaluations are attributable to the high broken-loop crossover frequency at 2.4 rad/s (compared to 1.6 rad/s for the 8 rad/s actuator) and manifest primarily in ride quality deficiencies: a “snappy” response, large lateral accelerations, etc. This high feedback gain configuration will impart higher frequency angular nacelle accelerations in response to pilot input and this is likely to generate a series of ride qualities issues at high frequency through off-axis couplings in addition to the primary longitudinal control axis response issues.

Response quickening

Control response augmentation by means of employing longitudinal rotor cyclic actuation in addition to nacelle actuation was demonstrated to confer significant handling qualities improvements to the lower nacelle actuation bandwidth cases, specifically the 3 rad/s actuator case, as shown in Figure 12.

Results for the three control cases in Figure 12 show that the weak increase in phase bandwidth and reduction in phase delay attained with the case that featured lower equivalent rise time, but nacelle-only actuation, were not sufficient to confer a significant improvement in the handling qualities. By comparison, however, the phase delay improvement of the cyclic-augmented control system compared to the baseline was of the order of 200 ms (Figure 4). With all other parameters remaining unchanged, including the X/δ_{lon} phase bandwidth, this is a strong indication of why the cyclic-augmented TRC conferred significantly improved handling qualities, even with a 5 s nominal equivalent rise time.

These results also suggest that whilst high, by ACAH standards, a phase delay of 450 ms (as was the case for this configuration and was shown in Figure 4) in the context of this TRC implementation would be sufficient to achieve desired precision in this Hover MTE. Again, these results track the phase delay findings of Ref. [18].

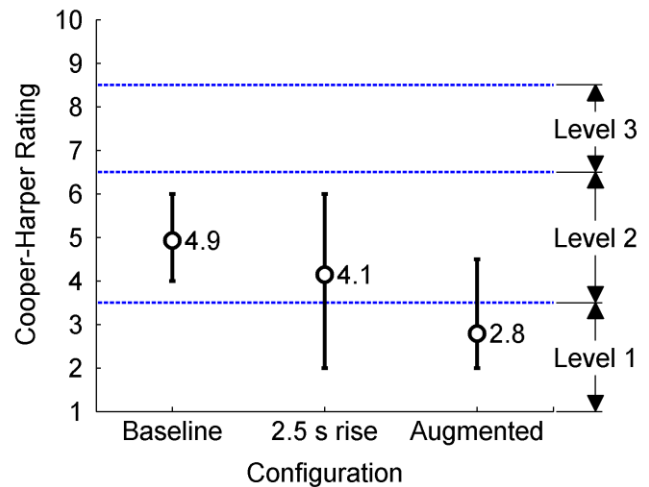


Figure 12. HQRs for baseline, 2.5 s rise time and rotor cyclic augmented configurations (3 rad/s actuator)

Only one pilot out of seven rated this cyclic-augmented control system Level 2. The main objection to it was an excessive pitch response coupling which led to a perception of heave motion taking place as has been documented for the large pilot to center of gravity offsets [2]. Trying to compensate for this perceived heave motion was not conducive to good handling qualities, forcing the pilot to have to stay out of the loop. While other pilots commented on this coupling, none felt it was problematic, other than it being a ride quality annoyance. This is, however, a consideration which needs to be taken into account if designing these types of control systems, that is, potential large pitching moments may be generated when using longitudinal cyclic for velocity control.

Importantly, very little noticeable lag in the response was apparent. As such the initial response was generally considered to be predictable and speed control easy. Only two pilots observed a slight amount of lag in the response, but considered it to be manageable and definitely not conducive to PIO. Again these issues all point to the reduced phase delay being the cause for the handling qualities improvements.

Also playing a potentially beneficial role, the system was unaffected by rate-limiting as discussed in the section on nonlinearities above, whereas the handling qualities of the un-augmented configurations degraded slightly as pilots may have transiently excited nonlinearities when increasing their control gain excessively.

Control sensitivity and equivalent rise time

Summarized in Figure 13, HQRs for the varying control/response sensitivity and equivalent rise time specifications highlight two salient results: firstly, that 10 (ft/s)/in was the preferred sensitivity, and secondly, that the increased phase bandwidth associated with the 2.5 s rise time conferred only a slight improvement in the handling qualities ratings over the 5.0 s cases.

Consequently, the experimental baseline design conferred the best handling qualities.

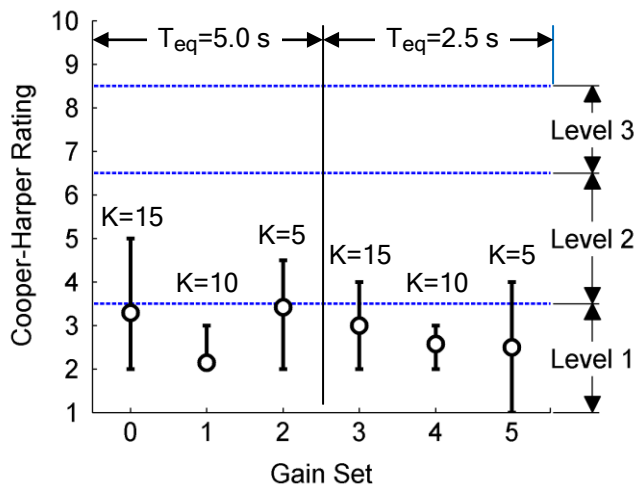


Figure 13. HQRs for varying equivalent rise times and control response sensitivities (8 rad/s actuator)

Regarding the control sensitivities, pilots generally indicated that the high stick sensitivity value resulted in the aircraft response being “too jerky”. It was noted that high control sensitivity also made this configuration much more susceptible to rate-limiting. On the other hand low stick control sensitivity elicited the complaint that excessively large inputs were being required. The control sensitivity did, however, offer an added layer of protection against rate-limiting.

In interpreting these results, it is important to note that while the control/response sensitivity was varied, the control stick force gradient was left invariant. The potential effect of this parameter should not be discounted when establishing overarching conclusions about the control sensitivity, since it has a direct effect on the forces and thus the dynamic response of the stick.

A X/δ_{lon} phase bandwidth improvement from just below 0.2 rad/s to 0.36 rad/s due to a shorter rise time did not appear to confer a significant improvement in the handling qualities, although it did appear to improve the worst case scenarios. The reduced rise time did convey to the pilots a slight sense of increased quickness in the response when decelerating, and thus improving the ability to decelerate within the required time constraints.

A more detailed analysis of the piloted evaluations indicates that three pilots rated the high sensitivity (15 ft/s/in), 5 s rise time case (gain set 0) in Level 2 (HQR 5/4/4). Salient comments from these pilots about the deficiencies that warranted these ratings pointed to, first, a tendency to over-control in the longitudinal axis, and second, a sharp lateral response. In particular, two of the pilots, and importantly, the pilot who rated the aircraft configuration HQR 5, indicated a tendency to over control in the longitudinal axis which became apparent during the deceleration and hover

stabilization phase of the maneuver. Other comments pointed to a very sharp lateral response, to the point of feeling disharmonious with respect to the longitudinal response, but did not necessarily intimate there was a deficiency in the longitudinal axis per se.

This observation was even more prevalent for gain set 3, where the increased dynamic response quickness afforded by the 2.5 s equivalent rise time appears to compound with the sensitivity, greatly exacerbating the sharpness of the initial response. This configuration was often described as “uncomfortable”, and pilots consistently felt they could not be aggressive with it because of the “choppy” nature of the response. Also showing up was a “noticeable and distracting” strong heave perception described as “objectionable” by some pilots. This configuration, however, presented no tendency to over control as gain set 0 did, which made it perform quite well, especially in the deceleration and hover stabilization phase. The lower rise time fundamentally allowed pilots to achieve desired precision in capturing the hover position simply by releasing the stick and bringing back to center, or with very minimal required input reversal.

The opposite end (low) of the control sensitivity range saw deficiencies in the aircraft characteristics of a different nature. The main objectionable characteristics were all derived from the fact that pilots now had to employ larger displacements, both steady and dynamic, in order to get a response of the aircraft. Associated with the large displacements were large forces, since the force gradient was not optimized for a given control sensitivity. Steady displacements were uncomfortable because of the large forces being sustained for prolonged periods of time, but these did not necessarily have an impact on the handling qualities. More importantly, in dynamic situations this combination of displacement and force gave the aircraft response a “false sense of sluggishness”, almost as if the aircraft felt “heavier”. This frequently induced some pilots to increase their aggressiveness in order to achieve the desired deceleration performance requirements. It also made velocity maintenance more difficult in the mind of some of the pilots. None of these issues were significantly improved by the low equivalent rise time, although this parameter did improve slightly the ability to capture a stable hover.

Pilot control activity

Figure 14 shows the computed pilot control input cut-off frequencies and RMS of the longitudinal control stick displacements for the majority of the cases discussed in the previous section. These were computed from time histories of the control input over the entire Hover MTE maneuver. Results shown herein are for every evaluation run executed by every pilot.

Pilot cutoff frequency, determined from the spectral analysis of the inceptor position time histories, 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. [29]). Additionally, the root mean square (RMS) of the piloted inputs is a statistical measure of the magnitude of control input during the maneuver.

A few key points should be considered when analyzing these results. Depending on the size of control inputs, the deceleration phase of the maneuver can introduce a significant amount of energy that will show in the auto-spectrum and this typically occurs around 0.8-1.0 rad/s. Frequency identification techniques are fundamentally limited in the lower frequency, so some amount of energy at low frequency will be unaccounted for. Considering these aspects it is not unexpected for the cut-off frequency estimates to slightly over predict the pilot operating frequency when looking at the entire time history. This complicates the task of precisely identifying the actual pilot normal regulatory operating frequency, for the frequency range in question, considering that pilots may legitimately operate beyond installed bandwidth, provided there is sufficient margin before the -180 deg phase crossover point.

With these points in mind, the results suggest that low phase delay control cases (higher actuator bandwidth) (Figure 14(a) and (b)) generally allowed pilots to operate in a more closely clustered frequency range, roughly between 0.2 and 0.6 rad/s, but possibly lower, whilst high phase delay control cases often resulted in high RMS control input runs at frequencies closer to 0.8 through 1.0 rad/s. The later cases would have clearly had the pilots operating at, or near, the -180 deg phase crossover point, which fully explains the consistent PIO tendencies reported. Not shown, time histories of these runs confirm this.

The critical sub-phase of the overall maneuver was consistently indicated by the evaluation pilots to be the deceleration from a steady velocity translation into a stable hover within the desired time and position performance criteria, because of the series of events it could trigger if not executed correctly. Mainly, that if not executed well it would force the pilot to get into the loop to correct for parameters outside of the desired performance criteria. This is an important consideration because, with TRC, position regulatory tasks such as the ingress and hover hold sub-elements of the Hover MTE may not require high installed control bandwidth. The deceleration sub-element, however, could easily require control bandwidths over 1.0 rad/s.

A clear correlation between control sensitivity and equivalent rise time (or phase bandwidth), and the cut-off frequency and RMS data can be seen in Figure 14(c). The data show how low control sensitivity elicited larger amplitude but lower frequency control inputs. High, and in a few instances, medium sensitivities led to higher operating frequencies and consequently resulted in a tendency to over-control as documented above (gain set 0 in particular).

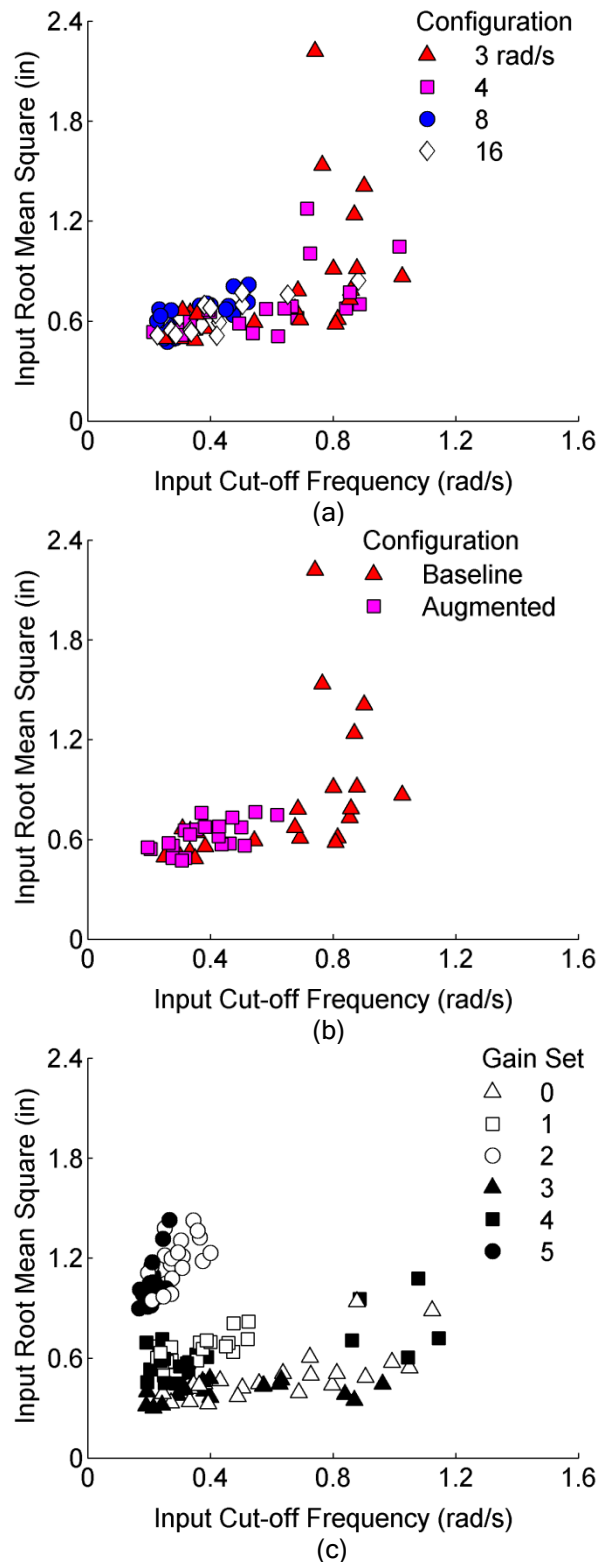


Figure 14. Longitudinal pilot control activity for entire maneuver: (a) baseline, varying actuator bandwidth, (b) cyclic-augmented (3 rad/s actuator), and (c) varying equivalent rise times and control response sensitivities (8 rad/s actuator)

The effect of a smaller (quicker) equivalent rise time can generally, with a few exceptions, be seen to have resulted in lower overall cut-off frequencies. The exceptions were where it led to a tendency to over control when combined with the medium and high control sensitivities. This can be explained by the documented result that lower rise time typically allowed for easier transitions into a stable hover without the pilots having to over-drive the controller.

Extending this discussion into the frequency domain, the implication is that higher phase bandwidth generally allowed the pilots to operate with lower control natural 'gains' (as reflected by the cut-off and RMS data) in order to meet the desired deceleration performance requirements. This seems to imply a fundamental inverse relationship between installed phase bandwidth and required pilot operating frequency.

Pilot longitudinal stick input frequency and magnitude data computed for the overall maneuver may obscure specific events happening at distinct moments in time. When computed for the 30 s the pilot is required to hold the hover position, pilot cut-off frequencies and RMS shown in Figure 15 confirm there can be significant residual pilot control activity in the 0.8 to 1.2 rad/s frequency range, following the enunciation that a stable hover had been reached, but also very minimal pilot control activity, as characterized by a RMS below the neighborhood of 0.4 in. High cut-off frequency values are meaningless in this context, other than to indicate that pilots were effectively staying out of the loop, as these are the result of the mathematical characterization of a signal with minimal energy.

Figure 15 shows strong correlation of pilot control activity with the handling qualities, where the Cooper-Harper ratings are seen to on average increase dramatically with the amplitude of pilot control inputs, as indicated by the RMS of the longitudinal control input time histories. These events consistently corresponded to the TRC configurations possessing high phase delay values. Although not identified individually, shown here are the composite results for all experimental configuration variants.

Time histories and auto-spectra analysis shown in Figure 16 highlight the different nature of the control inputs in these two distinct regions. These correspond to two different runs by the same pilot flying the same baseline 3 rad/s actuator configuration. Assigned a HQR 6 by this one pilot, this configuration exhibited widely different performance in each run. Run A highlights a situation where the pilot executed everything perfectly, remaining within desired parameters, and therefore did not need to get in-the-loop after calling stable. The control compensation employed by the pilot after stabilizing is characterized by infrequent pulse type corrections. This type of time history displays very little energy in its auto-spectrum (Figure 16(c)). Deficiencies with this configuration are

illustrated by Run B where, in this case, the same pilot remains in the loop close to 11 s after indicating a stable hover had been achieved. Examination of the control input and aircraft position time histories during this initial time period suggests significant compensation occurred around 1 rad/s, and the spectral analysis confirms this. Importantly, it is noted that the position response is nearly 180 deg out of phase with the input, which is not only indicative of a PIO; it correlates well with the X/δ_{lon} frequency response in characterizing the position regulation performance. These results illustrate the handling qualities effects of large phase delay.

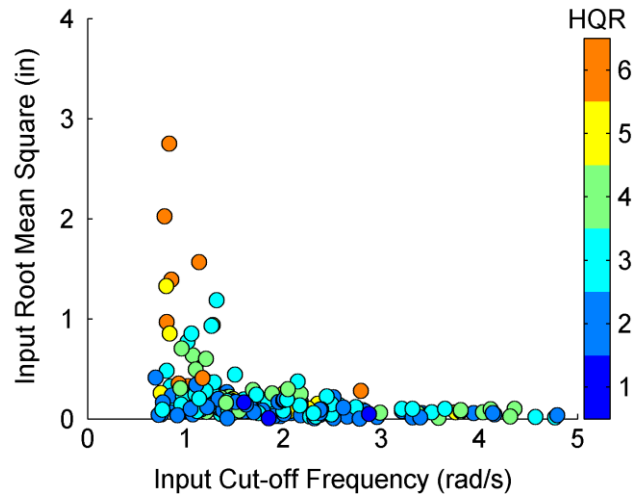


Figure 15. Longitudinal pilot control activity for the 30 s hover hold sub-task (all configurations)

As phase delay for other configurations was reduced (to less than 200 ms), this propensity to get out of phase during the stabilization was also diminished, a quality which was corroborated by the pilot evaluations, as discussed above. In terms of the pilot input frequency and magnitude characterization, configurations with lower phase delay show consistently low control RMS values in Figure 15, which is strongly indicative of pilots employing minimal compensation.

One last observation from these results is they confirm the piloted evaluations which indicated that very little compensation was generally required to hold position after stabilizing the aircraft, particularly for phase delays lower than 450 ms. These results highlight, thus, one of the most significant benefits of TRC; mainly, that the higher augmentation it confers translated into very low workload for position maintenance tasks.

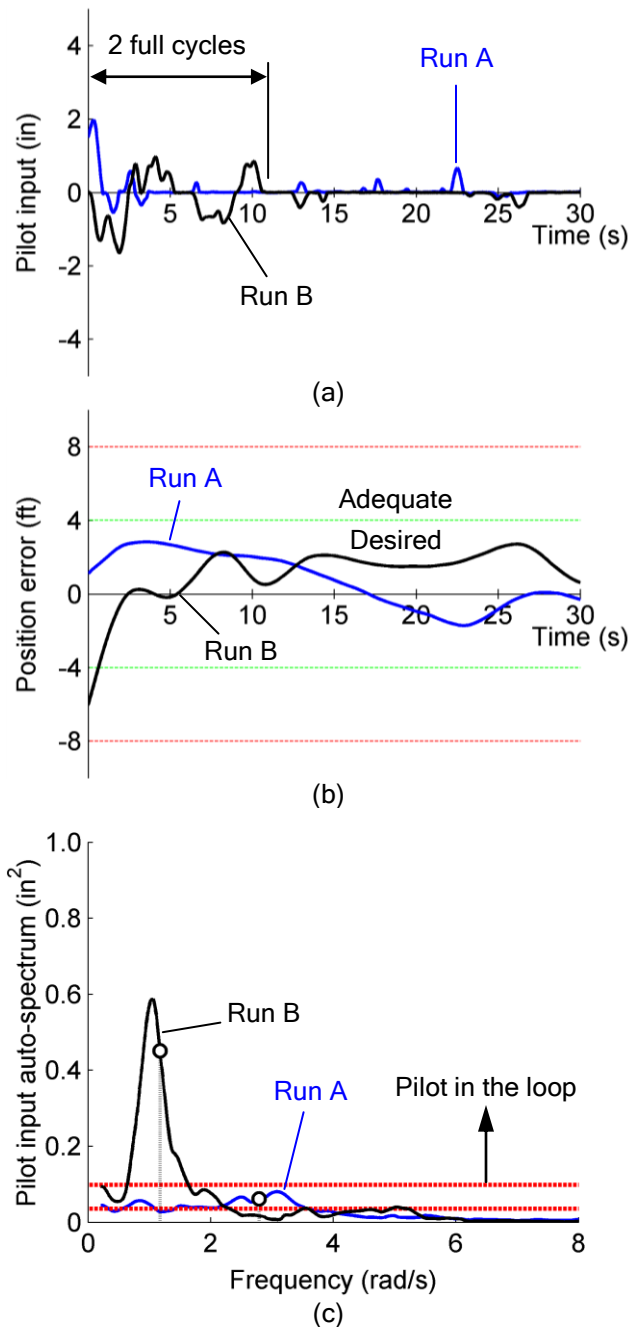


Figure 16. Comparison of different compensation levels in hover hold sub-task (3 rad/s actuator, same pilot), (a) input time history, (b) position error time history, and (c) input spectral analysis

Summary

Results were shown for a baseline nacelle-only actuated TRC architecture configured with varying nacelle actuator bandwidths (3, 4, 8 and 16 rad/s). Also, for the low bandwidth nacelle actuator, which showed consistent Level 2 handling qualities in the baseline form, several options aimed at quickening the response to improve the handling qualities were explored. A simple approach included the evaluation of

a quicker rise time in the command model. A more sophisticated approach involved the use of longitudinal cyclic rotor actuation to enhance the initial response. Finally, a set of control/response sensitivities and equivalent rise times were configured with the 8 rad/s actuator to investigate their influence independently of the effects of low bandwidth actuation.

A frequency-domain characterization of the closed-loop TRC response dynamics in terms of phase bandwidth and delay of the position response, X/δ_{lon} , was adopted. Varying actuator bandwidth was seen to be effectively characterized by the phase delay of the X/δ_{lon} frequency response. Response quickening by means of longitudinal cyclic control was shown to have conferred phase delay improvements of about 200 ms over the baseline configurations. Also, equivalent TRC rise times correlated directly with the phase bandwidth of the X/δ_{lon} frequency response, with 2.5 s and 5.0 s rise times resulting in 0.36 and 0.2 rad/s bandwidths, respectively. It should be noted that all control system configurations were designed to meet the current ADS-33 TRC design criteria in terms of the equivalent rise time for Level 1 handling qualities.

The task bandwidth for a TRC response type was hypothesized to be up to 1.2 rad/s, potentially, based on the deceleration requirements imposed by the Hover MTE. This result is emphasized because in its light, the TRC response phase bandwidth is found to be inherently low. The importance of phase delay is therefore, much more significant as it was considered very likely that pilots would be operating beyond the installed bandwidth.

Evaluated against a revised version of the Hover MTE, longitudinal phase delay showed the Level 1 boundary is around 0.4-0.5 s. Accordingly, Level 1 handling qualities were achieved either with a nacelle actuator bandwidth greater than 4 rad/s, or by employing longitudinal cyclic control to augment low bandwidth nacelle actuation. Additionally, the 0.36 rad/s X/δ_{lon} phase bandwidth showed beneficial handling qualities effects over the 0.2 rad/s configurations.

Conclusions

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

- Nacelle actuator bandwidths above 4 rad/s confer Level 1 handling qualities for the baseline nacelle-only TRC implementation.
- Augmentation of the nacelle-only TRC through the use of longitudinal cyclic was shown to be a viable solution for reducing the nacelle actuator bandwidth requirements by facilitating: (1) a reduction in longitudinal response phase delay and (2) nacelle rate-limiting prevention.

- A frequency-domain characterization of the closed-loop TRC position response based on X/δ_{lon} , in the context of this minimal-attitude TRC implementation, is a strong candidate handling qualities design metric, correlating well with the ratings.
 - The Level 1 handling qualities boundary is around 0.4-0.5 s of phase delay.
 - The TRC response phase bandwidth, measured from X/δ_{lon} and determined by the ADS-33 equivalent rise time requirements, is inherently low for the given task bandwidth defined by the deceleration component of the Hover MTE.
- An optimal 10 ft/s/in control/response gradient was found to confer Level 1 handling qualities whereas both higher (15 ft/s/in) and lower (5 ft/s/in) gradients conferred only Level 2 handling qualities. These results agree qualitatively with ADS-33 but suggest slightly higher gradients are needed.

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