High-Speed Rotorcraft Pitch Axis Response Type Investigation

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ABSTRACT

This paper presents a systematic investigation of high-speed rotorcraft pitch-axis response types, command models, and handling-qualities specifications. The investigation was done using two Future Vertical Lift-relevant rotorcraft configurations—a lift offset coaxial helicopter with a pusher propeller and a tiltrotor. Five response types were investigated, consisting of: a pitch rate-command/attitude-hold response type typically used for rotorcraft, a pitch rate-command/attitude-hold response type using a higher-order command model based on the conventional airplane pitch rate transfer function, a normal acceleration/angle-of-attack hold response type, a flight path rate command/flight path hold response type, and a "blended" flight path rate command response type which varies the command model bandwidth based on stick input size. Designs of varying levels of pitch attitude bandwidth, flight path bandwidth, control anticipation parameter, and pitch attitude dropback were evaluated in a piloted simulation experiment conducted at the Penn State Flight Simulator facility using two high-speed Mission Task Elements. The results of the piloted simulation suggest that both the pitch attitude bandwidth and the pitch attitude dropback requirements must be met for Level 1 handling qualities. In addition, the current fixed-wing boundary for pitch attitude dropback appears to be too loose for high speed rotorcraft, and should be tightened to better match with pilot ratings. A set of recommended specifications and associated updated Level boundaries is provided in the Appendix.

NOTATION

Symbols

α	Angle of attack [deg]
$\dot{}$	Derivative with respect to time
γ	Flight path angle [deg]
DB_θ	Pitch attitude dropback [deg]
ω	Natural frequency [rad/sec]
τ	Time constant or time delay [sec]
θ	Pitch attitude [deg]
φ	Frequency response phase angle [deg]
ζ	Damping ratio [-]
g	Acceleration due to gravity [ft/sec^2]
K	Gain
n_z	Normal acceleration [g]
T_γ	Flight path lag [sec]
T_{θ_2}	Flight path-attitude lag [sec]
V	Airspeed [kts]

Subscripts

BW	Bandwidth
cm	Commanded response
lon	Longitudinal
sp	Short period
s	Pilot stick input

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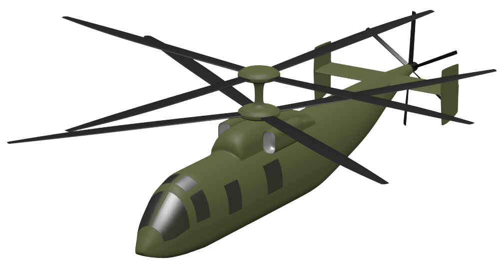
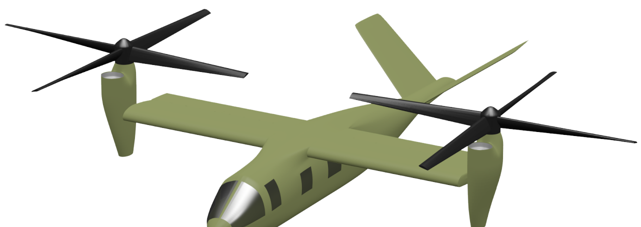
INTRODUCTION

With the development of advanced high-speed rotorcraft, through the U.S. Army Future Vertical Lift (FVL) modernization priority, new high-speed handling-qualities requirements are needed to ensure safe and low-workload piloting in the transition and high-speed regimes. The U.S. Army Combat Capabilities Development Command (DEVCOM) Aviation & Missile Center (AvMC) has developed high-fidelity flight-dynamics models of generic FVL configurations to provide the government with independent control-system design, handling-qualities analysis, and simulation research capabilities for advanced high-speed rotorcraft. Two of these generic models are a lift offset coaxial helicopter with compound thrust pusher propeller (herein referred to as *coaxial-pusher*) and a *tiltrotor* aircraft. The two generic aircraft models are representative of the FVL Capabilities Set #3 (Ref. 1), or Future Long Range Assault Aircraft (FLRAA) category. The models were developed using the comprehensive rotorcraft simulation code HeliUM (Refs. 2, 3), and are described in detail in Ref. 4. The models are generic in nature and not meant to represent specific aircraft. A rendering of the models is shown in Fig. 1. Reference 5 provides an overview of the modeling, control system design, and handling qualities research done for the coaxial-pusher and tiltrotor aircraft.



(a) Coaxial-pusher



(b) Tiltrotor

Fig. 1. Generic aircraft schematics.

A set of full-flight envelope control laws were previously developed and tested in piloted simulation for both aircraft (Refs. 6, 7). The control laws provided a Rate-Command/Attitude-Hold (RCAH) response type in the pitch axis at hover, low-, and mid-speed, and a normal acceleration command/angle-of-attack hold response type in the pitch axis at high-speed (Ref. 6). The control laws were tuned to meet Level 1 ADS-33E Target Acquisition & Tracking requirements to highlight the maneuverability and agility of both configurations.

In addition, a flight path rate command/flight path hold response type was also previously investigated (Ref. 7). Based on pilot feedback and handling qualities ratings, it was determined that pilots preferred the pitch RCAH response type for pitch pointing tasks, and the flight path rate command response type for gross maneuvering (Ref. 7). However, pilots described the pitch RCAH response type as "over-damped" and "sluggish" (Refs. 6, 7), even though it met Level 1 ADS-33E quantitative requirements.

Based on these previous results, this paper discusses a systematic variation of quantitative handling-qualities metrics (e.g., bandwidth, phase delay, etc.) for each response type, to explore the trade-offs and determine specification suitability and Level boundary locations. The different designs were tested in a fixed-based piloted handling-qualities simulation experiment that was carried out at the Pennsylvania State University (PSU) Flight Simulator facility. The evaluation consisted of two handling-qualities demonstration maneuvers tested at 180 kts flown by two Army experimental test pilots: Pitch Sum-of-Sines Tracking (Ref. 8) and Pitch Attitude Capture and Hold (Ref. 9). The results of the simulation experiment were used to determine the rotorcraft and fixed-wing pitch axis short-term requirements and boundaries that are applicable to high-speed rotorcraft.

The paper begins with a brief review of high-speed forward flight pitch-axis dynamics and short-term handling qualities specifications. Then the different response types and variations in the command models are described. Results for the simulation evaluation are provided for the two tasks for both coaxial-pusher and tiltrotor aircraft. Finally, a discussion of the results is provided along with conclusions and new proposed requirement boundaries where appropriate.

REVIEW OF FORWARD-FLIGHT SHORT-TERM PITCH DYNAMICS AND HANDLING QUALITIES

Dynamics

At high-speed forward flight, the dynamics of both coaxial-pusher and tiltrotor aircraft are similar to those of a typical fixed-wing aircraft (Ref. 4). In the mid-frequency range (short term response), the bare-airframe pitch rate q response to longitudinal input δ_{lon} is well represented by a first-over-second-order transfer function and time delay (Ref. 10):

$$\frac{q}{\delta_{\text{lon}}} = \frac{M_{\delta_{\text{lon}}}(s+1/T_{\theta_2})e^{-\tau_\theta s}}{(s^2+2\zeta_{\text{sp}}\omega_{\text{sp}}s+\omega_{\text{sp}}^2)} \tag{1}$$

while the bare-airframe normal acceleration n_z response to longitudinal input δ_{lon} is well represented by a zeroth-over-second-order transfer function and time delay (Ref. 10):

$$\frac{n_z}{\delta_{\text{lon}}} = \frac{n_{z_{\delta_{\text{lon}}}} e^{-\tau_{n_z} s}}{(s^2+2\zeta_{\text{sp}}\omega_{\text{sp}}s+\omega_{\text{sp}}^2)} \tag{2}$$

From Eqs. 1 and 2, it is clear that the normal acceleration response lags behind the pitch rate response by:

$$\frac{n_z}{q} = \frac{n/\alpha}{(s+1/T_{\theta_2})} \tag{3}$$

where the gain n/α is given by (Ref. 10):

$$\frac{n}{\alpha} = \frac{V}{gT_{\theta_2}} \tag{4}$$

The dynamic relationship in Eq. 3 also describes the flight path response γ to pitch attitude θ:

$$\frac{\gamma}{\theta} = \frac{1/T_{\theta_2}}{(s+1/T_{\theta_2})} \tag{5}$$

and hence T_{θ_2} is referred to as the *flight path-attitude lag*.

Figure 2 shows an example pitch attitude step response for the dynamics in Eqs. 1 and 2. The flight path response γ can be seen to lag behind the pitch attitude response θ by the flight path-attitude lag T_{θ_2}. The *flight path lag* T_γ shown on the figure is given from the first-order approximation (Ref. 10) of Eq. 2 as:

$$T_\gamma = \frac{2\zeta_{sp}}{\omega_{sp}} \tag{6}$$

and is a measure of the speed, or bandwidth, of the flight path response.

The pitch attitude response can be seen to have some overshoot before settling to its steady-state value due to the zero $(1/T_{\theta_2})$ in the numerator of the pitch rate transfer function (Eq. 1). This overshoot is referred to as pitch attitude dropback (Ref. 11), and is indicated as DB_θ in Fig. 2.

Note that since T_{θ_2} is in the numerator of the bare-airframe response it cannot be changed with feedback to a single control input. Therefore, given a value of T_{θ_2}, any attempt to reduce flight path lag T_γ (or equivalently increase flight path bandwidth ω_{BW_γ}) will result in increased pitch attitude dropback.

Handling Qualities Metrics

Rotorcraft The primary short-term handling-qualities criterion for rotorcraft response to pilot input is the attitude bandwidth requirement (Ref. 12). As with most requirements in ADS-33E, there are several different sets of Level boundaries for the forward flight pitch attitude bandwidth requirement based on the level of required agility (Target Acquisition & Tracking vs. All Other MTEs), operational environment (visual meteorological conditions, VMC vs. instrument meteorological conditions, IMC), and pilot attention (fully attended vs. divided attended).

The bandwidth requirement was originally developed for fixed-wing aircraft with direct force control (Ref. 13) and shortly thereafter adopted for rotorcraft (Ref. 14) and included in the Army's rotorcraft handling qualities specification, ADS-33. The bandwidth frequency ω_{BW} is defined as the: "lowest frequency for which the (open-loop) phase margin is at least 45 deg and the gain margin is at least 6 dB" (Ref. 13). Note that here, "open-loop" refers to the pilot-vehicle system, and the bandwidth is assessed for the augmented or closed-loop aircraft attitude response.

Table 1. Comparison Between MIL-STD-1797B Category/Class and ADS-33E Category/Agility Level

MIL-STD-1797B	ADS-33E
Category A	Target Acquisition & Tracking
Category B	All Other MTEs - VMC and Fully Attended Operations
Category C	All Other MTEs - IMC and/or Divided Attended Operations
Class I	Scout (Target Acquisition & Tracking Agility)
Class II	Utility (Aggressive Agility)
Class III	Cargo (Moderate Agility)
Class IV	Attack (Target Acquisition & Tracking Agility)

A second parameter used in the requirement is the phase delay τ_p, which relates to the slope of the attitude response phase curve above the frequency at which the phase curve crosses $\varphi = -180$ deg, and is a measure of total equivalent time delay between pilot input and aircraft response.

In addition to the pitch attitude bandwidth requirement, ADS-33E also includes a flight path control requirement. The requirement gives a lower limit on the frequency at which the vertical rate response (or equivalently, the flight path response) lags behind the pitch attitude response by $\Delta\varphi = 45$ deg (with the Level 1/Level 2 boundary at $\omega = 0.4$ rad/sec and the Level 2/Level 3 boundary at $\omega = 0.25$ rad/sec). From the relationship between flight path and pitch attitude shown in Eq. 5, it can be seen that this is a requirement on the maximum allowable value of flight path-attitude lag T_{θ_2}, with the Level 1/Level 2 boundary corresponding to $T_{\theta_2} = 2.5$ sec and Level 2/Level 3 boundary corresponding to $T_{\theta_2} = 4$ sec.

Fixed-Wing The current fixed-wing handling qualities specification, MIL-STD-1797B (Ref. 15), provides a number of alternate short-term pitch-axis handling-qualities requirements. Like ADS-33E, the requirements in MIL-STD-1797B typically have different sets of Level boundaries based on the aircraft Class and flight phase Category. Table 1 shows a rough comparison between the aircraft Class and flight phase Category as defined in MIL-STD-1797B and the rotorcraft category and required agility level as defined in ADS-33E.

The first set of MIL-STD-1797B short-term pitch-axis handling-qualities requirements are based on the equivalent modal parameters, as determined from a lower-order equivalent systems (LOES) fit to the closed-loop aircraft response (Ref. 16). These LOES-based requirements are limited in application to conventional response types, since they are based on open-loop databases.

One of the LOES criteria in MIL-STD-1797B is based on the Control Anticipation Parameter (CAP), which is defined as the ratio of the initial pitch acceleration to steady state normal acceleration:

$$\text{CAP} = \frac{\ddot{\theta}(0)}{n_{z_{ss}}} \tag{7}$$

From Eqs. 1–4, it can be seen that:

$$\text{CAP} = \frac{M_{\delta_{\text{lon}}}}{n_{z_{\delta_{\text{lon}}}}/\omega_{\text{sp}}^2} = \frac{\omega_{\text{sp}}^2}{\frac{V}{g}\frac{1}{T_{\theta_2}}} \tag{8}$$

The CAP requirement captures both the high-frequency gain of pitch acceleration, which is important in fine tracking tasks, and the steady-state gain of normal load factor, important in gross or outer loop tasks (Ref. 15).

In addition to the LOES-based requirements, MIL-STD-1797B also contains a pitch attitude bandwidth requirement and a transient flight-path response to pitch attitude change, or flight path bandwidth, requirement. The MIL-STD-1797B pitch attitude bandwidth requirement is more stringent than the ADS-33E version, both in terms of the required bandwidth value and the allowable phase delay.

There is also a time-domain requirement based on the pitch attitude dropback parameter DB_θ (Ref. 11). Pitch attitude dropback is shown in Fig. 2, and its value relative to the steady state pitch rate q_{ss} is given by (Ref. 15) as:

$$\frac{\text{DB}_\theta}{q_{\text{ss}}} = \left(T_{\theta_2} - \frac{2\zeta_{\text{sp}}}{\omega_{\text{sp}}}\right) \tag{9}$$

Note that in Eq. 9, the dropback is referenced to the pitch attitude when the δ_{lon} input is removed, and not the peak pitch attitude value, as is used in the MIL-STD-1797B dropback specification to reduce the sensitivity of the results to time delay. However, Eq. 9 is still useful to understand the relationship between the different response parameters.

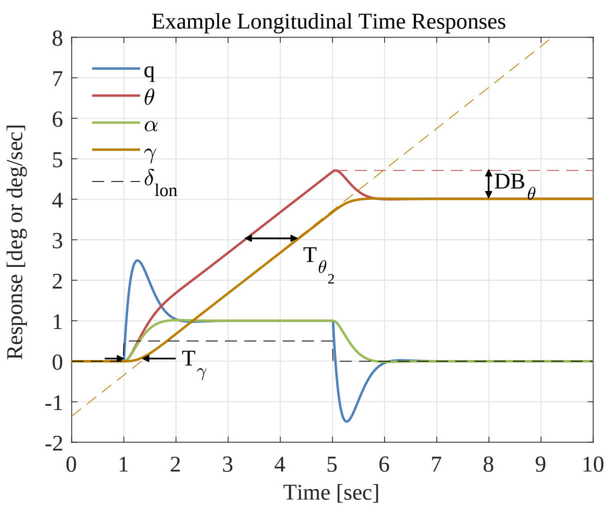


Fig. 2. Example pitch attitude step response time history showing definition of flight path-attitude lag T_{θ_2}, flight path lag T_γ, and pitch attitude dropback DB_θ.

VEHICLE MODELS AND CONTROL SYSTEM OVERVIEW

Flight Dynamics Models

The flight dynamics models of the lift offset coaxial-pusher and tiltrotor configurations were developed using HeliUM-A, the DEVCOM AvMC in-house flight-dynamics modeling software tool developed as an extension to the University of Maryland HeliUM simulation model (Refs. 2, 3). HeliUM-A uses a finite-element approach to model flexible rotor blades with coupled nonlinear flap/lag/torsion dynamics to capture structural, inertial, and aerodynamic loads along each blade segment, a key requirement for these advanced rotorcraft configurations. Blade, wing, and fuselage aerodynamics come from nonlinear lookup tables, and the rotor airwakes are modeled using a dynamic inflow model.

The models are generic and are not meant to represent specific industry designs. Both aircraft have gross weights of roughly 32,000 lbs and fall into the FVL Capabilities Set #3, or Future Long Range Assault Aircraft (FLRAA) category. The flight dynamics of both aircraft are modeled from hover to $V = 300$ kts, however, the maximum airspeeds of the models are limited to $V_{\text{H}} = 240$ kts for the coaxial-pusher and $V_{\text{H}} = 280$ kts for the tiltrotor using notional engine models. Reference 4 describes the models in detail.

Linear state-space point models and trim data were extracted from HeliUM-A at a range of airspeeds and altitudes. The linear models contain the rigid body states, the first two blade modes for each rotor (modeled as one collective, two cyclic, and one reactionless second-order rotor states), three (average, cosine, and sine) inflow states per rotor, as well as a pusher propeller inflow state for the coaxial-pusher and second-order nacelle angle dynamics for the tiltrotor. Overall the coaxial-pusher linear models contain 48 states and the tiltrotor linear models contain 51 states.

The linear point models were used to develop the flight control systems. Furthermore, the point models and trim data were combined to form continuous full-flight envelope quasi-linear parameter varying (qLPV) stitched simulation models (Ref. 17). These models were suitable for real-time simulation, and they formed the basis of the simulation models used in the experiment described here.

As discussed earlier, the flight path-attitude lag parameter T_{θ_2} is the time in seconds that the flight path γ response of the aircraft lags behind the pitch attitude θ response. This parameter is a function of the bare-airframe and cannot be changed using feedback to one control input alone. Figures 3 and 4 show the values of flight path-attitude lag T_{θ_2} for the coaxial-pusher and tiltrotor, respectively, as a function of airspeed and nacelle angle (tiltrotor only). Overall, the coaxial-pusher has lower values of T_{θ_2}, especially in the mid-airspeed range ($V = 100-200$ kts) as compared to the tiltrotor in airplane mode ($\delta_{\text{nac}} = 0$ deg). This is consistent with the findings of Cameron and Padfield (Ref. 18), who noted that large pitch rate overshoot is more severe in tiltrotors than conventional fixed- or rotary-wing aircraft due to proprotors making positive contributions to both the pitch damping derivative M_q and the static stability derivatives M_w, resulting in large values of T_{θ_2}.

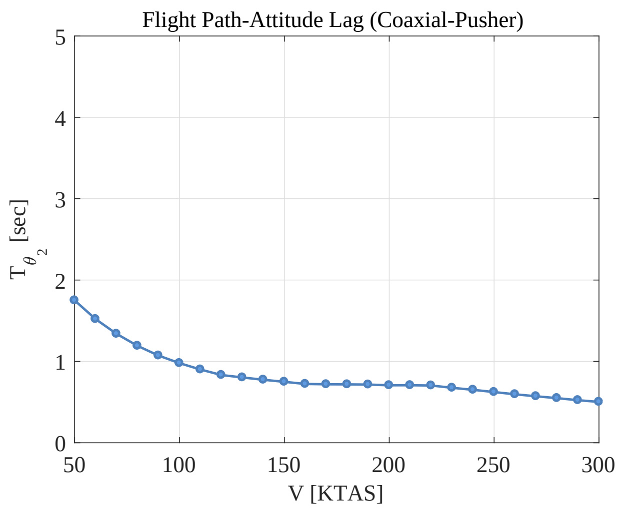


Fig. 3. Bare-airframe flight path-attitude lag T_{θ_2} values (coaxial-pusher).

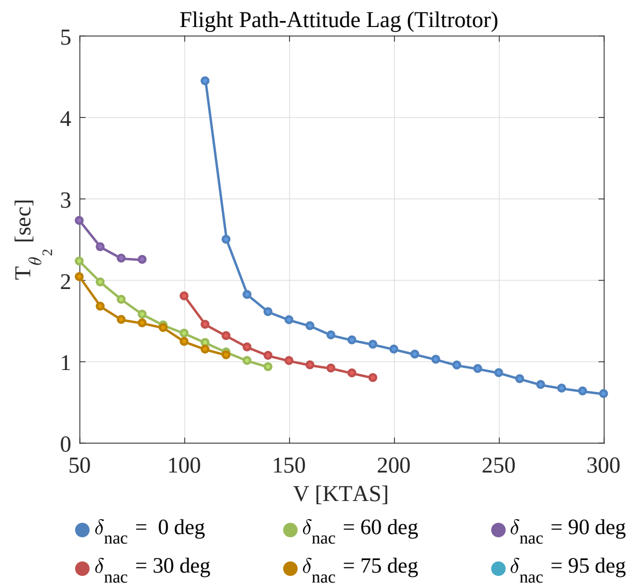


Fig. 4. Bare-airframe flight path-attitude lag T_{θ_2} values (tiltrotor).

Inner-Loop Control Systems

The inner-loop control laws of both aircraft are described in detail in Ref. 6. A common explicit model following (EMF) control system architecture was used for both aircraft, and the parameters of the control system were optimized using the Control Designer's United Interface (CONDUIT®, Ref. 19) to meet a common comprehensive set of stability, handling qualities, and performance specifications. For handling qualities specification from ADS-33E, boundaries for Target Acquisition & Tracking were used to highlight the maneuverability and agility of both configurations.

In the pitch axis, a Rate-Command/Attitude-Hold (RCAH) response type is used between hover and $V = 200$ kts, with a first-order command model given by:

$$\frac{q_{\text{cm}}}{\delta_{\text{lon}_\text{s}}} = \frac{K_{\text{lon}_\text{cm}}}{(s + 1/\tau_{\text{lon}_\text{cm}})} \tag{10}$$

Above $V = 200$ kts, the response type changes to stability axes normal acceleration n_z command with angle of attack α hold, using a second-order command model given by:

$$\frac{n_{z\text{cm}}}{\delta_{\text{lon}_\text{s}}} = \frac{K_{\text{lon}_\text{cm}}}{(s^2 + 2\zeta_{\text{lon}_\text{cm}}\omega_{\text{lon}_\text{cm}} + \omega^2_{\text{lon}_\text{cm}})} \tag{11}$$

Figure 5 shows the handling qualities ratings collected for both aircraft in two previous piloted simulation experiments (Refs. 6, 7) for the inner-loop pitch RCAH and n_z-command response types using the Pitch Attitude Capture and Hold (PACH) and Pitch Sum-of-Sines Tracking (Pitch SOS) tasks. For both aircraft, pilots preferred the pitch RCAH response type for the attitude capture task and the n_z-command response type for the tracking task, with the difference more pronounced in the case of the tiltrotor (with its higher value of T_{θ_2}).

Outer-Loop Control Systems

Outer-loop control laws to control airspeed and flight path angle/climb rate were also developed for both aircraft, and are described in detail in Ref. 7. A dynamic inversion (DI) control system architecture was used for the outer-loop control laws, which was tuned to meet a common comprehensive set of outer-loop stability, handling qualities, and performance specifications using CONDUIT®.

With the outer-loops engaged, the inner-loop pitch axis command model was switched from the RCAH command model in Eq. 10 to an Attitude-Command/Attitude-Hold (ACAH) command model given by:

$$\frac{\theta_{\text{cm}}}{\theta_{\text{cm}_\text{OL}}} = \frac{\omega^2_{\text{lon}_\text{cm}}}{(s^2 + 2\zeta_{\text{lon}_\text{cm}}\omega_{\text{lon}_\text{cm}} + \omega^2_{\text{lon}_\text{cm}})} \tag{12}$$

where $\omega_{\text{lon}_\text{cm}} = 10$ rad/sec and $\zeta_{\text{lon}_\text{cm}} = 1$ for the coaxial-pusher and 0.7 for the tiltrotor. These values for frequency and damping were chosen to ensure the inner loop was a fast enough actuator for the outer loop based on the outer-loop crossover frequency of $\omega_c = 1$ rad/sec, and to ensure that the inner-loop pitch axis stability margins did not degraded into Level 2 with the outer loops closed.

For the outer-loop control laws above $V = 40$ kts, longitudinal stick commands flight path rate $\dot{\gamma}$ using a first order command model:

$$\frac{\dot{\gamma}_{\text{cm}}}{\delta_{\text{lon}_\text{s}}} = \frac{K_{\text{lon}_\text{cm}}}{(s + 1/\tau_{\text{lon}_\text{cm}})} \tag{13}$$

Figure 5 shows the outer-loop handling qualities ratings previously gathered for the Pitch Attitude Capture and Hold (PACH) and Pitch Sum-of-Sines Tracking (Pitch SOS) tasks

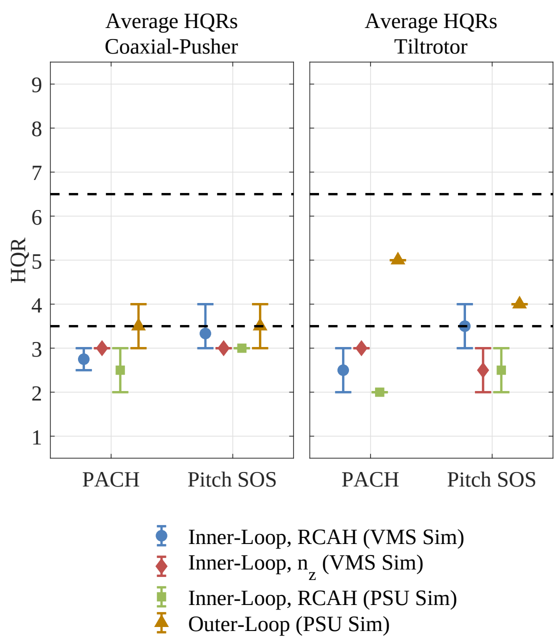


Fig. 5. Previously collected pilot handling qualities ratings (HQRs) for inner- and outer-loop response types (coaxial-pusher and tiltrotor, Refs. 6 and 7).

(Ref. 7). For both aircraft, pilots preferred the inner-loop response types over the outer-loop response types for both attitude capture and tracking tasks, with the difference more pronounced in the case of the tiltrotor (with its higher value of T_{θ_2}). It should be noted that pilots did prefer the outer-loop response type and hold modes for gross maneuvering tasks (Break Turn, High-Speed Acceleration/Deceleration, and formation flying) not shown here (Ref. 7).

The following pitch axis command model variations were chosen to further explore the reasons for these HQR differences.

PITCH AXIS COMMAND MODEL VARIATIONS

For the handling qualities experiment described in this paper, several different pitch axis response types and command models were investigated using both the inner- and outer-loop control laws described above. The variations consist of:

1. Pitch rate command using first-order command model (inner-loop)
2. Pitch rate command using higher-order command model (inner-loop)
3. Normal acceleration command (inner-loop)
4. Flight path rate command using first-order command model (outer-loop)
5. Flight path rate command using blended command model (outer-loop)

This section provides the details of the different command models and parameter variations tested in the simulator.

Rate Command First Order

The nominal inner-loop pitch axis command model for the RCAH response type is a first-order system given in Eq. 10. Assuming good model following, the closed-loop aircraft pitch rate response q to pilot input $\delta_{\mathrm{lon_s}}$ will track the command model:

$$\frac{q}{\delta_{\mathrm{lon_s}}} = \frac{K_{\mathrm{lon_{cm}}} e^{-\tau_\theta s}}{(s+1/\tau_{\mathrm{lon_{cm}}})} \tag{14}$$

with the additional time delay τ_θ accounting for the actual closed-loop response time delay.

The normal acceleration response to pilot input is then determined through the kinematic relationship in Eq. 3 as:

$$\frac{n_z}{\delta_{\mathrm{lon_s}}} = \frac{(K_{\mathrm{lon_{cm}}} V/gT_{\theta_2}) e^{-\tau_{n_z} s}}{(s+1/\tau_{\mathrm{lon_{cm}}})(s+1/T_{\theta_2})} \tag{15}$$

Figure 6 shows the characteristics of the pitch rate and normal acceleration frequency responses, as well as representative pitch attitude and flight path time histories to a step control input for the nominal inner-loop pitch axis command model (labeled as "q-RCAH (0/1)").

Pitch attitude bandwidth is a function of the pitch rate command model time constant $\tau_{\mathrm{lon_{cm}}}$ (as well as the overall closed-loop delay τ_θ), while the flight path bandwidth is a function of the flight path lag T_γ (Eq. 6). In this case, the flight path lag is given by:

$$T_\gamma = \tau_{\mathrm{lon_{cm}}} + T_{\theta_2} \tag{16}$$

and is seen to be constrained by the bare-airframe T_{θ_2} value.

Pitch attitude dropback is given by combining Eqs. 6, 9, and 16 as:

$$\frac{\mathrm{DB}_\theta}{q_{\mathrm{ss}}} = -\tau_{\mathrm{lon_{cm}}} \tag{17}$$

Note that dropback here is referenced to the pitch attitude when the stick input $\delta_{\mathrm{lon_s}}$ is removed, and not the peak pitch attitude value as is the convention in MIL-STD-1797B, which results in negative values of dropback being possible. From Eq. 17, it is clear that no possible tuning of the first-order pitch axis command model shown in Eq. 10 will result in zero or positive values of dropback.

Negative values of dropback are associated with the pitch attitude continuing to drift after the stick input is removed, as demonstrated in Fig. 7. Gibson (Ref. 11) notes that using this definition of dropback, negative values are associated with sluggish responses in flight path control and tracking. This is consistent with comments made by pilots that the inner-loop RCAH response was "too damped" and "sluggish" even though it met the ADS-33E Target Acquisition & Tracking pitch attitude bandwidth requirement (Refs. 6, 7).

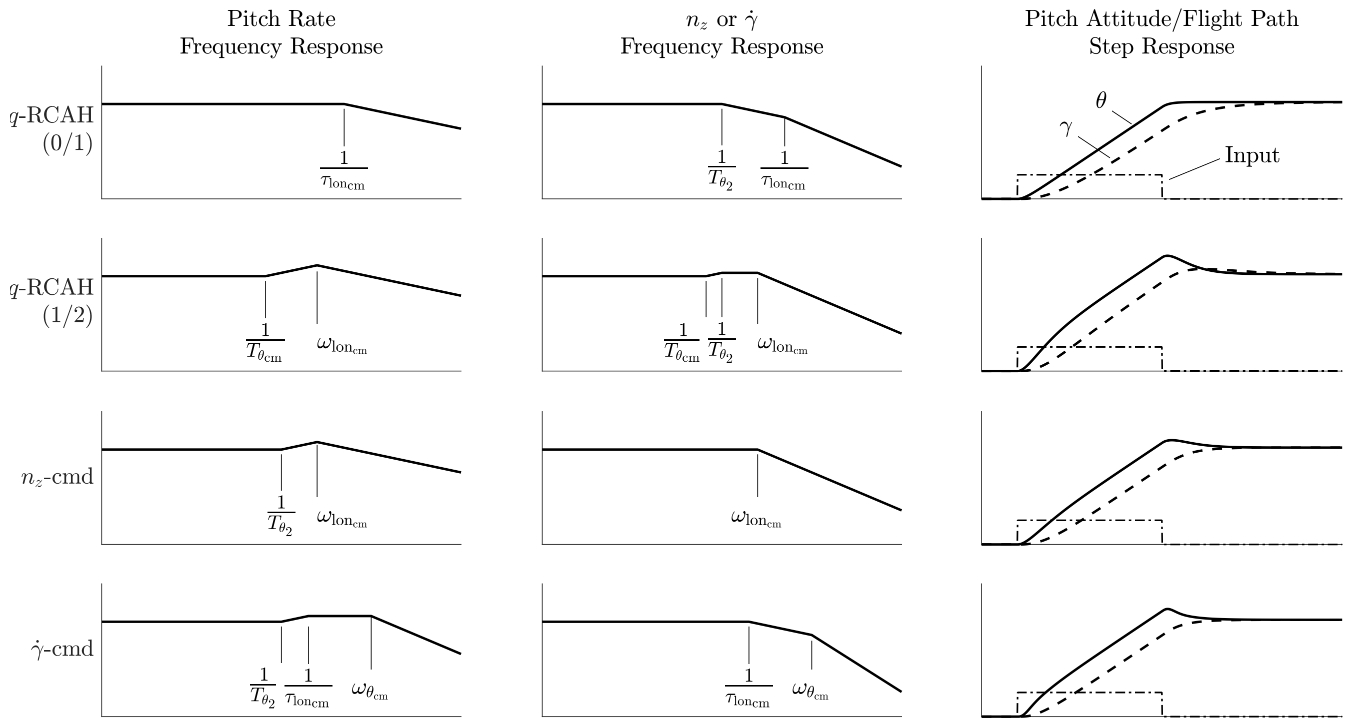


Fig. 6. Characteristics of pitch axis response types.

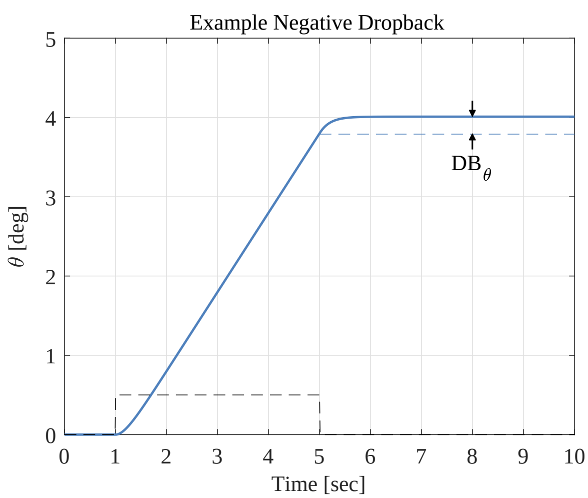


Fig. 7. Example pitch attitude step response time history showing definition of negative pitch attitude dropback DB$_\theta$.

Rate Command Higher-Order

The amount of negative dropback can be reduced (by decreasing the command model time constant $\tau_{\text{lon}_{\text{cm}}}$) but not eliminated with a first-order pitch rate command model. Therefore, a higher-order pitch rate command model was investigated, given by:

$$\frac{q_{\text{cm}}}{\delta_{\text{lon}_\text{s}}} = \frac{K_{\text{lon}_{\text{cm}}}(s+1/T_{\theta_{\text{cm}}})}{(s^2+2\zeta_{\text{lon}_{\text{cm}}}\omega_{\text{lon}_{\text{cm}}}s+\omega^2_{\text{lon}_{\text{cm}}})} \tag{18}$$

Assuming good model following, the closed-loop aircraft pitch rate and normal acceleration responses to pilot input $\delta_{\text{lon}_\text{s}}$ using the pitch rate command model in Eq. 18 are given by:

$$\frac{q}{\delta_{\text{lon}_\text{s}}} = \frac{K_{\text{lon}_{\text{cm}}}(s+1/T_{\theta_{\text{cm}}})e^{-\tau_\theta s}}{(s^2+2\zeta_{\text{lon}_{\text{cm}}}\omega_{\text{lon}_{\text{cm}}}s+\omega^2_{\text{lon}_{\text{cm}}})} \tag{19}$$

$$\frac{n_z}{\delta_{\text{lon}_\text{s}}} = \frac{(K_{\text{lon}_{\text{cm}}}V/gT_{\theta_2})(s+1/T_{\theta_{\text{cm}}})e^{-\tau_{n_z}s}}{(s^2+2\zeta_{\text{lon}_{\text{cm}}}\omega_{\text{lon}_{\text{cm}}}s+\omega^2_{\text{lon}_{\text{cm}}})(s+1/T_{\theta_2})} \tag{20}$$

The characteristics of the frequency and time responses for the higher-order pitch axis command model response type (labeled as "q-RCAH (1/2)") are shown Fig. 6.

Note that here, the normal acceleration response is first-over-third-order, which can result in undesirable "g creep" (Ref. 20) if $T_{\theta_{\text{cm}}}$ is set too far away from the bare-airframe T_{θ_2}.

The higher order command model used here can produce responses with lower flight path lag T_γ (or equivalently higher flight path bandwidth $\omega_{\text{BW}_\gamma}$), however this comes at the expense of increased pitch attitude dropback, as shown in Fig. 6.

Normal Acceleration Command

The normal acceleration command model, used in the inner-loop above $V = 200$ kts, is shown in Eq. 11. Assuming good model following, the closed-loop aircraft pitch rate and normal acceleration responses to pilot input δ_{lon_s} are given by:

$$\frac{q}{\delta_{\text{lon}_s}} = \frac{(K_{\text{lon}_{\text{cm}}} g T_{\theta_2}/V)(s+1/T_{\theta_2})e^{-\tau_\theta s}}{(s^2+2\zeta_{\text{lon}_{\text{cm}}}\omega_{\text{lon}_{\text{cm}}}s+\omega^2_{\text{lon}_{\text{cm}}})} \quad (21)$$

$$\frac{n_z}{\delta_{\text{lon}_s}} = \frac{K_{\text{lon}_{\text{cm}}} e^{-\tau_{n_z} s}}{(s^2+2\zeta_{\text{lon}_{\text{cm}}}\omega_{\text{lon}_{\text{cm}}}s+\omega^2_{\text{lon}_{\text{cm}}})} \quad (22)$$

The characteristics of the frequency and time responses for the normal acceleration command response type (labeled as "n_z-cmd") are shown Fig. 6.

Flight Path Rate Command First Order

The outer-loop flight path command model is given by Eq. 13. With the outer-loops engaged, the inner-loop pitch command model is given by Eq. 12. Then, assuming good model following, the closed-loop aircraft pitch rate and normal acceleration responses are given by:

$$\frac{q}{\delta_{\text{lon}_s}} = \frac{(K_{\text{lon}_{\text{cm}}}\omega^2_{\theta_{\text{cm}}} T_{\theta_2})(s+1/T_{\theta_2})e^{-\tau_\theta s}}{(s+1/\tau_{\text{lon}_{\text{cm}}})(s^2+2\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}}s+\omega^2_{\theta_{\text{cm}}})} \quad (23)$$

$$\frac{n_z}{\delta_{\text{lon}_s}} = \frac{(K_{\text{lon}_{\text{cm}}}\omega^2_{\theta_{\text{cm}}} V/g)e^{-\tau_{n_z} s}}{(s+1/\tau_{\text{lon}_{\text{cm}}})(s^2+2\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}}s+\omega^2_{\theta_{\text{cm}}})} \quad (24)$$

The characteristics of the frequency and time responses of the flight path rate command response type (labeled as "$\dot{\gamma}$-cmd") are shown Fig. 6. Note that even with the higher-order pitch rate and normal acceleration responses given in Eqs. 23 and 24, the pitch attitude and flight path step responses look conventional, although the pitch attitude dropback is sharper than the other cases.

Flight Path Rate Command Blended Command Model

Since having a quick flight path response results in large pitch attitude dropback for bare-airframes with large values of T_{θ_2}, a blended flight path command model was also investigated. The command model blends from a slower flight path response with less pitch attitude dropback for small stick inputs (associated with fine tracking) to a quicker flight path response with larger associated pitch attitude dropback for large stick inputs (associated with gross maneuvering).

Such a concept was previously used to blend a command path prefilter in a normal acceleration command controller and was investigated for short-range air-to-air combat maneuvers (Ref. 21). However the prefilter blending in Ref. 21 was done based on normal acceleration error instead of stick input magnitude, thus producing an undesirable feedback loop. Command model blending based on stick input magnitude has also previously been done to transition between attitude-command and rate-command modes (e.g., Refs. 22 and 23).

In this case, the nominal first-order flight path rate command model shown in Eq. 13 was used for large stick inputs. As can be seen from Eq. 23 and the lower row of plots in Fig. 6, this results in a certain amount of pitch attitude dropback.

Table 2. Flight Path Rate Blended Command Model Parameters

Parameter	$\lvert\delta_{\text{lon}_s}\rvert = 0$	$\lvert\delta_{\text{lon}_s}\rvert = 1$
k	$K_{\text{lon}_{\text{cm}}}$	$K_{\text{lon}_{\text{cm}}}$
a	T_{θ_2}	$\tau_{\text{lon}_{\text{cm}}}$
b	$1/(\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}})$	0

For small stick inputs, the flight path rate command model was selected as:

$$\frac{\dot{\gamma}_{\text{cm}}}{\delta_{\text{lon}_s}} = \frac{K_{\text{lon}_{\text{cm}}}(s+\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}})}{(s+1/T_{\theta_2})} \quad (25)$$

which assuming good model following, results in the following closed-loop aircraft pitch rate and normal acceleration responses:

$$\frac{q}{\delta_{\text{lon}_s}} = \frac{(K_{\text{lon}_{\text{cm}}}\omega^2_{\theta_{\text{cm}}} T_{\theta_2})(s+\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}})e^{-\tau_\theta s}}{(s^2+2\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}}s+\omega^2_{\theta_{\text{cm}}})} \quad (26)$$

$$\frac{n_z}{\delta_{\text{lon}_s}} = \frac{(K_{\text{lon}_{\text{cm}}}\omega^2_{\theta_{\text{cm}}} V/g)(s+\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}})e^{-\tau_{n_z} s}}{(s+1/T_{\theta_2})(s^2+2\zeta_{\theta_{\text{cm}}}\omega_{\theta_{\text{cm}}}s+\omega^2_{\theta_{\text{cm}}})} \quad (27)$$

which for values of $\zeta_{\theta_{\text{cm}}} \approx 1.0$ gives:

$$\frac{q}{\delta_{\text{lon}_s}} \approx \frac{(K_{\text{lon}_{\text{cm}}}\omega^2_{\theta_{\text{cm}}} T_{\theta_2})e^{-\tau_\theta s}}{(s+\omega_{\theta_{\text{cm}}})} \quad (28)$$

$$\frac{n_z}{\delta_{\text{lon}_s}} \approx \frac{(K_{\text{lon}_{\text{cm}}}\omega^2_{\theta_{\text{cm}}} V/g)e^{-\tau_{n_z} s}}{(s+\omega_{\theta_{\text{cm}}})(s+1/T_{\theta_2})} \quad (29)$$

The blended command model is implemented as shown in Fig. 8, with the parameters a, b, and k implemented in lookup tables as a functions of the magnitude of δ_{lon_s}. Table 2 shows the lookup table breakpoints, with the parameters linearly interpolated between no stick input ($|\delta_{\text{lon}_s}| = 0$) and full stick input ($|\delta_{\text{lon}_s}| = 1$).

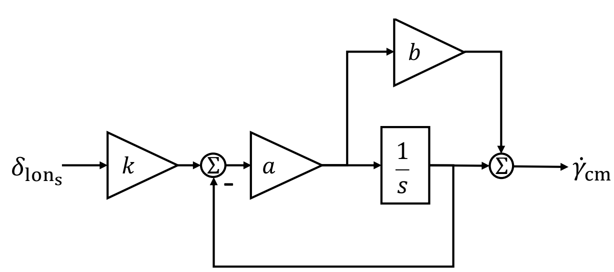


Fig. 8. Flight path rate blended command model.

Command Model Variations

This section discusses the specific command model variations that were tested for the coaxial-pusher and tiltrotor. The variations are grouped into "families" based on the command model type.

Coaxial-Pusher Configurations The parameters of the coaxial-pusher command models investigated are shown in Table 3. Figures 9 through 13 show where the designs lie on several handling qualities specifications. The hatch-marked lines on the specifications denote the Level boundaries.

There is no significant difference between any of the designs when evaluated against the ADS-33E flight path response to pitch attitude requirement (Fig. 13). In fact, the only difference seen is for Configuration 3, which was tested at a different airspeed, and therefore has a different bare-airframe value of T_{θ_2}. This demonstrates that this requirement is a function of the bare-airframe, and is not a good discriminator between different control system variations. Therefore, this specification was not included in the handling qualities simulation result analysis.

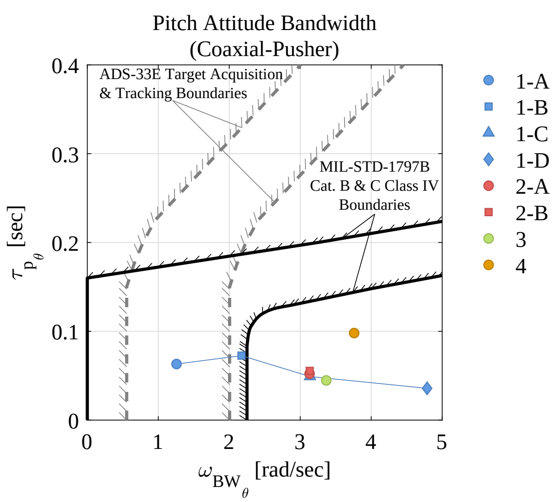


Fig. 9. Pitch attitude bandwidth values for command model variations (coaxial-pusher).

Family 1 was designed to span a range of pitch attitude bandwidth values (Fig. 9), with Configuration 1-C matching the baseline inner-loop pitch rate command model evaluated in Refs. 6 and 7. The designs in Family 1 also span a range of flight path bandwidth values as seen in Fig. 10. Since Family 1 uses a first-order pitch rate command model, all of the designs have negative dropback using the definition in Eq. 9, and zero dropback using the MIL-STD-1797B definition and shown in Fig. 11. Figure 12 shows the Control Anticipation Parameter (CAP) versus equivalent short period frequency ζ_{sp}. As seen in Eq. 15, the first-order pitch rate command model used in Family 1 results in equivalent $\zeta_{sp} > 1$.

Family 2 was designed using the higher-order pitch rate command model (Eq. 18). The parameters of the designs in Family 2 were chosen to have the same value of pitch attitude

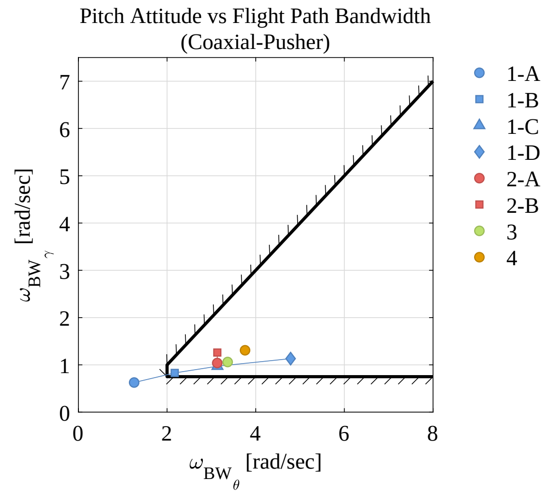


Fig. 10. Flight path versus pitch attitude bandwidth values for command model variations (coaxial-pusher).

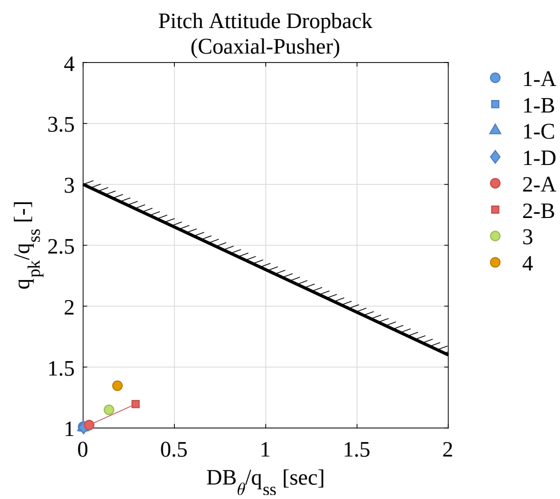


Fig. 11. Pitch attitude dropback values for command model variations (coaxial-pusher).

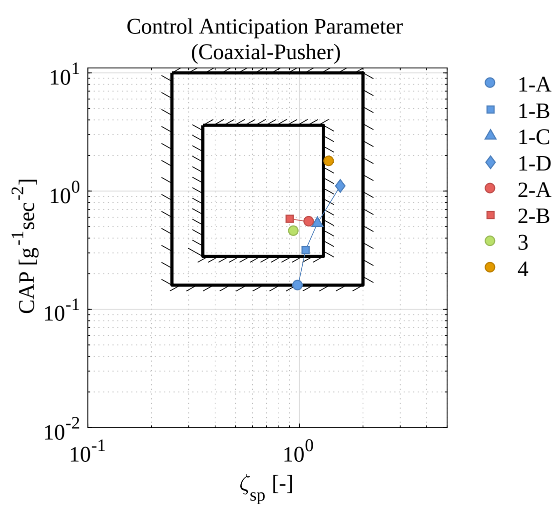


Fig. 12. Control anticipation parameters values for command model variations (coaxial-pusher).

Table 3. Command Model Configurations (Coaxial-Pusher)

Family	Response Type	Config.	$1/\tau_{\text{lon}_{\text{cm}}}$ [1/sec]	$\omega_{\text{lon}_{\text{cm}}}$ [rad/sec]	$\zeta_{\text{lon}_{\text{cm}}}$ [–]	$1/T_{\theta_{\text{cm}}}$ [1/sec]	$K_{\text{lon}_{\text{cm}}}$ [deg/sec/%]
1	q-RCAH	A	1.5	–	–	–	0.36
		B	3	–	–	–	0.36
		C	5	–	–	–	0.36
		D	10	–	–	–	0.36
2	q-RCAH	A	–	2.43	1	2	0.36
		B	–	3.16	1	1	0.36
3	n_z-cmd	–	–	3	1	–	0.25*
4	$\dot{\gamma}$-cmd	–	1.8	–	–	–	0.36

* Equivalent pitch rate command per stick displacement based on normal acceleration command per stick displacement evaluated at $V = 200$ kts

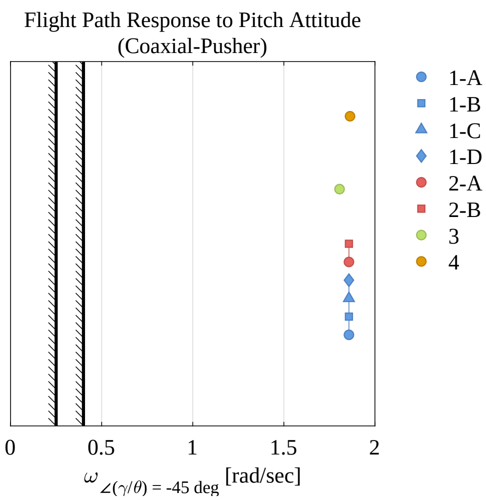


Fig. 13. Flight path response to pitch attitude values for command model variations (coaxial-pusher).

bandwidth as Configuration 1-C, but varying levels of flight path bandwidth (and therefore pitch attitude dropback). Figure 9 shows that the Family 2 designs all have the same pitch attitude bandwidth as Configuration 1-C, as designed. Figure 10 shows the increased flight path bandwidth of Configuration 2-B as compared to 2-A, and Fig. 11 shows the associated increased dropback of Configuration 2-B.

Finally, Family 3 consists of the normal acceleration command model tested in Ref. 6 and Family 4 of the flight path rate command model tested in Ref. 7.

Table 3 also lists the pitch command model gain $K_{\text{lon}_{\text{cm}}}$. Note that for the normal acceleration command design (Family 3), simulator evaluations were performed at an airspeed of $V = 220$ kts (while the rest were tested at $V = 180$ kts), and so the equivalent pitch rate per stick displacement was lower than the other designs (to maintain a common 2.5 g command limit).

No flight path rate blended command model testing was done with the coaxial-pusher configuration.

Tiltrotor Configurations The parameters of the tiltrotor command models investigated are shown in Table 4. In addition, Figs. 14 through 18 show where the designs lie on several of the handling qualities specifications. Note that as with the coaxial-pusher results above, there is no significant difference between any of the tiltrotor designs when evaluated against the ADS-33E flight path response to pitch attitude requirement (Fig. 18).

The tiltrotor command models were tuned similarly to the coaxial-pusher, as described above. For similar values of flight path bandwidth $\omega_{\text{BW}_\gamma}$, the tiltrotor designs have significantly higher values of pitch attitude dropback as compared to the coaxial-pusher designs. This is due to the tiltrotor's larger inherent flight path-attitude lag T_{θ_2}, as shown in Fig. 4.

The flight path rate blended command model was evaluated using the tiltrotor. Figures 19 and 20 show the variations in the resulting pitch attitude versus flight path bandwidth and dropback values for different input sizes. By design, flight path bandwidth and pitch attitude dropback are low for small magnitude inputs, and both parameters increase with increasing input magnitude. Figure 21 shows two comparisons of pitch attitude and flight path step responses for the baseline pitch RCAH inner loop design (Configuration 1-C), the baseline flight path rate command outer loop design (Configuration 4), and the blended flight path rate command outer loop design (Configuration 5) for two input magnitudes. For the small magnitude case ($|\delta_{\text{lon}_s}| = 0.05$) the blended outer loop design response matches the baseline inner loop response closely, with less pitch attitude dropback, but a slower flight path response. Conversely, for the large magnitude case ($|\delta_{\text{lon}_s}| = 0.9$) the blended outer loop design response matches the baseline outer loop response more closely, with a faster flight path response but more associated pitch attitude dropback.

Finally, Table 4 also lists the pitch command model gain $K_{\text{lon}_{\text{cm}}}$. Note that the tiltrotor command model gains were tuned slightly lower than the coaxial-pusher values (Table 3) due to the increased inherent pitch attitude dropback. In addition, as with the coaxial-pusher, the normal acceleration command design (Family 3) was evaluated at an airspeed of $V = 220$ kts, and so the equivalent pitch rate per stick displacement was lower than the other designs.

Table 4. Command Model Configurations (Tiltrotor)

Family	Response Type	Config.	$1/\tau_{lon_{cm}}$ [1/sec]	$\omega_{lon_{cm}}$ [rad/sec]	$\zeta_{lon_{cm}}$ [–]	$1/T_{\theta_{cm}}$ [1/sec]	$K_{lon_{cm}}$ [deg/sec/%]
1	q-RCAH	A	1.5	–	–	–	0.3
		B	3	–	–	–	0.3
		C	5	–	–	–	0.3
		D	10	–	–	–	0.3
2	q-RCAH	A	–	3.21	1	2	0.3
		B	–	2.53	1	1	0.3
		C	–	2.33	1	0.7	0.3
3	n_z-cmd	–	–	3	1	–	0.25*
4	$\dot{\gamma}$-cmd	–	3.9	–	–	–	0.3
5	$\dot{\gamma}$-cmd Blended	–	$0.82-3.9$	–	–	–	0.3

* Equivalent pitch rate command per stick displacement based on normal acceleration command per stick displacement evaluated at $V = 200$ kts

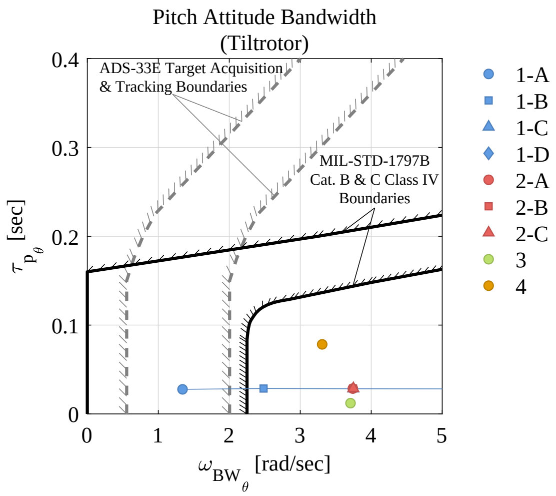


Fig. 14. Pitch attitude bandwidth values for command model variations (tiltrotor).

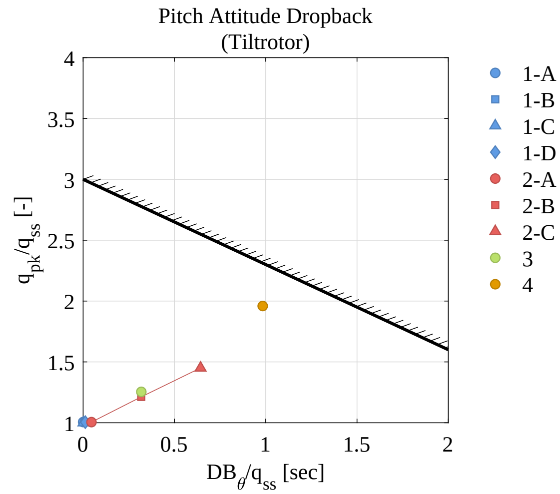


Fig. 16. Pitch attitude dropback values for command model variations (tiltrotor).

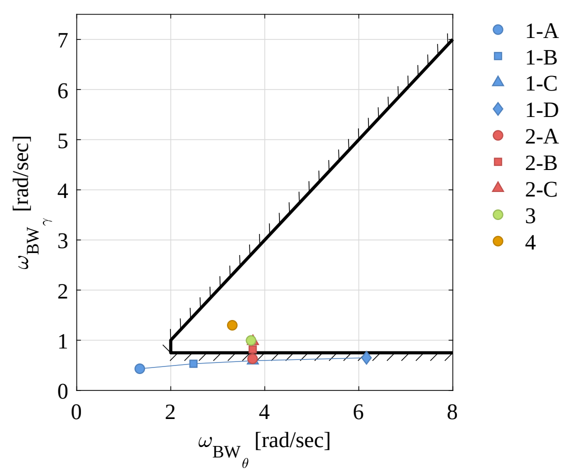


Fig. 15. Flight path versus pitch attitude bandwidth values for command model variations (tiltrotor).

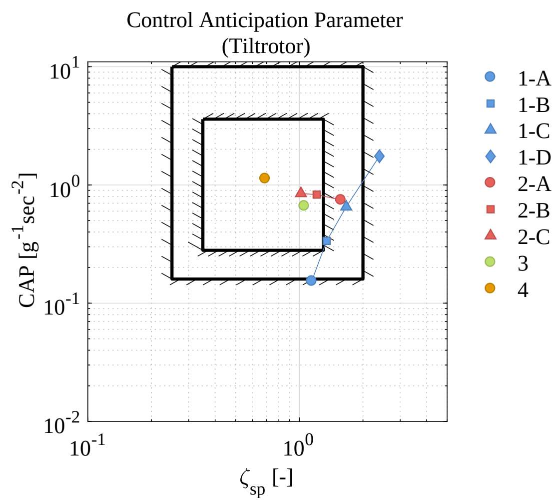


Fig. 17. Control anticipation parameters values for command model variations (tiltrotor).

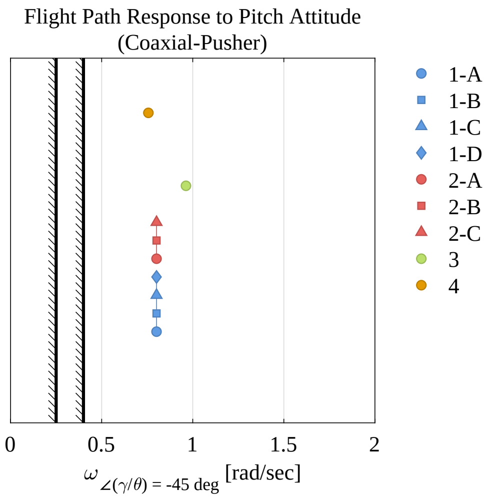


Fig. 18. Flight path response to pitch attitude values for command model variations (tiltrotor).

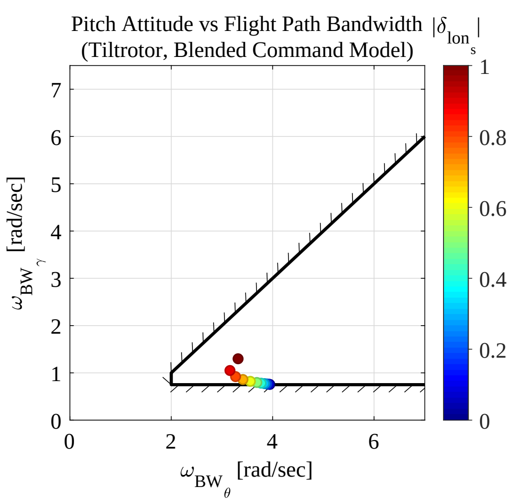


Fig. 19. Flight path versus pitch attitude bandwidth values for fight path rate blended command model (tiltrotor).

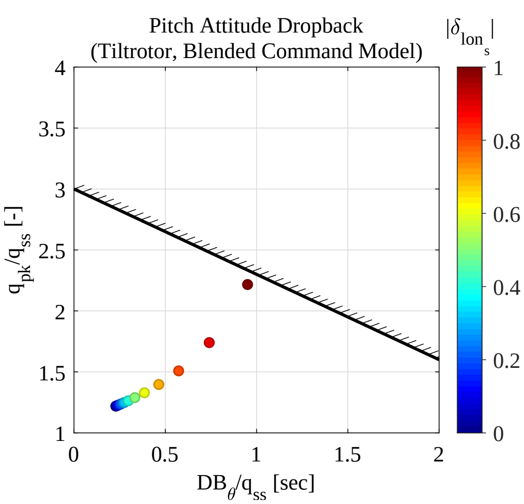


Fig. 20. Pitch attitude dropback values for fight path rate blended command model (tiltrotor).

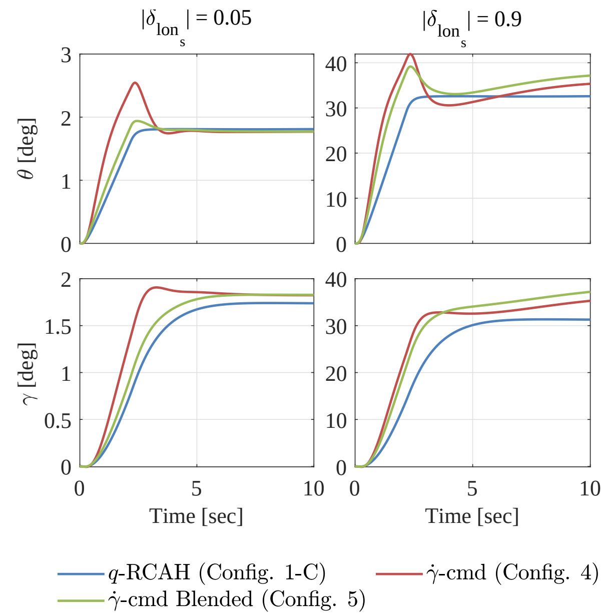


Fig. 21. Pitch attitude and flight path response comparison for q-RCAH (Inner Loop, Configuration 1-C), flight path rate command (Outer Loop, Configuration 4), and flight path rate blended command model (Outer Loop, Configuration 5) (tiltrotor).

HANDLING QUALITIES SIMULATION EXPERIMENTAL SETUP

The handling qualities experiment was conducted in the Pennsylvania State University (PSU) Flight Simulator facility. The simulator consists of a raised Bell Helicopter BA609 simulation cab and a 5 m diameter spherical screen which provides 210 deg horizontal field of view and 50 deg vertical field of view. The simulator has motion capabilities, but they were not exercised for this experiment (i.e., experiment was carried out fixed-based).

The inceptor configuration consisted of a passive sidestick attached on the right-hand side by the pilot seat, standard active pedals, and a standard active collective stick using pull-for-power logic. For the evaluations shown here, pilots were only required to make pitch axis inputs using the sidestick.

The experiment was done in two parts by two pairs of U.S. Army experimental test pilots (XPs). The first set of pilots rated Configurations 1-A,B,C,D, 2-A,B,C, and 4. Later, in a follow-on simulation experiment a different set of pilots looked specifically at the flight path rate blended response type and rated configurations 1-C, 4, and 5. Two of the pilots who participated in this simulation experiment also participated in the VMS simulation (Ref. 6) are were familiar with the tasks, aircraft models, and inner-loop control systems. One of the pilot also had experience flying the high-speed MTEs on a UH-60M Black Hawk (Ref. 24) and so was familiar with the tasks.

Two high-speed Mission Task Elements (MTEs) were used to evaluate the different response types and command model variations:

Pitch Sum-of-Sines Tracking (Ref. 8): Precision tracking task flown using a special display (shown in Fig. 22) driven by a reference attitude signal composed of a sum of sines. The objectives of this tasks are to evaluate handling qualities in a tight, closed-loop tracking task, evaluate the feel system, control sensitivity, and cross coupling, and identify any bobble or PIO tendencies. The Non-Aggressive version of the MTE was used in this test, in which the sum-of-sines frequency magnitudes are set via a second order Butterworth filter with a bandwidth of 0.65 rad/sec. In addition, the tracking signal RMS was set to 2.5 deg.

Pitch Attitude Capture and Hold (Ref. 9): Precision, non-aggressive maneuver flown using a special display (shown in Fig. 22) driven by a reference attitude signal composed of a series of step changes. The objectives of this tasks are to evaluate the ability to capture a desired attitude and identify maneuverability limitations, inceptor characteristics, cross coupling, and any PIO tendencies.

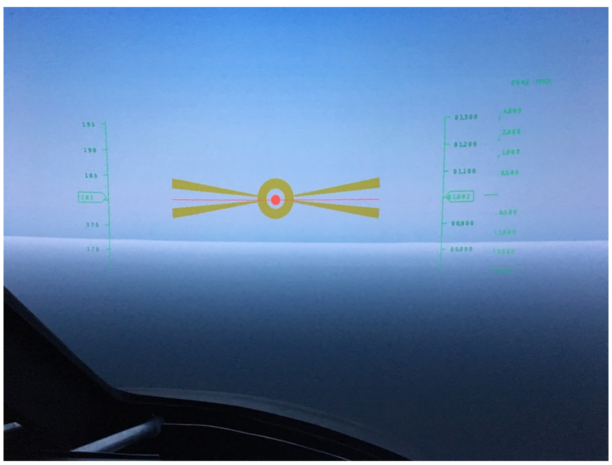


Fig. 22. Display for Pitch Sum-of-Sines Tracking and Attitude Capture and Hold tasks.

All testing was done at an airspeed of $V = 180$ kts, except for Configuration 3 (normal acceleration command response type), which was tested at $V = 220$ kts.

HANDLING QUALITIES RESULTS

The following sections show the Cooper-Harper Handling Qualities Ratings (HQRs) on several of the key specifications, first for the Pitch Sum-of-Sines Tracking task and then for the Pitch Attitude Capture and Hold task.

Pitch Sum-of-Sines Tracking

Figures 23 through 26 show the Pitch Sum-of-Sines Tracking task average HQRs on the pitch attitude bandwidth, flight path bandwidth, pitch attitude dropback, and CAP specifications.

As expected and can be seen in Fig. 23, cases with low pitch attitude bandwidth $\omega_{\mathrm{BW}_\theta}$ have Level 2 HQRs. The boundary between Level 1 and Level 2 ratings appears to match well with both the ADS-33E Target Acquisition & Tracking specification boundary plotted in dashed gray lines as well as the MIL-STD-1797B Category B & C, Class IV (analogous to ADS-33E Target Acquisition & Tracking, Table 1) boundaries plotted in solid black lines. Note that the MIL-STD-1797B Category A boundaries, which are also analogous to ADS-33E Target Acquisition & Tracking, are more stringent and not shown here.

Furthermore, meeting the bandwidth requirement alone does not guarantee Level 1 ratings. Cases that meet the pitch attitude bandwidth, flight path bandwidth, and CAP requirements but still have Level 2 ratings can be seen to have a large amount of pitch attitude dropback (Fig. 25). This is consistent with the fixed-wing findings of Ref. 25 which showed that a combination of the both the pitch attitude bandwidth and pitch attitude dropback criteria are highly effective in defining handling qualities for both pitch attitude and flight path control for all airplane Classes and all flight phase Categories.

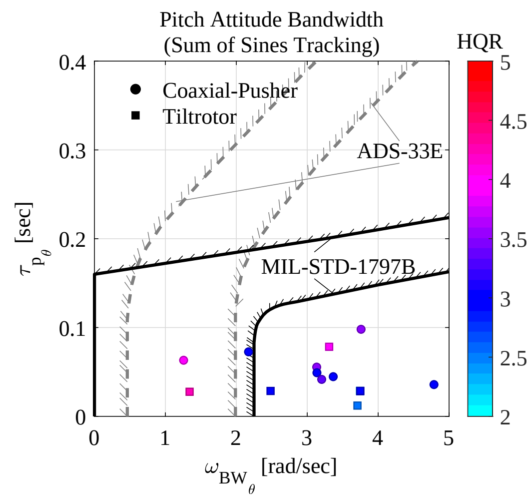


Fig. 23. Pitch Sum-of-Sines Tracking handling qualities ratings plotted on the pitch attitude bandwidth requirement (coaxial-pusher and tiltrotor).

Pilot comments for coaxial-pusher Configuration 1-A (first order command model, low pitch attitude bandwidth) included “bad,” “closest to PIO that I have gotten,” “tendency to overshoot,” and “very heavily damped.” For the tiltrotor Configuration 1-A pilot comments were similar and included “very sluggish,” “seems to coast, which causes overshoot,” and “need to lead input.”

For the coaxial-pusher Configuration 1-B, pilots commented that although it was not bad, “the most objectionable part [was] the amount of coast down after taking input out” (i.e., large negative dropback). For the tiltrotor Configuration 1-B, pilots commented that the response was sluggish and there was a potential to overshoot.

Comments about tiltrotor Configuration 1-C (baseline first order command model configuration) include “not a lot of overshoots” and “response well damped, but did not want quite as much [damping].”

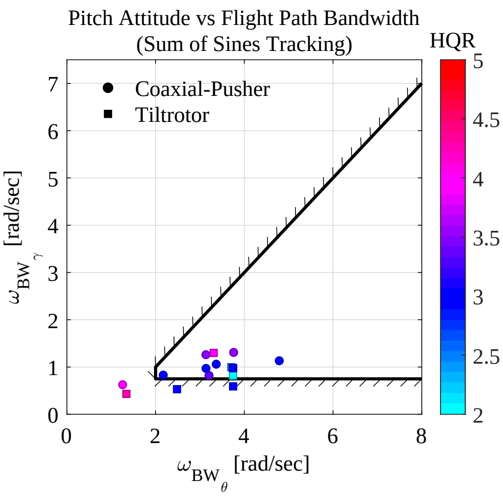


Fig. 24. Pitch Sum-of-Sines Tracking handling qualities ratings plotted on the pitch attitude versus flight path bandwidth requirement (coaxial-pusher and tiltrotor).

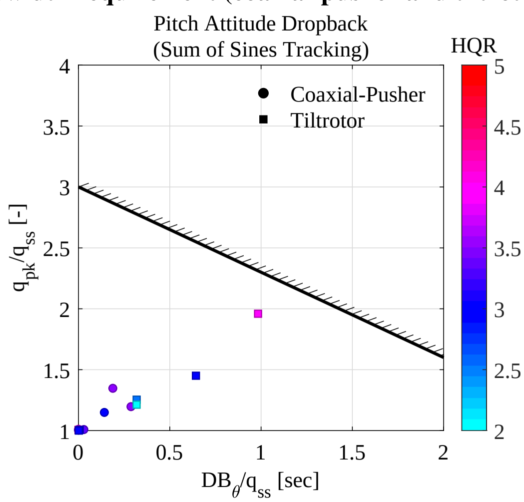


Fig. 25. Pitch Sum-of-Sines Tracking handling qualities ratings plotted on the pitch attitude dropback requirement (coaxial-pusher and tiltrotor).

Comments about coaxial-pusher Configuration 1-D (first order command model, high pitch attitude bandwidth) include "minimal overshoots, settles quickly," "compensation quantitatively decreased," and "by far the best one."

Comments about coaxial-pusher Configuration 2-B include "allows to be more aggressive since I can get faster rates, but needs more inputs for counter correction," "more overshooting," and "working harder."

Pitch Attitude Capture and Hold

Figures 27 through 30 show the Pitch Attitude Capture and Hold task average HQRs on the pitch attitude bandwidth, flight path bandwidth, pitch attitude dropback, and CAP specifications. Similar to the Sum-of-Sines Tracking task, the case with low pitch attitude bandwidth ($\omega_{BW_\theta} < 2$ rad/sec) received Level 2 HQRs (Fig. 27). Again, the boundary between Level 1 and Level 2 ratings appears to match well with

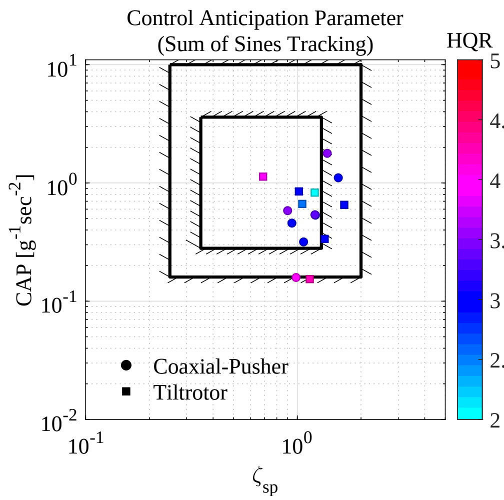


Fig. 26. Pitch Sum-of-Sines Tracking handling qualities ratings plotted on the Control Anticipation Parameter (CAP) requirement (coaxial-pusher and tiltrotor).

both the ADS-33E Target Acquisition & Tracking specification boundary plotted in dashed gray lines as well as the MIL-STD-1797B Category B & C, Class IV (analogous to ADS-33E Target Acquisition & Tracking, Table 1) boundaries plotted in solid black lines.

In addition, as with the Sum-of-Sines Tracking task, meeting the bandwidth requirement alone does not guarantee Level 1 ratings. Cases that meet the pitch attitude bandwidth, flight path bandwidth, and CAP requirements but still have Level 2 ratings have a large amount of pitch attitude dropback (Fig. 29).

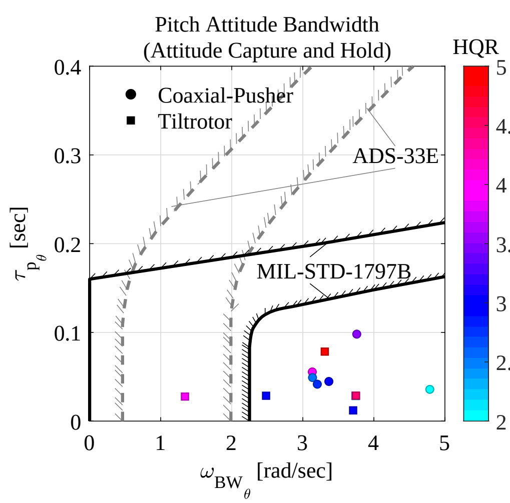


Fig. 27. Pitch Attitude Capture and Hold handling qualities ratings plotted on the pitch attitude bandwidth requirement (coaxial-pusher and tiltrotor).

Pilot comments for coaxial-pusher Configuration 1-A (first order command model, low pitch attitude bandwidth) suggested that their precision suffered and that they had to lead their inputs in order to make desired performance. Tiltrotor Configuration 1-B was described as "well damped" but not as good

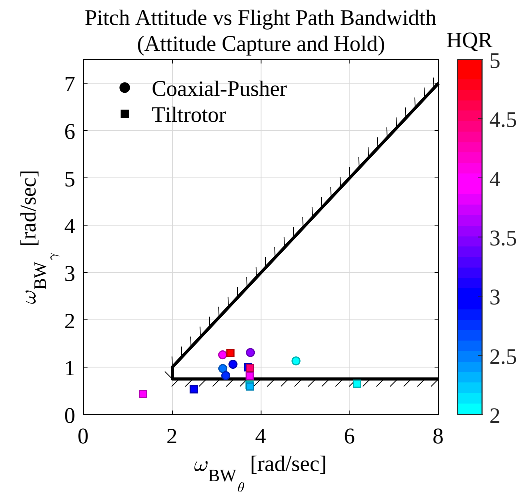


Fig. 28. Pitch Attitude Capture and Hold handling qualities ratings plotted on the pitch attitude versus flight path bandwidth requirement (coaxial-pusher and tiltrotor).

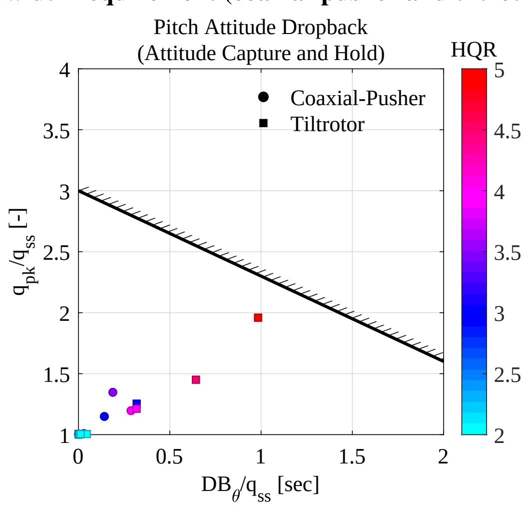


Fig. 29. Pitch Attitude Capture and Hold handling qualities ratings plotted on the pitch attitude dropback requirement (coaxial-pusher and tiltrotor).

as the baseline configuration (Configuration 1-C).

Configuration 1-C was described as predictable for both aircraft, but pilots also commented that it was "heavily/too damped" (tiltrotor). Configuration 1-D was described as "more predictable," "stops almost immediately," and "not having to lead input."

Configuration 2-A (tiltrotor) was overall liked by the pilots, although they did notice "ever so slight residual motion" (i.e., pitch attitude dropback). They also noted that it was comparable to Configuration 1-D, which is the highest bandwidth configuration.

Pilots noted that they could get very high pitch rates with Configuration 2-B (coaxial-pusher), but noted that the dropback characteristic was "annoying." Although they were still able to make desired performance, they noted they were "working too hard." Similar comments were made for the tiltrotor Configuration 2-B. For the tiltrotor Configuration 2-C,

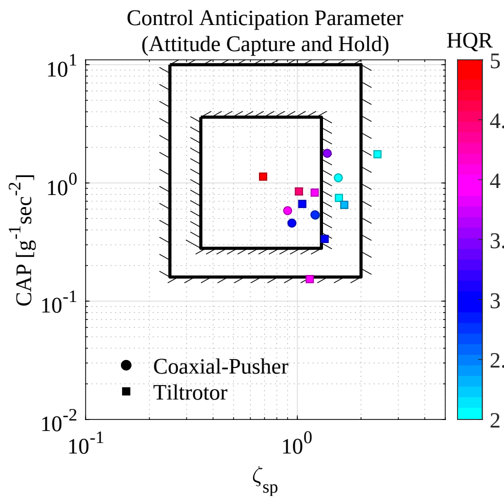


Fig. 30. Pitch Attitude Capture and Hold handling qualities ratings plotted on the Control Anticipation Parameter (CAP) requirement (coaxial-pusher and tiltrotor).

the response was described as "very aggressive, but not well damped."

Blended Command Model

Figure 31 shows the pilot HQRs collected for the baseline inner-loop pitch RCAH response type (Configuration 1-C), the baseline outer-loop flight path rate command response type (Configuration 4), and the outer-loop flight path rate command blended response type (Configuration 5) for the Pitch Attitude Capture and Hold and Sum-of-Sines Tracking tasks. Overall, the flight path rate command blended response type received Level 1 ratings similar to the baseline inner-loop pitch RCAH response type and significantly improved over the baseline outer-loop flight path rate command response type.

For the Pitch Attitude Capture and Hold task, pilots commented that with the baseline inner-loop pitch RCAH response type (Configuration 1-C), it was "easy to make desired performance" and they were "able to be aggressive and precise." However, one of the pilots also commented that there was "always some residual rate" when the input was removed, and that he "had to put in opposite inputs to stop it," likely due to the negative pitch attitude dropback.

For the Pitch Attitude Capture and Hold task with the baseline outer-loop flight path rate command response type (Configuration 4), pilots commented that they were accepting adequate performance, could not be aggressive or precise, and had to make "slow and deliberate movements with lots of lead compensation."

For the Pitch Attitude Capture and Hold task with the outer-loop flight path rate command blended response type (Configuration 5), pilots commented that they were "able to get desired [performance]" and "able to be both aggressive and precise."

For the Pitch Sum-of-Sines Tracking task, pilots commented that with the baseline inner-loop pitch RCAH response type

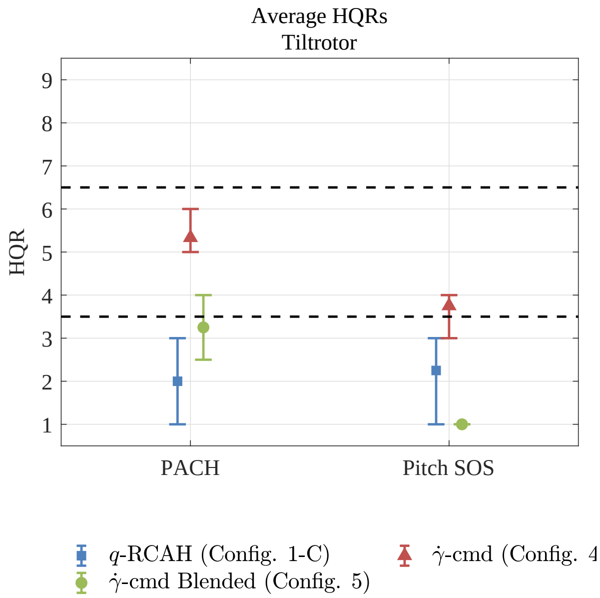


Fig. 31. Pilot handling qualities ratings comparison (tiltrotor)

(Configuration 1-C), they were able to meet desired performance and that precision and predictability were good.

For the Pitch Sum-of-Sines Tracking task with the baseline outer-loop flight path rate command response type (Configuration 4), pilots commented that it "was not as precise and was always overshooting," they had to make "more moderate slower inputs," and there was "a little loss in predictability in capture."

Finally, for the Pitch Sum-of-Sines Tracking task with the outer-loop flight path rate command blended response type (Configuration 5), pilots commented that they "could be aggressive and precise," that the response was "very similar to the [baseline inner-loop pitch RACH response type]," and that "precision was good."

DISCUSSION

The results presented above represent a limited number of pilots (most designs rated by two pilots), and the majority of the evaluations were conducted in a fixed-based simulator. Therefore, the work is preliminary and meant to guide future testing in flight and motion-based simulation with a larger pool of pilots. However, the subsequent discussion and conclusions presented here are based on clear trends from the data collected thus far. Recommended specifications and boundaries are summarized in Appendix A.

Pitch Attitude Bandwidth

Designs with pitch attitude bandwidth less than $\omega_{\mathrm{BW}_\theta} = 2$ rad/sec received Level 2 ratings. This corresponds to the boundary of the ADS-33E pitch attitude bandwidth specification for Target Acquisition & Tracking as well as the MIL-STD-1797B pitch attitude bandwidth specification for Category B & C flight phases, Class IV aircraft. Note though that the *non-aggressive* version of the Pitch Sum-of-Sines Tracking MTE was used, suggesting that $\omega_{\mathrm{BW}_\theta} = 2$ rad/sec Level 1/Level 2 boundary may need to be higher for the aggressive version of the MTE (which should correspond better to Target Acquisition & Tracking). The MIL-STD-1797B pitch attitude bandwidth specification for Category A flight phase (non-terminal flight phases that require rapid maneuvering, precision tracking, or precise flight path control) has a $\omega_{\mathrm{BW}_\theta} = 3$ rad/sec Level 1/Level 2 boundary, which may be more appropriate for high-speed Target Acquisition & Tracking. Further testing with the aggressive version of the Pitch Sum-of-Sines Tracking MTE should be done to assess the correct boundary location.

In addition, the MIL-STD-1797B pitch attitude bandwidth specification for Category B & C flight phases, Class IV aircraft has a more stringent phase delay requirement ($\tau_p \leq 0.12$ sec) as compared to the ADS-33E Target Acquisition & Tracking pitch attitude bandwidth specification. The more stringent MIL-STD-1797B phase delay requirement matches the ADS-33E Target Acquisition & Tracking roll attitude bandwidth specification. Although the effects of phase delay were not examined in this experiment (and all designs tested had $\tau_p < 0.12$ sec), it is recommended that the more stringent phase delay requirement of the MIL-STD-1797B pitch attitude bandwidth and the ADS-33E roll attitude bandwidth specifications be adopted for the ADS-33E pitch attitude bandwidth. Further investigation including designs with $\tau_p > 0.12$ sec should be done to confirm this.

Pitch Attitude Dropback

Several designs that met the pitch attitude bandwidth, flight path versus pitch attitude bandwidth, and CAP specifications received Level 2 ratings. These all correspond to designs with values of pitch attitude dropback above $\mathrm{DB}_\theta/q_{\mathrm{ss}} \approx 0.3-0.4$ sec. This suggests that the dropback specification should be adopted in ADS-33 and included as a Tier 1 requirement (Ref. 19) to supplement the bandwidth specification in control law design, consistent with the findings in findings of Ref. 25 and the guidance in MIL-STD-1797B.

In addition, the boundary of the fixed-wing dropback specification may need to be tightened for rotorcraft, such that designs receiving Level 2 rating are in the Level 2 region. Figure 32 shows the average HQRs for both tasks (Pitch Sum-of-Sines Tracking and Pitch Attitude Capture and Hold) and both aircraft plotted against the pitch attitude dropback $\mathrm{DB}_\theta/q_{\mathrm{ss}}$ (left plot) and pitch rate overshoot $q_{\mathrm{pk}}/q_{\mathrm{ss}}$ (right plot). Only the cases that meet the pitch attitude bandwidth are plotted (i.e., cases where $\omega_{\mathrm{BW}_\theta} \geq 2.0$ rad/sec). Trend lines for the results are also plotted on the figure, showing approximately where the Level 1/Level 2 boundary should be. Based on this, Fig. 33 shows a proposed updated boundary for the pitch attitude dropback specification that correlates with the evaluations conducted here.

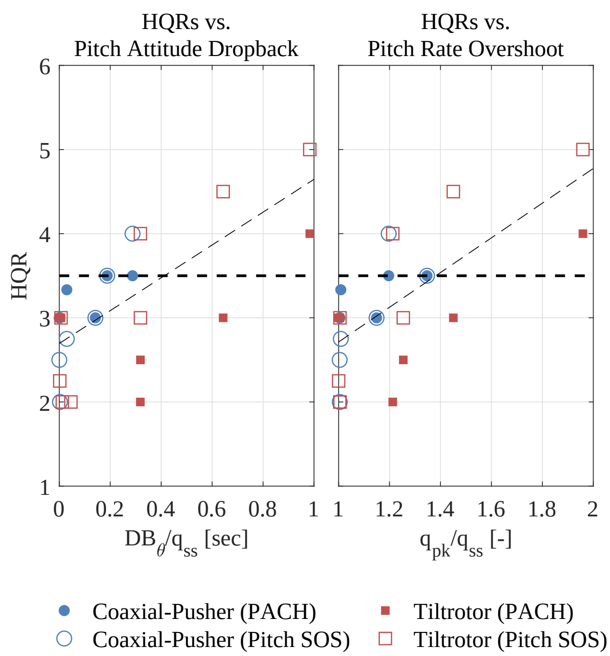


Fig. 32. Handling qualities ratings plotted as a function of pitch attitude dropback and pitch rate overshoot (coaxial-pusher and tiltrotor)

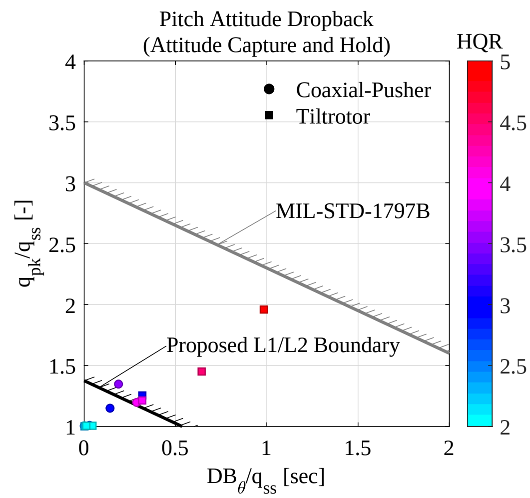


Fig. 33. Pitch Attitude Capture and Hold handling qualities ratings plotted on the pitch attitude dropback requirement with proposed Level 1/Level 2 boundary (coaxial-pusher and tiltrotor).

Flight Path Bandwidth

Several designs with flight path bandwidth values less than $\omega_{\mathrm{BW}_\theta} = 0.75$ rad/sec (corresponding to the Level 1/Level 2 boundary of the MIL-STD-1797B flight path versus pitch attitude bandwidth specification for Category B & C flight phases, Class IV aircraft) received Level 1 ratings. This may be due to that fact that both MTEs tested are pitch tracking tasks, and not flight path tracking tasks (e.g., formation flying). Further testing should be done with a separate flight path tracking task to assess the location of the flight path bandwidth Level 1/Level 2 boundary.

However, the flight path bandwidth specification should be included in ADS-33 to supplement the current flight path requirement (frequency at which the flight path response lags behind the pitch attitude response by $\Delta\varphi = -45$ deg), since the flight path bandwidth value is a closed-loop parameter affected by the control system and not a function of the bare-airframe alone.

Control Anticipation Parameters

Overall, configurations with Level 2 or 3 values of CAP received Level 2 ratings, although these same configurations were in the Level 2 of the pitch attitude bandwidth and flight path versus pitch attitude bandwidth specifications. In addition, the equivalent damping ratio value of the CAP specification does not correlate well with pilot ratings. Combined with the limited applicability of the CAP requirement to only conventional response types, it is recommended to keep this specification as a Tier 2 (check only, Ref. 19) requirement not enforced as part of control system optimization and not included in ADS-33.

Response Types

Figure 34 shows the overall best HQRs attained for each task and aircraft with each response type. Level 1 ratings were attainable for the Pitch Sum-of-Sines Tracking task with all of the response types examined. For the Pitch Attitude Capture and Hold task, for which even small amounts of pitch attitude dropback were noticeable to the pilots, the higher-order pitch RCAH response type and the flight path rate command response type received Level 2 ratings. The flight path rate blended command response type was able to achieve Level 1 ratings for both tasks.

CONCLUSIONS

This paper described an investigation into the effect of pitch response type and command model order on handling qualities for a generic lift offset coaxial and tiltrotor rotorcraft. A piloted simulation experiment was conducted in the PSU Flight Simulator facility with participation from two Army experimental test pilots. The results of the simulation experiment support the following conclusions:

1. For the non-aggressive version of the Pitch Sum-of-Sines Tracking tasks, the ADS-33E pitch attitude bandwidth requirement with Target Acquisition & Tracking boundaries and the MIL-STD-1797B pitch attitude bandwidth specification with Category B & C, Class IV boundaries match the assigned pilot Handling Qualities Ratings well. The MIL-STD-1797B pitch attitude bandwidth requirement with Category A boundaries seems to be too stringent, however, should be investigated using the aggressive version of the Pitch Sum-of-Sines Tracking tasks. In addition, the effect of phase delay should

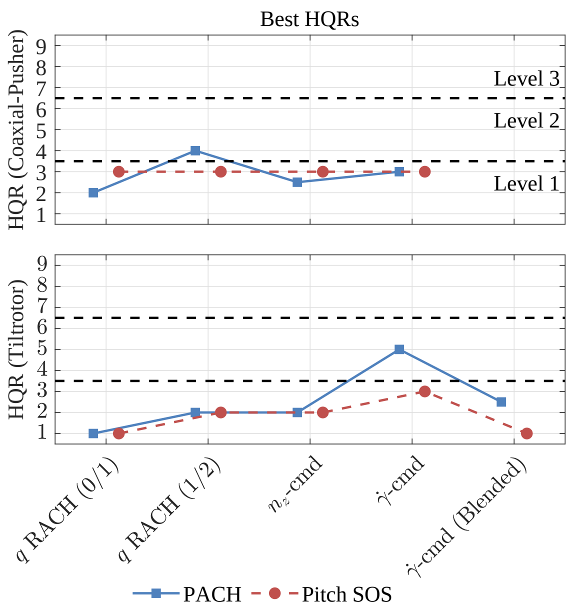


Fig. 34. Lowest (best) pilot handling qualities ratings attained for each response type for the Pitch Attitude Capture and Hold and Pitch Sum-of-Sines Tracking tasks (coaxial-pusher and tiltrotor).

be investigated to determine if the more stringent MIL-STD-1797B phase delay boundaries are more appropriate.

2. For both tasks tested, values of pitch attitude dropback that are within Level 1 of the pitch attitude dropback specification received Level 2 ratings. The pilot ratings and comments suggest that an upper boundary lies between $DB_\theta/q_{ss} = 0.3 - 0.4$ sec. A pitch attitude dropback requirement with the suggested more stringent boundaries should be included in ADS-33.

3. A flight path bandwidth requirement should be added to ADS-33 to supplement the current flight path requirement which is a function of the bare-airframe only and not affected by a control system. A flight path-oriented task such as formation flying is also needed to assess the location of the flight path bandwidth requirement level boundaries, as even designs with low values of flight path bandwidth received Level 1 rating for pitch tracking tasks.

4. The MIL-STD-1797B Control Anticipation Parameter (CAP) specification is best kept as a check-only (Tier 2) requirement in control law design. Designs that violate the lower CAP limit also violate the pitch attitude bandwidth requirement and designs that violate the upper equivalent short period damping boundary still received Level 1 ratings. The lower equivalent short period damping boundary is $\zeta_{sp} = 0.35$ which matches the ADS-33E damping requirement and is therefore redundant.

5. For bare-airframe configurations with large values of flight path-attitude lag T_{θ_2}, designs which meet the flight path bandwidth requirement have large values of pitch attitude dropback. For such configurations, a flight path rate blended command model which blends from a slower flight path response with less pitch attitude dropback for small stick inputs (associated with fine tracking) to a quicker flight path response with larger associated pitch attitude dropback for large stick inputs (associated gross maneuvering) provided good handling qualities for both tasks tested.

ACKNOWLEDGMENTS

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APPENDIX A: PROPOSED SPECIFICATIONS

The following are proposed specifications and boundaries for inclusion in ADS-33 for high-speed short-term pith attitude response to longitudinal controller and flight path response to pitch attitude.

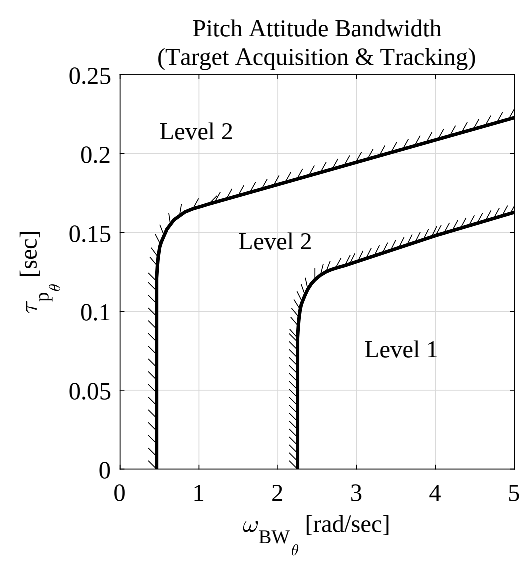

Fig. 35. Proposed requirements for small-amplitude pitch attitude changes (pitch attitude bandwidth) – forward flight (Target Acquisition & Tracking).

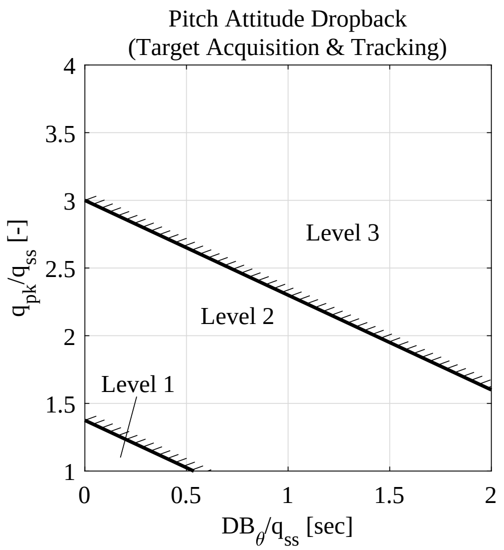

Fig. 36. Proposed requirements for pitch attitude dropback – forward flight (Target Acquisition & Tracking).

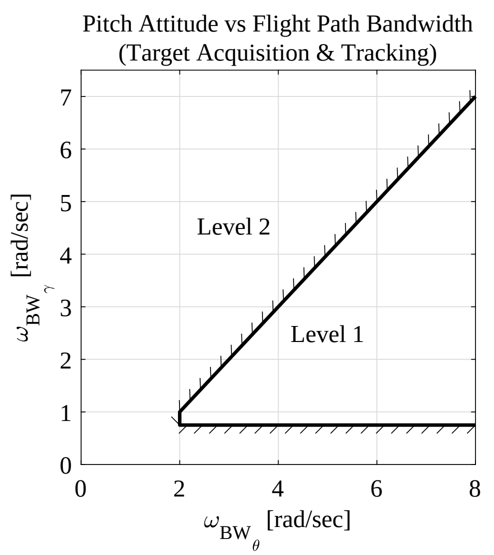

Fig. 37. Proposed requirements for transient flight-path response (flight path bandwidth vs pitch attitude bandwidth) – forward flight (Target Acquisition & Tracking).