Tilt Rotor Pitch/Flight-Path Handling Qualities

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2 authors:

Neil Cameron
Vertical Aerospace

Gareth D Padfield
University of Liverpool

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Neil Cameron*
Research Associate

Gareth D. Padfield
Professor of Aerospace Engineering

Flight Science & Technology, University of Liverpool, Liverpool, UK

Interest in so-called "bare-airframe" handling qualities stems from the need to quantify the level of degradation following failures in the control augmentation functions. For tilt rotor aircraft, the issue is complicated by the lack of dedicated criteria and supporting test data. The University of Liverpool is a member of a team working to fill the criteria gaps and to develop a database of piloted simulation results across the flight envelope, in support of the design of the European civil tilt rotor. During one of a series of piloted trials, the assigned handling qualities ratings did not show good agreement with the predicted pitch/flight-path handling qualities for such aircraft in airplane mode, according to fixed-wing criteria. Further investigation revealed that this was due to a large pitch rate overshoot, leading to a significant pitch attitude dropback in attitude/flight-path capture tasks. Current fixed-wing criteria such as control anticipation parameter and bandwidth need supplementary dropback parameters to accord with pilot opinion. This paper reports progress in the development of more unified handling qualities criteria, which properly integrate the pitch dropback phenomenon. Preliminary handling qualities boundaries are proposed for both flight-path and pitch attitude tracking tasks.

Nomenclature

g	acceleration due to gravity, ft/s^2
M_q	pitching moment derivative, 1/s
M_w	static stability derivative, rad/s·ft
M_η	pitching moment control derivative, 1/s^2
$n_z(\infty)$	steady-state normal acceleration, ft/s^2
q	pitch rate, deg/s
q_{ss}	steady-state pitch rate, deg/s
$\dot{q}(0)$	initial pitch acceleration, rad/s^2
s	Laplace operator
T_γ	flight-path delay, s
T_θ	pitch attitude dropback delay, s
$\overline{T_\theta}$	lag, s
$T_{\theta 2}$	flight-path incidence lag, s
U_e	flight speed, kt, m/s
w	vertical speed, m/s
Z_w	heave damping derivative, 1/s
Z_η	vertical force control derivative, ft/s^2 rad
α	angle of attack, deg
α_{ss}	steady-state angle of attack, deg
γ	flight-path angle, deg
γ_2	flight-path lag in relation to θ_{ss}, s
$\Delta\theta_{DB}$	pitch dropback, deg
η	control input, deg
θ	pitch attitude, deg
θ_{ss}	steady-state pitch attitude, deg
ζ_{sp}	short-period mode damping
ω_{sp}	short-period mode frequency, rad/s

Introduction

Response criteria and testing methodologies for helicopter handling qualities are now so well developed that all new aircraft can be designed to exhibit Level 1 handling qualities (HQs) throughout their operational flight envelope. Degradation to Level 2 handling is acceptable in emergencies or following system failures, but degradation to Level 3 should never be tolerated (Ref. 1). Thus, despite the potential for superb handling conferred by augmentation functions, there is still a keen interest in defining the Level 2–3 HQ boundary. Of particular interest to this study, are the effects of failures in the stability and control augmentation system (SCAS) and the consequent nature of the bare-airframe dynamics. During pull-up/pushover maneuvers in a tilt rotor in conversion or airplane modes, the short-period dynamics is excited, typically resulting in a large pitch rate overshoot (Refs. 2, 3) before the steady state is reached. This large pitch rate overshoot, leading to a pitch attitude dropback effect, is more severe in a tilt rotor than conventional fixed or rotary-wing aircraft due to the prop-rotors making positive contributions to both the pitch damping derivative M_q and the static stability derivative M_w. The high level of rotor inflow causes the thrust vector to lead the disk tilt and the consequent in-plane inflow tilts the disk in an unstable sense. The larger the dropback, the more difficult it is for the pilot to precisely command a pitch attitude. A well-designed SCAS should be able to reduce the negative impact of dropback, but there is still a need to quantify how much is tolerable for Level 2 HQs, in a degraded mode aircraft.

Central to good HQs are comprehensive, reliable design guidelines, which match the HQs criteria to mission task elements (MTEs). Despite a great deal of work undertaken with tilt rotor aircraft such as the XV-15,

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V-22, and BA609, no tilt rotor handling qualities design guide exists in the public domain.

The Flight Science and Technology research group (FS&T) at the University of Liverpool (UoL) has been involved in the European Commission's 5th Framework tilt rotor projects RHILP and ACT-TILT, and the continuing 6th Framework project NICETRIP, addressing tilt rotor handling qualities (Refs. 4, 5), structural load alleviation (Refs. 6, 7), and failure hazard analysis (Ref. 8). Building on this work, the project Optimizing Handling Qualities for Tilt Rotor Aircraft (OHQ-Tilt) funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) continued the development of such a HQ design guide. This paper reports progress in the development of new pitch/flight-path handling qualities metrics for the tilt rotor in conversion and airplane mode.

The project utilizes four tilt rotor FLIGHTLAB models, the Bell/NASA XV-15 (Ref. 9), the Eurocopter Eurotilt (Ref. 10) and EUROFAR (Ref. 11) concepts, and the AGUSTA ERICA concept (Ref. 12), representing a family ranging from small (5–7 "tons") to medium (10–12 "tons") and large (up to 20 "tons") aircraft. FLIGHTLAB models of the XV-15 and Eurotilt were developed during RHILP, the ERICA configuration was developed in the ACT-TILT project, and the EuroFAR model was developed in the OHQ-Tilt project. The FLIGHTLAB models are denoted by the prefix "F" for the remainder of the paper.

The handling qualities were assessed by test pilots in the UoL's HELIFLIGHT facility (Ref. 13). The overall evaluation began by predicting the handling qualities through off-line analyses, to determine the aircraft performance capabilities and to identify any issues for further investigation during piloted simulation trials. Test pilots then flew a range of MTEs based upon ADS-33E-PRF for helicopter and low-speed conversion modes, whereas airplane mode and high-speed conversion mode handling qualities were assessed through MTEs such as the heave–hop and roll-step (Refs. 4, 5). Cooper–Harper handling qualities ratings (HQRs; Ref. 14) were assigned to determine the handling qualities level (HQL), for comparison with the predicted HQs results.

The paper continues with the off-line handling qualities predictions for three of the tilt rotor models available at UoL, in bare-airframe configurations.

Pitch Short-Period Handling Qualities Review

Early pitch/flight-path handling qualities criteria were developed in the 1950s from pilot opinion using variable stability aircraft (Ref. 15). One such criterion stated that the short-period damping ratio (ζ_{sp}) should be at least 0.35 for satisfactory HQs (Ref. 16). Figure 1 shows the root loci for the short-period mode at 160, 200, and 240 kt for the aircraft. As the indicated airspeed increases, the short-period mode frequency increases and damping improves as expected (the short-period damping ratio remains essentially constant with airspeed). According to this early criterion, all tilt rotor configurations illustrated in Fig. 1 exhibit satisfactory HQs.

These results conform with predictions from the short-period mode thumbprint chart (Refs. 17, 18) illustrated in Fig. 2, showing short-period mode frequency vs. short-period mode damping ratio. The interpretation of these boundaries in terms of HQLs was not defined in the original thumbprint data. However, based on the short-period damping ratio of 0.35 in Fig. 1, the acceptable/poor boundary could be interpreted as being the Level 1–2 boundary (Ref. 3).

The root loci and thumbprint plots shown in Figs. 1 and 2 consider only the effect of the short-period mode frequency (ω_{sp}) and damping/damping ratio (ζ_{sp}). However, the approximate pitch short-period transfer functions, describing pitch rate response to elevator (Eqs. (1) and (2)), show the well-known result that an additional parameter, the

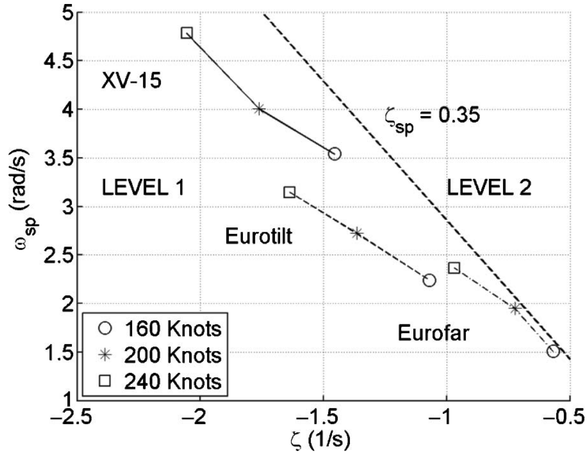


Fig. 1. Tilt rotor short-period mode root loci.

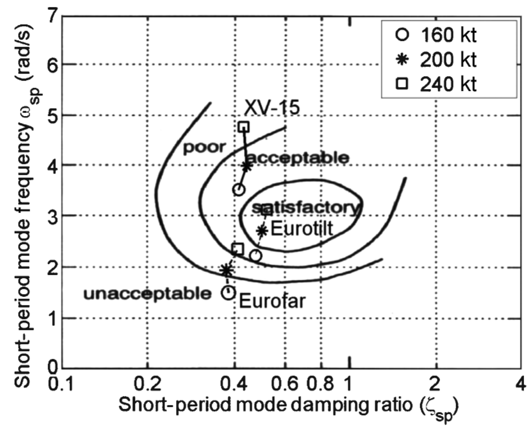


Fig. 2. Tilt rotor pitch thumbprint.

incidence lag ($T_{\theta 2}$), influences the pitch response and therefore handling qualities. The transfer functions for angle of attack and flight-path response to elevator are given in Eqs. (3)–(5) for completeness:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_w & U_e \\ M_w & M_q \end{bmatrix} \begin{bmatrix} w \\ q \end{bmatrix} + \begin{bmatrix} Z_\eta \\ M_\eta \end{bmatrix} \eta \tag{1}$$

$$\begin{aligned} \frac{q(s)}{\eta(s)} &= \frac{M_\eta\left(s + \dfrac{1}{T_{\theta 2}}\right)}{s^2 + 2\zeta_{\mathrm{sp}}\omega_{\mathrm{sp}}s + \omega_{\mathrm{sp}}^2} \\ &\approx \frac{M_\eta(s - Z_w)}{s^2 - (M_q + Z_w)s + (M_q Z_w - M_w U_e)} \end{aligned} \tag{2}$$

$$\frac{\alpha(s)}{\eta(s)} = \frac{\dfrac{Z_\eta}{U_e}\left(s + U_e \dfrac{M_\eta}{Z_\eta}\right)}{s^2 + 2\zeta_{\mathrm{sp}}\omega_{\mathrm{sp}}s + \omega_{\mathrm{sp}}^2} \tag{3}$$

$$\frac{\gamma(s)}{\eta(s)} = \frac{\left(\dfrac{M_\eta}{T_{\theta 2}}\right)}{s\left(s^2 + 2\zeta_{\mathrm{sp}}\omega_{\mathrm{sp}}s + \omega_{\mathrm{sp}}^2\right)} \tag{4}$$

$$\begin{aligned} 2\zeta_{\mathrm{sp}}\omega_{\mathrm{sp}} &\approx -(M_q + Z_w) \\ \omega_{\mathrm{sp}}^2 &\approx (M_q Z_w - M_w U_e) \\ T_{\theta 2} &= -\frac{1}{Z_w} \end{aligned} \tag{5}$$

The incidence lag is the time constant for lift generation and the lag between flight-path and the pitch attitude response after an elevator step

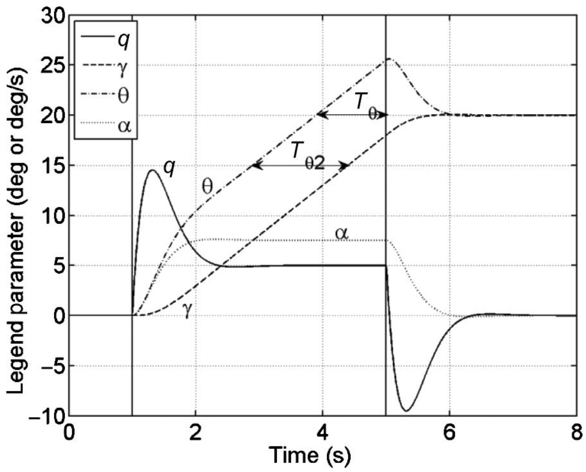


Fig. 3. Pitch rate, attitude, flight-path, and incidence responses to a step elevator input.

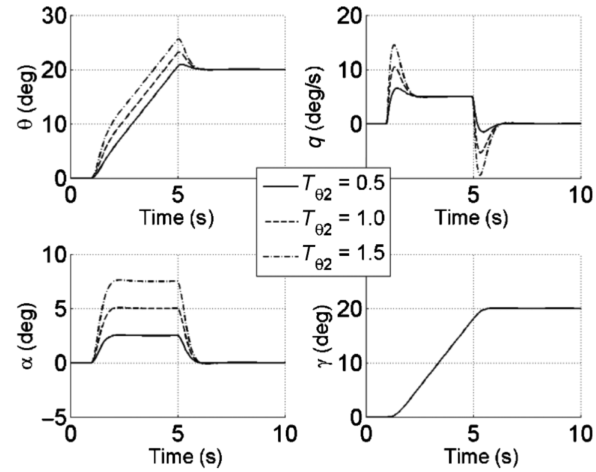


Fig. 4. Effect of $T_{\theta 2}$ on pitch, incidence, and flight-path response.

input is applied. Figure 3 shows the pitch rate and angle of attack changes associated with a unit step input applied at $t = 1$ s and removed at $t = 5$ s, with $\omega_{sp} = 4$ rad/s, $\zeta_{sp} = 0.8$; $T_{\theta 2}$ is 1.5 s. The rate response per inch of stick input is 5°/s. Figure 3 illustrates the pitch attitude dropback delay T_θ which is the time between the first crossing of the steady-state pitch attitude and when the pilot must center the control (in order that the attitude returns to the required steady state).

The incidence lag was neglected from very early handling qualities studies, where $T_{\theta 2}$ was not considered to be a significant contributor to the longitudinal handling qualities (Ref. 15). However, with the development of higher performance aircraft with higher wing loading and wide flight envelopes, incidence lags could vary between 0.5 s in high-speed/sea level flight to as much as 4 s in low-speed/high-altitude flight. Table 1 lists the values of incidence lag at sea level used in the present investigation; the incidence lag increases with aircraft size due to increased wing loading and correspondingly reduced heave damping Z_w.

Effect of varying incidence lag on the pitch–heave dynamic response

The effect of incidence lag on the dynamic response to a 1-deg elevator step is shown in Fig. 4, for incidence lags of 0.5, 1.0, and 1.5 s (step applied at $t = 1$ and removed at $t = 5$ s). Short-period mode damping ratio and natural frequency are constant at 0.8 and 4 rad/s, respectively: Varying the incidence lag changes the aerodynamic derivatives needed to maintain constant damping and frequency.

The pitching moment control derivative M_η is critical to the control sensitivity of the aircraft. M_η can be chosen to give a prescribed steady-state pitch rate for any given ζ_{sp}, ω_{sp}, or $T_{\theta 2}$, within aircraft limitations. Equation (1) can be written in the form

$$\ddot{q} + 2\zeta_{sp}\omega_{sp}\dot{q} + \omega_{sp}^2 q = M_\eta \left(\dot{\eta} + \frac{1}{T_{\theta 2}}\eta\right) \tag{6}$$

Table 1. Tilt Rotor Flight-Path Incidence Lag (s)

Speed (kt)	F-XV-15	F-Eurotilt	F-EuroFAR
160	1.239	1.454	3.899
200	0.950	1.027	1.906
240	0.795	0.812	1.411

The steady-state pitch rate to a step input is then given by

$$\omega_{sp}^2 q_{ss} = \frac{M_\eta}{T_{\theta 2}}\eta \tag{7}$$

Rearranging to give the pitching moment control derivative for a predefined rate sensitivity gives

$$M_\eta = (q_{ss}/\eta)\omega_{sp}^2 T_{\theta 2} \tag{8}$$

In the Fig. 4 case where a steady-state pitch rate response of 5 deg/s to a 1-deg elevator input was selected, the plots show that increasing the incidence lag results, as expected, in higher angles of attack being required to maintain the same flight-path response. Furthermore, from Eq. (8), as $T_{\theta 2}$ increases, the control derivative must also be increased to maintain the prescribed q_{ss}, causing an increase in initial pitch acceleration and also pitch rate overshoot. When the step input is removed, the aircraft attitude "drops back" to its final attitude after a period of time depending on the damping and frequency. The larger the pitch rate overshoot, the larger the dropback will be and the more difficult it becomes for the pilot to precisely command a pitch attitude change. An important note to this, however, is that pilots may prefer some overshoot as this gives a faster response to a control input. Furthermore, it is important to ensure that dropback is not negative (i.e., pitch attitude does not overshoot when the control input is removed) as this can lead to a sluggish, unpredictable response (Ref. 17).

Negative dropback is dependent on the relationship between the incidence lag and the flight-path delay T_γ, the delay in the flight path reaching a constant slope characterized by

$$T_\gamma = \frac{2\zeta_{sp}}{\omega_{sp}} \tag{9}$$

The effect that the relationship between the incidence lag and the flight-path delay parameters has on dynamic response is illustrated in Fig. 5 for a damping ratio of 2, a frequency of 4 rad/s and three incidence lags, 0.5, 1.0, and 1.5 s; the 1-deg step elevator input is applied at $t = 1$ and removed at $t = 5$ (note that this relatively high damping ratio has been selected only to demonstrate how the relationship between flight-path and incidence lag effects the pitch attitude dropback). Also shown are the flight-path and the delay in the flight path reaching steady state. Since flight-path angle is the same for all three cases, the flight-path lag is also constant.

The flight-path delay for the configurations shown in Fig. 5 is 1 s. If the incidence lag is equal to the flight-path delay, no pitch

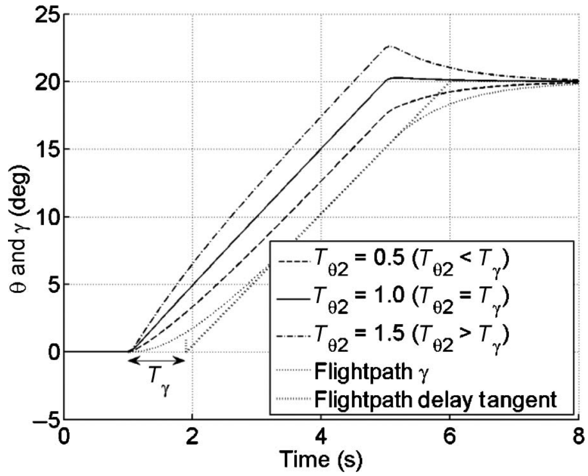


Fig. 5. Effect of T_γ on dropback.

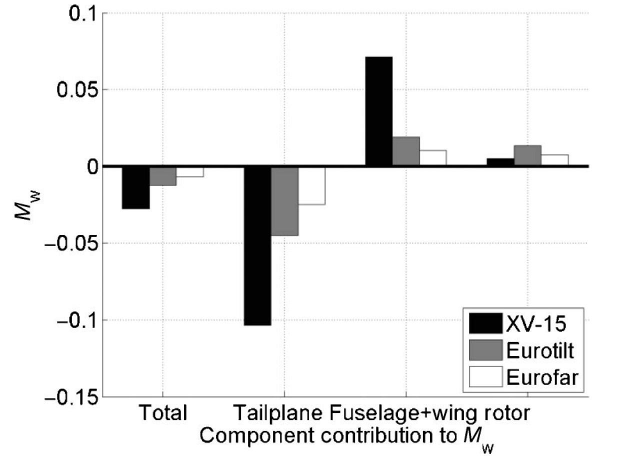


Fig. 7. Component contribution to the static stability derivative M_w.

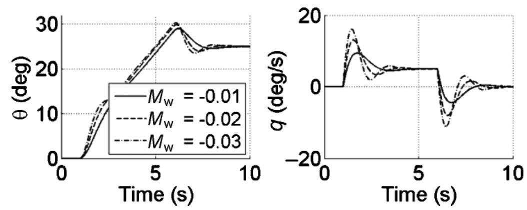


Fig. 8. Effect of M_w on pitch parameters.

attitude dropback occurs. If incidence lag is greater than the flightpath delay, dropback occurs and, conversely, pitch attitude overshoots when the step input is removed, if the incidence lag is less than the delay.

Effect of static stability derivative M_w on the dynamic response

Velocity perturbations in the rotor plane effectively act as a longitudinal cyclic input, causing the rotor blade to flap in the direction of the aircraft pitch change as illustrated in Fig. 6. The applied aerodynamic moment is then greater than that required to precess the gimbaled rotor, leading to an increased flapping in the direction of motion. This is also illustrated in Fig. 6 where, after a step input in elevator at $t = 1$, the initial response of the rotor disk is to lag the rotor shaft (i.e., flap back). However, velocity perturbations in the rotor plane result in the rotor advancing the shaft, further adding to the destabilizing effect of the static stability derivative term M_w, i.e., a positive contribution, as illustrated in Fig. 7, which shows the breakdown of the derivative M_w from the tilt rotor models. Overall, M_w is negative (stabilizing) and can be seen to decrease in magnitude as the tilt rotor size increases, the effect of which is highlighted in Fig. 8, using the linearized F-XV-15 derivatives at a speed of 200 kt ($Z_w = -0.8$, $M_q - 1.8$) with varying M_w (-0.01, -0.02, -0.03).

If the static stability derivative M_w is zero, the pitch and heave motions are decoupled and no pitch dropback occurs. However, as M_w increases negatively, the pitch rate overshoot becomes greater, as ω_{sp} increases and ζ_{sp} decreases. In fact, the $M_w = -0.06$ case shows that the pitch rate actually reverses during the first oscillation (Ref. 19). This is due to the fact that M_w increasing negatively represents an increasingly larger restoring moment. To produce the prescribed steady-state pitch rate of 5 deg/s (Fig. 8), increasing amounts of M_η and hence of initial pitch acceleration are required, resulting in an increasing pitch rate overshoot (M_η is 0.1571, 1.2608 and 2.3645 rad/s·ft for the negatively increasing values of M_w shown in Fig. 8).

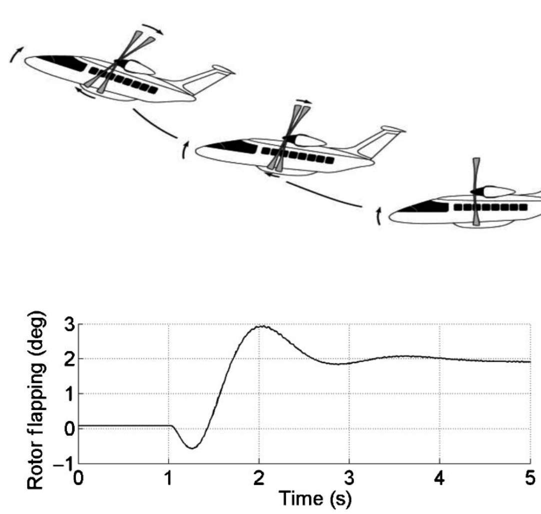


Fig. 6. Rotor flapping during pitch up.

Control anticipation parameter

In an attempt to capture and quantify the more complex pitch response, the control anticipation parameter (CAP), Eq. (10), was introduced and eventually became the recommended criterion in MIL-HDBK 1797 (Ref. 20). CAP is approximately proportional to the maneuver margin (Ref. 18) and is defined as the ratio of initial pitch acceleration $\dot{q}(0)$ to steady-state normal acceleration $n_z(\infty)$. Criteria are defined on the two-parameter chart with CAP plotted against the short-period mode damping ratio, as shown in Fig. 9:

$$\mathrm{CAP} = \frac{\dot{q}(0)}{n_z(\infty)} \approx -\frac{g\omega_{sp}^2}{Z_w U_e} = \frac{g\omega_{sp}^2 T_{\theta 2}}{U_e} \tag{10}$$

CAP defines HQ boundaries for Category A, B, and C maneuvers, where Category A represents tasks that involve rapid maneuvering, precision tracking, or precise flight-path control. Category A boundaries are not normally applicable to transport aircraft, but if the aircraft is to be used in a search and rescue role, the Category A in-flight

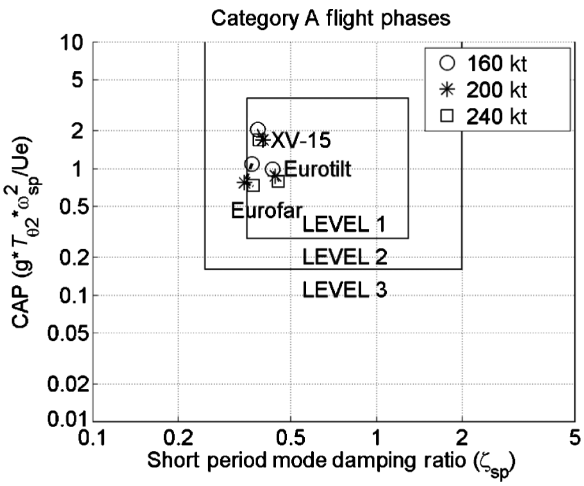


Fig. 9. Tilt rotor CAP.

refueling task and terrain following tasks, for example, are certainly relevant. The tilt rotor in airplane mode will mainly perform Category B tasks, accomplished using gradual maneuvering and defined as *"Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required"* (Ref. 20). Finally, a future civil tilt rotor may have the ability to land in airplane mode (Ref. 12), in which case Category C terminal flight phases will also apply. Only the Category A CAP criterion boundaries are plotted in Fig. 9 as the MTEs used to assess the pitch handling qualities were based on a search and rescue role.

Figure 9 shows that each of the FLIGHTLAB tilt rotor models lies within the Level 1 region on the CAP-damping chart. This is further substantiated when considering the bandwidth criteria.

Bandwidth criteria

Like CAP, the bandwidth criteria list several categories (Ref. 20), from which Fig. 10 shows the Category A pitch bandwidth for the same test configurations shown in Fig. 9 with the proposed boundaries from Ref. 21. The F-XV-15 is well within the Level 1 area, and F-Eurotilt is on the Level 1–2 boundary for low speed but moves into Level 1 with increasing speed. F-EuroFAR is Level 2. As all three aircraft have approximately the same short-period mode damping ratio, the decrease in bandwidth is primarily due to the decrease in the short-period mode frequency.

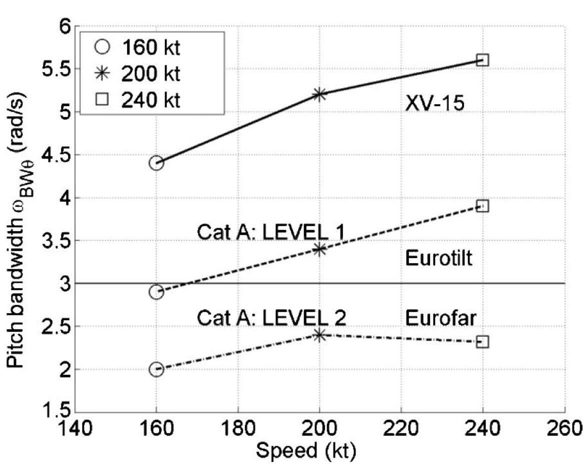


Fig. 10. Tilt rotor pitch bandwidth.

Piloted Simulation Tests

A preliminary off-line HQs investigation of the three tilt rotors has suggested that, at 200 kt, the F-XV-15 and F-Eurotilt models should exhibit Level 1 HQs, degrading to Level 2 for the much larger F-EuroFAR, for precision tracking or precise flight-path control tasks.

During a series of piloted simulation trials at UoL, the handling qualities of the tilt rotor models were assessed over a range of MTEs in all modes. The task selected to test the pitch/flight-path characteristics in airplane mode was the heave–hop MTE previously reported in Ref. 5.

The heave–hop task is illustrated in Fig. 11 with the pilot's center-screen view of the task in Fig. 12. The pilot approaches a "v"-shaped valley at low level. When entering the valley, two sets of white tramlines are visible, the first is located at 135 and 165 ft above ground level, respectively, to mark the adequate performance boundaries for starting the task and the second set is located 335 and 365 ft to mark the adequate performance boundaries at the end of the first phase of the task. A series of alternating black and white posts are located at 1000-ft intervals along the valley at a height of 250 ft. The task begins with the pilot entering the valley at a predefined speed and at the reference height

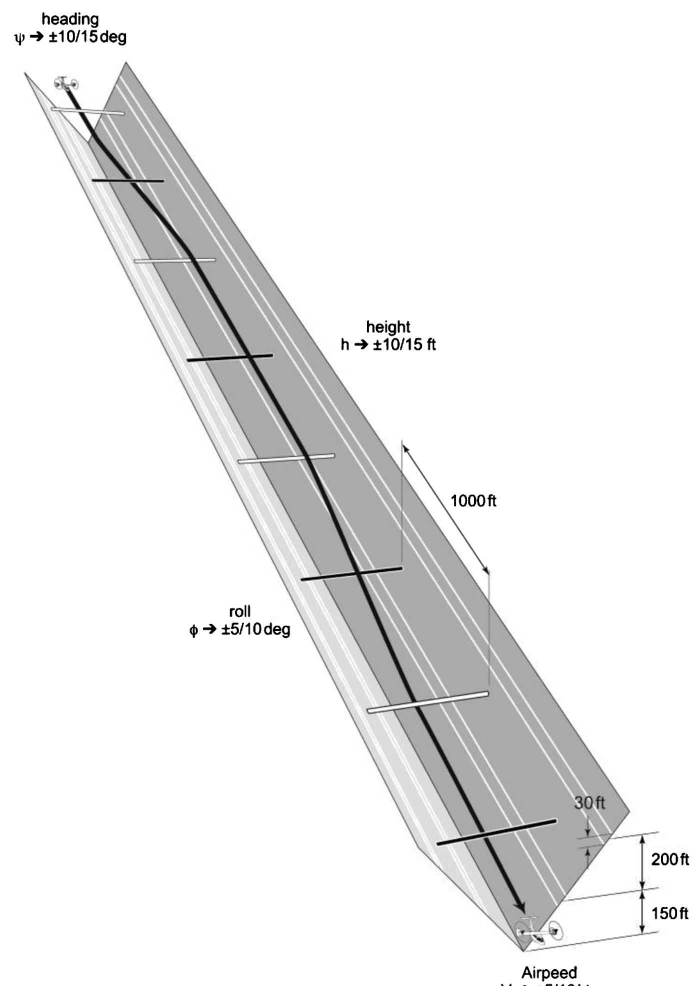


Fig. 11. Heave–hop MTE.

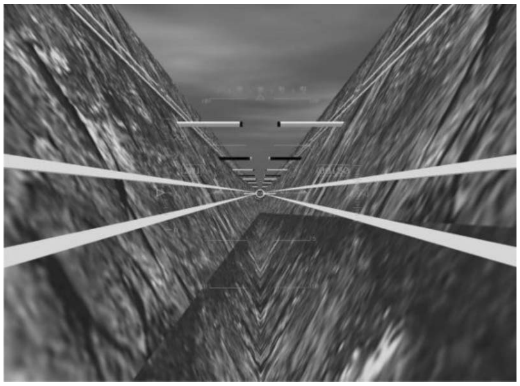


Fig. 12. Pilot view of the heave–hop task.

Table 2. Flight-Path Task Performance Requirements

Criteria	Desired	Adequate
Maintain speed throughout the task	±5 kt	±10 kt
Maintain roll angle throughout the task	±5°	±10°
Maintain heading throughout the task	±10°	±15°
Maintain altitude on altitude capture phase	±10 ft	±15 ft

of 150 ft. The task is then to climb to the desired altitude by the time the next post of that color is reached (climb 200 ft over a distance of 2000 ft) and then stabilize within the marked tramlines until the next set of posts of the chosen color is reached. The pilot is required to maintain speed, roll, and heading throughout the task and altitude on the height capture phases according to the performance criteria listed in Table 2.

The visual cues described have been developed to ensure that the pilot has all the information needed to regulate and assess task performance, ensuring that the flight simulation environment does not degrade the HQRs. In addition to the outside world visual cues, a head up display (HUD) is also provided displaying a flight-path symbol as well as attitude, height, and velocity cues. The maneuver kinematics was defined so that the pilot would need to use close to maximum/minimum operational envelope "g" levels during the pull-up and pushover phases ($+2.5g$, $0.0g$).

On completion of the task, the flight simulation was paused and the pilot completed an in-cockpit pilot questionnaire leading to the pilot returning a HQR based on the Cooper–Harper rating scale (Ref. 14). Before presenting the results of the heave–hop assessment, the HELIFLIGHT simulation facility at UoL is introduced.

The University of Liverpool Flight Simulation Laboratory

The HELIFLIGHT facility at UoL (Fig. 13) is a PC-based, reconfigurable flight simulator developed with five key components that are combined to produce a relatively high-fidelity system (Ref. 13), including selective fidelity, aircraft-specific, interchangeable flight dynamics modeling software (FLIGHTLAB) with a real-time interface; 6-degree-of-freedom motion platform; four axis dynamic control loading; a three-channel collimated visual display for forward view, plus two flat panel chin windows, providing a relatively wide field of view visual system; and computer-generated instrument panel and HUDs (reconfigurable).

The FLIGHTLAB software provides a modular approach to constructing flight dynamics models, enabling the user to develop a complete vehicle system from a library of predefined or newly created components. The flight dynamics models form a vital part of a flight simulator, the detail of which will ultimately contribute to the fidelity level of the simulation.

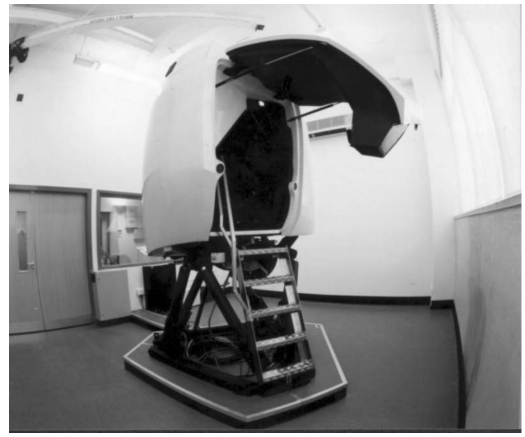


Fig. 13. The UoL "HELIFLIGHT" flight simulator.

Three collimated visual displays are used to provide infinity optics for enhanced depth perception, which is particularly important for hovering and low-speed flying tasks. The displays provide 135-deg horizontal by 40-deg vertical field of view, which is extended to 60-deg vertical field of view using two flat screen displays in the chin windows.

The sensation of motion is generated using a six-axis Maxcue platform, which is electrically actuated. To maximize the usable motion envelope, the drive algorithms feature conventional washout filters that return the simulator to its neutral position at acceleration rates below the perception thresholds.

Results of the piloted simulator tests

Three test pilots have been engaged in flying the heave–hop MTE, over a series of trials during the 5th Framework tilt rotor projects RHILP and ACT-TILT and more recently in the OHQ-Tilt project. The HQR range is shown in Table 3 alongside the predicted HQL from the off-line analysis. It is emphasized that these results are for the bare-airframe configurations.

For the F-XV-15, all pilots felt that the aircraft was Level 2 for the 200-kt case even though Level 1 handling qualities were predicted from the off-line analysis, whereas F-Eurotilt was also Level 2 (predicted Level 1) and F-EuroFAR rated as "borderline" Level 3 (predicted Level 2 from bandwidth analysis).

These results show that the bandwidth and CAP criterion do not adequately capture the bare-airframe handling characteristics of the tilt rotor. A solution to this dilemma is proposed in Ref. 21 by Mitchell and Hoh.

Pitch dropback parameter

Mitchell and Hoh (Ref. 21) proposed that the "Gibson dropback parameter" be used in conjunction with the CAP or bandwidth criteria for

Table 3. Heave–Hop Task HQRs

Aircraft	Speed (kt)	Predicted Off-line	HQR Range
F-XV-15	200	Level 1	5–6
F-Eurotilt	200	Level 1	5–6
F-EuroFAR	200	Level 2/3	6–7

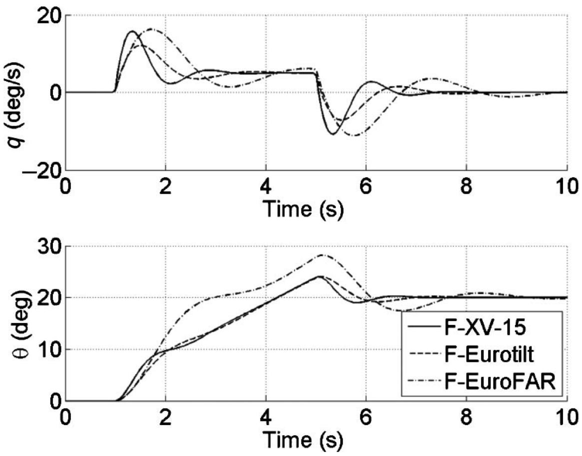
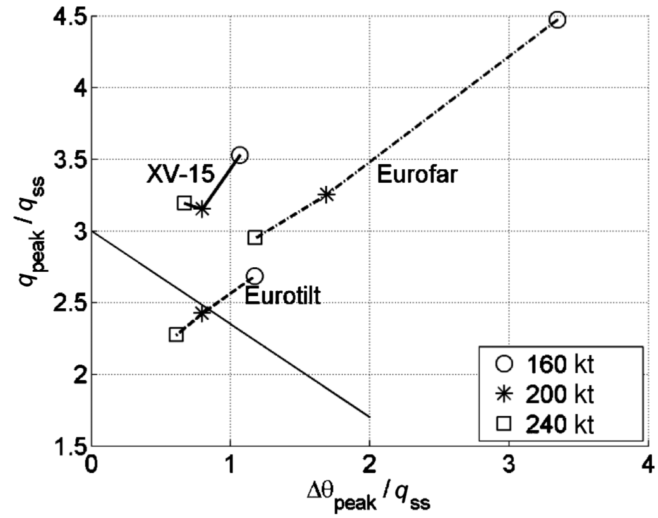


Fig. 14. Pitch responses to step elevator inputs.



If response is above the boundary, and

Level based on bandwidth (or CAP if applicable) is	The overall level is
1	2
2	3
3	worse than 3

Fig. 15. Tilt rotor pitch dropback.

responses with large pitch rate overshoots that do not satisfy the recommended CAP and bandwidth criteria in MIL-HDBK 1797 (Ref. 20). The dropback criterion compares the ratio of the peak to steady-state pitch rates with the ratio of pitch attitude dropback to the steady-state pitch rate. These parameters can be seen for the three tilt rotor models in Fig. 14, using the approximations in Eq. (2), when the step input is removed 4 s after the input (in these cases different magnitudes of control input have been used to give the same final pitch attitude change as the control sensitivities differ between the aircraft). Figure 15 shows the dropback calculated for each of these cases.

The Mitchell–Hoh criteria states that if the dropback lies above the boundary line, then the HQL calculated using CAP or bandwidth should be degraded by one level. If the dropback lies below the boundary line, the handling qualities remain the same. This suggests that the F-XV-15 pitch handling qualities are Level 2 even though the CAP and bandwidth criteria predict Level 1 HQs. F-Eurotilt (160 kt) will also degrade from Level 1 to Level 2 whereas the 200- and 240-kt cases are predicted to remain as Level 1. Finally, F-EuroFAR is degraded from Level 2 to Level 3 for category A MTEs.

The dropback parameter, in conjunction with the bandwidth criteria, correctly predicts the HQLs of the tilt rotor and is sensitive to the effect of the overshoot on the pitch short-period handling qualities. However, it does not presume to assign a HQL, only that the HQL assigned from CAP or bandwidth be degraded if the dropback lies above the limit shown in Fig. 15 (Ref. 21), boundary line. This highlights the need to develop new handling qualities criteria that better capture all aspects of the dynamics.

Development of a new pitch/flight-path handling qualities metric

The preceding discussion has exposed some of the complexities surrounding pitch short-period mode handling qualities. Indeed, Ref. 20 recognizes that the problem of solving the pitch short-period mode handling qualities is a controversial one and continues to undergo scrutiny from the flight dynamics community. With this in mind, UoL embarked upon a program aiming to develop a single handling qualities metric that suitably captured, among other short-period mode phenomenon, the pitch attitude dropback.

To ensure that only the characteristics of the pitch short-period mode were analyzed, the pitch short-period approximation (Eqs. (1)–(4)) was used to develop a simple linear FLIGHTLAB model called the "Generic pitch short-period model," readily reconfigurable to any defined combination of short-period mode frequency, damping, control power, and incidence lag. The matrix of short-period characteristics evaluated is shown in Fig. 16. Damping ratios of 0.4, 0.8, and 1.2, frequencies of 2, 3, 4, and 5 rad/s are shown in Fig. 16. Incidence lags of 0.5, 1.0, and 1.5 s were selected, and the speed was fixed at 200 kt.

MTE selection for the piloted tests

As the flight-path lags the pitch attitude by $T_{\theta 2}$, it was hypothesized that a flight-path oriented task is more dependent on the

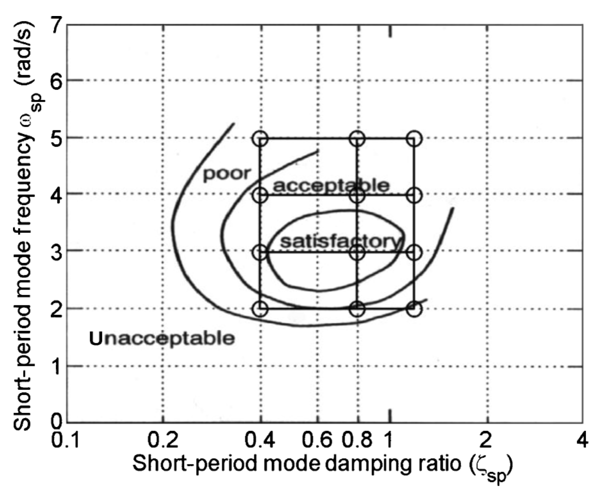


Fig. 16. Selected short-period mode frequencies and damping ratios.

incidence lag. Different boundaries and possibly even different metrics may be required to capture handling qualities in flight-path and pitch attitude oriented tasks, To investigate this further, a piloted simulation schedule was developed focusing on two MTEs, a flight-path capture task and a pitch attitude tracking task for the 36 test configurations. The flight-path capture MTE was essentially the heave–hop MTE already discussed; the control sensitivity for all configurations was fixed at 5 deg/s per degree of elevator (to use close to the maximum operational envelope during pull-up and pushover phases). The pitch attitude tracking task was based on an aerial refueling task and named the "drogue tracking task."

Drogue tracking task

After several task iterations and with help from test pilots in exploratory simulation trials, the final drogue tracking task was developed. The aim of the task was to force the pilot to apply continuous control inputs over the frequency range encompassing the short-period dynamics, to determine which combination of parameters was likely to induce oscillatory motion. A common control sensitivity of 3 deg/s per degree of elevator was selected for this task due to low inceptor breakout forces around the trim point making 5 deg/s too sensitive.

In this task, the pilot is required to follow behind a visual model of a refueling tanker at a constant speed of 200 kt and at a fixed distance from the tanker, tracking the drogue with the center of the HUD as illustrated by the screenshot shown in Fig. 17.

The drogue is connected to the tanker via a boom that was driven in the pitch axis by summing a series of sine waves of varying frequency and phase, carefully selected to be realistic and so that no rapid departures from its position occur. The drogue pitch attitude and resultant vertical motion of the drogue is as shown in Fig. 18.

The task was to maintain the center of the HUD within half a basket radius for desired performance and within the basket for adequate performance. In addition to this, the pilot was deemed to have maintained performance if, after exceeding desired or adequate performance due to not reacting quickly enough to the drogue motion, he recaptured without further overshoots.

Three pilots participated in the flight-path capture task assessment while only two performed the drogue tracking task, due to time constraints. Before presenting the results from the simulation trials, the results from the off-line handling qualities predictions are discussed.

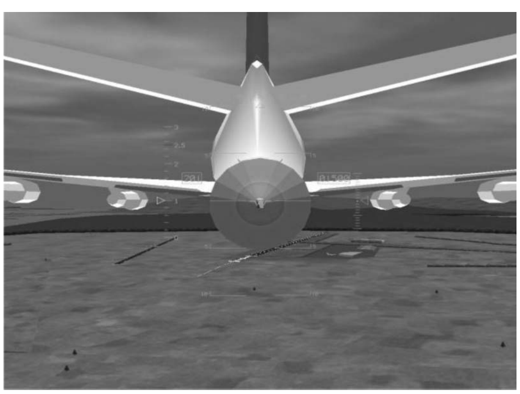


Fig. 17. Pilot view of the drogue tracking task.

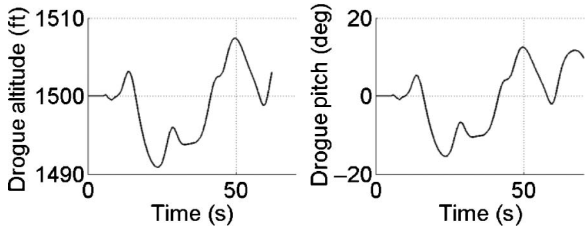


Fig. 18. Drogue pitch and vertical motion disturbances.

Off-line analysis of the generic short-period model

Figure 19 shows four Category A CAP charts, each one representing the range of damping and incidence lag values selected for a constant short-period natural frequency. The plots show that the configurations are Level 1, except for $\omega_{sp} = 2$ rad/s, and $T_{\theta 2} = 0.5$ s for all damping ratios, which are Level 2.

The bandwidth results are plotted in Fig. 20. The phase delay for the short-period approximation is shown as zero on the vertical axis as the results are determined from a second-order transfer function, although a value of about 40 ms stems from delays in the simulator visual system response. The results show good agreement with the CAP predictions. However, in addition to the previously discussed cases being Level 2, $\omega_{sp} = 2$ rad/s, and $\zeta_{sp} = 0.4$ are also Level 2 for all incidence lags.

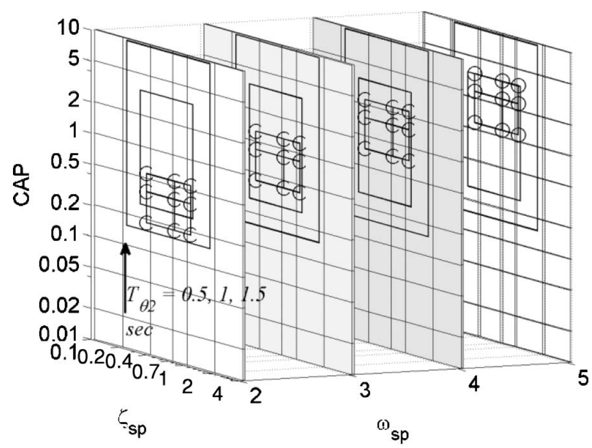


Fig. 19. CAP for the selected short-period mode configurations.

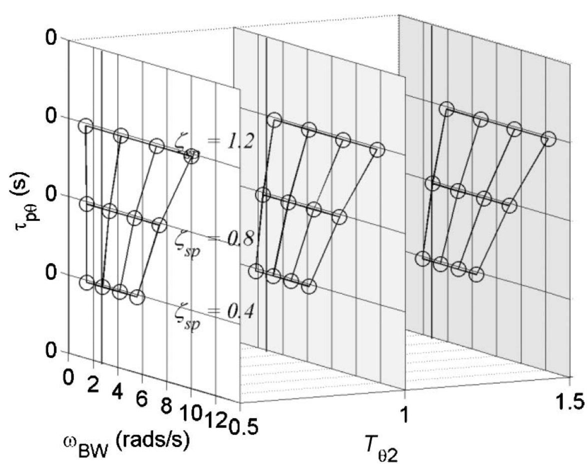


Fig. 20. Bandwidth for the selected short-period mode configurations.

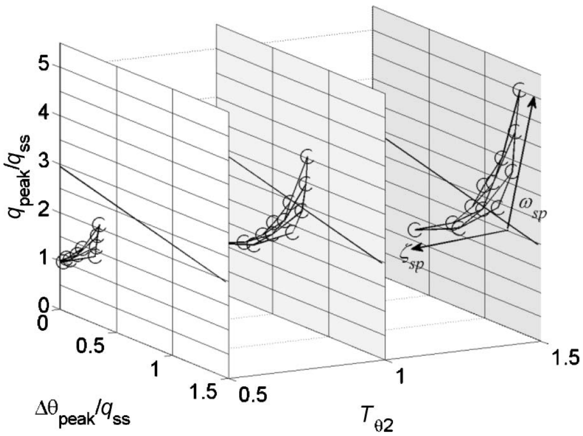


Fig. 21. Dropback for the selected short-period mode configurations.

It should be noted that neither criterion has yet predicted Level 3 HQs for any of the short-period mode configurations.

When the pitch dropback criteria are applied, the data appear as shown in Fig. 21. These can be used to degrade the handling qualities returned from the CAP or bandwidth results by one level, to produce new thumbprint charts as illustrated in Fig. 22, where light gray represents Level 1, medium gray Level 2, and finally dark gray Level 3.

Piloted Simulation Results

The HQRs awarded by the test pilots were checked for consistency between pilot opinion and recorded data. Where necessary, minor revisions were made to the HQRs, with pilot agreement. The HQRs are categorized into their HQLs and illustrated in Fig. 23 for the flight-path task and Fig. 24 for the drogue tracking task. This enables a comparison

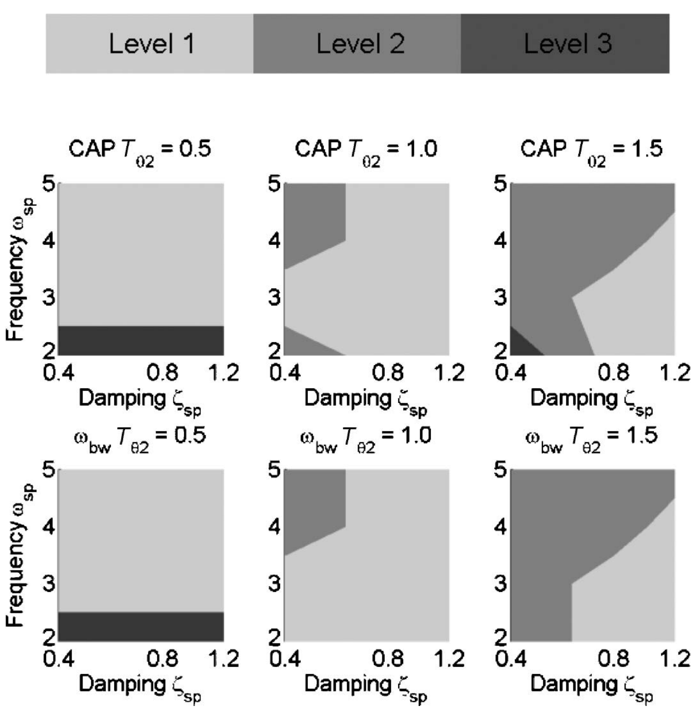


Fig. 22. Predicted HQ levels for the short-period model using existing CAP and bandwidth criteria.

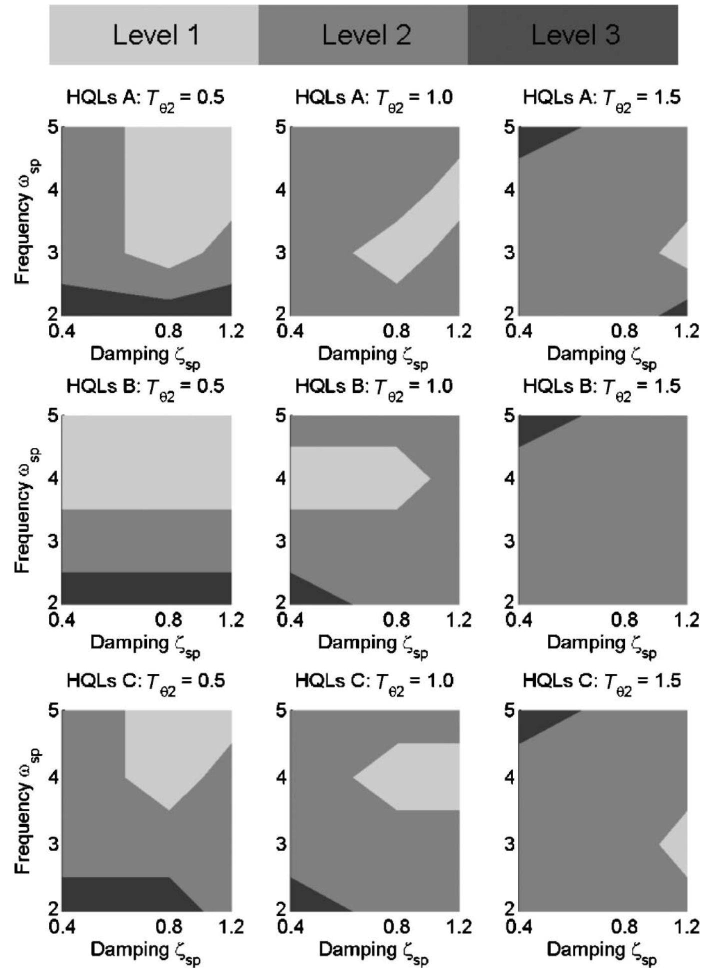


Fig. 23. Flight-path capture task HQLs.

with the HQLs predicted from the CAP/bandwidth/pitch dropback criterion in Fig. 22.

The results suggest that a low incidence lag is preferable for the flight-path task where, for example, with a value of 0.5 s, a large Level 1 area is evident from the three pilots. Likewise, when the incidence lag is increased to 1.0 s, a smaller Level 1 area is still maintained although it is now enclosed by a Level 2 handling qualities region. Finally, only one configuration revealed Level 1 HQRs with an incidence lag of 1.5 s.

These results follow the general trend of the HQL boundaries from the CAP/bandwidth/pitch dropback parameters illustrated in Fig. 22. However, Fig. 22 gives larger Level 1 regions, even for high values of incidence lag.

The drogue tracking task results are in sharp contrast to those predicted in the flight-path task. Low incidence lags see few Level 1 HQRs being returned and more Level 3 ratings. Furthermore, as the incidence lag increases, the HQLs show that the majority of the configurations tested became easier as the Level 1 area increases and the Level 3 area decreases in size.

After collating the HQLs for each task, a summary thumbprint chart is shown in Fig. 25 for the three incidence lags for the flight-path (top row) and the drogue tracking (bottom row) tasks. The top three subplots in Fig. 25 show that as the incidence lag increases, the Level 1 area moves down and to the right for the flight-path capture task, whereas for the pitch attitude tracking task the Level 1 area becomes increasingly larger with increasing incidence lag.

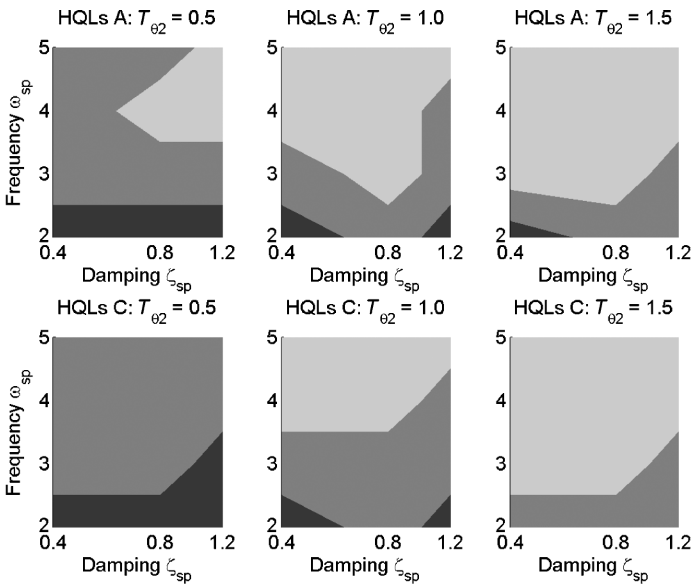


Fig. 24. Drogue tracking HQLs.

The difference between the predicted HQs for the two tasks can be explained by referring to the pitch attitude subplot shown in Fig. 3 and the control derivative definition in Eq. (8). As the incidence lag increases, a larger control derivative, hence larger control sensitivity, is required to achieve the same steady-state pitch rate. A larger control sensitivity results in a larger initial acceleration and a correspondingly larger peak pitch rate and overshoot. Therefore, for the drogue tracking task the pilots preferred to have high pitch acceleration as they were constantly applying small longitudinal stick inputs and a steady-state pitch rate was never achieved. For the flight-path capture task, however, the pilots applied a step input until a steady-state pitch rate was achieved, then removed the input to capture the desired pitch attitude. The task is essentially a much lower frequency one. If the configuration had a large incidence lag with a high pitch acceleration and pitch rate overshoot, large amounts of dropback were encountered, making control unpredictable. Conversely, if the pitch acceleration was low, with a pitch attitude overshoot (i.e., negative dropback), the configuration's response was equally difficult to predict.

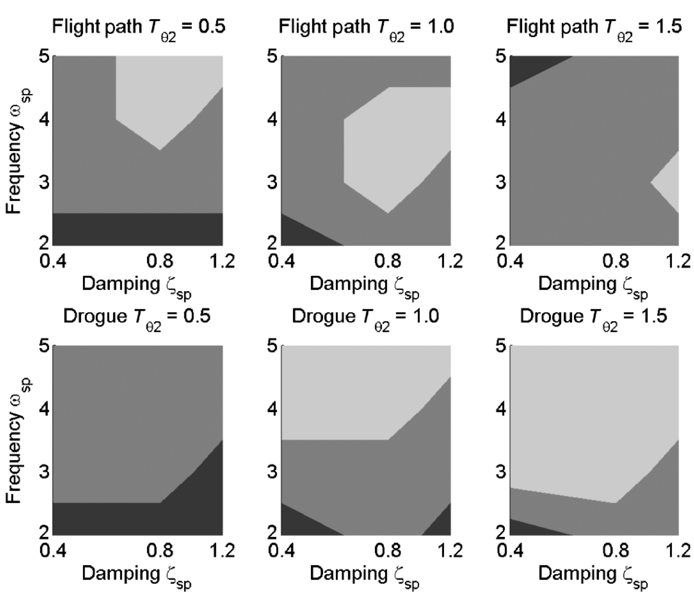


Fig. 25. Collated HQLs on the short-period thumbprint: Top row, flight-path capture task; and bottom row, attitude tracking task.

From the preceding analysis, although $T_{\theta 2}$ is the flight-path incidence lag, it still affects the handling qualities in the pitch tracking task. Therefore, it is proposed that one handling qualities criterion is suitable for rating both types of MTE, albeit with different handling qualities boundaries.

Derivation of a New HQ Parameter

Two areas of response characteristics have been identified as being critical during the preceding discussion. The first is the pitch acceleration characteristic to a longitudinal stick input. Research has shown that pilots prefer relatively large amounts of initial pitch acceleration for the drogue tracking task but only moderate amounts for the flight-path task. Second, the results show that pilots do not like large amounts of dropback or indeed negative dropback in either task as this makes the aircraft pitch response less predictable.

Previous handling qualities parameters such as CAP and dropback have gone some way to capturing these effects but neither, on its own, encapsulates all the related phenomena. A single HQ criterion based on pitch acceleration and dropback effects, integrated with the existing CAP criterion, is now proposed.

The existing CAP criterion has proven to be a successful tool in characterizing the initial pitch acceleration and furthermore, can be shown to be directly proportional to the maneuver margin (Ref. 18), which describes the aircraft maneuvering stability characteristics in terms of pitch damping properties of the tailplane and, in the case of the tilt rotor, the rotors. It is, therefore, proposed to maintain the CAP in the development of the new handling qualities parameter. However, instead of plotting damping on the x-axis, a technique for assessing the pitch attitude dropback is presented.

Pitch attitude dropback is illustrated again in Fig. 26, showing the pitch rate, attitude, flight path, and angle of attack response to a 4-s elevator step input.

Short-period mode parameter values used in the characteristic equation are $\omega_{sp} = 4$, $\zeta_{sp} = 0.8$, $T_{\theta 2} = 1.5$, and $U_e = 200$ kt.

As pitch dropback is of concern here, consider what happens between the control input being applied after 1 s and the control input being removed after 5 s. As the pitch angle θ is the sum of the flight-path angle (γ) and the angle of attack (α), after the initial transient response α is

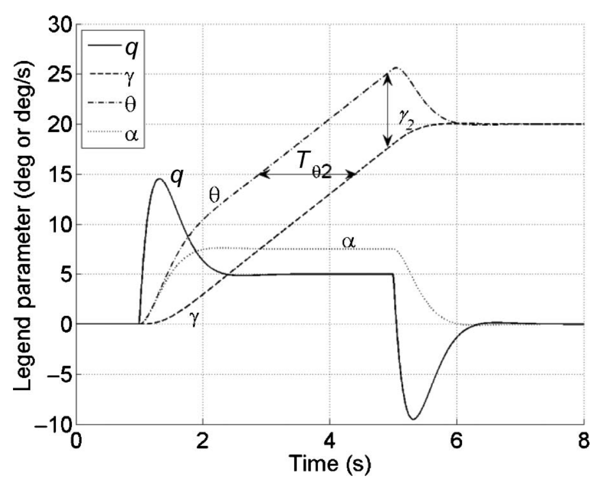


Fig. 26. Response to a step elevator input showing dropback effects.

constant. The steady-state angle of attack α_{ss} can be defined from the angle of attack equation

$$\ddot{\alpha} + 2\zeta_{sp}\omega_{sp}\dot{\alpha} + \omega_{sp}^2\alpha = M_\eta \eta \tag{11}$$

The steady-state solution is given by

$$\alpha_{ss} = \frac{M_\eta}{\omega_{sp}^2}\eta \tag{12}$$

Furthermore, α_{ss} can be redefined by substituting for M_η from Eq. (8) to give

$$\alpha_{ss} = q_{ss} T_{\theta 2} \tag{13}$$

As the flight-path attitude lags the pitch attitude by an angle of α_{ss} when the elevator input is removed, α_{ss} can be split into two further contributors, one the dropback, which contributes to the pitch attitude overshoot when the control is removed, and γ_2, the amount the flight-path lags θ_{ss}, defined as the flight-path lag time multiplied by the steady-state pitch rate

$$\gamma_2 = \frac{2\zeta_{sp}}{\omega_{sp}} q_{ss} \tag{14}$$

$$\alpha_{ss} = \Delta\theta_{DB} + \gamma_2 \tag{15}$$

Substituting Eqs. (13) and (14) into Eq. (15) and rearranging for $\Delta\theta_{DB}$ gives

$$\Delta\theta_{DB} = q_{ss}\left(T_{\theta 2} - \frac{2\zeta_{sp}}{\omega_{sp}}\right) \tag{16}$$

Finally, this can be converted to a flight-path lag ratio by dividing by α_{ss}

$$\frac{\Delta\theta_{DB}}{\alpha_{ss}} = 1 - \frac{2\zeta_{sp}}{\omega_{sp} T_{\theta 2}} = 1 - \frac{T_\gamma}{T_{\theta 2}} \tag{17}$$

If T_γ is greater than $T_{\theta 2}$ then $\Delta\theta_{DB}/\alpha_{ss}$ is less than zero and negative dropback or a pitch attitude overshoot will occur. Conversely, as $T_{\theta 2}$ becomes increasingly larger than T_γ, more and more dropback will be encountered. In addition, from Eq. (18), the time interval T_θ, between the first crossing of the steady-state pitch attitude and when the pilot must recenter the control (in order that the attitude returns to the required steady state) is equivalent to the dropback divided by the steady-state pitch rate. This time interval is crucial to the pilot and is a measure of the predictability of the pitch response. Furthermore, the ratio of this time to the flight-path delay is given by $\overline{T_\theta}$ and is equivalent to the flight-path lag ratio in Eq. (17), further emphasizing the significance of this dropback parameter, being a physically significant time measured in units familiar to the pilot:

$$T_\theta \approx \frac{\Delta\theta_{DB}}{q_{ss}} \tag{18}$$

$$\frac{T_\theta}{T_{\theta 2}} = \frac{\Delta\theta_{DB}}{\alpha_{ss}} = \overline{T_\theta} \tag{19}$$

Figures 27 and 28 show the proposed criteria of CAP vs. $\Delta\theta_{DB}/\alpha_{ss}$. On top of the data are the HQLs assigned by the pilots for the flight-path task in Fig. 27 and for the drogue tracking task in Fig. 28. For the flight-path task, all points assessed with negative dropback are Level 2 or Level 3. Level 1 handling qualities are only found in an area with small amounts of dropback and moderate values of CAP.

Owing to the clear separation between the HQLs in both figures, handling qualities boundaries, defined in Eqs. (20)–(25), can be drawn separating the Level 1–2 and 2–3 regions in both plots.

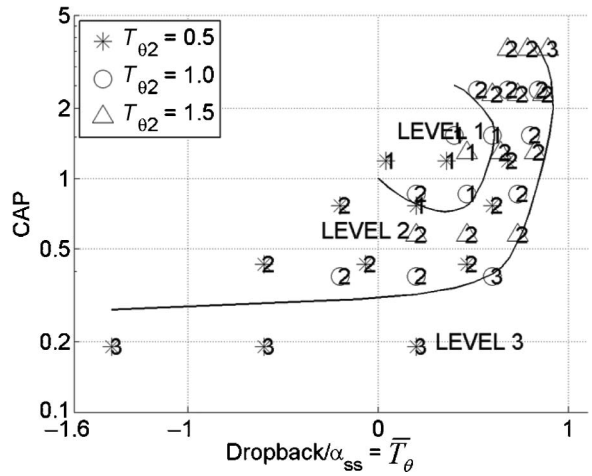


Fig. 27. Proposed HQ boundaries for the flight-path task.

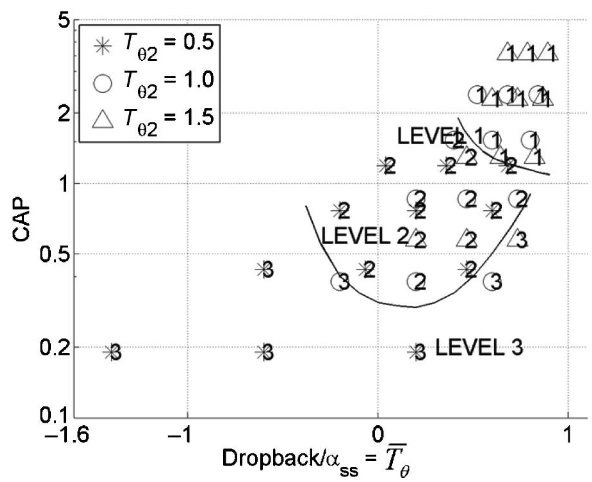


Fig. 28. Proposed HQ boundaries for the drogue tracking task.

Drogue tracking task:
1) Level 1–2 boundary

$$y = -16x^3 + 36x^2 - 27.4x + 8.25 \tag{20}$$

where $0.9 > x > 0.42$
2) Level 2–3 boundary

$$y = -0.1x^3 + 1.6x^2 - 0.5x + 0.3 \tag{21}$$

where $0.8 > x > -0.38$.
Flight-path task:
1) Level 1–2 boundary

$$y = 1.8x^3 + 1.2x^2 - 1.4x + 1 \tag{22}$$

where $0.5 > x > 0$

$$x = 0.03y^3 - 0.35y^2 + 0.86y + 0.02 \tag{23}$$

where $2.5 > y > 0.82$.
2) Level 2–3 boundary

$$y = 0.04x^3 + 0.11x^2 + 0.1x + 0.3 \tag{24}$$

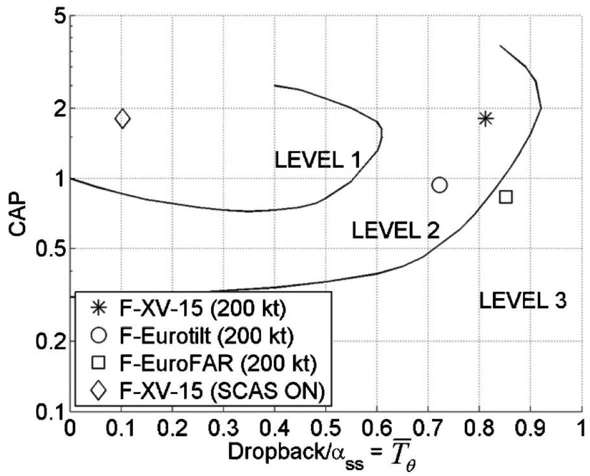


Fig. 29. Tilt rotor handling qualities on the CAP-dropback chart.

where $0.69 > x > -1.4$

$$x = 0.023y^3 - 0.2y^2 + 0.53y + 0.5 \tag{25}$$

$3.7 > y > 0.46$.

Only one ambiguous area exists in Fig. 27, where Level 2 and Level 1 are in close proximity, which could be interpreted as being the Level 1–2 handling qualities boundary. Figure 29 illustrates where the tilt rotor configurations listed in Table 3 lie on the flight-path boundary chart. F-Eurotilt and the F-XV-15 are both in Level 2, whereas the F-EuroFAR is close to the Level 2–3 boundary, but just into Level 3, showing good agreement with the pilot HQRs in Table 3. In addition to the configurations discussed throughout this paper, the FXV-15 with one possible SCAS solution (Ref. 22) is also displayed in Fig. 29. This configuration was shown to exhibit Level 1 handling qualities (Ref. 5) and is included here to demonstrate that the proposed pitch/flight-path criteria capture Level 1 HQ configurations with very low values of dropback.

The boundaries shown in Figs. 27 and 28 represent the integrated results and are described as preliminary, needing further validation. It should also be noted that the minimum values of CAP defining the level boundaries are much more demanding than the military standards defined in Ref. 20. This discrepancy does introduce some risk, but selecting values in the mid CAP Level 1 range (Fig. 9) will minimize this. A CAP value of 1.5 rad/s^2/g and $\overline{T_\theta}$ of 0.3 provides a robust design point, giving margin for change during any subsequent trade-off against other requirements.

Although the proposed criterion shows a distinct separation in HQLs, the boundaries are based on research with only a few configurations, with short-period mode natural frequencies between 2 and 5 rad/s, damping ratios from 0.4 to 1.2, and incidence lags from 0.5 to 1.5 s. Many more configurations need to be assessed to validate fully the proposed criteria and boundaries to HQLs.

Concluding Remarks

Inconsistencies between pilot assigned and predicted tilt rotor handling qualities in airplane mode led to an investigation into the variation of HQRs over a range of short-period mode parameters. These results were used to develop a new pitch/flight-path handling qualities metric using the existing CAP and a new pitch dropback parameter. Furthermore, it has been demonstrated that the hypothesized handling qualities metric can be used to assess the HQs of both attitude tracking and flight-path capture tasks. Different level boundaries are derived for the different task types: the pitch attitude tracking task allowing larger pitch accelerations and pitch attitude dropback than those shown to be good for a flight-path task.

The proposed boundaries are based on a limited number of short-period mode configurations (combinations of damping, frequency, and incidence lag, with constant pitch rate) with fixed speed. It is, therefore, recommended that further configurations are examined for a range of speeds that apply to both airplane and conversion modes.

Acknowledgments

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