Progress in Civil Tilt-Rotor Handling Qualities

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Abstract

Travellers should expect future transport aircraft to have excellent handling qualities. With the levels of augmentation available from active control, under normal circumstances, no task should require more than minimal pilot workload. Good handling underpins flight safety and validated criteria underpin good handling. This paper reports progress in the development of Handling Qualities criteria for a civil tilt rotor aircraft. The emphasis in the paper is on pitch/flight-path handling, particularly in airplane mode. The large prop-rotors serve to degrade handling, reducing damping and the manoeuvre margin. Current fixed-wing handling criteria, such as bandwidth and CAP, do not adequately pick up these effects and supplementary parameters need to be introduced. Results from piloted simulation trials conducted at Liverpool are presented that confirm the analysis and define the Level 2/3 HQ boundary.

Symbols/Acronyms

M_q, Z_w	stability (acceleration) derivatives
n_z	normal acceleration
$T_{\theta 2}$	incidence time lag
V	flight speed
δ_x	pilot's longitudinal control
θ, q	pitch attitude and rate
γ	flight path angle
λ_{sp}	short period eigenvalue
$\tau_{p\theta}$	pitch attitude phase delay
ω_{sp}	short period natural frequency
ζ_{sp}	short period damping ratio
ACT	Active Control Technology
ADS	Aeronautical Design Standard
CAP	Control Anticipation Parameter
CTR	Civil Tilt Rotor
DRC	Dynamic Response Criteria
FTM	Flight Test Manoeuvre
HQR	Handling Qualities Rating
HQs	Handling Qualities
IAS	Indicated Airspeed
MTE	Mission Task Element
OFE	Operational Flight Envelope
SAR	Search and Rescue
SCAS	Stability and Control Augmentation System
TAS	True Airspeed

Introduction

In any new aircraft featuring fly-by-wire, active flight control technology (ACT), the possibilities for tailoring the handling qualities to the mission tasks seem almost limitless. Yet the history of the application of such technology over 30 years has shown that the potential can be severely limited and mis-haps can easily result unless significant care is taken in design. At the heart of good design are comprehensive, reliable design standards and guidelines. In particular, handling qualities design criteria are central to the matching of active control functions to mission tasks. Tilt rotor aircraft represent a special class of vehicle in this respect, since they operate as both rotary and fixed wing aircraft and also as hybrids in the unique conversion corridor. The complexity of the flight management functions makes ACT mandatory for such vehicles, thus opening the opportunity to tailor HQs to the different tasks in the different flight modes and missions. Despite five decades (half the aerospace age!) of flight experience with tilt rotor aircraft, no comprehensive HQ design criteria are available in the public domain. As evidence of this, Ref 1 notes that three quarters of the certification basis for Performance and Handling Qualities of the BA609 had to be newly-created.

Within the last few years a number of Tilt rotor critical technology project have been initiated under the auspices of the European Commission's Framework V Programme, aimed at underpinning the development of a future European Civil Tilt Rotor. Specifically, the RHILP project (Rotorcraft Handling, Interactions and Loads Prediction) has focused on a number of complementary goals concerned with handling qualities, aerodynamic interactions and structural load alleviation. Progress on RHILP activities have been reported in Refs 2-5. A major objective of the project was to integrate the results of the HQ criteria development, improved inter-actional aerodynamic modelling and control concepts for load alleviation into Eurocopter's HOST modelling and simulation environment and the SPHERE piloted simulation facility at Marignane. As a companion to the present paper, Ref 6 reports on this integration activity, particularly the handling qualities and associated piloted simulations for the EUROTILT concept. The present paper reports on the

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handling qualities (HQ) criteria development, with emphasis on the pitch-heave dynamics, in much the same way that Ref 3 focused on roll handling qualities. The RHILP Project will be briefly reviewed, followed by an outline of the mission-oriented HQ methodology adopted in the project. The Modelling and Simulation approach is then described before Pitch-Flight Path handling criteria are discussed and results from piloted simulations carried at The University of Liverpool presented. A short discussion on the implications of the results for flight control system development is followed by a summary of the main conclusions.

Framework for HQ Engineering in RHILP

The RHILP project (2000-2003) is one of 6 critical technology projects underway to enable European Industry and Research Organisations to develop a knowledge base on tilt rotor technology, and with it sufficient confidence to design, build and test a prototype aircraft and thence towards a production civil tilt rotor. The RHILP project team, led by Eurocopter, includes DLR, ONERA, NLR, CIRA and The University of Liverpool. Ref 2 describes the project goals and plan. With respect to HQs, a concern was how the existing comprehensive military standards might be adapted to the operational requirements of a civil tilt rotor. Another question concerned the harmony between fixed and rotary wing criteria. A third centred around the potential requirements for new criteria, perhaps better adapted to flight in the conversion corridor. An emphasis in RHILP was to determine the Level 2/3 HQ boundary (i.e. the boundary between the operational and service (manoeuvre) flight envelopes, OFE and SFE) so that the requirements for the core stability and control augmentation system could be established.

Early in the project a decision was made to adopt the mission-oriented framework of the helicopter HQ standard, ADS-33E (Ref 7), in particular the mission analysis and mission task element (MTE) approach. The complementary fixed-wing HQ Handbook, MIL-HDBK 1797 (Ref 8) adopts a different approach, setting criteria for aircraft classes and categories and flight phases. ADS-33 simply says that, irrespective of the aircraft class or size, the key HQ issues centre on the mission tasks required to be flown. This approach is readily applied to civil operations and, in RHILP, the mission analysis identified 2 primary roles – Transport (T) and Search and Rescue (SAR) – and 14 HQ-critical MTEs, listed below;

1. Rapid vertical re-position (RVP)
2. Accel-Decel (aborted take-off) (A-D)
3. Rapid conversion/re-conversion (RC/RRC)
4. Collision avoidance (CA)
5. Terrain following (TF)
6. Valley following (VF)
7. Rapid teardrop re-conversion (RTR)
8. Precision hover capture (PHC)
9. Rapid side-step (RS-S)
10. Glide slope re-capture (GSR)
11. Multi-segment approach (MSA)
12. Missed approach/obstacle avoid (MA/OA)
13. Approach and landing in cross wind (ALXW)
14. Hover turn (HT)

It is well known that the HQs of a particular aircraft depend on a number of factors, in addition to the dynamic response characteristics, e.g. visual cues, turbulence level and level of aggressiveness adopted by the pilot. This third factor can be taken into account by designating a maximum level of urgency for each MTE – low (L), medium (M) or high (H). The precision requirements of a task also drive the HQs. Table 1 gives the defined urgency level for the 14 MTEs. With more than 40% of the MTEs at H level, the SAR mission defines the HQs of the civil tilt rotor (CTR).

MTE	Level of urgency		Configuration		
	SAR	T	HM	CM	AM
RVP	H	-	✓		-
A-D	H	M	✓	-	-
RC/RRC	H	L	-	✓	-
CA	H	H	-	✓	✓
TF	M	-	✓	✓	✓
VF	M	-	✓	✓	✓
RTR	H	-	✓	✓	✓
PHC	H	L	✓	-	-
LS-S	M	-	✓	-	-
GSR	M	M	✓	✓	✓
MSA	M	M	✓	✓	✓
MA/OA	M	M	✓	-	-
ALXW	M	M	✓	-	-
HT	M	L	✓	-	-
HM – helicopter mode, CM – conversion mode, AM – airplane mode					

Table 1 CTR Mission-Task-Elements

MTEs are defined in terms of the mission context, the specific piloting requirements and associated handling qualities. The requirements are normally developed by a group of experts comprising test/operational pilots, engineers and user/operators. Table 2 describes the terrain-following MTE in the SAR mission that can be flown in any of the three aircraft modes (AM, CM, HM).

The accompanying Fig 1 shows a simple sketch of the MTE.

Mission Context: During SAR missions, the aircraft may have to fly near the surface in order to identify the rescue site and to search and detect the injured personnel. In such a situation, the aircraft will typically have to fly the terrain contours at speed ranges between 70 to 200 knots, depending on the search zone size. This speed range means that the task can be flown in Conversion, Airplane or Helicopter Modes.

Piloting Requirements: Initially the pilot will start from a level non-accelerated flight and will achieve as rapidly as possible a (maximum) positive load factor and maintain it for a few seconds to follow the terrain profile. The pilot will then initiate a symmetrical ‘negative’ (minimum) load factor and maintain this, also to follow the terrain profile. Finally, the pilot will recover to level flight as rapidly as possible. During the manoeuvre the pilot should control flight path, airspeed, roll angle and heading within defined constraints. The piloting strategy may change depending on the aircraft mode. In airplane mode, the pull up/pushover is achieved through elevator control. In conversion/helicopter mode, depending on the nacelle tilt angle, a combined elevator/cyclic//collective control can be used.

Handling Issues: The ability to establish and sustain a load factor as rapidly as possible will depend on the aircraft pitch and flight path response characteristics to the elevator in airplane mode and to the combined elevator/cyclic/collective inputs in conversion or helicopter mode. Short term pitch and flight path responses will be critical. The sufficiency of control power, attitude quickness and manoeuvre stability will need to be checked with both positive and negative load factors. Degraded visual conditions will also contribute to the workload.

Table 2 Description of the Terrain-Following MTE

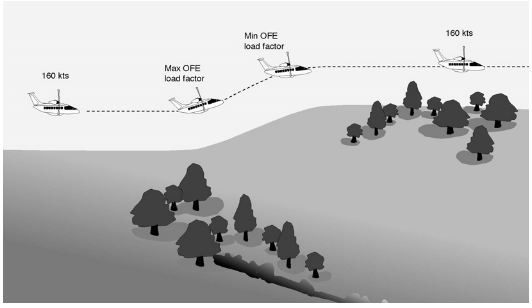


Figure 1 Sketch of Terrain Following MTE

The definition of the MTE’s forms a key stage in the HQ framework summarised in Fig 2. They represent a de-construction of the mission from which test manoeuvres can be developed and the response types and characteristics can be identified. The MTEs should embrace the whole operational flight envelope and flight in degraded visual conditions or reduced usable cue environments.

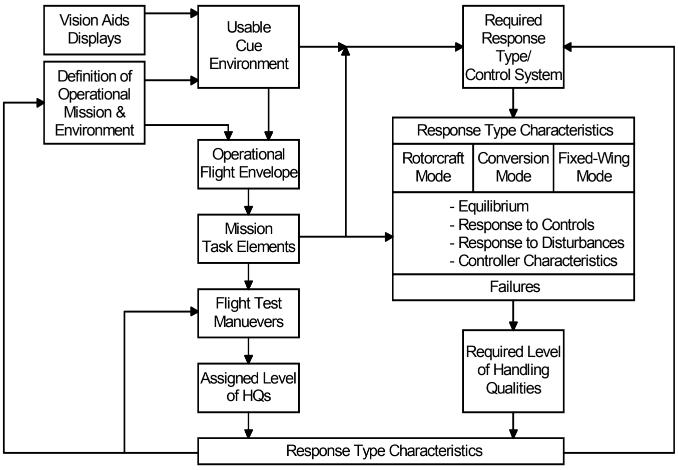


Fig 2 Handling Qualities Engineering Framework

At the heart of the approach are the Dynamic Response Criteria (DRC) representing flight behaviour in response to controls and disturbances. Fig 3, from Ref 9, describes the DRC in 4 groups, 2 relating to agility (large-moderate amplitude manoeuvres) and 2 relating to stability (low-high frequency modes). The criteria in ADS-33 are theoretically related for classical rate or attitude response types, so that, for example, attitude quickness tends to control power at large amplitude and bandwidth at small amplitude; the character of the high frequency modes determines the closed-loop stability at degree of precision achievable in tracking tasks. These theoretical considerations are discussed in detail in Ref 10. The general structure in Fig 3 is common to both rotary and fixed wing aircraft, but ADS-33 and MIL-HDBCK 1797 differ in detail in several areas. Particular interests in the present paper are the criteria for pitch and flight path handling qualities in the small amplitude-high frequency region, and we shall return to discuss these later in the paper.

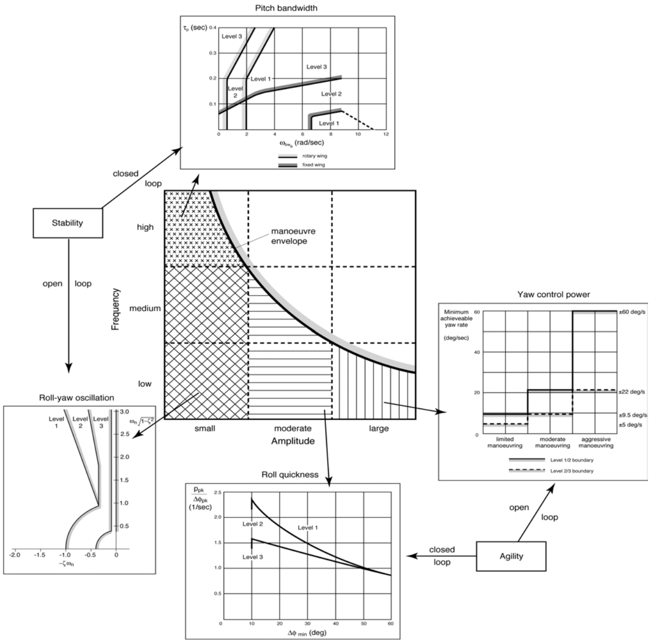


Fig 3 Dynamic Response Criteria

Having defined the DRC and hence the required (or predicted) level of HQs, the process in Fig 2 continues with the determination of the actual or assigned HQ level through piloted tests using the Cooper-Harper HQ rating scale and associated HQ levels (Ref 11). The flight test manoeuvres (FTM) are developed from the MTEs and the descriptions include the desired and adequate performance standards, level(s) of aggressiveness and critical areas for assessment. In the present paper, attention is focused on pitch-flight path HQs and the terrain following MTE has been developed into a 'heave-hop' FTM, described later in the paper.

A particular concern in the RHILP project was the location of the Level 2/3 boundary on the various HQ charts. The core flight control system in a future CTR, defined by a failure probability of 1 in 10^9 flying hours, must confer Level 2 HQs across the OFE, including 'maximum' manoeuvres. The approach taken was to check, through analysis and piloted simulation, the compatibility of criteria for flight in helicopter and airplane modes. The conversion mode was used as a bridge between the two 'conventional' modes. The conversion process itself was important in this regard as the manoeuvre could be initiated in helicopter mode, at say 60kts, and completed in airplane mode at 180kts. Beyond the Level 2/3 boundary, the risk of loss of control increases and MTEs cannot be flown within the mission performance standards. The handling qualities are unacceptable.

Modelling and Simulation

Within the RHILP project, modelling and simulation activities were conducted within both the HOST (Eurocopter, DLR, ONERA) and FLIGHTLAB environments (NLR, Liverpool), providing a degree of dissimilarity to support verification and validation activities. Ref 6 discusses the HOST implementation and Refs 3 and 5 have discussed the FLIGHTLAB implementation at Liverpool. The project aircraft was Eurocopter's CTR concept, EUROTILT, shown in Fig 4. Within the FLIGHTLAB environment, models of both EUROTILT and the XV-15 aircraft (designated FXV-15, Fig 5) were constructed and the latter was used for validating the prediction of flight mechanics and rotor loads (Refs 3, 5).

Fig 4 Eurocopter's EUROTILT Concept

Fig 5 Bell XV-15

The main aeromechanics features in the FXV-15 (and EUROTILT) models are summarised as follows:

- rigid prop-rotor blades with non-linear, quasi-steady aerodynamics in table look-up form as functions of angle of attack and

Mach number, computed on 5 equi-annulus segments,

- Two 3-bladed counter-rotating gimbal rotors; the gimbal is modeled with torsional spring-damper components in pitch and roll. No individual blade flapping is allowed,
- 3 degree-of-freedom, finite-state rotor inflow model (Peters-He),
- The unique engine-governor system of the XV- 15 was modeled as a simple first order relationship between output and commanded torque, the latter is a function of throttle setting and atmospheric conditions, with throttle and collective geared together as a function of nacelle tilt,
- The rigid drive train system was modeled as a collection of gear, drive, clutch and bearing components with the interconnect shaft as the single degree of freedom driven by the resultant torque,
- The wing/flap lift, drag and pitching moment coefficients are defined as functions of angle of attack, nacelle angle and flap setting. 4 aero segments are used with the outer left and right segments immersed in the rotor slipstream and the 2 inner sections assumed to be unaffected by the rotor wake,
- Rotor-wing-empennage interactions are modeled by superimposing the uniform component of the rotor induced velocity onto the wing empennage velocities; wing-empennage downwash angle included,
- Nonlinear fuselage aerodynamics are functions of angle of attack and sideslip,
- Empennage aerodynamics modeled in a similar manner to the main wing,
- The FXV-15 control system features the mechanical interlinks between the pilot's controls and the rotor and fixed-wing control surfaces, with gearings set as functions of nacelle angle; the system also includes the 3- axis stability and control augmentation system, featuring rate damping and feed-forward response quickening,
- For the tricycle undercarriage, the FLIGHTLAB generic rotorcraft component was selected and modified to the appropriate location and size,
- Ground effect was modeled as a rotor image system.

In rotorcraft mode, pitch control is achieved through longitudinal cyclic, roll control through differential collective (note that lateral cyclic is also provided for trimming), yaw through differential longitudinal cyclic and heave through combined collective. In airplane mode, the pilot's controls command conventional elevator, aileron and rudder (with a small proportion of differential collective included).

The FLIGHTLAB environment and HELIFLIGHT flight simulator are described in detail in Ref 12.

Pitch-Heave Handling Qualities

As a starting point in this discussion of the longitudinal handling qualities of tilt rotor aircraft, Fig 6 shows the maximum pitch attitude quickness lines for all three aircraft modes; the airplane mode data are shown for flight at 200kts Indicated AirSpeed (IAS) at sea level and at density altitude 6000m. The aircraft are shown with SCAS disengaged. On the quickness charts are shown the ADS-33 HQ boundaries for low speed helicopter mode flight (< 45kts) and also the HQ boundary proposed for fixed wing aircraft in Ref 13. The rotary wing boundaries are applicable to target acquisition and tracking. The FXV-15 in hover has Level 2 performance, and just meets Level 1 performance for 'other MTEs' (not shown, but lies just above Level 2 tracking boundary). At 60kts, the FXV-15 as a helicopter exhibits close to Level 1 tracking performance and in conversion mode at 120kts, a 30-50% performance margin above the Level 1 boundary is predicted. In airplane mode at 200kts a significant margin above the Ref 13 boundary is predicted. The aircraft should possess adequate pitch axis performance to fly moderately aggressive tasks in all modes, particularly at the higher speeds.

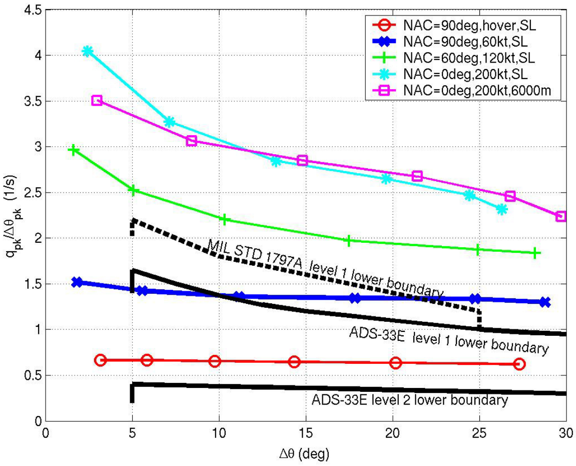


Fig 6 Pitch Attitude Quickness
FXV-15 SCAS off

Long-term stability is poor, particularly in helicopter mode, but it is a known problem and is easily rectified with rate damping in the core SCAS. This paper is more concerned with the short-term response characteristics that govern the ability to acquire and track, as with the moderately aggressive manoeuvring required of a CTR in the terrain following MTE. Fig 7 illustrates the loci of the short period modes for the different aircraft configurations as functions of IAS. As the IAS increases and the aircraft moves from helicopter to airplane mode, the short period frequency increases, but the relative damping (ζ) reduces. At 200kts IAS, 6000m density altitude, ζ has reduced to below the $\zeta = 0.35$ boundary and the $\zeta = 0.3$ Level 1 boundary (Cat B aircraft, Ref 8, slightly to right of 0.35 line in Fig 7).

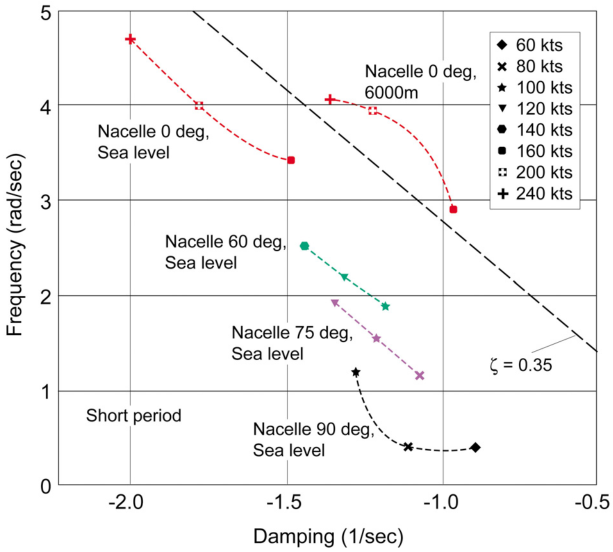


Fig 7 FXV-15 Short Period Mode Root Loci

Focussing on the airplane mode HQs, the results shown in Fig 7 conform broadly to the predictions on the 'thumbprint' chart (short period natural frequency vs damping ratio) shown in Fig 8 (Refs 14, 15). As the aircraft IAS increases from 160kts to 200kts at sea level, the HQs are predicted to improve from poor to acceptable and as the density altitude increases from sea level to 6km at the higher speeds, HQs are predicted to degrade from acceptable to poor. The interpretation of these boundaries in terms of HQ levels is not defined in the original thumbprint data (preceded Cooper-Harper), but based on the damping ratio, the acceptable/poor boundary could be interpreted as Level 1/2.

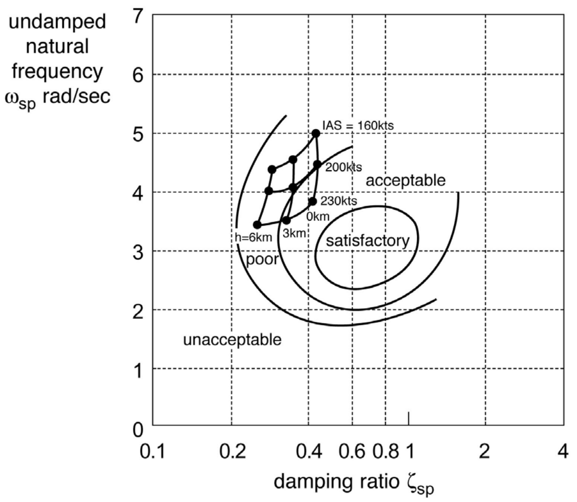


Fig 8 Short Period Thumbprint Chart (Ref 14)

The pitch/flight path handling qualities are known to depend not only on the short period characteristics, but also on the incidence lag, $T_{\theta 2}$ (Ref 15). The impact of this parameter can be assessed from simple approximations to the short-term pitch behaviour at constant speed. The pitch rate q and normal velocity w are governed by the approximate equations in body axes;

$$\begin{aligned} &\dot{w} - Z_w w - Vq = Z_{\delta e}\delta_e \\ &\dot{q} - M_w w - M_q q = M_{\delta e}\delta_e \end{aligned} \qquad (1)$$

The force and moment derivatives, Z_w, M_q, etc. are normalised by mass and moment of inertia respectively and V is the constant flight speed. The pitch attitude to longitudinal stick (δ_e) transfer function is then given by the expression;

$$\begin{aligned} \frac{\theta(s)}{\delta_e(s)} &= \frac{M_{\delta e}(s + 1/T_{\theta 2})}{s\left(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}{}^2\right)} \\ &\approx \frac{M_{\delta e}(s - Z_w)}{s\left(s^2 - (M_q + Z_w)s + (M_q Z_w - M_w V)\right)} \end{aligned} \qquad (2)$$

where,

$$\begin{aligned} &2\zeta_{sp}\omega_{sp} \approx -(M_q + Z_w) \\ &\omega_{sp}{}^2 \approx (M_q Z_w - M_w V) \end{aligned} \qquad (3)$$

The lag in the transfer function numerator results in the pitch response experiencing an overshoot before the stiffness due to the incidence change comes into effect (M_w). This overshoot, if large, can lead to piloting difficulties in terms of the ability to predict the control movement required to achieve a given attitude change. In an attempt to capture this effect in a handling qualities parameter, the control anticipation parameter (CAP) was introduced and became the reference criterion in Ref 8 (see also Refs 14, 15). CAP, the ratio of initial pitch acceleration to steady state normal acceleration $n_z(\infty)$, is proportional to the manoeuvre margin of the aircraft and can be approximated by the expression (Ref 14);

$$CAP = \frac{\dot{q}(0)}{n_z(\infty)} \approx -\frac{g\omega_{sp}{}^2}{Z_w V} = \frac{g\omega_{sp}{}^2 T_{\theta 2}}{V} \qquad (4)$$

$$(T_{\theta 2} = -1/Z_w)$$

Ref 8 sets limits to the damping ratio so that the CAP chart takes the form of Fig 9. The boundaries for Cat B flight phases are included and the FXV-15 predictions are shown as a function of speed and altitude. In a similar fashion to the data on the thumbprint chart, the configurations are shown to straddle the Level 1/2 HQ boundary. The stability derivatives and HQ parameters for the various configurations are given in Table 4. The exact and approximate short period characteristics are shown for comparison; both damping and frequency are predicted by the constant speed approximation to within a few percent for all three aircraft modes.

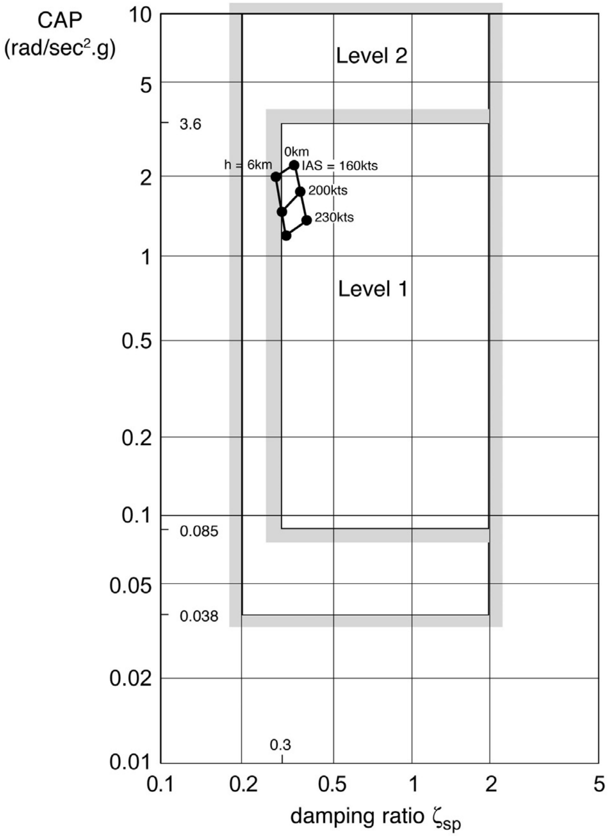


Fig 9 FXV-15 on Control Anticipation Parameter Chart (Ref 8, Cat B Flight Phases)

Mode (IAS)	HM 60kts (SL)	CM 120 kts (SL)	AM 200 kts (SL)	AM 200kts 6000m
$-Z_w$	0.504	0.882	1.05	0.766
$-M_w$	0.0085	0.032	0.052	0.035
$-M_q$	1.309	1.72	2.55	1.66
TAS (V) ft/sec (m/sec)	99.5 (30.4)	198.6 (60.6)	325 (99.1)	440 (134)
$2\zeta_{sp}\omega_{spapprox}$	1.81	2.60	3.6	2.43
$\omega_{sp}{}^2{}_{approx}$	1.505	7.91	19.58	16.87
$\omega_{spapprox}$ rad/sec (exact)	1.23 (1.2)	2.81 (2.81)	4.43 (4.41)	4.08 (4.07)
$\zeta_{spapprox}$ (exact)	0.74 (0.76)	0.46 (0.47)	0.41 (0.4)	0.298 (0.295)
CAP ($-g\omega^2$ / VZ_w) rad/sec^{2}per g	0.966	1.45	1.85	1.61
$\Delta\theta_{pk}/q_{ss}$ (sec)	-	1.00	1.75	1.6
q_{pk}/q_{ss}	-	3.3	4.7	5.4
$M_{\delta\varepsilon}$	0.397	0.727	1.907	1.86
λ_{sp} (Re, Im)	-0.91, 0.79	-1.3, 2.48	-1.78, 4.04	-1.2, 3.89

Table 4 FXV-15 Short Period HQs

The traditional quickness and short period/CAP criteria thus suggest that the FXV-15 configuration should exhibit near Level 1 pitch HQs in airplane mode, except perhaps at reduced density altitude, when some degradation to Level 2 can be expected. These conclusions are also substantiated by the application of the bandwidth criteria to the aircraft. The results are shown on the phase-delay/bandwidth chart in Fig 10; the data points were derived from controls sweeps flown in the flight simulator, averaged over three runs. Strictly, ADS-33 does not set bandwidth criteria for helicopters in forward flight, but the 60kts case is shown relative to the low speed, Level 1/2 HQ boundary for general MTEs. The tracking boundary is set at 2 rad/sec (not shown), making the helicopter pitch HQs Level 2 for such tasks. As forward speed increases, so bandwidth also increases, closely related to the increasing pitch natural frequency ω_{sp}. The fixed wing HQ boundaries are taken from the recommendations in Ref 13 and refer to Categories B and C, Classes I, II and III in Ref 8 parlance. Cat B refers to non-terminal flight phases requiring gradual manoeuvring and accurate flight path control. Ref 13 recommends a bandwidth of 3 rad/sec for highly manoeuvrable aircraft to attain Level 1 HQs. The FXV-15 easily meets this requirement in conversion mode at 120kts and airplane mode at 200kts.

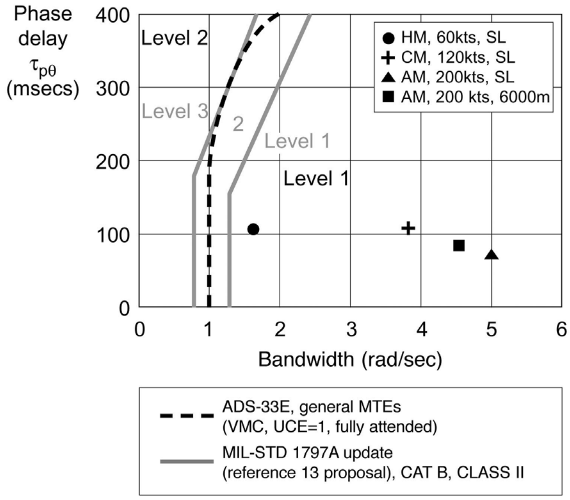


Fig 10 Pitch Attitude Bandwidth vs Phase Delay Results for FXV-15

Before presenting the results of piloted simulation trials, it is useful to compare the pitch response of the different aircraft configurations to a 1 inch (2.54cm) step input on longitudinal stick. Fig 11 presents results for the nonlinear FXV-15, showing (clockwise from top left) pitch rate, pitch attitude (θ), incidence (α) and flight path angle (γ).

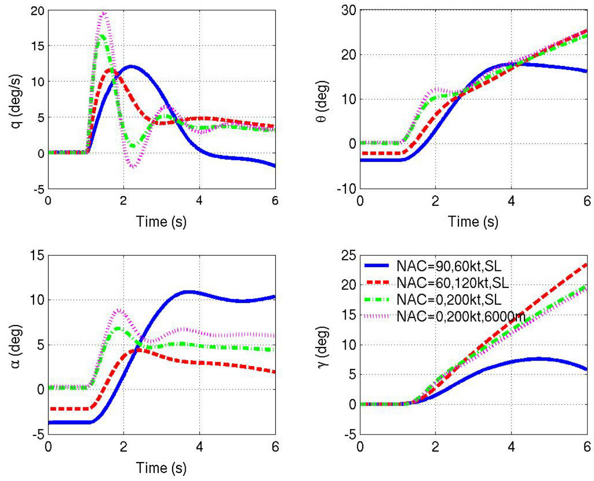


Fig 11 FXV-15 Response to a I inch Step Longitudinal Control Input SCAS off

There is a noticeable difference between the helicopter mode and airplane mode responses. The helicopter features an attitude-like response type, with the pitching moment due to speed reduction counteracting the initial pitch up within a few seconds. At 200kts in airplane mode the response settles to a steady rate after about 4 seconds but there is a marked overshoot within the first second. This overshoot has already been discussed and is caused by several effects. First, the rather low value of $-Z_w$ ($T_{\theta 2}$ ~ 1 second) delays the aerodynamic stiffness effect from M_w. Second, the values of $-M_w$ and $-M_q$ are significantly reduced for a tilt rotor aircraft due to the large in-plane rotor loads acting to increase further the pitch moment when pitching up (rotor contributions to both derivatives are positive). This results in a smaller manoeuvre margin than in a conventional propeller airplane.

In reviewing the applicable criteria for fixed wing aircraft, the authors of Ref 13 noted that responses with large attitude rate overshoots do not satisfy the conventional 1797 criteria. Supplementary criteria were recommended utilising Gibson's drop-back parameter (Ref 16), in conjunction with the overshoot ratio. The criteria parameters are defined in Figs 12 and 13. The key parameters are the ratio of pitch rate peak (overshoot) to steady state pitch rate and the ratio of the 'drop-back' in pitch attitude to the steady state pitch rate. This second parameter is shown in Fig 12 to be equivalent to the lead time associated with the effective start of a pure rate response. The criteria boundary recommended in Ref 13 is given in Fig 13 – applicable to all aircraft classes and flight phases. If the response lies above the Level 1 boundary line, then HQ Levels based on CAP or bandwidth are degraded by one Level, as indicated in the legend below the Figure. As seen in Fig 13, the pitch responses of the FXV-15 in both conversion and airplane modes lie above the line, suggesting that the predicted HQs discussed earlier need to degrade one Level.

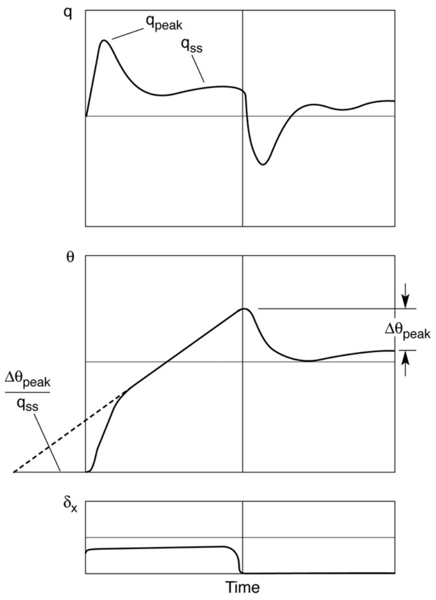
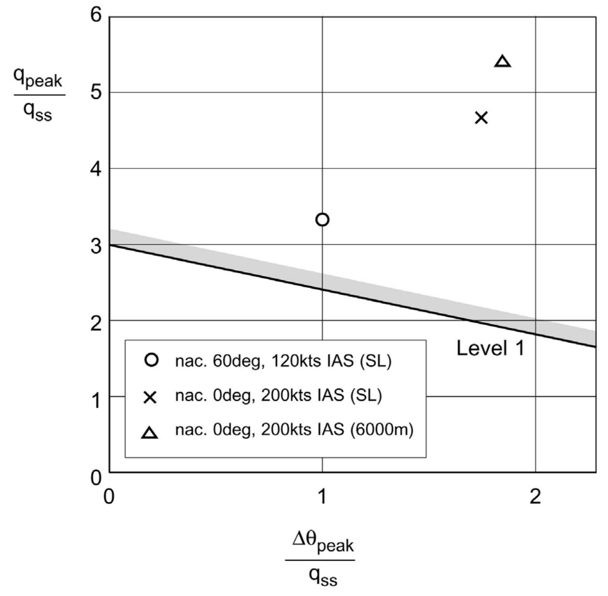


Fig 12 Pitch Response to Pulse Longitudinal Control Input – drop-back definition



If response is above the limit, and

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

Fig 13 Pitch Drop-back – Overshoot HQ Criteria

The previous discussion has exposed some of the complexities surrounding fixed-wing pitch HQs. To quote from Ref 13, "This section (*short term, small amplitude pitch response*) of the military standard is clearly the most controversial and it continues to undergo scrutiny from the flight dynamics community". Fig 14 shows the FXV-15 response to the control pulse in airplane mode. For the sea-level case, an 8 degree attitude drop-back can be observed, which, according to the criteria, will be the source of adverse pilot comments. The drop-back HQ parameters are included in Table 4 for completeness.

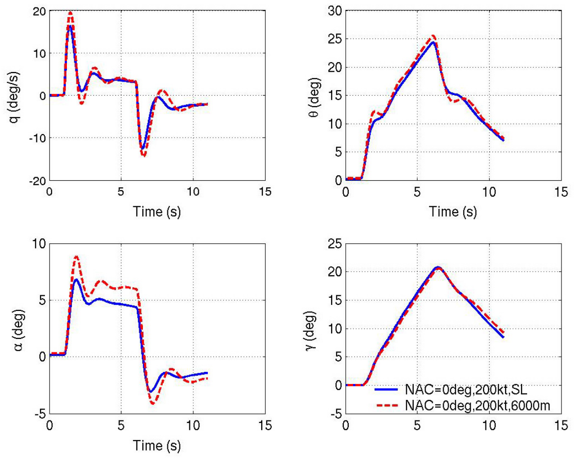


Fig 14 FXV-15 Response to Longitudinal Pulse

Piloted Simulation Trials

A series of piloted trials have been conducted on the Liverpool Flight Simulator (Fig 15) in support of RHILP. Following the review of HQ criteria and their applicability to a future civil tilt rotor aircraft, the major gaps were identified, MTEs/FTMs defined and the trials conducted using 4 test pilots. Six HQ trials took place during the period April 2001-January 2003, accumulating 150 hours of piloted tests.

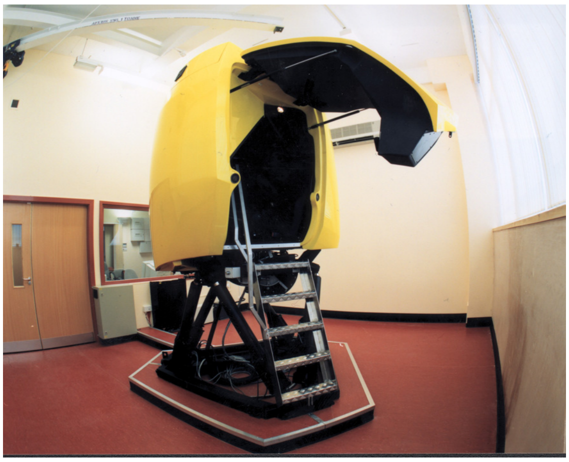


Fig 15 The Liverpool Flight Simulator

The simulation facility is described in detail in Ref 12 and its use in RHILP outlined in Refs 3 and 5. It features 6 axes of motion and 5 outside world screens and a dynamic force feel system. FLIGHTLAB models typically run in real-time at 200Hz. To investigate pitch/flight-path HQs, the terrain-following MTE (SAR mission) was developed into the Heave-Hop FTM, shown in Fig 16, with the view from the cockpit shown in Fig 17. Various Heave-Hop aspect ratios (AR = 0.067, 0.1, 0.2; ratio of height change to horizontal distance between poles) were flown at speeds from 160kts to 225kts. The maximum (2.5g) and minimum (0g) load factors for the CTR operational manoeuvre envelope were achieved at about 180kts at an AR=0.2. The performance tolerances are given in Fig 16 and summarised in Table 5. For the trials reported here the pilot only flew and rated the initial climb and recover to level phases. The pilots completed an in-cockpit questionnaire before awarding a Handling Qualities Rating (HQR).

	desired	adequate
Height	±10ft	±15ft
Speed	±5kts	±10kts
Bank angle	±5deg	±10deg
Track	±15ft	±30ft
Yaw angle	±10deg	±15deg

Table 5 Performance Standards for Heave-Hop

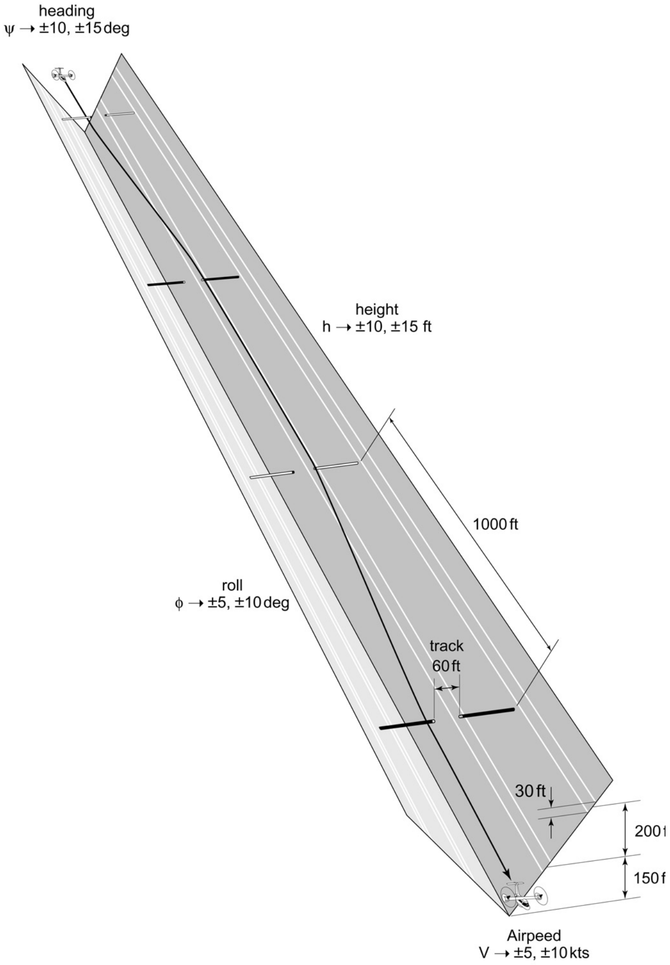


Fig 16 Sketch of the Heave-Hop Test Manoeuvre with Desired and Adequate Performance Standards

Fig 17 Pilot's View of the Heave Hop

Tests with both the FXV-15 and EUROTILT aircraft have been flown. The former aircraft was used for the majority of the HQ criteria development. The mean and spread of the pilot ratings for FXV-15 flown in airplane mode, at 3 speeds and 2 density altitudes, are given in Fig 18 for the AR=0.2 manoeuvre (3 test pilots participated in the trials). For the manoeuvre flown at the lower AR's, the HQs remained in the Level 1-2 ranges. In Fig 18, at 200kts and above, the aircraft is borderline Level 2/3. It is noteworthy that one of the pilots experienced the highest workload with maintenance of heading and track during the manoeuvre (the Dutch roll mode suffers from the similar adverse effects on directional stability and yaw damping). All three pilots experienced the pitch bobble/dropback as a source of unpredictability, in the initial climb and during the pushover at the high bar. Based on the results shown in Fig 18, the CAP/Bandwith criteria do need to be supplemented with the drop-back/overshoot condition of Fig 13.

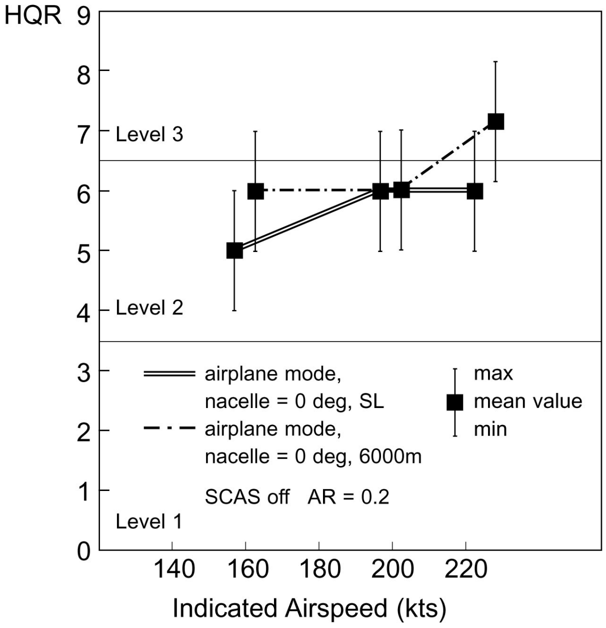


Fig 18 HQRs for FXV-15 flying Heave-Hop in Airplane Mode

Ref 6 reports on the Eurocopter SPHERE evaluations of the EUROTILT concepts as part of RHILP. The short period natural frequency of EUROTILT is about 30% lower than on the FXV-15 and pilots experienced similar problems to those in the Liverpool simulations, although the test manoeuvres were different. In the SPHERE trials, the control forces had to be increased significantly to reach an acceptable level of sensitivity in cruise for the evaluation pilots. In an operational CTR, an option is to vary control forces during a manoeuvre to provide a improved 'cue' to the pilot. Flight envelope protection is also common in ACT aircraft. Both tactile cueing and envelope protection are designed to reduce workload and enhance HQs and are being explored in the continuing ACT-TILT project.

Discussion

The analysis of pitch axis handling qualities for tilt rotor aircraft has proved more challenging than the roll axis reported in Ref 3. In roll, the primary dynamics remain fairly constant across flight modes, although the inherent bandwidth, quickness and control power of the natural aircraft vary significantly. In particular, in low speed helicopter flight, the roll bandwidth is so low that it is difficult to imagine any aggressive, high 'bandwidth' tasks being accomplished successfully. Unlike a conventional helicopter, the pitch axis of a CTR in helicopter mode tends to have improved performance relative to roll, largely due to the moment of inertia ratio. The pitch attitude quickness meets the Level 2 requirements for tracking tasks and the Level 1 requirements for general MTEs. As forward flight increases and the conversion and airplane flight modes are entered, the pitch dynamics change significantly. The large prop rotors contribute adverse pitching moments during manoeuvres, and it is left to the tail-plane to maintain natural damping and static stability. The extent of the pitch overshoot during attitude changes leads to a general unpredictability of the pitch change from an applied elevator command. The various handling qualities requirements for pitch attitude and flight path control have been investigated to establish the appropriate criteria for the tilt rotor aircraft. ADS-33 is clearly appropriate for low speed flight helicopter mode, but fixed wing criteria are required for pitch manoeuvres in conversion and airplane modes. Specifying HQ requirements in terms of the damping and frequency of the short period dynamics, control anticipation parameter or bandwidth, all fail to capture the adverse effects of the attitude drop-back caused by the slow heave response combined with the weak manoeuvre stability. Supplementing the requirements with Gibson's drop-back parameter, in the form given in the proposed MIL-1797 update (Ref 13), correctly predicted the handling degradation.

The tests conducted on the Liverpool Simulator confirmed this theoretical analysis. In such tests, the chosen manoeuvre is critically important. If the performance parameters are tightened, or level of manoeuvre aggressiveness increased, the pilot's workload increases and HQR's will degrade. The geometry of the Heave-Hop was selected to require the pilot to demand the maximum (OFE) performance during the pull-up, which made the manoeuvre very demanding. At the higher speeds, 200kts and above, the 'g' level increased beyond the 2.5g OFE limit. The Level 2/3 boundary was identified in roughly the place where the HQ criteria predicted. The performance demanded by the Heave-Hop with aspect ratio = 0.2, would certainly not be typical of the normal levels adopted by a pilot when terrain following in a civil SAR mission. However, it is considered that testing to these extremes is important to explore the potential for serious pilot-induced-oscillations to occur at the Level 2/3 boundary.

While the supplemented CAP/bandwidth criteria has served as a 'way through' this initial investigation, we are left with HQ criteria for the helicopter mode on the one hand and conversion and airplane mode on the other that do not naturally match. It is the intention in the continuing work on CTR HQs to continue the development of pitch/flight path criteria and one candidate for examination is the flight path quickness parameter introduced in Ref 17, and associated bandwidth. For surface following or approach and landing tasks, flight path is the natural flight variable under control, although the pilot normally does not always have clear visual information of flight path changes. This situation has partly detracted from serious attention to flight path HQ criteria, but the opportunities presented by head-up, visual guidance systems may change this.

The RHILP project formally closed in Spring 2003 and the continuing research on CTR HQs is being conducted by the same European team within the sister ACT-TILT project. The focus here is on establishing the Level 1/2 boundary for all modes of flight. The active control system on a future CTR that confers Level 1 HQs is likely to be considerably more sophisticated than the core SCAS that delivers Level 2 HQs throughout the OFE (Ref 6). The pitch axis will be an important challenge in this respect. Fig 19 shows a comparison of the pitch response for the FXV-15 with and without the basic SCAS featured on the aircraft. The SCAS has suppressed the rate overshoot, while achieving a conventional rate response. However, the attitude (and hence flight path) response has been reduced by about 30% after 2 seconds.

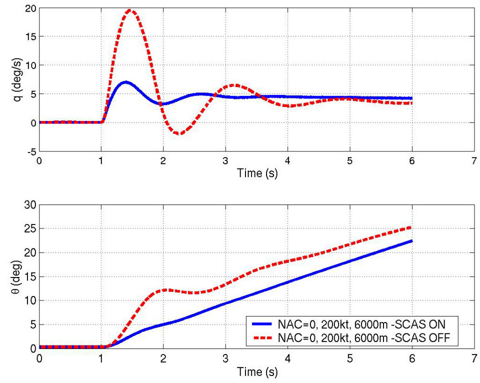


Fig 19 FXV-15 Pitch Response with SCAS Engaged, 200kts IAS, 6000m

Reducing the manoeuvre envelope is sometimes the only way of conferring sufficient stability, but the control system has also to take account of structural load alleviation functions and these inevitably reduce performance (Ref 5). Progress on the continuing development of CTR HQs, taking such constraints into account, will be reported in the future.

Concluding Remarks

This paper has reported progress on the development of handling qualities criteria for tilt rotor aircraft, with particular attention to civil operations. Mission analysis identified the Search and Rescue mission as containing a number of HQ-critical mission-task-elements that would represent the design cases for key functions an active control system. The ADS-33 approach was selected as a holistic engineering framework for defining and analysing HQs across all three aircraft modes – helicopter, conversion and airplane. Helicopter mode HQ requirements can be drawn directly from ADS-33, using the appropriate performance standards. The paper has presented results from the RHILP investigations into the HQs which define the Level 2/3 boundary for pitch/flight-path control in conversion/airplane modes – essentially the boundary between the operational and service (manoeuvre) flight envelopes. A review of the theoretical basis and appropriateness of the various helicopter and airplane HQ criteria has been supported by a series of simulation trials at the University of Liverpool, aimed at filling gaps and establishing compatibility between criteria formats. All HQ investigations reported in this paper were performed using the FLIGHTLAB XV-15 (FXV-15), with SCAS disengaged. The main conclusions of the study are as follows;

1. 14 SAR HQ-critical MTEs have been defined as the basis for HQ development,
2. The terrain following MTE provides appropriate levels of agility and precision of flight path control to set the standards for pitch and flight path HQs for flight in conversion and airplane mode.
3. The agility parameter, pitch attitude quickness, for flight in conversion and airplane modes has a 30% margin above the relevant Level 1/2 boundaries,
4. The HQ parameters - short period damping/frequency and CAP suggest HQs at borderline Level 1/2 for the FXV-15; attitude bandwidth and phase delay are well within the Level 1 region,
5. According to the attitude drop-back/overshoot criteria, the HQ Levels predicted by CAP/bandwidth need to be degraded by one Level,
6. For Tilt Rotor aircraft in airplane mode, the large prop-rotors make a de-stabilising contribution to the pitching moment derivatives M_q and M_w, hence reducing the relative damping of the short period mode. In addition, the relatively low value of heave damping Z_w, leads to a slow build up in lift and, in combination with the reduced manoeuvre margin, results in a large pitch rate overshoot and attitude drop-back,
7. Results from the piloted simulation trials (4 pilots) confirmed the degrading effects highlighted in Conclusion 6.

Although the RHILP Project is now complete, the HQ research continues within the sister, ACT-TILT, project with emphasis on establishing requirements for Level 1 HQs.

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