Capturing requirements for tiltrotor handling qualities – case studies in virtual engineering

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ABSTRACT

Handling qualities are expressed as requirements at the interface of the pilot and the machine. In this way, the key functionality questions facing the design engineer are seen from the perspective of the interaction of the human pilot with the aircraft system and the environment in which it operates. In this paper, the author takes a 'virtual engineering' approach to handling qualities, emphasising the importance of conducting 'requirements capture' and preliminary design as an iterative process. When stretched capabilities are required, this approach minimises the risk to finding appropriate technology solutions, through developing explicit relationships between capability and design parameters, thus facilitating fully informed trade studies and predictions. Case studies from the development of a civil tiltrotor aircraft are presented that show how the difficult challenges facing the designer first need to be structured in terms of HQ predictions and assignments. This then provides the basis on which handling qualities improvements can be constructed within the multidisciplinary context of rotorcraft engineering.

NOMENCLATURE

Symbols

g	gravitational constant (ft/sec^2, m/sec^2)
M_q	pitching moment derivative with pitch rate q (1/sec)
Mw	pitching moment derivative with heave velocity w (rad/m.sec)
M_η	pitching moment derivative with elevator control (1/sec^2)
q, q_{ss}	pitch rate, steady state pitch rate (rad/sec)
s	Laplace variable
T_θ	time from first crossing of commanded pitch attitude to that when the pilot should return control to trim (sec)
$T_{\theta 2}$	flight path lag behind attitude response (sec)
$\overline{T}_\theta = \dfrac{\Delta\theta_{pk}}{q_{ss} T_{\theta 2}}$	T_θ normalised by $T_{\theta 2}$
U_e	trim or equilibrium velocity (ft/sec, ms^{-1})
V_{con}	conversion velocity (ms^{-1}, kt)
Z_w	heave damping derivative (1/sec)
$\Delta\theta_{DB}$	pitch attitude dropback (rads)
η	elevator angle (rads)
ζ_{sp}	short period damping factor
ω_{bw}	bandwidth frequency (Fig. 10)
ω_{sp}	short period undamped natural frequency (rad/sec)
X_B	pilot's control input in pitch axis (rad/sec.inch (mm))

Acronyms

ACT-TILT	active control technology-TILTrotor
CAD	computer aided design
CAM	computer aided manufacturing
CAP	control anticipation parameter
CM	carefree manoeuvring
CTR	civil tiltrotor
DRC	dynamic response criteria

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ERICA	enhanced rotorcraft innovative concept achievement
FR	failure rating
HQR	handling qualities rating
HQs	handling qualities
IAS	indicated air speed
IMC	instrument meteorological conditions
INCOSE	International Council for Systems Engineering
IRCPD	integrated requirements capture and preliminary design
JAR	Joint Aviation Requirements
KXB	gain in command transfer function
MTE	mission task element
NICETRIP	Novel, Innovative Concept Tiltrotor Integrated Project
OFE	operational flight envelope
PI	proportional integral
PIO	pilot induced oscillation
RHILP	rotorcraft handling, interactions and load prediction
SAR	search and rescue
SCAS	stability and control augmentation system
SE	systems engineering
VE	virtual engineering
VIVACE	value improvement through a virtual aeronautical collaborative enterprise

1.0 INTRODUCTION

System level qualities or properties are those that define behaviour at the interface with the world in which a system functions. Flight handling qualities are system level properties of an aircraft at the pilot-vehicle interface, and, in this sense, design for good handling qualities is about ensuring that the pilot can perform the task of flight management, for the specified missions, safely. Establishing suitable handling qualities for new missions involves the analysis of existing criteria and selection of an appropriate subset. The term 'capturing' is used in requirements analysis when the process of quantifying what is actually required involves combining together validated material with other fragments of knowledge and information, often available in a variety of disparate forms. Capturing implies a certain degree of detective work, as users can be uncertain, inconsistent and often unrealistic in stating their requirements. Also, users often express their requirements in non-technical, textural terms, so a process of translation is required. Combining the technical requirements into a consistent whole can be a creative process involving sophisticated engineering tools. It forms the initial stage of the systems engineering process[1].

Systems engineering (SE) embraces the whole product life cycle, spanning requirements capture, preliminary design, detailed design and development, manufacturing, test and qualification, operational, support and disposal phases. Motivated by the economics of 'getting in right first time', organisations are more and more developing integrated digital simulations of the life cycle to aid decision making ahead of critical milestones (e.g. European Commission funded VIVACE project[2]). While this virtual engineering (VE) process creates no hardware as such, the interrogation of sufficiently high fidelity simulations can provide clear guidance to the designer on what is possible in terms of customer expectation. When fully implemented, such a systems engineering process can be used to predict the effects of perturbations, at any stage in the product life cycle, on capability and cost at downstream stages and also, when fully engineered, connect such perturbations to upstream processes, effectively creating a dynamic life cycle simulation. In this paper, it is argued that the front end SE processes – requirements capture and preliminary design – need to be treated in an iterative cycle to minimise the risk to achieving operational capability. The arguments are constructed in terms of tiltrotor aircraft handling qualities, synthesised as system-level operational attributes.

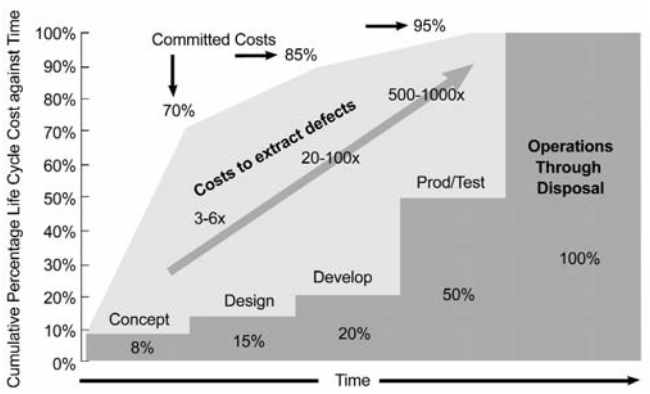


Figure 1. Cumulative life-cycle cost *vs* time showing early cost commitment and cost to extract defects[1].

1.1 The 'requirements-capture ↔ design' iteration cycle in virtual engineering

It is practically a truism that the front-end, requirements capture, phase in the life cycle of a new or upgrade system is where both operational capability and cost of ownership, in all senses, are established. This viewpoint is emphasised in the SE handbook published by INCOSE[1].

Figure 1, taken from Ref. 1, suggests that 70% of the cost to service entry can be committed by the end of the conceptual design phase. The figure also shows the corollary of the above, that the 'cost to extract defects' is two to three orders of magnitude greater in the development, production and test phases than in the early concept phase. The case for appropriate investment in requirements-capture and conceptual/preliminary design is strongly made by these data; the lack of substantial design and technology validation in these early phases has, undoubtedly, been a major contributor to some high profile project overruns and failures to deliver customer expectations.

When new, stretched, capabilities are required, innovative ways of integrating 'new' technologies are required and the messages conveyed by Fig. 1 are particularly germane. Classic questions posed in requirements capture may include 'is this requirement realistic?', 'will this technology work?', and perhaps 'will the new capability/technology integrate with legacy systems?' The greater the stretch, the greater the risk that positive answers to these kind of questions cannot be found, or at least, the less likely that positive answers can be found without substantial effort. For this reason, requirements capture and analysis are best conducted as an iterative process with conceptual-preliminary design – thus we define the integrated requirements capture – preliminary design (IRCPD) phase. This constructive and creative iteration is essentially a trade study, where sufficiently robust syntheses and analyses are performed to reduce risk to manageable levels. Constructive in the sense that various models of the system in operation need to be hypothesised, developed and tested; creative in the sense that new 'value' metrics need to be conceived and new ways of achieving the capability need to be explored. The trade-off nature of the study allows the user to examine the impact of technology cost on capability and cost thus evolving a balanced set of requirements. The outcome is then validated requirements, with clearly defined technology development programmes, risk reduction schedules and alternate solutions. The iterative nature of these front-end processes also motivates the key stakeholders, the customer and supplier, to cooperate in finding answers to the questions, and forms a spur to the creation of, so-called, 'integrated project teams'.

Requirements come in all shapes and sizes and levels of importance, but it is those at the system, as opposed to sub-system and

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Table 1
Summary of performance and workload in HQ levels

HQ level	Performance/safety	Workload/compensation
1	well within mission and safety standards	low
2	just within mission and safety standards	moderate to extensive
3	mission performance not attainable flight safety at risk	maximum tolerable to intense
4	High risk of loss of control	

component, level that contain the measures of overall capability, e.g. operational performance, supportability, affordance, handling etc. A useful way of approaching the IRCPD process is to pose the system level questions at the interfaces with the 'outside world', e.g. with fare-paying passengers, legacy systems, with the natural environment, with maintenance crew, or in the case of handling qualities, with the flight crew. This 'outside-in' approach, in contrast with top-down or bottom-up 'descriptions' (which can be very useful explaining what has been done, but less helpful in design), puts the emphasis on creative thought and design at the interfaces where the system-level capabilities are defined. In turn, technical requirements expressed as numerical criteria, should reflect these capabilities. Thus, for handling qualities, the concept of mission-oriented criteria has emerged and underpins the relationship between, for example, the pilot's task and the operational function of a manoeuvre, or the definition of the quality levels and the aircraft role; modern mission-oriented handling requirements need to provide a framework for such complex system formulation at the IRCPD phase. This outside-in approach to IRCPD as described in this paper is derived from the fundamental principles of Jackson system development[3] and was earlier applied by the author to flight control system design in Ref. 4.

1.2 Handling qualities as a system property

The classical Cooper-Harper definition of handling qualities (HQs)[5], 'Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role', still holds, after 40 years, the essential meaning of these system level properties. System level for several reasons, including:

(a) they are derived from mission requirements, including environmental aspects, hence connecting with the outside world,

(b) they are specified within a comprehensive, hierarchical, structure including response types, dynamic response criteria, failures, etc., are defined within quality levels (1 to 4), and include compliance demonstration tests,

(c) they impact, and are impacted by, the technologies of most of the major and minor sub-systems,

(d) most significantly, they pose the design questions at the interface between the aircraft and the crew (Fig. 2).

The requirements of a HQ specification are set and applied in order to ensure that no limitations on flight safety or the capability to perform intended missions will result from deficiencies in handling qualities (Aeronautical Design Standard, ADS-33,[6]). In this sense HQ deficiencies should not define the boundaries of the operational flight envelope. Specifically, HQs should be Level 1 for normal operations within the operational flight envelope (OFE). Operations within HQ levels are defined by the performance attainable with

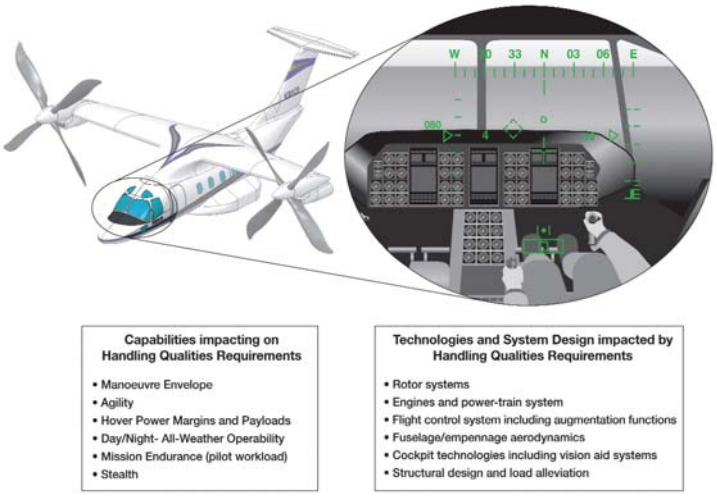


Figure 2. Handling qualities are the system level capabilities at the crew–aircraft interface.

degrees of pilot workload, or compensation[7]. A summary of the performance and workload/compensation within the different HQ levels is given in Table 1.

The Level 1 requirements emphasise that the flying task should never demand significant levels of pilot effort, so that other duties including mission management, navigation and system health monitoring can be carried out as and when required. Even when engaged in tactical manoeuvres, a pilot needs sufficient spare mental capacity to maintain broad situation awareness and be able to respond rapidly to developments; intuitively, the greater the concentration required for piloting, the higher the workload and the higher the risk to safety. This textural requirement for spare capacity is intuitive but difficult to quantify; however, the developments in HQ engineering, particularly those for rotorcraft over the last two decades, have made it possible to predict HQs, in terms of parameterised criteria, and also assign HQs, in terms of handling qualities ratings (HQRs) awarded by test pilots flying test manoeuvres; together, the predicted and assigned HQs, when in agreement†, form the basis for HQ design[8].

While Level 2 HQs increase the risk to safety, they are allowed in non-normal states, e.g. following flight system failures, excursions beyond the OFE (but within the safe flight envelope), or inadvertent entry into harsh atmospheric conditions or degraded visual environments. A user may also allow operations with Level 2 HQs in certain limited parts of the OFE, provided exposure is brief and manageable, e.g. recovering to a ship in rough weather or landing zones prone to brown/white-out conditions. Operations with Level 3 HQs should never be allowed or attempted because of the severe degradation in performance and risk to flight safety. Establishing, and staying within, the Level 1-2 boundary is important in the IRCPD process

† The need for agreement is emphasised here since the pilot can expose some aspect of the aircraft's behaviour not catered for in the prediction criteria, in which case, further requirement-design iteration will be necessary.

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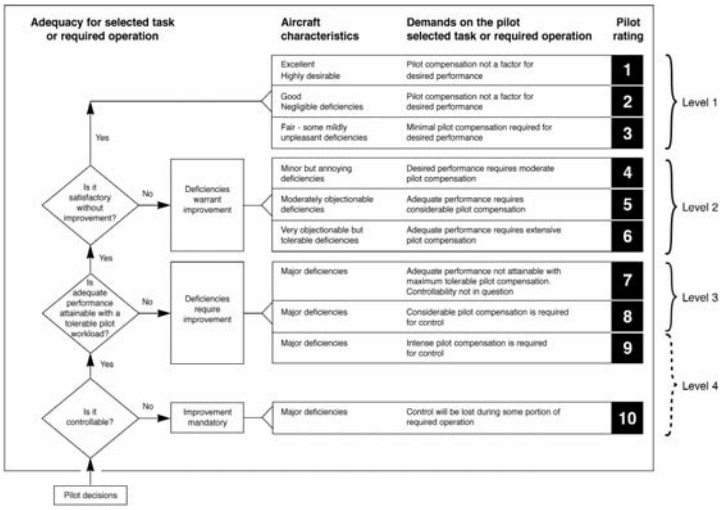


Figure 3. Handling qualities rating scale, from Cooper-Harper[5].

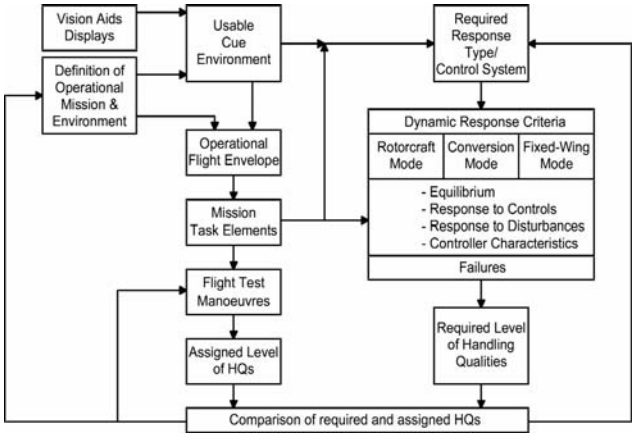


Figure 4. A systems approach to handling qualities engineering for a civil tiltrotor aircraft[9].

but, equally, the Level 2-3 boundary must be known to inform the failure modes and effects analysis and to establish margins for emergency operations.

The predicted HQs are largely derived from the aircraft response types (e.g. rate or attitude command) and associated dynamic response criteria (DRC) that define the aircraft's stability and agility. It is important to note that requirements for these two handling characteristics will be finely balanced in good designs. Too much stability can reduce agility, unless measures are taken to relax stability when the pilot wants to use the full manoeuvre performance of the aircraft. Examples are Aerospatiale's 'transparent' system on the Puma, which disengages the attitude hold function when the pilot moves the cyclic, or the system on the Westland Lynx, where the response type effectively changes from attitude to rate when the pilot manoeuvres outside the trim attitude region. In the case studies presented in Section 3 of this paper, some of the DRC will be examined in more detail and their importance in requirements capture discussed.

The way the aircraft responds to the clinical control inputs, applied in an open-loop fashion to form the data from which the DRC are computed, is only one part of the HQ 'jigsaw'. The human-factors of the pilot-aircraft interface are also part of HQ engineering, including the flight inceptors‡ and displays. The requirements at the interface can often be quantified, particularly such things as force breakouts and gradients, display characteristics, etc. Ultimately the integrated whole has to be used by a pilot and the assigned HQs are the summary of pilot comments and opinions in the form of the HQRs[5] awarded for performance achieved and workload experienced when flying a mission-task-element (MTE). The MTE set for a given aircraft role represent the handling qualities design cases – the ultimate expression of the interface between man and machine, discussed further in Section 2 of this paper. The Cooper-Harper HQR scale ranges from 1 to 10 (Fig. 3) and mirrors the HQ levels in which the DRC are defined. Meeting the Level 1 standards requires the collective agreement of several independent test pilot assessments. Some of the important 'rules' for the awarding and interpretation of HQRs are discussed in Refs 7 and 8. Critical amongst these is that pilots must strive to achieve the agreed performance standards, but not wholly at the expense of workload. For example, if the desired standards can be met, but only with extensive pilot compensation, the aircraft is not Level 1.

Figure 4[9] shows how the predicted and assigned HQs come together to form components in the systems approach to HQ engineering.

The design of nearly all major subsystems and components, e.g. overall vehicle layout, rotors and lifting surfaces, structural flexibility, power and transmission systems, flight control system, pilot's controls and displays, impact on an aircraft's handling qualities. Modern concurrent, multi-disciplinary design will feature HQs as one of the system level requirements that 'fight for attention' in the trade-off. Fortunately, HQ deficiencies can be cured through active control solutions and the civil tiltrotor presents several unique challenges in this respect. In this paper, it will be shown that the classical tiltrotor configuration features few Level 1 characteristics in its natural form, but several Level 2 and 3 characteristics. The focus will be on explaining the physical origin of these deficiencies and the level of control augmentation required to cure them.

In Section 2, the anatomy of an MTE is discussed, while in Section 3 results are presented for four case studies from research conducted over the last seven years at Liverpool in support of the design of the European Civil tiltrotor (CTR). Section 4 discusses some outstanding issues and the paper closes with conclusions and recommendations in Section 5.

2.0 THE ANATOMY OF A MISSION TASK ELEMENT – HQ DESIGN CASES

Requirements at all levels need to have methods to assess and judge compliance and HQs are no exception. The predicted HQs can be derived from the analysis of the aircraft response to clinical test inputs, e.g. the cyclic frequency sweep for the attitude bandwidth or the pedal pulse for the yaw quickness. The assigned HQs are derived from the pilot flying manoeuvres that have a defined start and finish, in which the pilot can exercise the response of the aircraft up to, and beyond, the Level 1 capability of the DRC, and that are representative of a real mission task – a mission task element (MTE). The MTE set should be derived from a systematic analysis of the mission phases. For example, the search and rescue (SAR) mission of the civil tiltrotor might be made up of the 14 different phases shown in Table 2. Within each mission phase, distinct MTEs can be defined from which the handling qualities compliance manoeuvres can be constructed. Nowadays it is common to regard the test manoeuvres and the MTEs as synonymous but it is important to recognise that the performance standards for the MTEs need to be drawn from the mission phases within which they lie. It is also important that the MTEs are truly challenging for the HQs, and we refer here to 'handling qualities critical' MTEs.

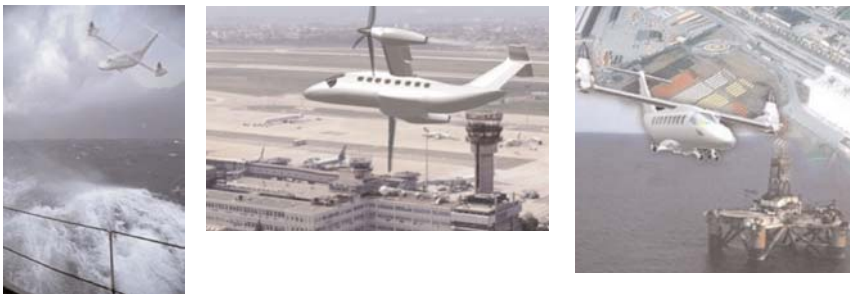
‡ Any device the crew can use to make inputs to the flight management system, including control sticks and levers, but also such things as trim buttons and the various pilot-select switches.

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Table 2
The CTR search and rescue mission phases

Mission phases

(a) take off into low hover in ground effect
(b) nacelle to 75º, accelerate to best climb speed
(c) nacelle to 60º, climb and accelerate to *Vcon*
(d) convert to aircraft mode, level at cruise altitude
(e) decelerate, descend and re-convert to 60º nacelle
(f) loiter in search zone and best conversion speed
(g) re-convert to helicopter mode at search point
(h) low speed manoeuvres around the rescue area
(i) repeat of b, c and d
(j) descend in aircraft mode
(k) re-convert to conversion mode 60º nacelle
(l) approach manoeuvres
(m) re-convert through 75º to helicopter mode
(n) decelerate to hover and land



The Eurocopter EUROTILT concept[10]

By handling qualities critical are meant manoeuvres that exercise the vehicle's handling qualities to their operational limits in order to expose any shortcomings (e.g. lack of control power, tendency for adverse aircraft-pilot couplings), but also manoeuvres:

- that fully exercise the functions of the stability and control augmentation system (SCAS) and other pilot-aircraft interface technologies, e.g. displays, inceptors,
- where full or partial automation of some functions is required,
- that push the agility or manoeuvre 'attack' level, so that the pilot workload increases, to check if any combinations of marginal Level 1 HQs result in the aircraft being downgraded to Level 2.

Examples of HQ critical MTEs for the SAR mission include;

- Rapid take-off and departure, including conversion
- Terrain/valley following loiter in conversion mode
- Rapid re-conversion
- Lateral re-position and hover capture
- Multi-segment decelerating approach in IMC

The transformation into the MTE and associated test manoeuvre is illustrated conceptually in Fig. 5.

The ability to follow the terrain, loitering in the rescue zone, is an important capability of the CTR, best exploited in conversion mode, in the speed range between 80 and 120kt; here, the aircraft is more efficient than a helicopter and would stall in airplane mode. The format and descriptions in Fig. 5 are normally constructed for the whole MTE set, for all missions, by a team of pilots and engineers. The importance of this activity cannot be over-stated; it forms the basis for the HQ design cases. Just as there are design cases for structural components and avionics systems, so there are for the piloting and all flight control functions

With this foundation stone laid, the paper continues with a series of HQ case studies, all taken from the research at Liverpool supporting the IRCPD, 'virtual engineering', of the European Civil tiltrotor aircraft.

3.0 CASE STUDIES – THE TILTROTOR SAR MISSION

Tiltrotor aircraft present numerous and significant 'novel' challenges to the rotorcraft designer. After more than 50 years of development, tiltrotors are, at the time of writing, only just entering service. No other aircraft type has taken so long to bring to maturity. Following successful concept technology demonstration with the Bell/NASA/Army XV-15[11], the concept definition phase of the JVX (later V-22) project commenced in early 1982. Some of the technical issues that challenged engineers on the V-22 project were candidly presented by Dunford in his 'lessons learned' presentation to the American Helicopter Society in 2003[12]. Concept definition of the JVX ended with the start of the pre-design phase in 1984. Full scale development (FSD) of the V-22 then commenced in 1986, first flight in 1989, but FSD was terminated six years later, for a number of reasons including empty weight growth 10% above the FSD specification. An engineering manufacturing and development (EMD) phase was initiated with first flight of the EMD configuration in 1997. The development programme was further hindered by the loss of several aircraft; all related to flight control and associated handling problems. The hiatus resulting from these accidents ended with the 'return to flight' for operational demonstration in May 2002.

In his appraisal, Dunford highlights the importance of clearly defined requirements and a 'close relationship between user, customer and contractor', noting that a significant issue related to the changing requirements from a transport to utility vehicle. At the technical level Dunford makes the point that 'Rotorcraft aeromechanics may be too complex to ever predict with high confidence, and therefore programmes must reflect this reality and plan for change in areas of high risk or technical complexity.' Handling qualities are heavily influenced by the aeromechanics technologies and the continuous development of (virtual engineering) high fidelity prediction methods and the skills to use and validate them must surely be part of risk management strategies in complex systems like tiltrotor aircraft. Dunford, referring to the V-22 as 'transformation technology' strongly advocates the use of systems engineering and particularly the 'use of integrated product-process development for the insertion of new technology'. An excellent example of the use of virtual engineering

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The terrain-valley following MTE in the SAR mission



Mission context: This mission task element is based on the search-loiter phase in a SAR mission. The aircraft may have to follow the surrounding landscape, e.g. a valley in a mountainous region. The pilot performs turns in either direction at low altitude, occasionally needing to fly a precision track through a narrow gap.

The manoeuvre is typically flown in conversion mode, with nacelles at 60º, with a speed range respecting a 20% margin from the corridor edges.

Piloting requirements: The pilot has to maintain height above ground and a lateral safety margin from the surrounding terrain while following the landscape. The pilot must be prepared for an abrupt change of altitude or roll angle to follow a precise track; speed control is important so that turn rate from a given roll angle is predictable.

Handling issues: The control axis of primary concern is roll, with secondary concerns in the pitch, yaw and heave axes. Control power and quickness are both critical during the manoeuvre phases while bandwidth and couplings are more critical during the closed-loop tracking phases. Precise speed control during manoeuvres is important for low workload, so couplings between speed and height control need investigation. Degraded visual conditions and the need for the pilot to monitor aircraft states, particularly safety margins and height, will also contribute to the workload.

Handling qualities critical MTE – the roll-step

Critical HQs: response bandwidth (PIO tendency), cross couplings, control power, attitude quickness

Objectives	Check ability to manoeuvre within confined spaces Check roll and heave co-ordination in turns Check roll-yaw turn co-ordination Check for speed-height coupling when nacelles tilted Check for objectionable inter-axis coupling	
Manoeuvre description	Start with a constant forward flight condition lined up with the runway edge Speeds; 80-120kt	Height: 100ft above ground level
	Perform a series of alternating turns to the right and left from one runway edge to the other Fly through the designated gates (runway width 200ft) with precision	
Test course description	See figure below	
Performance Standards	Desired	Adequate
	Speed: ± 5kt	± 10kt
	Height: ± 10ft	± 15ft
	Lateral deviations at runway edge: ± 15ft	± 30ft
	Roll angle through gates: ± 5º	± 10º
	Heading angle through gates: ± 10º	± 15º

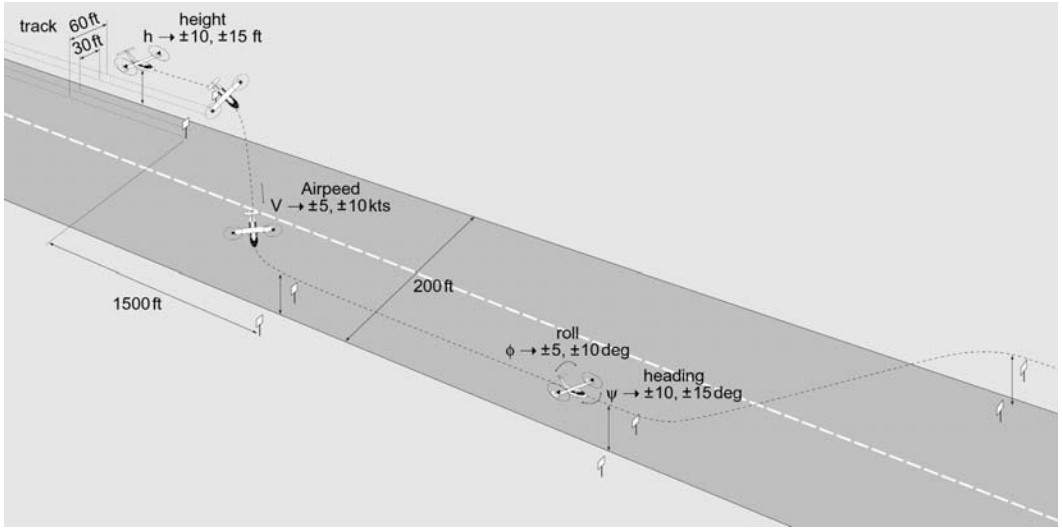


Figure 5. Development of the roll-step MTE for the SAR mission.

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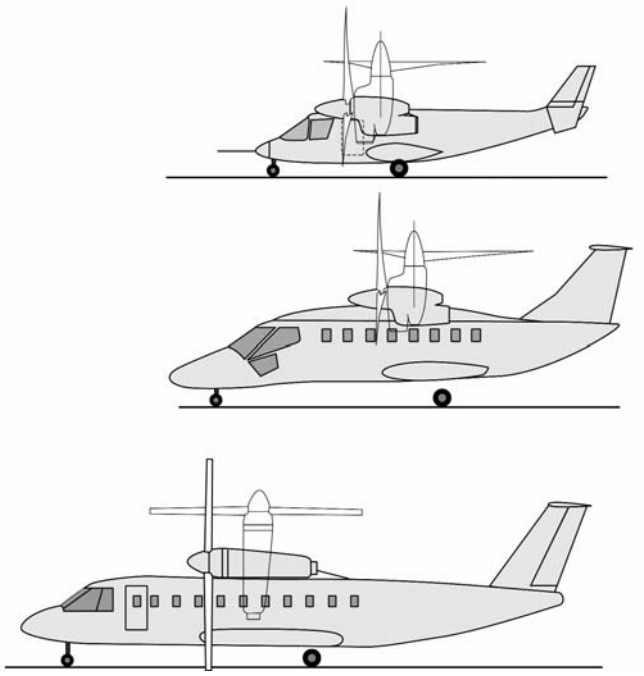


Figure 6. Three tiltrotor configurations; top to bottom – the Bell/NASA/Army XV-15 (CTR-S), Eurocopter EUROTILT (CTR-M) and EUROFAR (CTR-L) concepts.

Table 3
Configuration data for the three tiltrotor designs

	CTR-S	CTR-M	CTR-L
Mass	13,003lb (5,897kg)	22,416lb (10,166kg)	33,110lb (15,016kg)
Rotor radius	12·5ft (3·81m)	16·4ft (4·99m)	18·4ft (5·61m)
Disc loading	13·24lb/ft^2 (64·6kg/m^2)	13·26lb/ft^2 (64·9kg/m^2)	15·56lb/ft^2 (75·9kg/m^2)
Number of blades per rotor	3	3	4
Rotor speed (rad/sec)	59·2	43·98	39·25
Length (12·8m)	42ft (15·25m)	50ft (19·4m)	63·6ft
Wing span	32·2ft (9·815m)	41·6ft (12·68m)	48·0ft (14·63m)

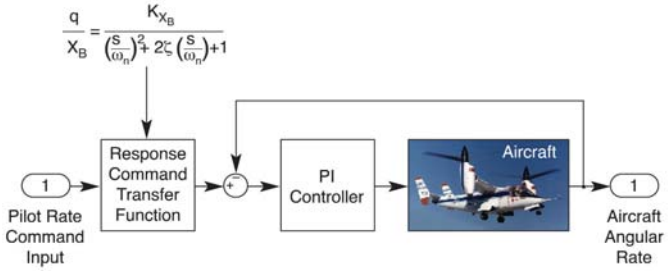


Figure 7. Simplified control concept for HQ augmentation.

principles to the development of the V-22 flight control system can be found in Ref. 13. In this paper, Miller *et al* present a design solution, validated and tested, to the so-called roll-on-deck 'problem' experienced by the aircraft.

There were no public documents presenting the handling qualities requirements for the V-22, but, in Ref. 14, Troy Gaffey, describing the civil regulatory requirements for the smaller civil BA609 tiltrotor (first flight March 2003), made the point that almost three quarters of the certification basis for the performance and handling qualities of this civil transport had to be either adapted from FAR Part 25 (Transport Category Aeroplanes) and Part 29 (Transport Category Rotorcraft) or newly-created. In this aircraft, experience drawn from the V-22 programme formed a strong foundation. In Ref. 15, King *et al* describe how SE was used to successfully capture the requirements, design, integrate and certify the aircraft's carefree manoeuvring (CM) system (including new techniques to account for system-structure interactions), as part of the vehicle management system. King presents the paper as a 'case study' with trade-off analyses conducted, in an iterative fashion, to specify the best balance between the CM system and structural design, utilising analytical models of candidate systems together with piloted simulation.

The principal role of the CTR is a passenger carrying transport aircraft. The European CTR programme is also examining the requirements of a SAR aircraft. In the following sections, some of the HQ and related carefree handling/load alleviation issues that are being examined are presented. Aircraft featured in the studies include the FLIGHTLAB models of the XV-15[11], Eurotilt[10] and Eurofar[16] and the current configuration of the European CTR, ERICA[17], with the piloted simulations conducted on Liverpool University's Bibby Simulator[18]. In the spirit of virtual engineering applied in requirements capture each case study will be presented as the solution to a challenging question.

3.1 Unification of low speed HQs

'Is it feasible to confer equivalent HQs on different members of a family of tiltrotor aircraft of different sizes, with all up mass varying between 6 and 16 tonnes?' This question was tackled in Refs 19 and 20, taking the three configurations shown in Fig. 6, designated as CTR-S (small), CTR-M (medium), CTR-L (large). The specific question related to the helicopter hover-low-speed manoeuvring capability. Could all three tiltrotors meet the ADS-33 Level 1 requirements sufficiently well that they could be considered to have 'unified' handling, allowing pilots to convert from one type to another with minimal training?

The nominal configuration data for the three aircraft are given in Table 3. The aircraft differ in several respects, not only size and all up weight, although tip speed is roughly constant at about 240ms^{-1}. For the unification challenge, it is assumed that the basic design configuration is frozen and the HQs are to be conferred through flight control augmentation.

The HQ analysis and piloted tests reported in Ref. 19 examined all low speed requirements but particularly the trade-off between agility (quickness and control power) and stability (bandwidth/phase delay and low frequency modal damping). The basic control augmentation concept reported in Ref. 20 is shown in Fig. 7. The parameters of the 'rate-command' transfer function essentially defined the response type and agility characteristics while the parameters in the proportional-integral (PI) element defined the stability. The HQ challenge was concerned with achieving Level 1 performance, while respecting actuation rate and displacement limits, on all types.

The assigned HQs were given by two test pilots flying four different MTEs (hover turn, pirouette, bob-up and hover capture) at three levels of agility – low, medium and high – reflected in parameters such as task time and control power used. The tests were

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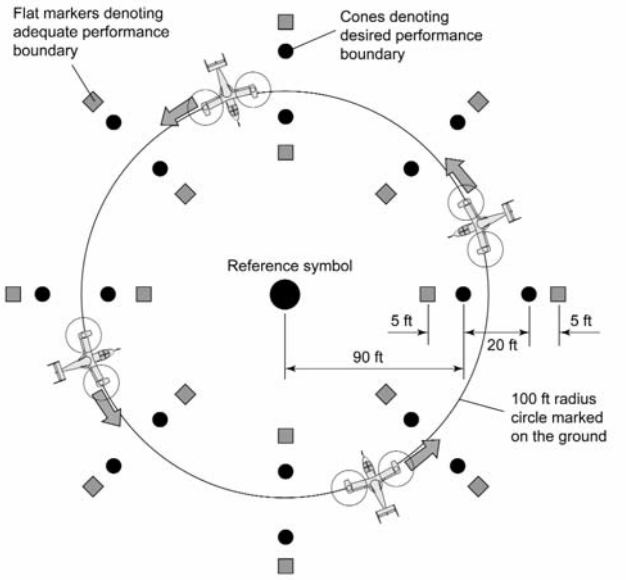


Figure 8. The pirouette MTE showing performance standards.

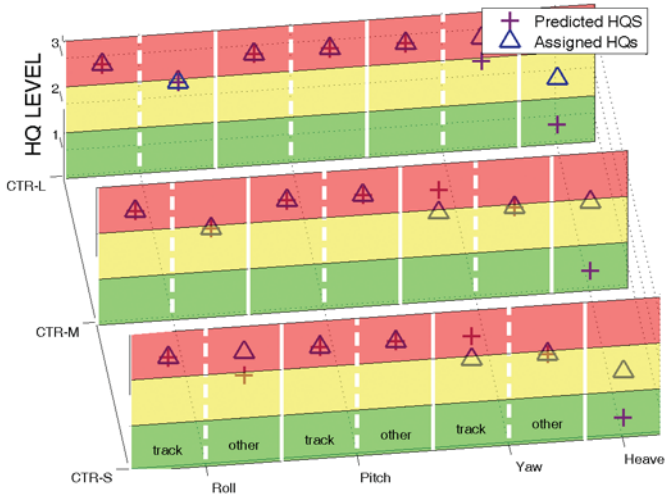


Figure 9. Predicted and assigned HQs for the three tiltrotor configurations.

flown in still air and a moderate level of horizontal turbulence, simulated through the application of pseudo-random pitch, roll and yaw moments. Pilots were given the opportunity to practice flying the MTEs before awarding the HQR. They were presented with the MTE standards in the form of the tabular description shown in Fig. 5, together with a summary figure of the course layout, e.g. the pirouette shown in Fig. 8.

Comparisons of the poorest HQ levels derived from the predicted and assigned data are shown in Fig. 9. Results are presented for both 'precision tracking' and 'all-other' MTEs, in accordance with the ADS-33 mission-oriented standards. If we assume that the SAR mission of the CTR does not need to comply with the high agility and precision tracking standards, then the 'all-other' MTEs apply. The moderate level of turbulence will, however, result in the pilot having difficulty maintaining the precision hover for all four MTEs. It could be argued that the precision tracking standards are therefore more relevant. This is an issue that would have to be resolved early in the requirements capture phase, since the consequences are significant.

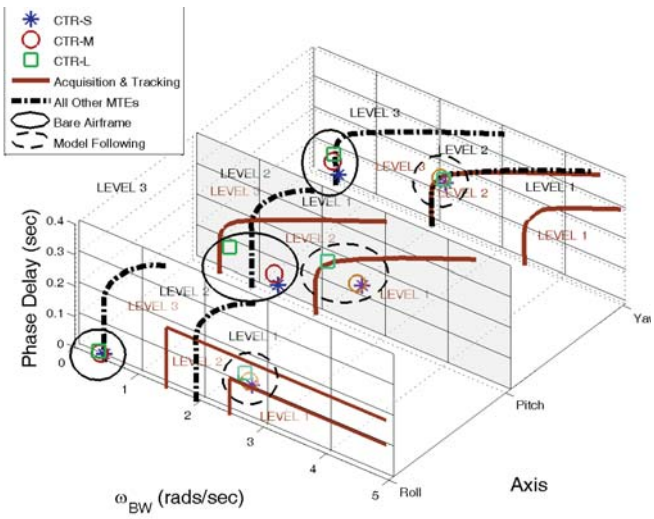


Figure 10. Bandwidth and phase delay comparisons.

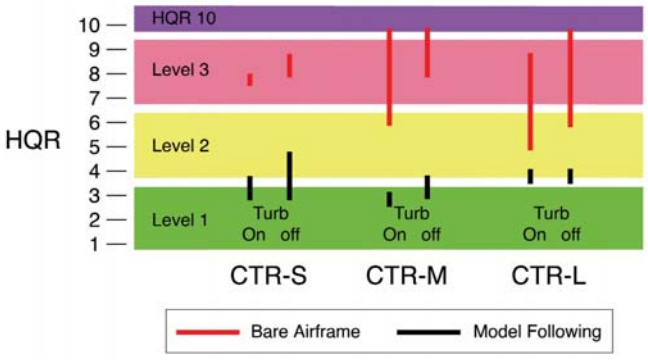


Figure 11. Comparison of HQRs for the pirouette MTE.

The results for pitch, roll and yaw all show marginal Level 2/3 or Level 3 HQs. The only inconsistency is shown for the heave axis, where the predicted HQs are shown to be Level 1 while the assigned HQs are Level 2; the inconsistency is explained by piloting difficulties due to the poor fore-aft cueing in the simulator, leading to problems stabilising the hover at the top of the bob-up. Cueing problems also led to poorer HQRs than might be expected in flight for the pirouette MTE.

A comparison of pitch, roll and yaw bandwidth/phase delay for the three configurations, with and without control augmentation is shown in Fig. 10. Boundaries for both tracking and regular MTEs are shown. Before augmentation, the aircraft all lie close to the (all-other-MTEs) Level 2/3 boundary; augmentation has conferred significant improvements on all aircraft, although the yaw HQs could not be raised above the Level 1/2 boundary. It should be emphasised that this level of performance is only achievable for small amplitude control inputs, due to the levels of gain used (O(1deg/deg/sec) for proportional and O(0·1deg/deg) for the integral) and the consequent saturation of the actuation system.

The overall comparison of the assigned HQRs for the pirouette MTE is shown in Fig. 11. The augmentation has brought the results to the Level 1/2 boundary, the pilots generally being able to achieve the desired performance standards with a moderate amount of compensation. The chief difficulty was again the maintenance of the radial position with fore-aft control, degraded by the 'limited' horizontal field-of-view in the simulator (135º). The PI controller was very effective in suppressing the upsets caused by the pseudo-turbulence for all three aircraft.

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Figure 12. Bell/NASA/Army XV-15.

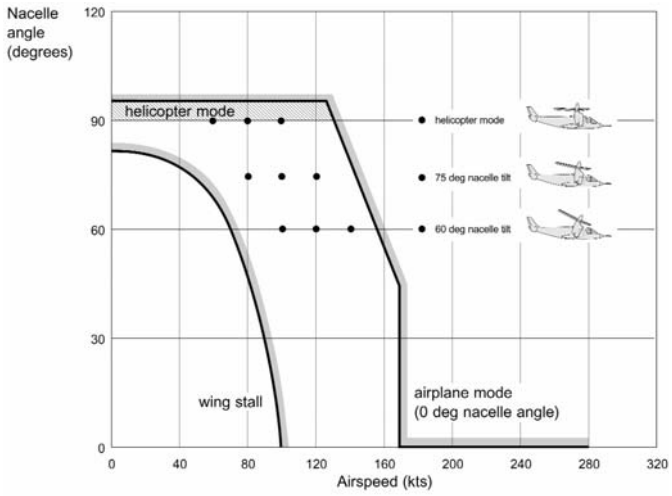


Figure 13. XV-15 Configurations used in the RHILP study within the conversion corridor[10].

The results reported in Refs 19 and 20 give a positive answer to the fundamental question regarding the potential for unification of hover-low speed HQs for different classes of vehicle designed for the same missions. There are similar questions relating to HQs in conversion and airplane modes that need study. Also, the integration of HQs laws with load alleviation and other carefree handling laws needs investigation; the consequent trade-off of actuation demands when these functions are properly integrated is part of the process. The IRCPD activity involves all these things and links the system level HQ requirements with other requirements to achieve a balanced aircraft design.

Helicopter mode HQs are based on the ADS-33 requirements, and additionally have to meet the certification requirements of JAR-29. A similar statement can be made concerning the airplane mode HQs and relevant airplane standards. In the conversion corridor the hybrid nature of the configuration raises the question – from a HQ stand-point, is a tiltrotor a fixed or rotary wing aircraft? The answer is that it is both and the HQs must be such that they blend smoothly from rotary to fixed wing characteristics. In the next case study, the conversion configuration will be examined from a helicopter perspective.

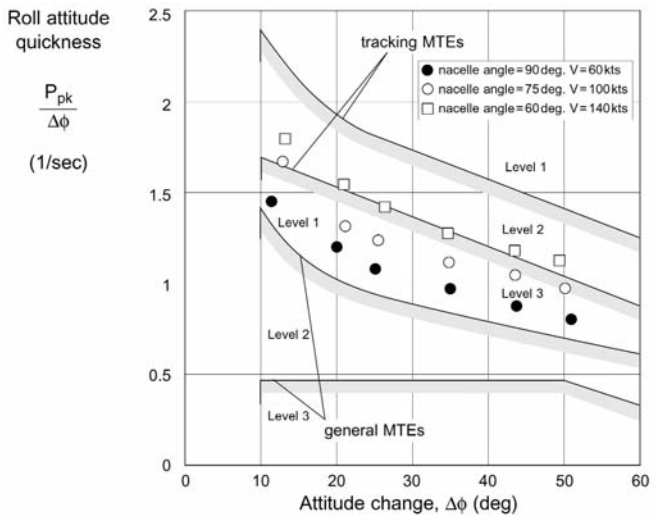


Figure 14. Roll attitude quickness for the F-XV-15.

3.2 Flight in the conversion corridor

'How do HQs degrade as agility is increased when flying in loiter mode?' The question of how much agility can be used safely is an important one for any aircraft. In a study as part of the RHIP project[6,10,21], this issue was addressed within the context of the location of the Level 2/3 HQ boundary. In particular, if some of the augmentation functions failed, could the aircraft still continue its mission, albeit with increased pilot workload?

The aircraft used in this study was the FLIGHTLAB XV-15 (Fig. 12) in the configurations shown within the conversion corridor in Fig. 13.

The roll-yaw agility requirements were assessed using the roll-step manoeuvre shown in Fig. 5. For a given course aspect ratio (ratio of runway width to distance between gates), the level of agility could be increased systematically by varying the entry speed. A critical agility parameter for this manoeuvre is the roll attitude quickness (ratio of roll rate to roll attitude change in a manoeuvre).

Values of roll quickness for the FLIGHTLAB XV-15 in its various configurations, overlaid with the ADS-33 forward flight boundaries are shown in Fig. 14. The tracking and general MTE boundaries are shown along with the data for the XV-15 in helicopter mode and conversion mode with the nacelles at 75º and 60º. At the higher speeds the aircraft is operating close to the conversion corridor boundary – the outer adequate speed boundary is within 5kt of the higher boundary of the conversion corridor. Operations in this area of the flight envelope are expected to be conducted during low level loiter and search phases of the SAR mission. In the fully developed CTR it is anticipated that there will be flight envelope protection through active control in conversion mode, but tests without this level of augmentation aid in defining the requirements for such systems. At the higher speeds in conversion mode the pilot will experience different couplings than in helicopter mode. For example, proverse roll-yaw coupling is introduced through differential collective control, although adverse aileron yaw will act to counteract this effect. Such influences will impact the design of the gearing between airplane and helicopter controls as a function of nacelle angle. A heave-surge coupling is introduced through application of collective pitch, which upsets speed control during flight-path adjustment; the gearing between elevator and helicopter controls becomes an issue here.

According to Fig. 14, the F-XV-15 should be Level 1 for general MTEs, with the performance margin increasing with decreasing nacelle tilt angle. This latter effect results from the increased control power from the combined helicopter and airplane controls for manoeuvring in conversion mode. For the 60° nacelle configuration,

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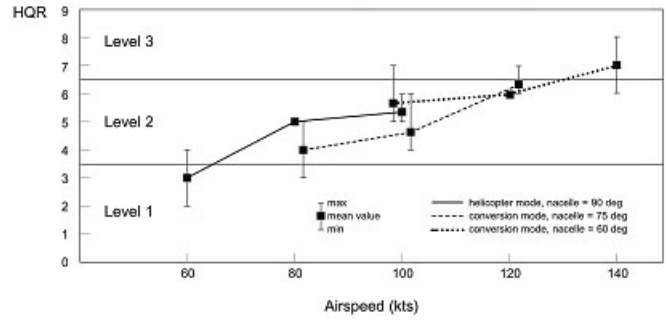


Figure 15. Handling qualities ratings for the roll-step MTE[9].



Figure 16. Bell/NASA/Army XV-15 and Eurocopter's EUROTILT concept in aircraft mode.

the F-XV-15 has about a 50% quickness margin above the general Level 1-2 boundary. In contrast, compared with the tracking Level 1-2 boundary the same configuration has about a 20% shortfall.

The roll-step tests were flown by three pilots and their combined HQRs are presented in Fig. 15. HQs degrade as speed is increased reaching the Level 2/3 boundary with the 60º nacelle configuration at about 120kt. At this speed the pilot was demanding nearly maximum roll quickness to achieve roll angles of about 50º during the turns. Precision during the roll out phases through the gates was also degraded and eventually led to the pilots being unable to achieve the adequate performance standards. The assigned and predicted HQs are thus again consistent, but only if the tracking boundaries are considered. Roll – yaw HQs thus degrade 'gracefully' as agility is increased with the bare-airframe (unaugmented) configuration. These results would need to be re-checked when the control and load alleviation augmentation functions are incorporated since, although the attitude bandwidth will be increased by design, the augmentation will undoubtedly increase the phase delay of the response (see Fig. 10, for example), increasing the potential for adverse aircraft-pilot couplings.

3.3 Flight-path HQs in airplane mode

Another question addressed in the RHILP project was 'are the pitch/flight-path handling qualities in airplane mode satisfactory without augmentation?' In Refs 21 and 22 this question is addressed within a more general framework of the location of the Level 1-2 and 2-3 HQ boundaries for tiltrotor longitudinal HQs. A particular issue arose in the investigation of pitch/flight-path HQs. Several of the tiltrotor configurations operational in the simulator at Liverpool were used in the exploration, including the XV-15 and EUROTILT concept (Fig. 16).

According to the classical short period and control anticipation parameter (CAP) criteria, the pitch/flight path HQs were predicted to be borderline Level 1/2 (see Figs 17 and 18 for FLIGHTLAB XV-15 results from 160-230kt IAS and from sea level to 6,000m altitude)[21].

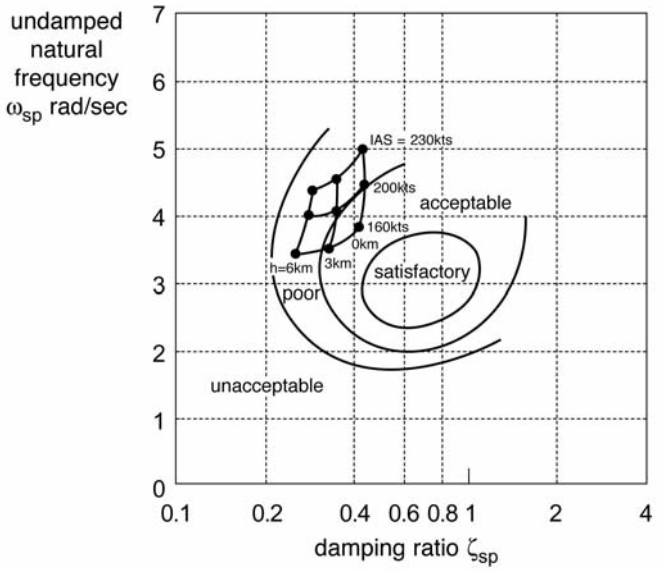


Figure 17. Short period dynamic characteristics for the F-XV-15 in aircraft mode – thumbprint chart.

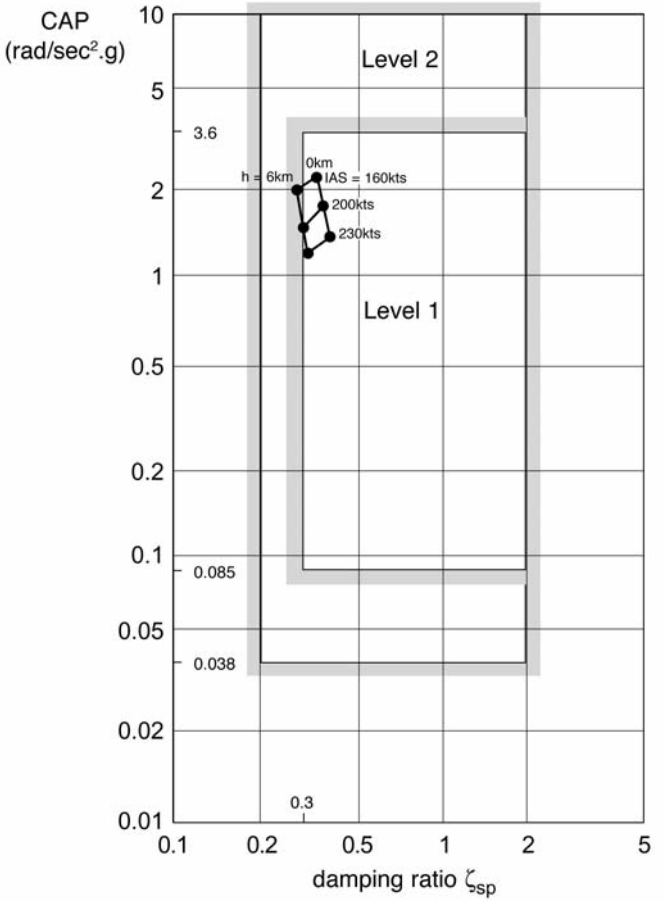


Figure 18. Short period dynamic characteristics for the F-XV-15 in aircraft mode – CAP chart (CAT A).

In addition, the aircraft were predicted to be 'solid' Level 1 according to the bandwidth-phase delay criteria[21]. However, when the aircraft was tested in the simulator, the assigned HQs were at the Level 2/3 boundary, Fig. 19. Three pilots took part in the evaluations and were required to fly the heave-hop MTE (Fig. 20), climbing

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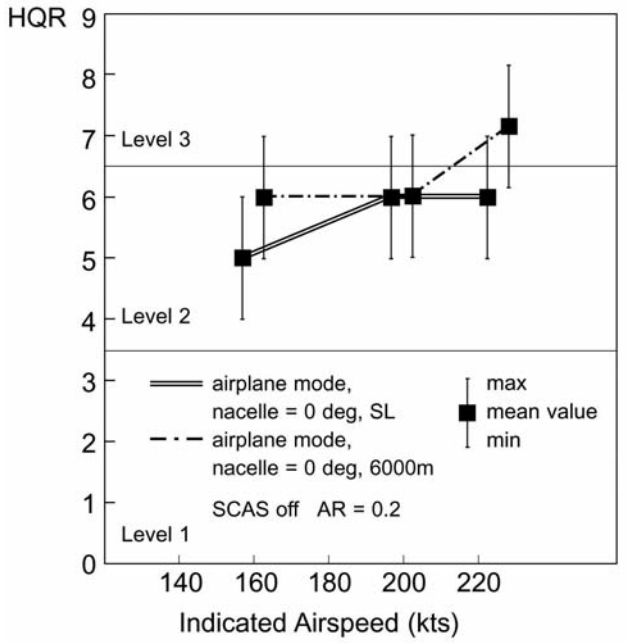


Figure 19. HQRs for the F-XV-15 in aeroplane mode flying the heave-hop MTE[21].

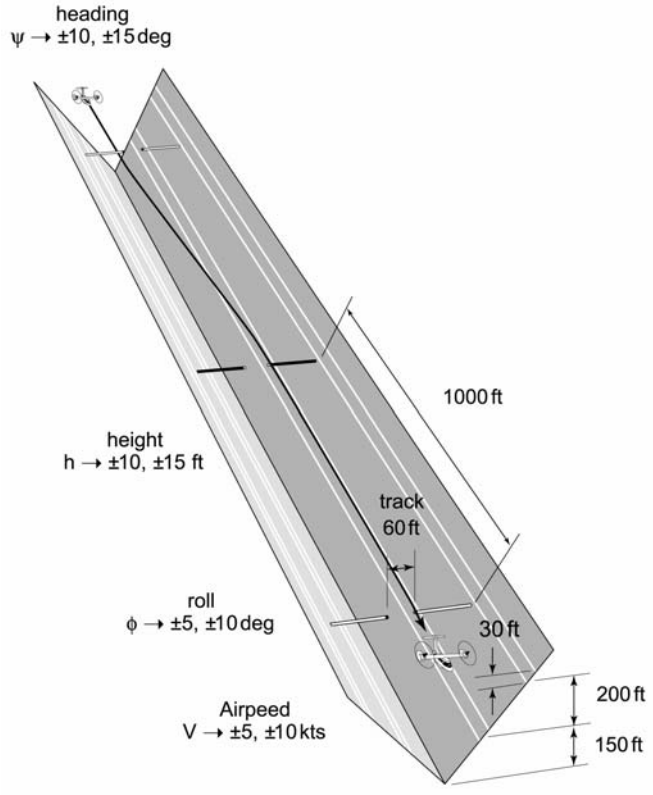


Figure 20. The heave-hop terrain-following MTE.

200ft (61m) in 1,000ft (304m) and levelling off, achieving the performance standards shown in Fig. 20. The MTE was designed to force the pilot to pull and push to the OFE load factor boundaries of +2·5 (1·5 above 1g) and 0·0g when flying at 200kt. The situation where the predicted and assigned HQs differ by a whole HQ level

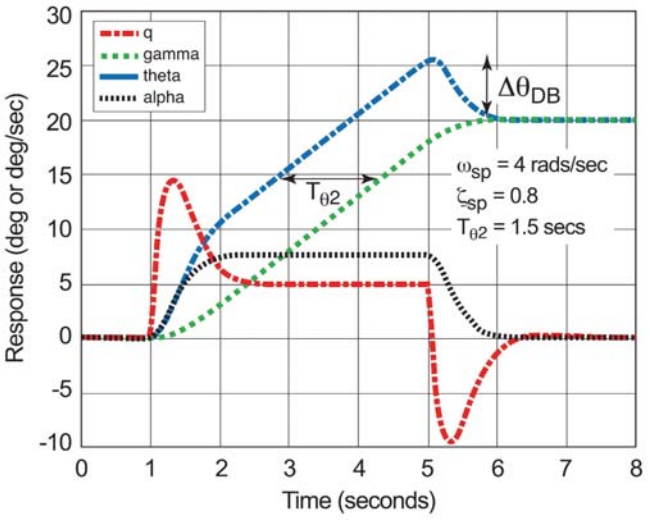


Figure 21. Pitch and flight-path response to a pulse input in elevator control showing the dropback effect.

required further investigation. The pilot complained of significant difficulty in predicting the final attitude and flight path, hence when to apply the control input to level out in the climb or settle back into level flight. The initial pitch rate and 'g' onset were considered satisfactory.

The pitch predictability problem is a result of the way in which the gimballed rotors 'flap' during manoeuvres. The contribution of the rotors to the pitch damping (M_q) and pitch stiffness (Mw) aerodynamic derivatives is, in fact, positive. The relatively high wing loading results in low heave damping (Z_w), and these three effects couple together to increase the drop-back of the pitch attitude. The effect is illustrated in Fig. 21, with the aid of Equation (1), which shows the short period transfer function between pitch rate and elevator. ω_{sp}, ζ_{sp}, $T_{\theta 2}$ are the short period natural frequency, relative damping and incidence (alpha) lag respectively. In Fig. 21 the elevator input is applied at one second and removed at five seconds. The short period parameters used in this case are shown in the figure. The short period natural frequency is 4rad/sec, relative damping is 0·8, giving acceptable response characteristics according to Fig. 17. The lag between flight path (gamma) and pitch attitude (theta) response is 1·5 seconds. This relatively long delay in the flight path response means that the stabilising contribution from the short period stiffness is also delayed, leading to the initial high value of pitch rate (q) overshoot shown in Fig. 21. When the control input is centred, the reverse occurs so that the large negative pitch rate response leads to the pitch attitude drop-back, in this case of about 20%.

$$\frac{q(s)}{\eta(s)} \approx \frac{M_\eta\left(s+\frac{1}{T_{\theta 2}}\right)}{s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}{}^2} = \frac{M_\eta\left(s-Z_w\right)}{s^2-\left(M_q+Z_w\right)s+\left(M_qZ_w-M_wU_e\right)} \quad \ldots (1)$$

The presence of an unusual HQ deficiency prompted another question; could a more suitable HQ parameter be found to quantify the drop-back effect and where were the corresponding HQ level boundaries?" This question was addressed in Ref. 22, developing the drop-back concept introduced by Gibson in Ref. 23. Using the short period equivalent system model in Equation (1), it can be shown that the normalised drop-back parameter given in Equation

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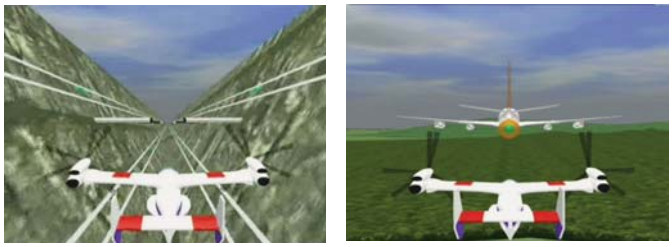


Figure 22. The heave-hop and refuelling drogue tracking MTEs.

(2) is approximately equal to the time interval, T_θ, between the first crossing of the steady state pitch attitude and when the pilot must re-centre the control in order that the attitude returns to the required steady state. This time interval is crucial to the pilot and is a measure of the predictability of the pitch response.

$$T_\theta \approx \frac{\Delta\theta_{DB}}{q_{ss}} \quad \ldots (2)$$

Here, $\Delta\theta_{DB}$ is the dropback and q_{ss} is the steady state pitch rate in Fig. 21. Furthermore, it can be shown that the ratio of this time to the flight path delay is given by Equation (3). This parameter is hypothesised as a critical measure of the pilot acceptability of the drop-back phenomenon, being a physically significant time, measured in units familiar to the pilot, i.e. units of T_θ. To evaluate the merits of this parameter, a piloted simulation trial was undertaken at Liverpool. Recognising that the pilot is concerned both with flight path response and pitch attitude response, two different MTEs were designed, one similar to the heave-hop previously described, the second a refuelling, drogue tracking task, concerned more with pitch attitude tracking, Fig. 22.

$$\overline{T}_\theta = \frac{\Delta\theta_{DB}}{q_{ss}T_{\theta 2}} = \frac{T_\theta}{T_{\theta 2}} = 1 - \frac{2\zeta_{sp}}{\omega_{sp}T_{\theta 2}} \quad \ldots (3)$$

Thirty six different configurations were considered, spanning the Level 1-2 ranges of CAP and values of $\overline{T}_\theta$ from zero to unity[22]. Three pilots participated in the simulation trials and based on the mean HQRs awarded the HQ boundaries appear as in Fig. 23. The data presented in Ref 22 suggest more restricted values of $\overline{T}_\theta$ and CAP give Level 1 HQs for the drogue tracking task than the flight path command/tracking task. The boundaries shown in Fig. 23 represent the two different results and are described as preliminary, needing further validation. Nevertheless, they provide an answer to the question posed and can be used as the basis for the design of the control augmentation system. It should be noted that the minimum values of CAP defining the Level 1-2 and 2-3 boundaries are more demanding than the military standards shown in Fig. 18. This discrepancy does introduce some risk but selecting values in the mid range will minimise this. A CAP value of 1·5rad/sec^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.

In the two cases studied in 3.2 and 3.3, the questions addressed the selection of parameters suitable for designing an aircraft to meet HQ standards. An equally important set of questions revolve around the criteria for failures of flight control functions, the topic of our final case study.

3.4 Degraded HQs following system failures

The HQ levels provide a framework for analysing and quantifying not only what the response of the aircraft should be in normal conditions, but also the effects of flight failures, which can occur in three ways;

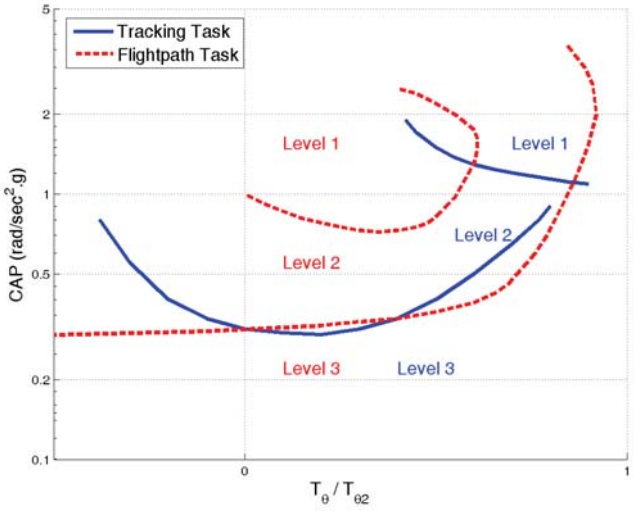


Figure 23. Preliminary HQ level charts for CAP *vs* $\overline{T}_\theta$.

Table 4
Failure classification for civil aircraft[24]

Failure Severitty	Maximum Probability of Occurrence per Flight Hour	Failure Condition Effect
Catastrophic	Extremely Improbable < 10^{-9}	All failure conditions that prevent continued safe flight and landing.
Hazardous	Extremely Remote < 10^{-7}	Large reductions in safety margins or functional capabilities. Higher workload or physical distress such that the crew could not be relied upon to perform tasks accurately or completely. Adverse effect upon occupants.
Major	Remote < 10^{-5}	Significant reductions on safety margins or functional capabilities. Significant increases in crew workload or in conditions impairing crew efficiency. Some discomfort to occupants.
Minor	Probable < 10^{-3}	Slight reduction in safety margins. Slight increases in workload. Some inconvenience to occupants.

(a) Loss; e.g. when a control becomes locked at a particular value and the control surface no longer responds to a control input,

(b) Malfunction; e.g. when a control surface no longer moves consistently with the input, as in a hard-over, slow-over or oscillatory movement,

(c) Degradation; the function is still operating but with degraded performance, e.g. low voltage power supply or reduced hydraulic pressure.

Failure assessments involve drawing up a failure hazard analysis table, where every control function is examined for the effects of loss, malfunction and degradation, categorised as minor, major, hazardous or catastrophic. Table 4 summarises the hazard categories for civil aircraft in terms of both the effects of the failure, and the allowable maximum probability of occurrence per flight hour[24].

In the HQ standard ADS-33[6], the safety approach is defined in five key steps (author's italics for emphasis);

(a) Tabulate all rotorcraft failure states (*loss, malfunction, degradation*),

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Table 5
Levels for rotorcraft failure states[6]

Probability of Encountering Failure	
within operational flight envelope	within service flight envelope
Level 2 after failure $< 2.5 \times 10^{-3}$ per flight hr Level 3 after failure $< 2.5 \times 10^{-5}$ per flight hr Loss of control $< 2.5 \times 10^{-7}$ per flight hr	$< 2.5 \times 10^{-3}$ per flight hr

(b) Determine the degree of handling qualities degradation associated with the *failure transient* for each rotorcraft failure state,
(c) Determine the degree of handling qualities degradation in the *subsequent steady* failure state,
(d) Calculate the probability of encountering each identified failure state *per flight hour*,
(e) Compute the total probabilities of encountering Level 2 and Level 3 flying qualities in the *operational and service flight envelopes*. This total is the sum of the rate of each failure only if the failures are statistically independent.

Degradation in the handling qualities level is only permitted if the probability of encountering the degraded level is less than the values shown in Table 5. Note that the military requirements are not nearly as demanding as the civil requirements in Table 4, where the probabilities are typically two orders of magnitude lower.

Fitting the safety analysis within the HQ framework is important for the integration of requirements capture and preliminary design. In particular, the control system architecture is critically dependent on the failure characteristics. Within the ACT-TILT project[25] a failure hazard analysis was conducted on the ERICA tiltrotor (Fig. 24) as part of the architecture optimisation. Some of the results of this investigation were presented in Ref. 26 and our final case study is drawn from this paper. Table 4 suggests that failures in the hazardous and catastrophic categories are flight critical while those in the major category are mission critical. A question that arises from this interpretation is how this can be expressed in HQ terms. In particular, for those failures that need assessment in piloted simulation, can the pilot's impression of the failure effect, and ability to recover, be directly related to the assigned HQRs? One type of failure that can be investigated in this way concerns the partial loss of power in the powered control system. Typically, hydraulic power is provided in a duplex system to provide the flight critical level of reliability (total failure extremely improbable). The question then arises as to what performance should be achievable if one of the systems fails? If it is assumed that the loss of power results in a 50% reduction in the maximum rate at which the control actuators can be driven, the question then becomes – what actuator rate degrades the HQs to Level 3?

The extent of the degradation actually depends on the pilot's control inputs since the same power system drives collective and cyclic, and, for example, the same actuators are used for pitch and yaw control on a tiltrotor. Our question can be answered in the usual fashion by first examining the degradation in the HQ predictions, i.e. the dynamic response parameters, in particular attitude quickness for agility and attitude bandwidth/phase delay for closed loop stability. Because it is possible that several of the predicted HQ parameters are likely to degrade at the same time, it is especially important to check the predictions by carrying out piloted evaluations. So, the assigned HQs are delivered by pilots flying suitable MTEs at appropriate levels of agility. In the present case study results will be



Figure 24. The AgustaWestland ERICA concept in helicopter and conversion modes[17].

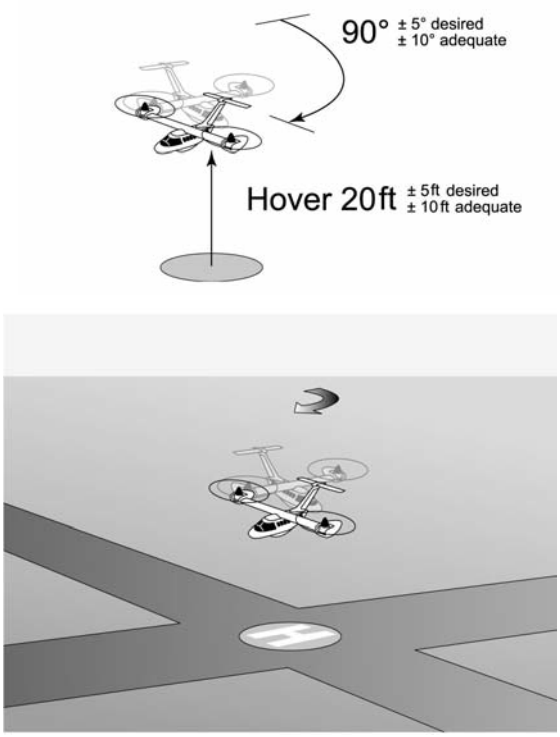


Figure 25. The hover turn MTE.

shown for pilots flying a hover turn MTE (Fig. 25), attempting to achieve similar levels of performance to those achieved in normal operations. The importance of this requirement is emphasised in Ref. 27 where the point is made that anything less than the same performance requirements as demanded in normal operational flight, would lead to pilots relaxing their control strategy and consequently not fully experiencing the adverse effects of degradation. While this might be possible to do in some conditions, flight through heavy turbulence, recovering to a moving deck or a confined area in poor

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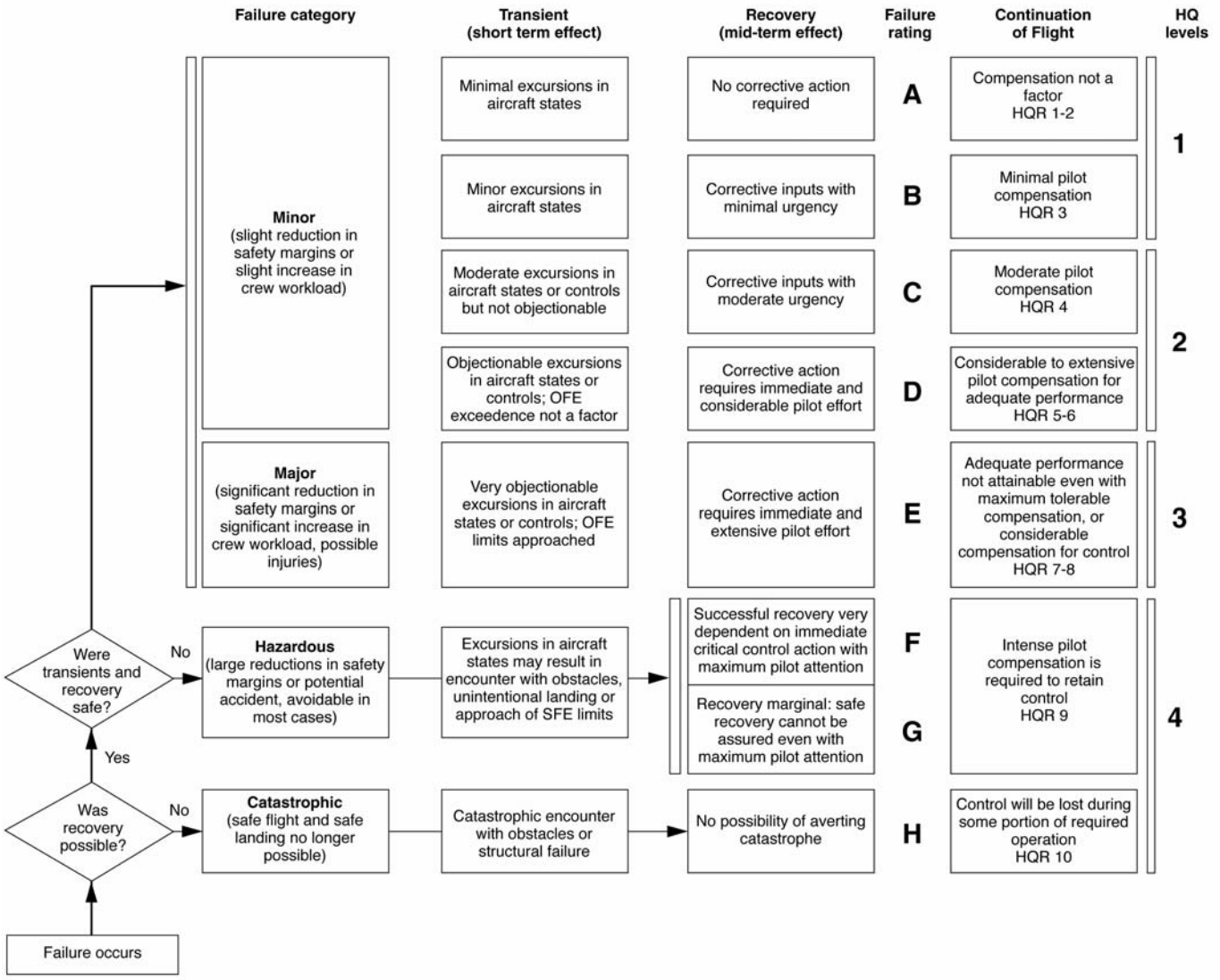


Figure 26. Integrated classification of failure effects and handling qualities[7].

visibility may be unavoidable, hence some assessment of the likely consequences needs to be conducted.

For the investigations reported in Ref. 26, pilots rated both the transient effect of the failure and the consequent ability to recover to a safe equilibrium state. Failure ratings (FR) A to E refer to tolerable failures, F to G intolerable, with a marginal recovery capability, while a rating of H means there is 'no possibility of averting a catastrophe'. In the programme to develop the European Civil tiltrotor this methodology has been extended to produce an integrated classification of failures as illustrated in Fig. 26[25], and is itself an extension of that adopted in the development and certification of the NH-90 helicopter. The integration brings together the failure category concept (minor-catastrophic), the failure rating and the handling qualities rating. A 'minor' failure that elicits a FR of A or B, results in the aircraft maintaining its Level 1 HQs. If the ratings degrade to C or D, the aircraft falls into the Level 2 category. Major failures correspond to degradations to Level 3 HQs while hazardous or catastrophic failures correspond to the aircraft falling into the Level 4 region, where loss of control is threatened.

The results shown in Fig. 27 capture the utility of the integration and the previous point referring to performance standards very well. The data are for two test pilots flying the F-XV-15 in the 90º hover-turn manoeuvre to the ADS-33 performance standards. The actuation rate for the yaw control function, provided by differential longitudinal cyclic pitch, was reduced incrementally until Level 3 ratings were awarded. The case shown in Fig. 27 corresponds to a reduced cyclic pitch actuation rate of 3deg/sec. It can be seen that Pilot B flew the manoeuvre with an initial step control input, allowing the aircraft to yaw gradually to the required heading with minimal closed-loop action. In stark contrast, Pilot A attempted to stop the yaw rate with a more abrupt input but immediately entered a pilot-induced-oscillation. Over a period of about ten seconds, the oscillatory pedal inputs increased to the stops with yaw rate building up to greater than 20deg/sec. The rate limiting on the cyclic pitch can be seen clearly in the saw-tooth pattern in the lower right figure.

Pilot B returned an HQR 4 for this case, the same rating that both pilots had returned for the case with no rate limiting. Pilot B had continued to adapt his strategy as the system performance degraded to achieve the task with moderate levels of compensation. Pilot A, with each new configuration, initially attempted the manoeuvre with

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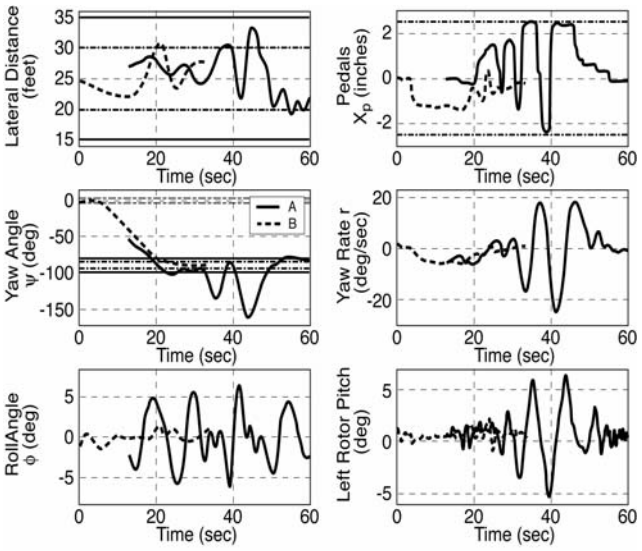


Figure 27. Comparison of results for Pilot A and B flying the F-XV-15 in the hover turn MTE.

a similar strategy, deliberately to focus on changes in handling. For the case shown, Pilot A returned an HQR of 10, on the basis that he had to stop flying the aircraft (get 'out-of-the-loop') for several seconds. The aircraft had not, however, drifted outside the adequate performance limits on position and bank, only yaw angle and, arguably, a Level 3 rating would have been more appropriate. However, the pilot was holding right pedal on the stops for more than five seconds to bring the aircraft onto heading before coming out of the loop and his impression was that he had, indeed, lost control.

The Level 2-3 boundary rate limit for the longitudinal cyclic actuation function was set at 4deg/sec, similar to that defined for pitch control in the acceleration-deceleration manoeuvre. The normal power actuation rate authority was eventually set to be 10deg/sec in this preliminary design study, 2·5 times the rate at which the Level 2-3 boundary had been predicted, hence giving a safety margin for compensation in harsher environmental conditions.

As this author points out in Ref. 7, studying the effects of system failure brings home the importance, and associated cost, of safety in aviation, by far the safest sector in the transport industry. Ensuring that the effects of flight system loss, malfunction and degradation do not lead to a worsening of handling beyond Level 2 provides a major contribution to this safety. Players in this 'safety theatre' include regulatory bodies, requirements formulators, design engineers, manufacturers, certification agencies, operators, maintenance engineers, training organisations and the pilots themselves; in other words, practically the whole aerospace community is involved. Nothing less than a total commitment to safety by the whole community will lead to an eradication of accidents resulting from system failures.

4.0 DISCUSSION

The four case studies have been presented in this paper in the form of questions and answers. In this way, handling qualities requirements and design solutions are coupled together and the importance of undertaking creative synthesis, supported by analysis, during the formulation of requirements is underscored. Handling qualities are described at the interface between pilot and machine, and involve a wide range of technologies and technical disciplines. In this way, HQs are presented as a system level attribute, faceted with the external world within which the system is intended to operate, the facet in this case being the pilot. To focus on the solutions to the HQ aspects, the case studies have been presented without the constraints and trade-offs that normally take place in multi-disciplinary optimisation, where other system and sub-system level requirements have to be taken into account.

There are therefore two ways in which virtual engineering extends to be fully effective.

First is the extension to include all system and sub-system requirements, and the ensuing multi-disciplinary optimisation. Within this process, models of ultra-high fidelity will be required to predict, for example, rotor and airframe loads accurately for use in the design of the detailed external shaping for aerodynamic efficiency and layout for structural efficiency and integrity. All system level facets interfacing with the external world need to be defined and described, along with their quality metrics and performance standards. These then need to link with requirements at sub-system and component levels.

Second is the extension of virtual engineering to the middle and later stages of the system life cycle (Fig. 1) – design, development, manufacturing, qualification, production, operation and beyond. Some of the same models can and need to be used throughout the cycle. For example, to understand the implications of a 'requirements-design' trade-off decision on operational capability, mission simulations may need to include the same high fidelity modelling as used in preliminary design. The design-for-manufacture process has received attention over the years with the development of integrated computer-aided-design and computer-aided-manufacturing (CAD/CAM) packages. These now need further integration with the front-end IRCPD and operational modelling and simulation to connect the virtual engineering process model. The implications of such developments for the future of computer architectures and processing power are, of course, very significant.

The ability to predict accurately the impact of all decisions on future capability and cost is a crucial requirement of virtual engineering. Organisations that fully embrace this practice are more likely to be able to manage innovation effectively, communicate efficiently with the supply chain, and offer higher quality products at lower cost, while meeting the continuously growing safety and environmental constraints.

5.0 CONCLUDING REMARKS AND RECOMMENDATIONS

In this paper the author has taken the opportunity to place current activities in support of the integrated requirements capture and preliminary design of the European Civil tiltrotor into a virtual engineering context. Handling qualities have been described as system level requirements at the interface between the aircraft and the pilot, contributing crucially to both operational performance and safety. A comprehensive methodology has been illustrated with four cases studies. Posing requirements as questions allows the user and designer to develop common understandings and to prioritise solutions during trade studies better.

The principles of virtual engineering emphasise the importance of closely linking the various stages in the life cycle process, particularly at the front end, with requirements capture and preliminary

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design. Constructive and substantial modelling and simulation performed at this stage can massively reduce the risk that innovation, introduced to achieve stretched goals, will not be successful in operation. The INCOSE claim that having to fix problems during development can be three orders of magnitude more costly than at the early concept stage is very compelling in this regard.

There is a need for much greater investment in virtual engineering throughout the life cycle to aid getting things right first time, particularly at the front end when leverage is greatest. This means investing in very high fidelity simulations and the necessary computing power, and it means integrating processes across the life-cycle. The paper has just touched on this subject in a handling qualities context; the whole is multi-disciplinary and there is a real need for developing engineering skills and knowledge in the associated synthesis and analysis techniques and digital processes. All engaged in the business of conceiving, designing, testing and bringing new aviation systems, for example civil tiltrotor aircraft, to market would, in the author's opinion, be better served by such investment.

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