FIRST STEPS IN THE DEVELOPMENT OF HANDLING QUALITIES CRITERIA FOR A CIVIL TILTROTOR

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Abstract

This paper describes an approach to the development of Handling Qualities criteria for a civil tiltrotor. The work presented is the outcome of a combined effort of European research organizations and helicopter industries, working together in an European Commission sponsored critical technology program – RHILP (Rotorcraft Handling, Interactions and Loads Prediction). The RHILP approach to Handling Qualities has developed from the systems methodology in ADS-33. An important exercise has involved assembling a consistent set of Handling Qualities criteria appropriate to flight in rotorcraft, conversion and fixed-wing aircraft modes. Within this process a compatibility analysis has revealed inconsistencies and, more critically, gaps in the available data, particularly relating to flight in conversion mode. The paper outlines the approach taken and presents results from a series of piloted simulation trials carried out to provide supporting data which can be used to fill the gaps. The results presented are considered to be unique since there are no open publications available to date on tiltrotor aircraft Handling Qualities criteria.

Introduction

As part of an European initiative to develop tilt rotor aircraft technologies and work towards bringing such aircraft into commercial service, a series of Critical Technology Programs (**CTP**) has been launched under the sponsorship of the European Commission's 5th Framework Program. The general motivation behind this initiative is to expand the short-range transport system while, at the same time, lessening congestion at busy airports. With a vertical take-off and landing capability and relatively high cruise speed and range, a tilt rotor configuration fits naturally into a modern, efficient transport network [1]. From a technology standpoint, and in an European context, a number of areas need further development to reduce the risk prior to a commitment to detailed design and manufacture. Handling Qualities and flight control has been identified as one of these critical areas and in March 2000 a three-year collaborative CTP was launched, entitled "Rotorcraft Handling, Interactions and Loads Prediction (**RHILP**)" [2]. The project consortium consists of seven partners from five European countries: Eurocopter S.A.S. (project leader), Eurocopter Deutschland GmbH, Centro Italiano Ricerche Aerospaziali S.C.p.A. (**CIRA**), The University of Liverpool (**UoL**), Deutsches Zentrum für Luft- und Raumfahrt e.V. (**DLR**), Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (**NLR**) and Office National d'Etudes et de Recherches Aérospatiales (**ONERA**).

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The RHILP project aims, through detailed design, modelling, testing, analysis, and simulation, to reduce the risks associated with flight control and Handling Qualities (**HQs**) of a future European Civil TiltRotor (**CTR**). Within the project critical technology aspects are captured that have a strong influence on aircraft design, especially in aeromechanics and flight dynamics. The specific technical areas addressed in RHILP are:

- Handling Qualities criteria
- Aerodynamic interactions
- Transient structural loads

The project objectives and scope are detailed in Reference [2].

An operational civil tilt rotor must possess Level 1 Handling Qualities throughout its normal flight envelope. Within the Framework 5 CTP structure, developing the requirements to achieve this goal is being achieved in 2 steps. Initially in RHILP, the requirements for the Level 2 characteristics of the bare airframe plus rudimentary stability and control augmentation system are being explored and defined. In a sister-CTP Active Control Technologies for TILT-rotor (**ACT-TILT**), which started in late 2001, the work is being extended to establish the requirements for the Level 1 system.

When it comes to Handling Qualities an aircraft designer has two closely related, but distinct, challenges. First, what flight characteristics are required and, second, how should the design be arranged and proportioned to achieve these characteristic. The work presented in this paper addresses the investigations and resulting findings of the first of these challenges. To date, a generic HQs specification for tiltrotor aircraft does not exist. The current effort is aimed at the development of such a document, building on existing know-how related to RotorCraft (**R/C**) and Fixed-Wing (**F/W**) aircraft.

Handling Qualities are considered critical in terms of passenger and crew safety and will therefore have a strong influence on the design process of a future CTR. The need for carefully tailored control laws to confer excellence in HQs is now well understood [3]. Also, aircraft are more likely to possess good Handling Qualities if they are designed using comprehensive requirements criteria and standards than if they are not. Comprehensive in this context is taken to mean criteria that are complete and appropriate in their coverage, substantiated by data and verifiable in flight test. Furthermore, such an aircraft will be certified according to civil aviation airworthiness regulations within which safety standards play a major role. Other important reasons for an early assessment of HQs are to help quantify the mission effectiveness and developing the requirements for the stability and control augmentation system.

Within RHILP, the final validation and demonstration of the Handling Qualities will be conducted as piloted simulations at the Eurocopter SPHERE facility in Marignane (France). The EUROpean TILTrotor (**EUROTILT**) aircraft concept, featuring high fidelity modeling on aerodynamic interactions, structural load alleviation and the established HQs criteria will be the main focus of the assessments.

The EUROTILT concept builds on the achievements gained in the European Future Advanced Rotorcraft (**EUROFAR**) program [4] which was active until the mid nineties. Figure 1 shows an artistic impression of the EUROTILT concept.

Figure 1: EUROTILT artist's impression

The major difference between EUROFAR and EUROTILT is the size of the aircraft. The EUROTILT configuration is planned for 12 to 19 passengers, compared with about 30 passengers for the EUROFAR. EUROTILT's weight is in the 10t class, with a design cruise speed of 300kts. Both concepts tilt only the nacelles rather than the complete engines. An advantage is that no modifications are required for the power plant to run vertically.

The EUROFAR concept development was supported by piloted simulations [5] with the aim of investigating the flying and operational capabilities of that aircraft. Within the RHILP project, first assessments of CTR Handling Qualities are being performed at the motion-base **HELIFLIGHT** [6] simulator facility at the University of Liverpool. It was considered important to gain this early experience with an aircraft with known capabilities, hence a FLIGHTLAB XV-15 (**FXV-15**) was created to develop an improved understanding of the critical issues and as a vehicle with which the team could begin to narrow the gaps. This model was also partially validated with published data on this aircraft and serves as a baseline configuration in the activity. These piloted simulations were not planned originally in the project. However, the contributing partners found it necessary as a support to the analytical approach and to close some of the critical Handling Qualities gaps.

The paper begins with a description of the RHILP approach to CTR Handling Qualities. The underlying system approach is introduced, and the steps taken from a specification review to piloted simulations are demonstrated. The following section describes the simulation environment at the University of Liverpool and the FXV-15 model used for the piloted simulations. This also includes a summary of the matrix of simulation configurations flown. The paper goes on to present results from analysis and simulation aimed at establishing a HQ database from which improvements can be developed. A particular focus of the work has been to fill the gaps associated with HQs during flight in conversion mode. Results are presented for the roll axis and compared with ADS-33E criteria. Finally the paper is drawn to a close with a conclusions and recommendations section.

RHILP Approach to CTR Handling Qualities

The RHILP project aims to assemble an integrated set of HQs criteria primarily to define the design requirements for a CTR control system. The Handling Qualities approach adopted by the RHILP team builds on the latest developments in rotorcraft and fixed wing aircraft design methodologies. In particular, the HQs will be mission-oriented and flight test maneuvers will be constructed from Mission Task Elements (**MTEs**) that feature essential aspects of pilot skill, task difficulty and workload, and exercise the aircraft's characteristics over the full range expected in operation. This advanced design philosophy was applied in the development of the ADS-33 [7], the current aeronautical design standard for military R/C. ADS-33 incorporates several concepts that form into mission oriented HQs requirements [3], contrary to the "ancient" classifications depending on the aircraft size and performance. These features include for example the mission task elements and the Usable Cue Environment (**UCE**), which differentiate HQs as a function of the visibility and outside visual cues.

The development of a CTR Handling Qualities manual and design guide is a very unique and challenging task. The challenge is to merge R/C and F/W criteria within one specification. In addition a third flight condition, the conversion mode, has to be considered and must be harmonized with the other two flight modes. Hence, a holistic approach is needed that leads all efforts through the project and helps to assure a high quality of the final outcome. The systems approach to CTR Handling Qualities was chosen according to the ADS-33, as shown in Figure 2.

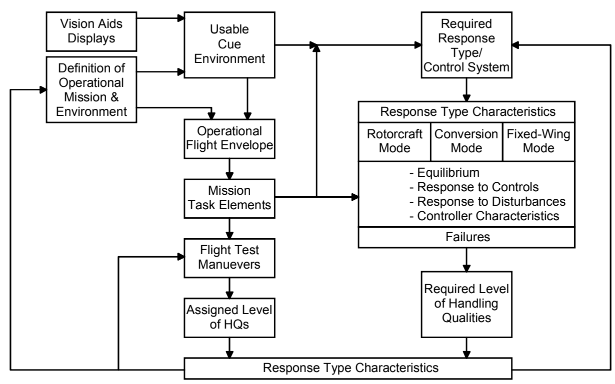


Figure 2: CTR HQs systems approach

Figure 2 illustrates a process that begins with defining the required operational envelope and environment, continues through the development of the required MTEs and UCEs and Response Types, broadens out into the response characteristics and includes testing to compare assigned with required HQs. Developing HQs is a long and iterative process where not all aspects can be considered or fixed initially due to the lack of information, time or resources (note that the period between publication of the early versions of ADS-33 and ADS-33E was 15 years). The RHILP project focuses on the requirements to achieve Level 2 Handling Qualities in a good visual environment and with full pilot attention on the control and flying task. In addition, the location of the Level 2/3 boundary is a major concern, particularly where Level 3 qualities emerge as a result of degrading aircraft-pilot couplings or other "cliff-edge" type phenomena.

Based on the system approach given in Figure 2, Figure 3 demonstrates the steps taken within the RHILP project.

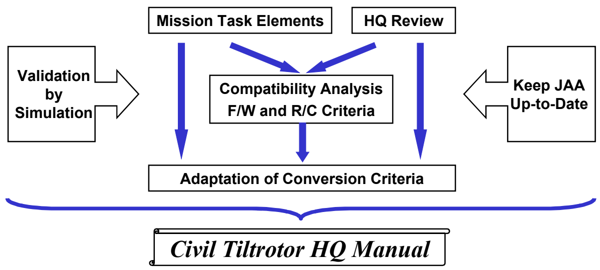


Figure 3: RHILP approach to CTR HQs

After the definition of the required missions, the mission task elements and test maneuvers were defined which would later help to expose any Handling Qualities deficiencies in the aircraft characteristics. A review of the existing HQ specifications would deliver the basis for an analysis of the compatibility between applicable R/C and F/W criteria.

The analytical approach was supported by piloted simulations at the University of Liverpool. The knowledge gained from the compatibility analysis and the simulations then allowed an adaptation of the criteria to flight in conversion mode. The RHILP approach and goals were introduced to the Joint Aviation Authorities (**JAA**), represented by the Joint Harmonization Working Group. This sub-organization of the JAA harmonizes Joint Aviation Rules (**JAR**) and Federal Aviation Rules (**FAR**). This linkage with the regulators early in the project is considered vital to ensure a smooth transition of this type of aircraft into service.

Handling Qualities Criteria Review

A presentation on the BA609 civil tiltrotor certification at the European Helicopter Association Symposium in The Hague in 2000 [8] demonstrated the challenges and effort necessary in the certification process of a CTR. Almost three-quarters of the certification basis for performance and Handling Qualities had to be either adapted from FAR Part 25 (Transport Category Airplanes) and Part 29 (Transport Category Rotorcraft) or newly-created as depicted in Figure 4.

A review of the current JAR and FAR reveals that design guidance for Handling Qualities, for example that is required for the definition of the stability and control system, is given very limited attention. This situation resulted in these documents being given a compliance check status within the RHILP Handling Qualities approach.

Consequently, existing military rotorcraft and fixed-wing specifications were reviewed. However, it must always be kept in mind that military missions and hence the associated HQs criteria, are normally much more demanding with respect to the required aircraft agility.

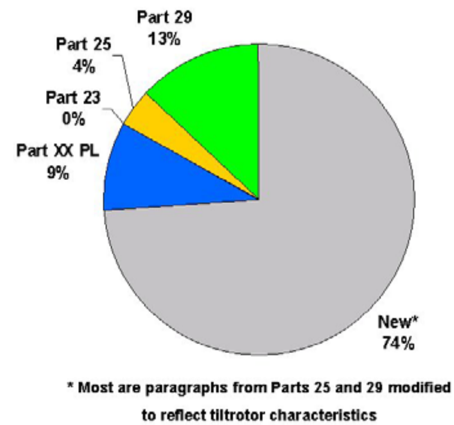


Figure 4: Performance and HQ certification basis of the BA609 [8]

The HQ literature search aimed to gather and select relevant published material applicable to the three tiltrotor flight modes. This search showed that, as expected, there are no specific tilt rotor Handling Qualities criteria; in fact there are no criteria for the conversion mode available in the open literature. Former tilt rotor designs appear to have been based on a mix of military rotorcraft and fixed-wing aircraft requirements and, in the case of the BA609, also the civil airworthiness specifications. The absence of public-domain Handling Qualities standards tailored for tilt rotor aircraft may appear at first sight to be a impediment to the development of these aircraft. However, the premise of this paper is that a careful selection from existing fixed-wing and rotorcraft Handling Qualities criteria forms an elevated starting point from which further development and refinement can take place.

Table 1 shows a list of specifications which were found to be suitable for further study.

Table 1: Suitable HQ Specifications

Specification	Rotorcraft Mode	Conversion Mode	Fixed-Wing Mode
MIL-STD-1797A [a]			D/C
1797 update [b]			D/C
FAR/JAR 25 [c]			C
MIL-F-83300 [d]		D/C	
ADS-33E [e]	D/C		
DEF STAN [f]	D/C		
FAR/JAR 29 [g]	C		

[a][9], [b][10], [c][11][12], [d][13], [e][7], [f][14], [g][15][16] D → *Design* C → *Certification*

The table documents how the specifications apply to the three tiltrotor flight modes. As already discussed, there are specifications like the FAR and JAR for example that address mainly the certification needs but not the quantification and rigorous assessment of handling characteristics and hence are not particularly helpful in the design process. This rather global distinction is indicated in Table 1 by the letters "D" and "C". Table 1 lists one document under the conversion category, the MIL-F-83300 [13] – a military specification that contains Handling Qualities requirements for military V/STOL aircraft operating at speeds up to the conversion speed. This document captures requirements for the "transition" between flight phases. These criteria are of a qualitative nature and can be identified by the "C" for certification.

Mission Analysis

As noted in the previous discussion, the future European CTR is expected to fly in three modes:

- Rotorcraft mode: flight with the nacelles between 80° and 100° with 90° being the nominal value (shaft normal to the fuselage)
- Fixed-Wing mode: flight with the nacelles at 0° (shaft aligned with the fuselage)
- Conversion mode: flight with any other nacelle angle (steady or transient)

Generally two kinds of mission are envisaged for a future CTR:

- Transport mission (passengers or freight)
- Search and Rescue (**SAR**) mission

Both missions include offshore tasks, e.g. supply and service flights for oil-rigs or maritime salvage. The missions were analyzed and divided in mission phases. From the mission phases a suit of HQs critical mission task elements could be identified for all three flight modes.

A phase where all three modes are relevant is the search or loiter phase of the SAR mission where the aircraft may need to operate at a low altitude, possibly close to the surrounding terrain. The aircraft is flown mainly with reference to outside visual cues. The flight mode will depend on the selected speed, which itself will depend on the characteristics of the search zone. If the search zone is wide, the CTR will loiter in airplane mode to benefit from higher airspeeds, typically in the 140 - 160kts range. Wing flaps will be slightly extended as necessary to keep sufficient margin with respect to stall speed. If the search zone is small, or (and) if detection/identification of the rescue site requires lower speed flight, the CTR will loiter in rotorcraft mode with the nacelles tilted forward at approximately 80°, typically around 70kts airspeed. Continuous flight in partially converted configuration (e.g. nacelles around 60° - 75°) should also be considered. This would allow the CTR to loiter at intermediate airspeeds, typically around 100 - 120kts within the conversion corridor, thus extending its operational capabilities. Operations in this configuration, in partial wing-borne flight, will be particularly efficient at these intermediate speeds.

As a Handling-Qualities-critical mission task element, the valley following was identified as shown in Figure 5.

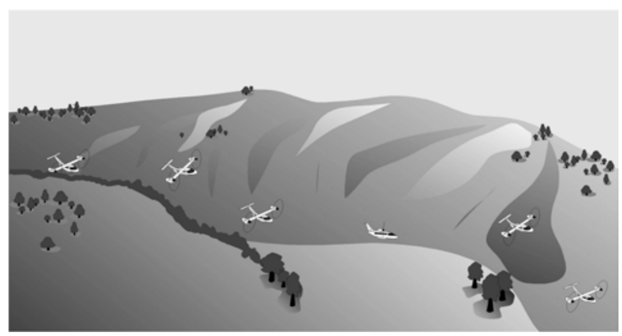


Figure 5: Valley following MTE

This MTE evolved from the search task when the CTR follows the surrounding landscape like a valley or river bed. The aircraft performs turns in either direction at low altitude and the pilot has to maintain the altitude with respect to the ground and a horizontal safety margin from the surrounding terrain. He must always be prepared for an abrupt change in the roll angle to avoid the terrain and obstacles when flying in the speed ranges indicated.

Altogether more than a dozen HQs-critical MTEs have been defined, including,

- low speed MTEs like the sidestep, bob-up, accel-decel, precision hover and yaw turn,
- mid-speed maneuvers like the valley following, terrain following, obstacle avoid,
- conversion maneuvers in level, climb/descent and turning flight,
- take-off/climb and approach/landing maneuvers

In defining the performance standards for Handling Qualities test Maneuvers (**HQM**) it is important to select constraints that will expose any handling deficiencies, yet still be realistic in terms of the intended mission. Experience has shown that constraints need to be tightened relative to the expected normal operating conditions to ensure that any adverse aircraft-pilot couplings or tendencies are exposed [17].

The next stage of the mission analysis is to transform the MTEs into equivalent engineering test maneuvers. The valley following MTE was transformed into a HQs test maneuver, called the roll-step maneuver shown sketched in Figure 6. The pilot is required to fly the maneuver at different speeds depending on the flight mode, crossing from one side of the runway to the other, flying a precise flight path through the gates. The higher the speed, the less time available to cross the runway, hence the higher the required bank angle and turn rate. The pilot is required to fly to the desired and adequate performance standards, as defined in Figure 6. Throughout the task he has to monitor the speed and height constraints, whereas the remaining performance parameters (lateral position, bank angle and heading) are only an issue between the gates along the runway edge.

The roll-step is flown mainly with reference to outside world cues, and the primary axis of interest is the roll axis. In Handling Qualities terms, the task has two main elements - the initiation of the roll motion tends to be flown open-loop, whereas the lineup with the runway edge requires a closed-loop tracking control strategy. The response bandwidth and cross-couplings are critical aspects for the closed-loop control, while control power and attitude quickness are important to initiate roll movements (i.e. open-loop control phases). The need for the pilot to monitor aircraft states, particularly speed and height, will contribute to the workload.

Compatibility analysis

The compatibility analysis compares the R/C and F/W requirements identified in the HQs criteria review. The compatibility analysis is interpreted as a search for the commonality and distinctions between the R/C and F/W criteria. The main focus thereby was on the formats and measures of the evaluated criteria. The approach taken evolves from two standpoints: first, a specific tiltrotor HQs manual should ideally combine the criteria of the three modes into one single criteria or if possible at least in one single format. Second, any gaps with respect to the CTR mission and aircraft characteristics must be identified. Clearly any selected criterion must result in HQs which are consistent between the three modes; achieving commonality in format and structure also eases the

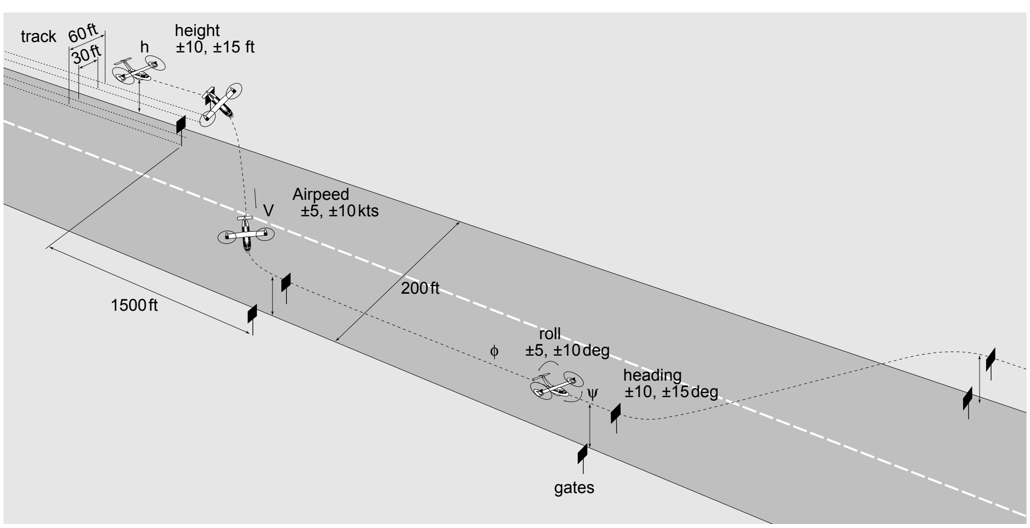


Figure 6: Layout of the roll-step Handling Qualities test maneuver

design optimization. The analysis therefore requires a very deep survey of the boundary conditions of each criterion. The applied analysis also aims to adapt the format or boundary of a selected criterion if possible/necessary to the CTR mission/aircraft characteristic.

As expected, this analysis identified several compatibility issues between R/C and F/W mode HQs criteria, and also HQs gaps, particularly relating to the conversion mode. Indeed, the absence of data on the aircraft characteristics and HQs criteria in the conversion mode, were judged to be the major gaps. Results from efforts to close these gaps are discussed in the following sections.

The criteria from the documents listed in Table 1 were ordered according to the dynamic maneuver envelope. Figure 7 illustrates the origin of this classification.

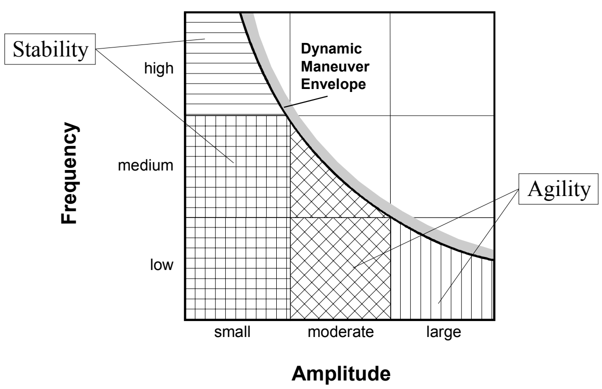


Figure 7: Dynamic maneuver envelope [3]

Within this classification the criteria are arranged by type into bandwidth criteria, equivalent system criteria, quickness, control power etc., and analytically compared.

Figure 8 illustrates the result of such an analysis for the case of the small amplitude/high frequency stability criteria for the roll axis.

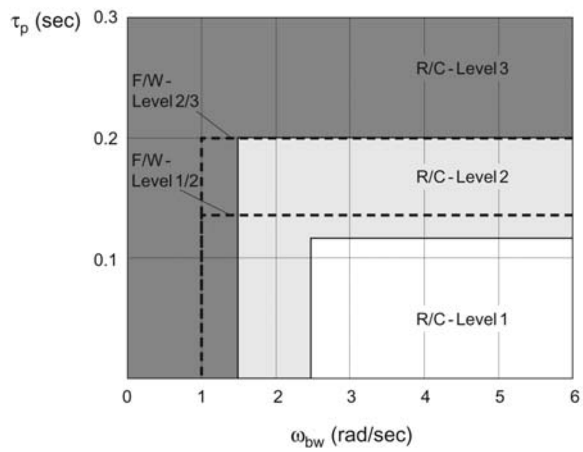


Figure 8: Comparison of the R/C and F/W roll axis bandwidth criterion

For this particular case the bandwidth/phase delay format was found to apply to both flight modes and was therefore selected for further evaluations. A future CTR is expected to be a highly augmented aircraft embodying various response types, tailored to mission and operational demands. The bandwidth/phase delay criteria which is considered to be insensitive to different response types ([10],[19]) is therefore particularly suitable.

By pure analysis however it is not possible to answer the key questions like, for example, is it possible to co-locate the rotorcraft and fixed-wing boundaries? or, how do the conversion mode dynamics fit into this framework? Answering this last question within the "Adaptation of Conversion Criteria" step in the Figure 3 process requires the support of pilot-in-the-loop experiments.

In order to create a complete HQ manual, comprehensive simulations and flight tests are necessary. This was outside of the scope of the RHILP project and will be left for future research projects. However, some critical issues were judged to be so important that limited piloted tests could usefully close the gaps or inform the compatibility solutions. These tests are being conducted within the RHILP project at the University of Liverpool’s HELIFLIGHT facility. The aircraft configuration selected was based on the Bell XV-15 research aircraft [18].

HELIFLIGHT in the University of Liverpool

HELIFLIGHT [6] is a PC-based re-configurable flight simulator developed by the Motionbase/ART partnership, with five key components that are combined to produce a relatively high-fidelity system, including:

- selective fidelity, aircraft-specific, inter-changeable flight dynamics modeling software (**FLIGHTLAB**) with a real time interface,
- 6 degree of freedom motion platform,
- four axis dynamic control loading,
- a three channel collimated visual display for forward view, plus two flat panel chin windows, providing a wide field of view visual system,
- re-configurable, computer-generated instrument panel and head up displays.

A view of the cockpit pod is shown in Figure 9.

The software at the center of operation of the facility is FLIGHTLAB [20], providing a modular approach to developing flight dynamics models, and enabling the user to develop a complete vehicle system from a library of predefined components. FLIGHTLAB also provides a range of tools to assist in the generation of highly complex, non-linear, multi-body models. To aid the generation and analysis of flight models, three Graphical User Interfaces (**GUIs**) are available: **GSCOPE**, FLIGHTLAB Model Editor (**FLME**) and Xanalysis.

Figure 9: HELIFLIGHT at the University of Liverpool

A schematic representation of the desired model can be generated using a component-level editor called GSCOPE. Components are selected from a menu of icons, which are then interconnected to produce the desired architecture and data is assigned to the component fields. Figure 10 shows the collective and lateral stick control system for the FXV-15.

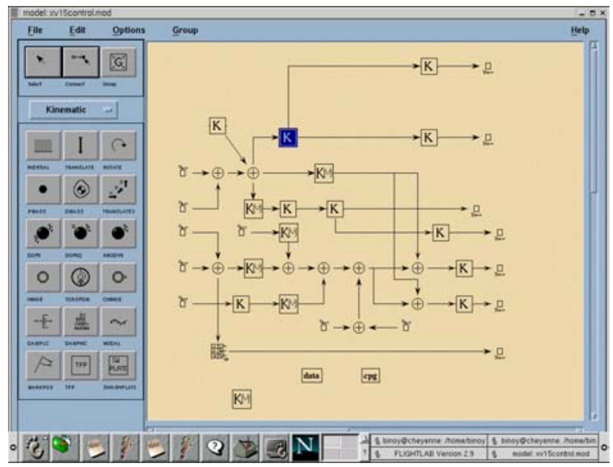


Figure 10: GSCOPE representation of the FXV-15 collective lever and lateral stick channel

FLME is a subsystem model editor allowing a user to develop models from higher level primitives such as rotors and airframes. Models are created hierarchically, with a complete vehicle model consisting of lower level subsystem models, which in turn are collections of primitive components. This is the Model Editor Tree, which puts all the predefined helicopter subsystems into a logical "tree" structure. A model tree for the FXV-15 rotorcraft is shown in Figure 11.

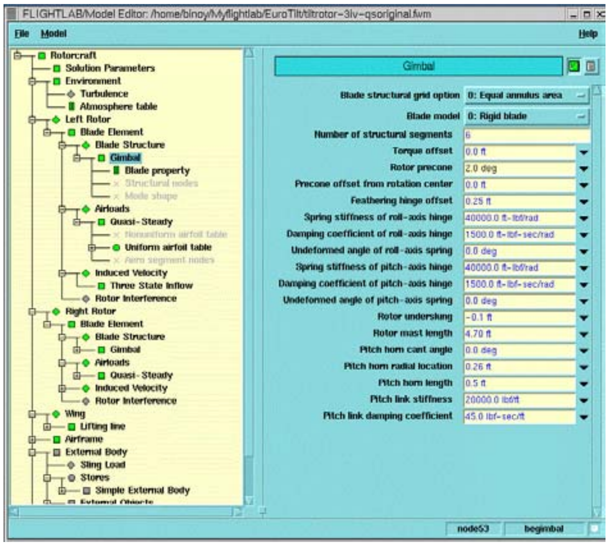


Figure 11: FLME expanded tree view and data input for the FXV-15 aircraft

Prior to running a real-time simulation, the model generated using the above tools can be analyzed using Xanalysis. This GUI has a number of tools allowing a user to change model parameters and examine the dynamic response, stability, performance and Handling Qualities of design alternatives (see Figure 12).

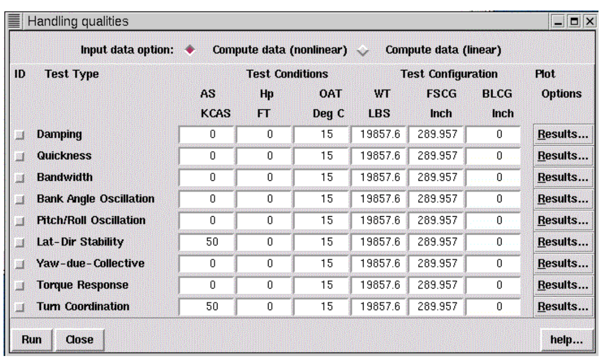


Figure 12: FLIGHTLAB Handling Qualities toolbox

The flight dynamics models form a vital part of a flight simulator, the detail of which will ultimately define the fidelity level of the simulation. Of equal importance is the environment into which a pilot is immersed. HELIFLIGHT uses a Maxcue 600 series motion platform together with Optivision collimated displays and Loadcue electronic control loading systems to create the virtual flying experience.

Three collimated visual displays are used to provide infinity optics for enhanced depth perception, which is particularly important for hovering and low speed flying tasks. The displays provide 135° horizontal by 40° vertical field of view which is extended to 60° vertical field of view using two flat screen displays in the footwell chin windows (see Figure 13). The displays have a 1024 x 768 pixel resolution, refreshing at 60Hz giving excellent visual cues when displaying a texture-rich visual database.

Figure 13: Typical pilot's eye view in HELIFLIGHT capsule

The sensation of motion is generated using the Maxcue platform, which has a significant movement envelope (see Table 2). The motion system is a six-axis, electrically actuated platform with a position resolution of 0.6μm. To ensure that the pilot does not receive "false" cues, the motion cueing algorithms can be tuned to correspond with the desired vehicle performance. To maximize the usable motion envelope, the drive algorithms feature conventional washout filters that return the simulator to its neutral position at acceleration rates below the perception thresholds, after a period of simulator motion.

Table 2: HELIFLIGHT motion envelope

Motion Parameter	Range [a]
Heave Range	500 mm
Peak Heave Velocity	± 0.6 m/sec
Peak Heave Acceleration	± 0.6 g [b]
Surge Range	930 mm
Peak Surge Velocity	± 0.7 m/sec
Peak Surge Acceleration	± 0.6 g
Sway Range	860 mm
Peak Sway Velocity	± 0.7 m/sec
Peak Sway Acceleration	± 0.6 g
Roll Range	± 28°
Peak Roll Rate	40°/sec
Pitch Range	+34°/-32°
Peak Pitch Rate	40°/sec
Yaw Range	± 44°
Peak Yaw Rate	60°/sec

[a] All motions are stated from mid heave with all other axes neutral. By coupling one or more motions, a larger range may be obtained.
[b] Measured over whole motion envelope. Heave accelerations of +1g/-2g may be produced near the centre of the motion envelope.

An important aspect of the overall fidelity of the system is the amount of delay or latency present. In HELIFLIGHT the flight dynamics model is running typically at 200Hz producing a 5msec delay. A delay of less than 16msec occurs as the output from the flight model is converted to produce a corresponding change in the simulator motion system. Latency in the visuals occurs due to the terrain texture density being displayed and varies with the specification of the graphics card. Currently this causes delays of between 16 - 30msec in the re-drawing of the terrain. In addition to this, the monitors are refreshing at 60Hz. Overall transport delay between pilot stick and motion base and visual response is estimated to be below 50msec.

HELIFLIGHT was commissioned for research and teaching use at the University of Liverpool in September 2000. During its first 18 months of operation the facility has been used extensively in a variety of research projects [6], undergraduate projects and laboratory classes as well as allowing students to experience a range of different handling characteristics.

FXV-15: The Baseline HQs Test Aircraft

As part of the activities of the RHILP Handling Qualities and Structural Load Alleviation work packages, Liverpool developed a FLIGHTLAB model of the Bell XV-15 aircraft (see Figure 14) based on published data [21]; this model is designated as the FXV-15.

Figure 14: XV-15 aircraft in conversion mode

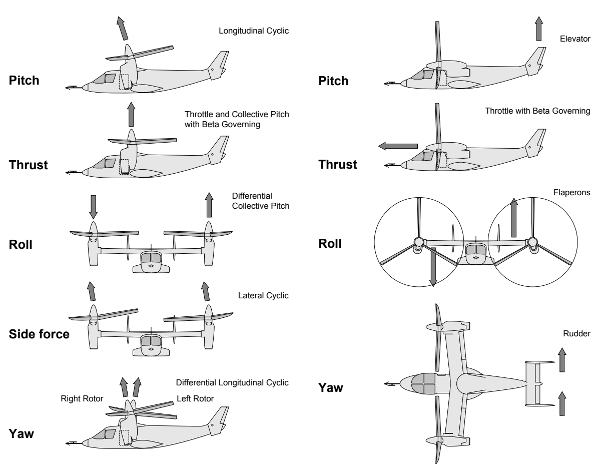
The main aeromechanics features in the FXV-15 are listed below;

- 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 in the FXV-15 implementation,
- 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 segments are used with the outer left and right segments immersed in the rotor slipstream and

2 inner sections assumed to be unaffected by the rotor wake,

- Rotor-wing-empennage interaction 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 rotor image system.

For reference, the XV-15 controls operate as shown in Figure 15.

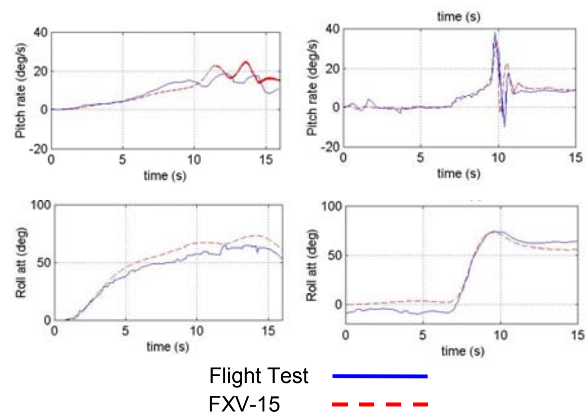


(a) R/C mode (b) F/W mode

Figure 15: XV-15 controls

In rotorcraft mode, pitch control is achieved through longitudinal cyclic, roll control through differential collective (note that lateral cyclic is also shown on Figure 15, although this is not commanded by the pilot with lateral stick), yaw through differential longitudinal cyclic and heave through combined collective. In conversion mode, the rotor controls are gradually blended out. The fixed wing control surfaces, ailerons, elevators and rudder operate in all modes. In airplane mode the rotor controls are locked out.

The limited published test data ([21],[22]) on this aircraft was used for validation and to generally build confidence in the modeling and simulation activity. Comparison with the test data have included trims, stability and response to control inputs. Figure 16 shows the FXV-15 behavior in response to a 1.8g turn in rotorcraft mode (85kts) and 4g turn in fixed-wing mode (235kts), compared with flight test data [22].



(a) rotorcraft mode (b) fixed-wing mode

Figure 16: Comparison of the FXV-15 with flight test data [22]

The comparisons are good and give confidence that the basic flight dynamic characteristics of the aircraft have been correctly modeled in FLIGHTLAB. Most of the testing to date has been confined to flight in rotorcraft and conversion modes, at hover/low speed and in forward flight in the conversion corridor as shown in Figure 17.

The RHILP HQs Trial Series

The FXV-15 has been flown in a series of Handling Qualities Trials (**HQTs**) on the HELIFLIGHT facility to set a baseline referenced to an existing aircraft, and to attempt to fill the HQs gaps and address the compatibility issues. To date 4 trials have been conducted or are planned, with 3 test pilots participating;

- HQT_1 (April 2001); low speed maneuvers in rotorcraft mode including effects of pilot aggressiveness,
- HQT_2 (August 2001); mid speed maneuvers in rotorcraft and conversion modes, including effects of pilot aggressiveness,
- HQT_3 (December 2001); mid speed maneuvers in conversion mode, including effects of varying attitude bandwidth and phase delay,
- HQT_4 (April 2002); mid-high speed maneuvers in fixed-wing mode, including effects of pilot aggressiveness.

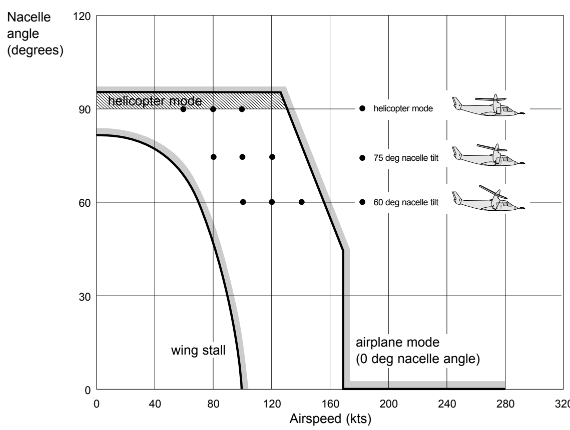


Figure 17: The XV-15 conversion corridor [18]

During HQT_1, the pilots flew what we describe as compressed missions, comprising a contiguous sequence of the full set of MTEs. The pilots were required to comment on the level of realism, the piloting techniques, mission constraints, performance requirements and general suitability/criticality of the MTEs as the basis for the HQs developments. The pilots also evaluated the Handling Qualities test Maneuvers as clinical representations of the MTEs. Each HQM was flown to develop/verify the performance standards, levels of aggressiveness and the adequacy of simulation cueing arrangements. In this way the HQMs were defined in a manner that would exercise the full range of Handling Qualities of interest. As noted earlier, there were two major objectives of the trials; first to understand and define what constitute Level 2 HQs and, second, to establish the Level 2/3 boundaries and particularly any HQs cliff edges.

In this paper we focus on two aspects of the results from the HQT series. The first concerns flight in rotorcraft and conversion mode and the impact of increasing speed on the ability to fly tightly defined maneuvers close to the ground. The second concerns the impact of changing attitude bandwidth on the ability to fly the same constrained task. The HQTs have examined both roll and pitch axis HQs but in this paper we present only the results for the roll tests.

The FXV-15 was flown with standard SCAS engaged for the majority of the trials. As noted earlier, the XV-15 SCAS features rate damping in 3-axes plus a degree of response quickening, particularly in the roll axis. Generally this configuration gave Level 1 Handling Qualities at low levels of aggressiveness, while the SCAS-off configuration gave Level 2 HQs at the same conditions. Any attempt to fly the SCAS-off configuration at even moderate levels of aggressiveness led to HQs degrading rapidly, particularly in rotorcraft mode, largely as a result of the low control power and bandwidth in roll and yaw. It is likely that the core SCAS system (i.e. 10^{-9} system) of a civil tilt rotor aircraft will have sufficient augmentation functions to confer Level 2 Handling Qualities up to moderate levels of pilot aggressiveness. Higher levels of augmentation, designed to 10^{-5} or 10^{-6} standards will then confer the Level 1 HQs throughout the operational envelope. In this context, we interpret the XV-15 SCAS as typical of a core system.

Handling Qualities in the Roll-Step HQM

The 9 test configurations flown in the Roll-Step are identified in Figure 17 and cover the speed range from 60 to 140kts. At the higher speeds the aircraft is operating close to the conversion corridor boundary - the outer adequate speed boundary is within 5kts 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 rotorcraft mode. For example proverse roll-yaw coupling is introduced through differential collective control, although the 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. Once again the gearing between elevator and helicopter controls becomes an issue.

Roll attitude quickness

While new Handling Qualities issues emerge during flight in conversion mode, the requirements on roll axis response can, in principal, be analyzed in terms of the helicopter criteria defined in ADS-33E. The response quickness, for example, was introduced into ADS-33 as an agility parameter across the moderate amplitude range. For roll, quickness is defined for attitudes between 10° and 60°. Figure 18 illustrates the ADS-33 Level 1/2/3 boundaries and included are the configuration points for the FXV-15 in rotorcraft mode (90° nacelle angle, 60kts) and for two different conversion mode configurations (75° nacelle angle, 100kts – 60° nacelle angle, 140kts).

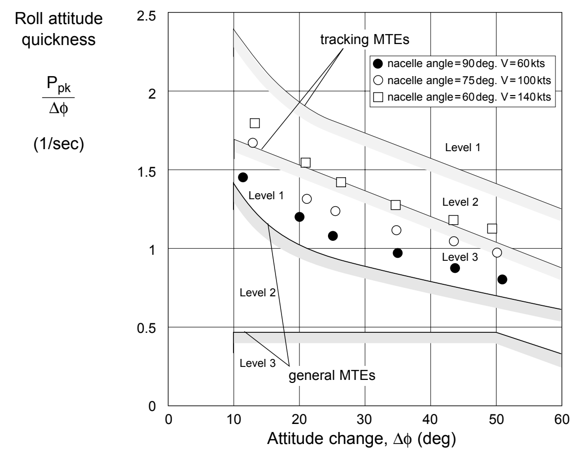


Figure 18: Roll attitude quickness for the FXV-15 in rotorcraft and conversion modes

Quickness is derived as the ratio of peak rate to attitude change following a pulse control input in lateral stick. It is closely related to the time to achieve a given roll angle and at large amplitudes conforms with control power criteria while at small amplitude, quickness conforms with attitude bandwidth. The FXV-15 points on Figure 18 were derived from the FLIGHTLAB Handling Qualities toolbox and are compared with the ADS-33E boundaries for both tracking and general MTEs. According to Figure 18, the FXV-15 should be Level 1 with the performance margin increasing with decreasing nacelle tilt angle. This results from the increased control power from the combined helicopter and airplane controls for maneuvering in conversion mode. For the 60° nacelle configuration, the FXV-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.

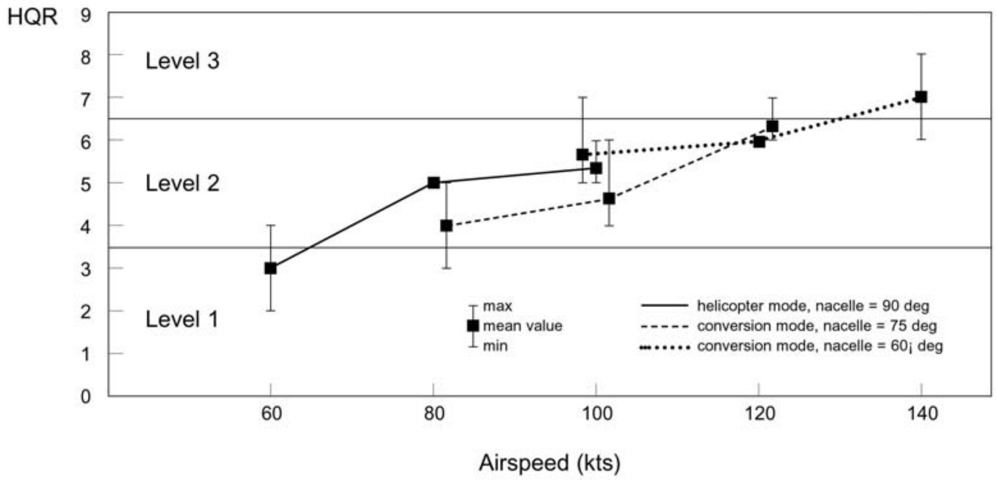


Figure 19: HQRs for the roll-step maneuver

The roll-step tests were flown by three pilots and their combined Handling Qualities Ratings (**HQRs**) are presented in Figure 19. The level of aggressiveness is increased by increasing the forward speed as shown.

With both acquisition and tracking phases, the roll-step maneuver was found to be well suited to piloted evaluations of the Handling Qualities derived from roll attitude bandwidth and phase delay changes. The line up or tracking phase task (see Figure 6), has proved to be highly dynamic and hence able to uncover any adverse aircraft-pilot couplings. The acquisition phase exercises the control power and quickness of the aircraft. Pilot comments clearly identified the suitability of this HQM also against the background of the FXV-15 inherent roll axis characteristics. Typical pilot comments include:

- Characteristics of flight path control: *"Achieving lateral position task* [through the gates] *was the main driver for roll activity."* or *"Difficult to be precise about lateral position due to roll characteristics"* or *"Control of lateral tracking was the most workload demanding"*
- Roll response predictability: "*Predictable for slow, gentle inputs. PIO prone for higher gain tasks."* or *"Predictability poor"*

After each evaluation run, the pilot completed an in-cockpit questionnaire. This captures all the critical issues of the pilot self-assessment. These include the task cues, the perceived level of aggression and task performance, the task workload, the system characteristics and finally the HQR. The pilot comments and ratings on these topics allows the engineer in the post-analysis to judge if a recorded run is valid or not with respect to the consistency between the perceived and achieved performance standards. A very high discrepancy would imply that the given rating is unlikely to accurately represent the achieved or actual performance flown. A possible cause could be the task cues; if they are not good enough to allow the pilot a proper judgement of whether he achieved the desired or the adequate performance standard or not. Normally this should not occur as the experimental design process should have ensured that sufficient task cues are available to provide a UCE 1 ([3],[7]). The pilot fatigue can also influence the perceived performance. If the pilot is in the simulator for too long without any break his ability to concentrate can deteriorate. An improperly assigned HQR will irrevocably distort the result. Such an HQR has consequently to be canceled and the run must be repeated. Besides the in-cockpit questionnaire, a much more detailed de-briefing questionnaire was applied where the pilot could comment on many other aircraft and performance issues. Due to the very intense simulation schedule however, not every evaluation run could be de-briefed in this detailed manner. The post analysis then revealed the match between the perceived and achieved performance. Figure 6 presents the performance standards of the roll-step maneuver.

Figure 19 shows the major trend to be a degradation of 1 HQR per 20kts airspeed. This is the underlying trend due to the requirement to turn more quickly as the speed increases. At 60kts the pilot has about 15seconds to roll-step the 200ft across the runway and at 120kts this time is halved. During this maneuver the pilot has to roll to generate the bank and turn rate, reverse the turn and roll out on the line to fly through the gate within ±10° roll and ±15° heading. This proved too demanding at the higher speeds and the pilot typically required 5 seconds to stabilize flight path after passing through the gate. Large sideslip perturbations were generated during the roll maneuvers and this required very close co-ordination of stick and pedal, resulting in high workload. In the Level 3 conditions, height and speed excursions during the maneuvering phase were typically just within the adequate boundary. The additional lift provided by the wing above about 100kts eased the flight path management task compared with flight at lower speeds, relieving the pilot of workload associated with fine collective adjustments and consequent speed changes.

Figure 20 shows a comparison of a typical Level 1 (60kts) with Level 3 (140kts) case. Note the different reference heights flown in the 2 cases (100ft vs. 50ft).

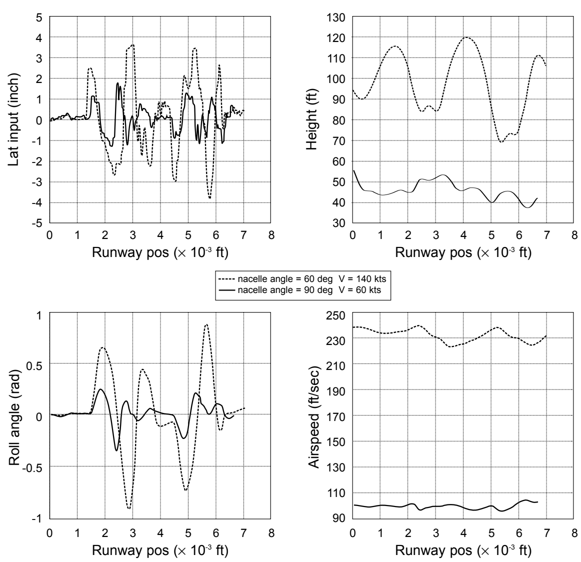


Figure 20: Comparison of Level 1 and Level 3 cases

It transpired that the quickness required to fly the acquisition phase was about 1/rad, irrespective of the forward speed or configuration. This meant that at the higher speeds, and with roll angles approaching 60° in the acquisition phase, the pilot was using close to the maximum capability of the aircraft. The HQs approach adopted by RHILP (à la ADS-33) is that there should always be a performance margin when flying maneuvers. With the current roll-step, this margin is clearly eroded at the higher speeds and the more relevant boundaries on Figure 18 appear to be those related to tracking.

The results suggest that the FXV-15 with its core SCAS is Level 2 for these maneuvers, with excursions into Level 1 and Level 3 at the lower and higher speeds respectively. Significantly, it is the tracking phase of the maneuver that caused the major piloting problems, although nearly full lateral stick was required to initiate the turns at the higher speeds when the pilot has very little time to cross the runway and line up with the gate. The emphasis on deficiencies in the stabilization phase reinforces the point that for the CTR flying the roll-step task, the relevant boundary on Figure 18 is the tracking boundary. It would be very difficult if not impossible to achieve roll quickness at the ADS-33E tracking performance with a CTR that features large prop-rotors and engines on the wing tips, however. Nevertheless, a full authority active control system would certainly be able to provide significant help to the pilot, particularly during the tracking phases. To explore the tracking issues further, HQT_3 focused on the effects of varying roll attitude bandwidth and phase delay on perceived Handling Qualities.

Roll Attitude Bandwidth and Phase Delay

The investigations of the roll attitude bandwidth and phase delay have mostly concentrated on the conversion flight mode of the CTR. The RHILP HQ-team wanted to improve their understanding of the relevance of aircraft bandwidth and phase delay as HQ parameters to flight in this unique mode and also develop answers to the questions that arose during the compatibility analysis. How can the small amplitude/high frequency response be classified? Will the aircraft respond more like a rotorcraft or more like a fixed-wing aircraft, or perhaps exhibit new characteristics that need a new criterion? The RHILP project aims to define the required standards for the Level 2 area in particular the location of the Level 2/3 boundary. Therefore a flight configuration was chosen which is clearly identified as a Level 2 tending towards the Level 3 boundary. According to Figure 19, the low-aggression (100kts case) conversion configuration with a nacelle angle of 60° fulfils this requirement. This configuration is designated the baseline configuration for the bandwidth-phase delay analysis. The 60° case is expected to be a typical loiter flight condition of a future European CTR, and is therefore of special interest.

Starting from this baseline configuration, two parameters were varied to “simulate” changes in bandwidth and phase delay. First, the roll inertia was increased and decreased with respect to the baseline configuration in order to expose any extreme roll characteristics. Second a pure time delay was introduced, affecting both the bandwidth and phase delay, to open up a wider area on the bandwidth/phase delay chart. The baseline configuration was defined as having zero pure time delay as such. The time delay adjusting screw was then opened up to about 300msec in steps of roughly 25msec. Using both parameters permits the engineer to “walk around” on the bandwidth/phase delay plane. For all tests the core SCAS in all axes remained enabled.

Roll frequency sweep tests were flown by the pilots to derive the HQ parameters, according to the ADS-33E principles [7]. In the analysis of the roll frequency-sweep data, an additional time delay of 35msec was introduced. This time delay “simulates” the flight simulator’s inherent motion latency from both visual and vestibular sources. Without this additional delay the bandwidth/phase delay points would not properly reflect the aircraft as the pilot “feels” it in the simulator.

About 15 different bandwidth/phase-delay configurations were evaluated by the 3 pilots in the simulator, amounting to almost 50 Handling Quality ratings gathered in the conversion mode. Figure 21 compares the FXV-15 data (averaged HQRs) with the ADS-33E bandwidth criteria boundaries for tracking tasks. Three levels of roll inertia with varying time delays are shown. The data suggests that for the roll axis in the conversion mode with a nacelle angle of 60° and a speed of a 100kts, the aircraft HQs resemble a helicopter when flying a roll step maneuver. Note, that the bandwidth/phase delay points in Figure 21 assume a simulator time delay of 35msec. Small errors in this assumption however are unlikely to change the general conclusions.

The presented result is a good example of how the simulation supports the RHILP approach to CTR Handling Qualities (see Figure 3), closing a considerable gap in the existing knowledge. Even though only a relatively small amount of data are available to reinforce any conclusions, one can see that no HQs cliff-edges emerged across quite a wide range of HQs configurations. Such “cliff-edges” would be noticeable by rapid deterioration of the HQs into the Level 3 region. Only further simulations and flight tests with a tiltrotor aircraft can add to the existing database and substantiate the above conclusions.

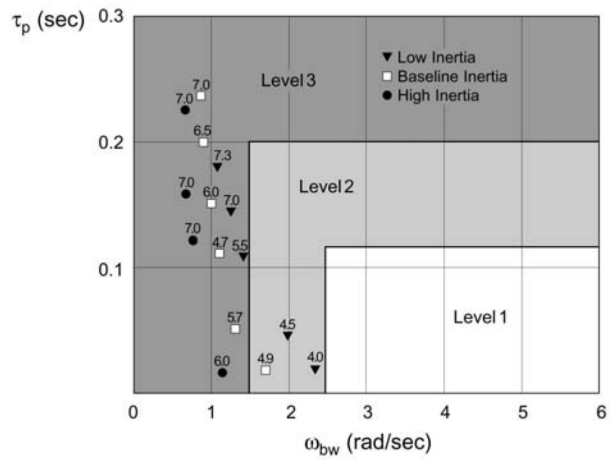


Figure 21: Comparison of FXV-15 with ADS-33E

For the sake of completeness it should be stated that during HQT_3, a small number of roll axis frequency sweeps were gathered in the conversion and rotorcraft modes. Configurations with nacelle angles and speeds at 60°/120kts and 75°/100kts, with different combinations of roll inertia and time delay, were considered. In the rotorcraft mode with the nacelles at 90° frequency sweeps were performed at 50kts and 80kts. Compared with the data presented in Figure 21, the bandwidth/phase delay values for these configurations globally fit in the overall scheme.

Conclusions

This paper has presented the first results from the Handling Qualities work package of the Framework 5 RHILP project. A step-by-step approach to the development of civil tiltrotor Handling Qualities (HQs), based on the ADS-33 systems approach, has been outlined. The methodology has developed requirements and criteria in a mission context, establishing test maneuvers from MTEs and mission phases. An extensive review of existing fixed and rotary wing HQ specifications and requirements has highlighted relevant existing criteria for validation and also identified criteria gaps. In this constructive phase of the project, support from piloted simulation trials has proved valuable and some key results have been presented in this paper. From the HQs analysis and simulation trials reported, the following observations and conclusions can be drawn:

- Suitable rotorcraft and fixed-wing aircraft HQ specifications have been identified as a basis for the development of a civil tiltrotor HQ manual.

- Gaps were exposed in these existing documents through a compatibility analysis between the rotorcraft and airplane criteria, with respect to the European civil tiltrotor and its mission. It is clear that there are no dedicated Handling Qualities criteria for tiltrotor aircraft in the public domain, particularly for the conversion flight mode.
- Maneuvers which are described as critical from a Handling Qualities standpoint have been defined for the three flight modes of the tiltrotor aircraft, including low speeds maneuvers in rotorcraft mode, take-off and approach maneuvers and loiter maneuvers in conversion mode.
- The FXV-15 (FLIGHTLAB XV-15) was developed and flown in a series of HQ trials on the Liverpool HELIFLIGHT simulator to establish a baseline of HQ data. This forms the starting point for developing a future civil tiltrotor Handling Quality manual.
- The roll-step HQs test maneuver was designed as a suitable test maneuver for evaluating roll HQs, particularly relating to any tendency to adverse aircraft-pilot couplings, in all three modes.
- The FXV-15 test aircraft, flown in the roll step with SCAS engaged, exhibited Handling Qualities across all 3 HQ levels depending on the speed flown, the nacelle angle and the bandwidth/phase delay values. With respect to speed changes, HQs degraded from Level 1 to Level 3 at the rate of approximately 1 HQ rating per 20kts.
- Attitude quickness was used to define the roll performance (agility) of the aircraft across the moderate range of attitude changes (10° - 60°) exercised in the roll-step. There was a positive HQ margin above the Level 1/2 boundary for general mission task elements (defined in ADS-33) for the aircraft in both rotorcraft and conversion modes. At the higher speeds this margin was almost completely used up by the pilot, with the suggestion that the tracking boundary may be more appropriate if this kind of maneuver is to remain critical in the civil tiltrotor envelope.
- A mid Level 2 configuration was identified as the conversion mode, with nacelle at 60°, flown at 100kts. This configuration was then used as the baseline for assessing a wide range of ω/τ values to establish the location of the Level 2/3 HQ boundary and to compare with the existing ADS-33 boundaries.
- Pilot comments generally correlated well with the location of the ADS-33 boundaries. From this first assessment of the roll bandwidth and phase delay (in the conversion mode), it appears that a civil tiltrotor is well characterized according to the ADS-33E HQ boundaries for helicopters in forward flight.

The RHILP project is continuing to develop HQ criteria through analysis and piloted simulation. The first evaluations in fixed-wing mode are scheduled to take place in Spring 2002, with special attention paid to pitch maneuvers, the impact of flight altitude on Short Period and Dutch Roll damping and HQs at low speed. The complementary work package on structural load alleviation has already identified the critical loads and associated maneuvers where active control can usefully provide the required alleviation. This activity will also examine the impact of load alleviation functions on HQs, and develop a multi-disciplinary approach to optimization. The EUROTILT civil tiltrotor configuration is now flying on both SPHERE and HELIFLIGHT facilities and the intention is to focus the activity on this aircraft during the final year of the project, in preparation for the final demonstration on SPHERE in Spring 2003.

Within the European Commission tiltrotor critical technology programs, ACT-TILT commenced in late 2001. This project will build on the RHILP results but aims to develop control augmentation to confer Level 1 Handling Qualities throughout the operational flight envelope, including structural load alleviation and carefree handling functions. This emphasis on developing excellence in Handling Qualities for a future European civil tiltrotor reflects the importance Handling Qualities have to safety, public acceptability and ultimately commercial viability.

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