

Flight Simulation in Academia

HELIFLIGHT in its First Year of Operation

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Abstract

The challenges of helicopter simulation are being tackled across a broad front as technology is developed to meet the needs of Industry. Traditionally the most powerful driver has been the training community and this is likely to continue for some time as simulation technology advances at increasing pace, raising fidelity standards. The development of PC-based simulation technologies is providing a significant spur in this development and lowering the cost, making complete simulation systems of reasonably high fidelity available to smaller organisations. This paper describes the first year of operation with such a system at the University of Liverpool – HELIFLIGHT – developed by the Motionbase plc/ART Inc. partnership. With its full motion, wide field-of-view visuals, programmable force feel system and the comprehensive FLIGHTLAB modelling environment, we describe the system as high fidelity and the first year of utilisation has shown that such a facility is fit for extensive use in a variety of handling qualities and pilot-vehicle technology research and teaching. From a year of many highlights, the EU-funded programme to develop handling qualities for a civil tilt rotor aircraft is selected to demonstrate the capability of the HELIFLIGHT system.

1 INTRODUCTION

The essence of flight simulation is in creating an illusion of reality for the pilot to experience. The quality or 'fidelity' of this illusion will ultimately determine the boundary for what can and cannot be accomplished in terms of read-across to the real world. Fidelity thus determines the fitness for purpose. Simulation technology is advancing at such a pace that this boundary is expanding rapidly, opening up new possibilities for training, the assessment of flight technologies and in design. Until recently high-fidelity simulation has only been affordable to large corporations, but new PC-based modelling and visual systems are bringing costs down and a new generation of flight simulators are becoming affordable by smaller research and training organisations, including academia.

The requirement specification for the Flight Simulation Laboratory at The University of Liverpool was drawn up and published in October 1999. The facility was to have a motion capability, reasonably wide field-of-view, programmable force-feel and a modelling environment compatible with the comprehensive FLIGHTLAB system running under Linux on a PC-based architecture. Very few requirements were quantified precisely as the limited budget did not allow for extensive development and it was expected that solutions

based largely on existing systems would be offered. The requirement to be able to simulate both rotary and fixed-wing aircraft was mandatory, however. The system was to be operational in a purpose-built laboratory by the beginning of the academic year 2001-2. From the 5 different solutions offered, the Motionbase plc/Advanced Rotorcraft Technology Inc. HELIFLIGHT system was selected as providing the best solution in terms of the ratio of technical quality to price. The system was first installed in Liverpool in June 2001 and a series of commissioning activities took place over the summer including a piloted assessment conducted by an ETPS-trained test pilot. At the beginning of the 2001-2 academic year, the system was fully operational and scheduled to be utilised in 4 funded research projects, 6 undergraduate projects and an extensive teaching programme including laboratory classes. These activities would be the base from which the Flight Science and Technology Group at Liverpool would develop experience with the unique facility, developing best practices for the use of simulation in research and teaching in academia. This paper describes the activities of the first year of operation of HELIFLIGHT. Section 2 describes the technologies involved in HELIFLIGHT – its motion and visual sub-systems and the FLIGHTLAB modelling environment. Section 3 draws on some of the research and teaching experiences,

particularly the development of tilt rotor handling qualities and some of the undergraduate projects underway. Section 4 discusses other activities and future plans and the paper is drawn to a close with some concluding remarks in Section 5.

2. HELIFLIGHT – the Technology

2.1 General

The main research and simulation tool of the Flight Simulation Laboratory (FSL) at the University of Liverpool is the HELIFLIGHT system. HELIFLIGHT is a relatively low cost, turnkey and re-configurable flight simulator developed by the Motionbase/ART partnership, with five key components that are combined to produce a high fidelity system, including:

- selective fidelity, aircraft-specific, interchangeable flight dynamics modelling software (FLIGHTLAB) with a real time interface (PilotStation),
- 6 degree of freedom motion platform (Maxcue),
- four axis dynamic control loading (Loadcue),
- a three channel collimated visual display for forward view, plus two flat panel chin windows, providing a wide field of view visual system (Optivision), each channel running a visual database,
- a re-configurable, computer-generated instrument display panel and head up display.

HELIFLIGHT takes advantage of the increased processing power of the current generation of PCs and the advent of PC-based graphics accelerator boards to produce a PC-based visual system and PC-based processing of sophisticated dynamics models in real time.

A schematic of the HELIFLIGHT configuration is shown in Figure 1.

The main host is a dual processor Pentium III 750 MHz PC running Linux. One processor runs FLIGHTLAB and PilotStation, whilst the second processor drives the control loaders via a NextMove PCI card. In addition, this machine acts as both a file server and a DHCP server for other hosts. Using two Ethernet cards (one to access the Internet and the other to access the HELIFLIGHT network via a hub) isolates the local area network from the Internet, maximising throughput and security. There are seven other hosts (Pentium III 650 MHz PCs) running Windows 98. These hosts in turn run the motion base (via a NextMove ISA card), the two chin

windows, the three forward Out the Window (OTW) displays and the instrument display. The HUD on OTW centre can be toggled on/off. All the Windows computers are equipped with 3D Voodoo 3 graphics cards that send signals to the cockpit displays and 2D graphics cards that are multiplexed to a single monitor (not shown in Figure 1 to simplify the diagram). The keyboard and mouse of each computer is also multiplexed allowing each Windows computer to be controlled from a single station.

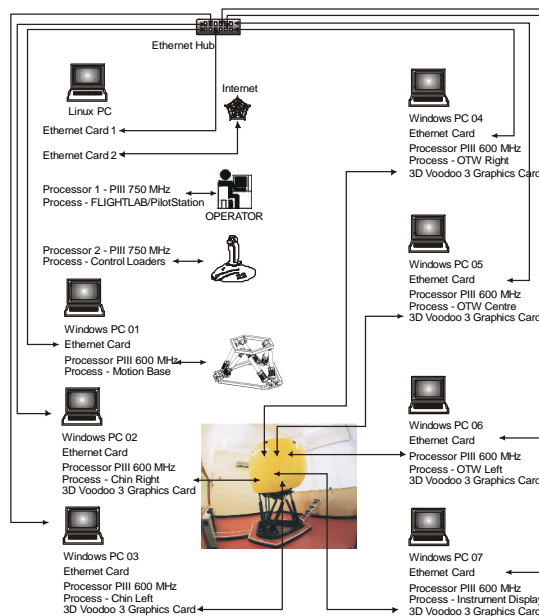


Figure 1 Schematic of HELIFLIGHT Configuration

The FSL has two main areas: the simulator control room and the cockpit pod room. An authorised simulator operator controls the real-time operation of the simulator from the main host running PilotStation in the control room and interacts with the pilot in the cockpit room using a two-way communication system. From this viewpoint, the operator can observe both the motion of the cockpit and also the displays which are duplicates of those present in the capsule (OTW left, right, centre and chin left/chin right), see Figure 2.

During real time operation, the operator is responsible for ensuring the safe operation of the motion base and can override a pilot's inputs in the event of loss of pilot control. A lap belt is worn by the pilot during motion and is part of the safety interlock system that incorporates electromagnetic door releases on the gull wing capsule door and a cockpit room door interlock. Emergency stop buttons are available to both the pilot and the operator. In the case of an emergency or power

failure, the simulator parks returning the capsule safely to its down position and the cockpit pod door opens.



(a) Simulator Control Room



(b) Simulator Cockpit Room and Capsule

Figure 2 Flight Simulation Laboratory at The University of Liverpool

Throughout a sortie, a video record is taken of OTW Centre generating both a visual and audio log of the mission for use in post mission analysis. PilotStation also has a data logging function, allowing a range of aircraft performance parameters, flight model outputs and pilot control inputs to be captured for subsequent processing.

2.2 FLIGHTLAB

The software at the centre of operation of the facility is FLIGHTLAB, a proprietary software package produced by Advanced Rotorcraft Technology Inc (Ref 1). FLIGHTLAB provides a modular approach to developing flight dynamics models, producing a complete vehicle system from a library of predefined components. In particular, FLIGHTLAB provides a range of tools to assist in the rapid generation of highly complex, non-linear, multi-body models, reducing the effort required for computer coding that are typical of most flight simulation activities. Although

FLIGHTLAB was originally developed for rotorcraft simulations using Blade Element Models, it can be used as a simulation tool for fixed wing aircraft.

To aid the generation and analysis of flight models, three graphical user interfaces (GUIs) are available: GSCOPE, FLIGHTLAB Model Editor (FLME) and Xanalysis.

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 3 shows the collective and lateral stick control system for the FXV-15 (see Section 3). When the representation is complete, the user selects the script generation option and a simulation script in FLIGHTLAB's Scope language is automatically generated from the schematic. Scope is an interpretive language that uses MATLAB syntax together with new language constructs for building and solving non-linear dynamic models.

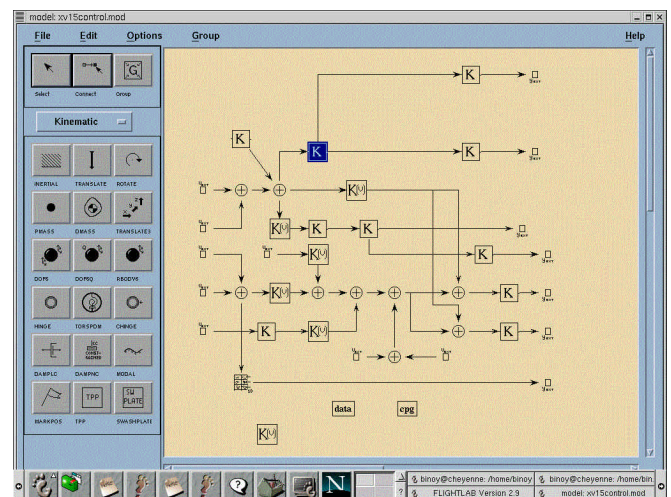


Figure 3 GSCOPE representation of the FXV-15 collective lever and lateral stick channel

FLME is a subsystem model editor allowing a user to develop models from higher level primitives such as rotors and airframes. Typically a user will select and configure the subsystem of interest by inputting data values and selecting options that determine the level of sophistication providing a selective fidelity modelling capability, maximising computational efficiency. 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. This tool facilitates configuration

management by keeping all models in a predefined structure while allowing the engineer a great deal of flexibility in defining the individual aircraft structure and subsystems. A model tree for the FXV-15 rotorcraft is shown in Figure 4.

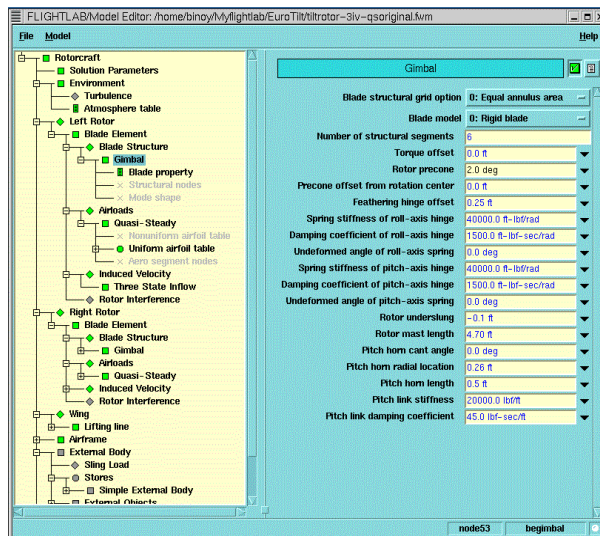


Figure 4 FLME Expanded Tree View and Data Input Table for the FXV-15 Aircraft

Prior to running a real-time simulation, the model generated using the above tools can be analysed using Xanalysis. This GUI has a number of tools allowing a user to change model parameters and examine the dynamic response, static stability, performance and handling qualities characteristics of design alternatives (Figure 5). Additional tools are available to generate linear models, perform eigen-analysis, time and frequency response analyses and control system design. The non-linear model may also be directly evaluated through utilities that support trim, static equilibrium, and time and frequency response.

The real time simulation is co-ordinated using PilotStation. PilotStation controls and interfaces image generation for OTW, instrument and head up displays with the control loaders, motion base and flight dynamics models generated using FLIGHTLAB in real time. Typically a simulation is running at 200 Hz. During a simulation, a circular buffer is continuously updated containing pre-defined output variables. Selecting the “History” option makes the buffer accessible to the operator, which can be plotted or saved for off-line analysis. The operator console can be used to modify vehicle configuration and flight conditions and initiate faults, e.g. tail rotor failure, on-line.

The image shows the Handling Qualities Toolbox GUI. It features a table with columns for ID, Test Type, AS, Hp, OAT, WT, FSCG, BLCG, and Plot Options. The table lists various test types such as Damping, Quickness, Bandwidth, Bank Angle Oscillation, Pitch/Roll Oscillation, Lat-Dir Stability, Yaw-due-Collective, Torque Response, and Turn Coordination. Each test type has corresponding numerical values for AS, Hp, OAT, WT, FSCG, and BLCG. The GUI also includes input data options for 'Compute data (nonlinear)' and 'Compute data (linear)', and buttons for 'Run', 'Close', and 'help...'.

ID	Test Type	Test Conditions			Test Configuration		Plot Options	
		AS KCAS	Hp FT	OAT Deg C	WT LBS	FSCG Inch		BLCG Inch
<input type="checkbox"/>	Damping	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Quickness	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Bandwidth	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Bank Angle Oscillation	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Pitch/Roll Oscillation	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Lat-Dir Stability	50	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Yaw-due-Collective	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Torque Response	0	0	15	19857.6	289.957	0	Results...
<input type="checkbox"/>	Turn Coordination	50	0	15	19857.6	289.957	0	Results...

Figure 5 FLIGHTLAB Handling Qualities Toolbox

2.3 Immersive Pilot Environment

The flight dynamics models are an important 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 supplied by Motionbase plc to create a virtual flying experience.

A pilot will derive information about the vehicle behaviour from a number of sources. The basic mechanisms are visual perception, perception through the vestibular system of the inner ears and perception through the proprioceptors distributed throughout the body. Each of these mechanisms provides important information or “cues” to the pilot. Visual perception is the human’s only means of directly sensing one of the primary motion cues - translational speed. In the vestibular system, the semi-circular canals detect angular velocity and acceleration and the otholiths detect linear acceleration. Joint position and muscle effort is detected mainly by the proprioceptors. For a compelling simulation the cues for these mechanisms must be included and activated in a positive manner.

Three collimated visual displays (Figure 6) 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 (Figure 7). The displays have a 1024 x 768 pixel resolution, refreshing @ 60 Hz giving excellent visual cues when displaying a texture-rich visual database (Figure 8). Visual cues dominate when vestibular motion cues are not present or detectable and are exploited when dealing with the limited range of motion platforms.

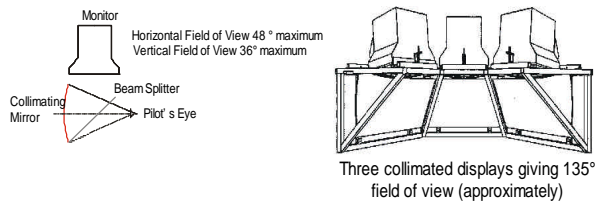


Figure 6 Collimated Display System in the HELIFLIGHT

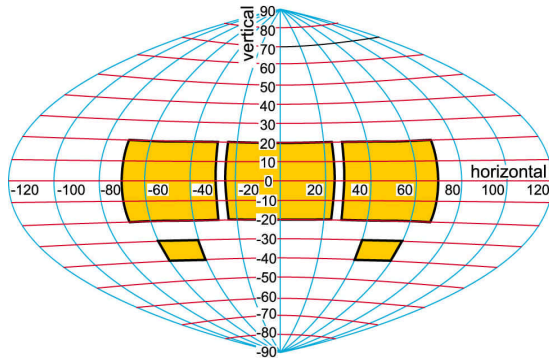


Figure 7 Outside World Field of View in HELIFLIGHT Simulator



Figure 8 Typical Pilot's Eye View in HELIFLIGHT Capsule

The capsule has a main instrument panel that can be easily reconfigured to represent displays from different aircraft presented on a flat screen monitor. The HUD is displayed in OTW Centre and contains an attitude indicator, vertical speed indicator, airspeed and altitude indicator and has a "hover box" to aid helicopter control at low speed.

The sensation of motion is generated using the Maxcue platform, which has a significant movement envelope (Table 1).

Motion Parameter	Range
Heave Range	500 mm ¹
Peak Heave Velocity	± 0.6 m/s
Peak Heave Acceleration	± 0.6 g ²
Surge Range	930 mm ¹
Peak Surge Velocity	± 0.7 m/s
Peak Surge Acceleration	± 0.6 g
Sway Range	860 mm ¹
Peak Sway Velocity	± 0.7 m/s
Peak Sway Acceleration	± 0.6 g
Roll Range	± 28°
Peak Roll Rate	40°/s
Pitch Range	+34°/-32°
Peak Pitch Rate	40°/s
Yaw Range	± 44°
Peak Yaw Rate	60°/s

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

Table 1 HELIFLIGHT Motion Envelope (Ref 2)

This is a six-axis, electrically actuated platform with a position resolution of 0.6mm. The human visual system is relatively slow to detect changes in speed, compared with the vestibular system, which is much quicker to react to accelerations. As a result, certain tasks may be difficult to perform without motion cues, in particular helicopter hovering. To ensure that the pilot does not receive "false" cues, the motion cueing algorithms can be tuned to correspond with the desired vehicle performance. The parameters are accessible in a configuration file, which can be made aircraft specific. A major limitation with motion platforms is the stroke available. To maximise 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.

Pilots can gain significant information about the behaviour of the aircraft by the feel and position of the controls. HELIFLIGHT uses Loadcue electric control loaders for the three primary pilot helicopter inceptors: cyclic, collective and pedals. The collective lever also hosts one button and one switch; the cyclic stick has several switches for various functions associated with PilotStation (e.g. run/pause, trim release). The HELIFLIGHT capsule contains two secondary controls - a joystick and a throttle lever. All of the controls, buttons and switches are configurable, e.g. the hat button on the cyclic controls nacelle tilt in the FXV-15 and the collective button is configured as a

brake for the undercarriage wheels on the Grob 115 Tutor fixed wing aircraft model. Digital control of the stick gradient and control position is carried out with a resolution of 2.5 °m. Such accuracy allows a pilot to utilise the force trim release feature to zero control forces at the trim position. The force feel characteristics are re-configurable through software to obtain an aircraft specific control system.

Humans associate some indirect cues with movement and the general sensation of flying. Vibration and audio cues can contribute significantly to the realism of the simulation. Aircraft specific noise is played through two loud speakers in the HELIFLIGHT cockpit to provide some general audio cues to the pilot. Whilst this is currently implemented at a fairly basic level in HELIFLIGHT (noise does not change with aircraft attitude, speed, engine loading), it is possible to implement an audio cue environment, reacting to variables output from the flight model. Vibration can be detected directly through the motion platform driven by variables in the model. A low frequency audio actuator is mounted under the floor of the capsule, directly beneath the pilot. This can transmit sounds of frequency 20 - 100 Hz into the floor of the capsule to provide vibration or impact cues.

An important aspect of the overall fidelity of the system is the amount of delay or latency present. The latency is produced by the transport delays in the transfer of information between the various components of the simulator, from the control inputs to the flight model outputs through the motion base and the visual system to the pilot and back through to the flight model via the pilot's controls. If the degree of latency is high, the pilot is likely to notice a lag between an input control command and perceived response of the system. This can seriously affect perceived handling particularly for tracking tasks. In HELIFLIGHT the flight dynamics model is running typically at 200 Hz producing a 5 ms delay. A delay of less than 16 ms occurs as the output from the flight model is converted to produce a corresponding change in the simulator motion system. The graphics cards receive a signal broadcast across the HELIFLIGHT network near the start of each time frame. However, 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 – 30 ms in the re-drawing of the terrain. In addition to this, the monitors are refreshing at 60 Hz. Finally, the Loadcue system introduces a potential 5 ms delay into the system. Overall transport delay between pilot stick and motion base and visual response is estimated to be below 50ms.

Creating the illusion of reality for a pilot requires a combination of high-fidelity cueing devices that work together in synergy. HELIFLIGHT, with its FLIGHTLAB core, is one of a new-generation of flight simulators that offers such high-fidelity in re-configurable form, ideally suited to the research and education needs of academia. During its first year of operation at The University of Liverpool, the facility has been extensively used in a variety of research projects, undergraduate projects and laboratory classes as well as allowing students to experience a range of different handling characteristics. In the next section we describe some of the highlights from this first year of operation.

3 HELIFLIGHT in its First Year

On June 29 2001, HRH the Duke of York officially opened the Bibby Flight Simulation Laboratory at The University of Liverpool. During the proceedings, HRH flew the initial leg of a mock search and rescue mission, developed to evaluate the handling qualities of a civil tilt rotor aircraft. The Prince took off, accelerated out to 110kts and proceeded to convert, achieving full conversion into airplane mode at 180kts and accelerated out to 250kts before re-converting into helicopter mode, decelerating and landing at the rendezvous area. The success of this celebrated demonstration reflects the considerable effort expended on modelling and simulation fidelity in developing the HELIFLIGHT facility. Other highlights of the first year's operation have been the successful creation of a simulation of the Grob 115 Tutor, the RAF's new basic trainer. The simulation was developed by 2 undergraduate students using data provided by the manufacturer. As part of the assessment, pilots from the University's Air Squadron flew the simulation to compare with the flight characteristics of the actual aircraft. The students prepared laboratory scripts defining the test objectives and procedures, data capture and analysis. The intense interactions between students and pilots during this 4-hour session provided a major learning experience. Another student required a test pilot to evaluate feed-forward control concepts designed to enhance the agility of a helicopter when performing low speed manoeuvres.

HELIFLIGHT provides a close-to-real experience for students developing their project ideas. Two students are designing stability and control augmentation systems that recover the stability of helicopters that have been deliberately degraded to improve agility. They are working to the design standard ADS-33 (Ref 3) and are designing to achieve a sufficient performance margin to ensure Level 1 handling qualities when the pilot flies

manoeuvres at moderate to high levels of aggressiveness. The test pilot will ultimately determine if they have been successful.

In all the uses of HELIFLIGHT, a disciplined approach to experimental design, test procedures and operational context, communication protocols, data capture and analysis, is proving critical to preserving the illusion of a flight test environment. These aspects, and many others, make up what are considered to be best practices in using simulation in an academic environment. For the academic community, the most challenging applications of simulation are in research into flight technologies at the pilot-aircraft interface and associated handling qualities. In the following sub-section we describe results from one such applications from the first year in HELIFLIGHT.

3.1 Civil Tilt Rotor Aircraft Handling Qualities

In March 2000, the first of a series of EU-funded (Framework V) programmes was launched to reduce the risk for the critical technologies in a future civil tilt rotor aircraft (CTR). The goals of the RHILP project (Rotorcraft Handling Interactions and Loads Prediction) were: to establish handling qualities criteria for the aircraft plus a core stability and control augmentation system, improve modelling and understanding of low speed aerodynamic interactions and to define the options for the active control of structural load alleviation (Ref 4). With Eurocopter as the project leader, the team includes DLR, NLR, CIRA, ONERA and The University of Liverpool. The handling qualities activity is focussed in Work Package 1 and, during the first year, the team constructed a methodology and criteria set that would be usable across helicopter, conversion and airplane flight modes. As expected, this analysis identified several compatibility issues between helicopter and airplane mode HQ criteria, and also HQ gaps, particularly relating to the conversion mode. It was agreed that a series of piloted simulations would be conducted on the HELIFLIGHT facility at Liverpool to develop a better understanding of these issues and to narrow the gaps. As part of the activities of the structural load alleviation work package, Liverpool had developed a FLIGHTLAB model of the Bell XV-15 aircraft based on published data (Ref 5); we designate this model as the FXV-15. The published test data on this aircraft, albeit limited, would be used for validation and generally build confidence in the modelling and simulation activity, before transfer to the Eurocopter CTR configuration EUROTILT (Fig 10).



Fig 9 Bell XV-15 Aircraft in Airplane, Conversion and Helicopter modes



Fig 10 Artist's Impression of the Eurocopter EUROTILT CTR Configuration

Figure 11 shows the FXV-15 behaviour in response to a 1.8g turn in helicopter mode (85kts) and 4g turn in airplane mode (235kts), compared with flight test data (Ref 6). The comparisons are good and indicate that the basic flight dynamic characteristics of the aircraft have been properly modelled in FLIGHTLAB.

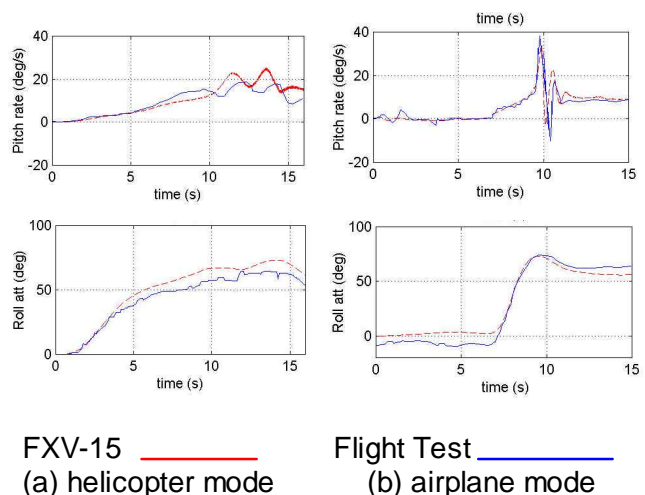


Fig 11 Comparison of FXV-15 with Flight Test Data (Ref 6)

Tilt rotor conversion mode handling qualities can be considered in 2 categories: (i) HQs during the conversion process, and (ii) HQs when flying with

nacelles fixed at intermediate settings. During summer 2001 a simulation trial was conducted at the FSL, supported by a CAA test pilot, a DGA test pilot and a former RN test pilot. Test engineers from DLR, ONERA, CAA and DGA were also present. The objective of the trial was to establish boundaries for roll/sway and pitch/heave HQ for manoeuvres with nacelles fixed at 75deg and 60deg and to compare these with the HQs in helicopter mode. Previous mission analysis had identified a suite of HQ-critical mission task elements (MTEs) for all three flight modes. Those selected for the conversion mode trial were the valley-following and terrain-following MTEs in the search and rescue (SAR) mission. From these, handling qualities test manoeuvres were defined and the courses laid out on the 'FLY' visual database. The valley-following MTE was transformed into the roll-step test manoeuvre shown in Fig 12. The pilot was required to fly the manoeuvre at different speeds, 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 was required to fly to the desired and adequate performance standards defined in Fig 12. The mean height was 50 ft in helicopter mode increasing to 100ft in the 60deg conversion mode.

In defining the performance standards for HQ test manoeuvres 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 are exposed (Ref 7). The standards in Fig12 reflect this philosophy.

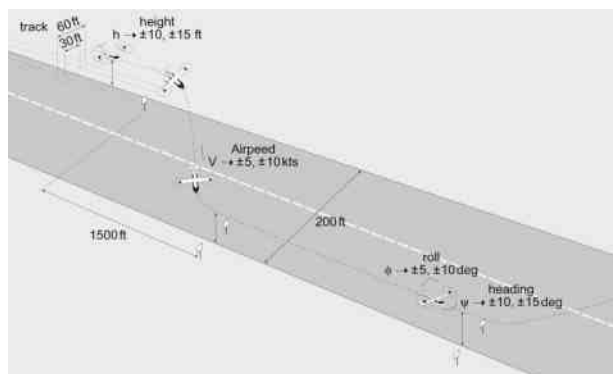


Fig 12 Layout of the Roll-Step Handling Qualities Test Manoeuvre

The conversion corridor for the XV-15 aircraft is illustrated in Fig 13.

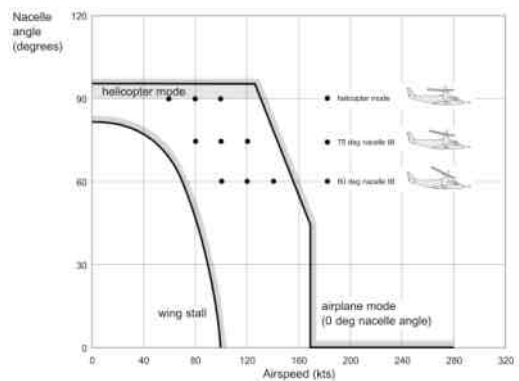


Fig 13 Conversion Corridor for XV-15 Aircraft

The 9 test configurations flown in the simulation are identified in the Figure 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 in manual mode 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. A 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.

While new handling qualities issues emerge during flight in conversion mode, the requirements on roll axis response can, in principal, be analysed in terms of the helicopter criteria defined in Ref 3. The response quickness was introduced by ADS-33 as a quantification of agility across the moderate amplitude range; for roll, quickness is defined for attitudes between 10 and 60 deg. Fig 14 illustrates the ADS-33 Level 1/2/3 boundaries and included are the configuration points for the FXV-15 in helicopter mode (90 deg nacelle angle, 60kts), conversion mode (75 deg nacelle angle, 100kts), conversion mode (60 deg nacelle angle, 140kts).

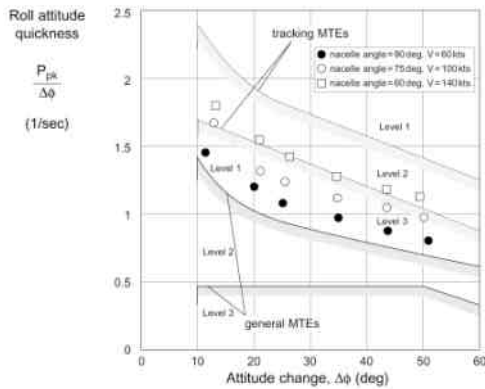


Fig 14 Roll Attitude Quickness for the FXV-15 in Helicopter and Conversion Modes

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 Fig 14 were derived from the FLIGHTLAB HQ toolbox. Shown on Fig 14 are the ADS-33 boundaries for both tracking and general MTEs. The starting assumption is that the general boundaries are applicable to the CTR, although it has to be pointed out that the aim of these and continuing tests is to re-position these boundaries if the data suggests this. According to Fig 14, 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 manoeuvring in conversion mode. The FXV-15 configuration for the tests included a simple SCAS providing additional damping in pitch, roll and yaw.

The roll-step tests were flown by 3 pilots and their combined handling qualities ratings (HQRs) are presented in Fig 15. The level of aggressiveness is increased by increasing the forward speed as discussed previously.

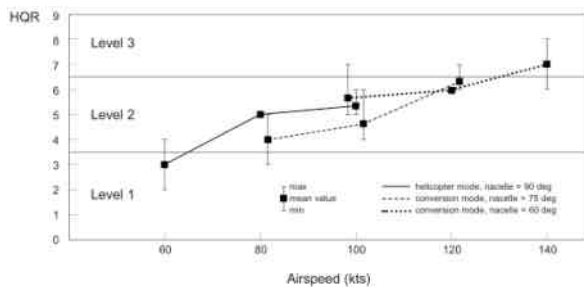


Fig 15 HQRs for the Roll-Step Manoeuvre

Figure 15 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 15 seconds to roll-step across the runway and at 120kts this time is halved. During this manoeuvre 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 deg roll and ± 15 deg heading. This proved too demanding at the higher speeds and the pilot typically required 5 seconds to stabilise flight path after passing through the gate. Large sideslip perturbations were generated during the roll manoeuvres and this required very close co-ordination of stick and pedal, resulting in high workload. In the Level 3 condition, height and speed excursions during the manoeuvring 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.

The results suggest that the FXV-15 with its core SCAS is Level 2 for these manoeuvres, with excursions into Level 1 and Level 3 at the lower and higher speeds respectively. Significantly it is the tracking phase of the manoeuvre that caused the piloting problems, although nearly full lateral stick was required to initiate the turns at the higher speeds when the pilot only has 6 seconds to cross the runway and line up with the gate. The emphasis on deficiencies in the stabilisation phase suggests that the boundaries on Fig 14 should be raised above the general toward the tracking positions. 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, a full authority active control system would certainly be able to provide significant help to the pilot, particularly during the tracking phases.

The HELIFLIGHT CTR simulations are providing a unique database of handling qualities from which criteria can be further developed in the continuing RHILP programme and a future ACS can be designed. It is recognised that the levels of agility and precision demanded from the pilot in these initial trials are challenging and would normally only be used in emergencies. The data shows that the safe HQ boundary (between Level 2 and 3) is reached progressively as the manoeuvre aggressiveness is increased; no cliff-edges were identified. However, the core SCAS system did not feature any structural load alleviation control functions that have the potential for introducing phase delay into the system in addition to control

limiting. The impact of such functions on handling qualities and the propensity to adverse aircraft-pilot couplings is being explored in the continuing RHILP programme.

4 Discussion

The design case for the HELIFLIGHT system was helicopter low level, low speed manoeuvring. Synergy between the visual and vestibular motion cues is paramount in such an application (Ref 8) but it is the visual system resolution and field of view that tends to dominate when overall fidelity is being assessed. The 135x40(60) field of view (FoV) in HELIFLIGHT is probably close to the limit that can be achieved with this scale of simulator. The next step up would appear to require hydraulic actuation for motion and a dome-based visual system, both increasing the cost and complexity of simulation. With the HELIFLIGHT FoV, a pilot turning at 10deg/sec the pilot can see about 6 seconds into a flat turn and about 4 seconds into the turn at 30deg bank. Similar 'scaled' reductions can be expected in a real aircraft depending on the cockpit layout. This is probably close to the limit of acceptability if the pilot did not know what was around the corner as the cockpit frame now begins to obscure the centre of optical expansion ahead of the aircraft at moderate forward speeds. A most important aspect of the design of experiments when working with a less than perfect field-of-view is to ensure that manoeuvres are restricted to levels where the natural viewing area in the scene remains in view at all times. The pilot will then be able to close the loop on visual cues in a realistic manner.

The whole topic of visual perception in helicopter flight is the subject of collaborative research with QinetiQ for MoD and CAA. In Ref 9, the theory of optical flow is exploited to develop guidelines for the design of pilot vision aids. The approach is based on the premise that the pilot controls an approach to the surface or objects by picking up temporal information from the optical flowfield through which the aircraft is moving – the optical ω -field or time to reach surfaces/objects. Restoring degraded cues synthetically should therefore be based on establishing sufficiency in the so-called optical ω 's present in the display. The research has involved a sequence of simulation trials on HELIFLIGHT over the past 12 months into how pilots use different natural cues for manoeuvring at low level. This example is illustrated in this discussion because it demonstrates the flexibility in visual

database modelling offered by the system. Pilots are required to fly a set of manoeuvres in various levels of micro-texture and macro-texture on the surfaces. The quality of the cues in the visual scene is determined by the pilot-rated visual cue ratings and associated Usable Cue Environment (UCE) and also the strength of the correlation between the optical ω 's in the flowfield and certain ω -guides postulated by theory (Ref 9). The UCE is a construct from ADS-33 developed to establish the level of control augmentation required when flying in a degraded visual environment. UCE 1 refers to a scenario when the pilots has good cues to control translational and rotational motion with precision and aggression. As the cues degrade to UCE 3 the pilot has lost the ability to control precisely and with any aggression. Fig 16 shows the UCE chart for an hover-to-hover, acceleration-deceleration manoeuvre flown by a test pilot in 5 different environments. With B1 (corridor of 15 trees on detailed micro-textured surface) the pilot returned a UCE 1, while as the surface cues were degraded the UCE fell into 2, 3 and finally outside 3.

The solid UCE 1 and accompanying Level 1 HQR for the best database demonstrates the quality of the scene detail even with the relatively modest performance of the Voodoo 3 graphics cards. The level of detail is considerably less than in the real world and yet is sufficient to fly quite complex manoeuvres within realistic performance constraints. The correlation analysis has demonstrated that even in the severely degraded cases of B4 and B5 (no surface texture, limited macro-cues) the pilot is still able to use limited cues very effectively although the probability of collision with surfaces increases considerably.

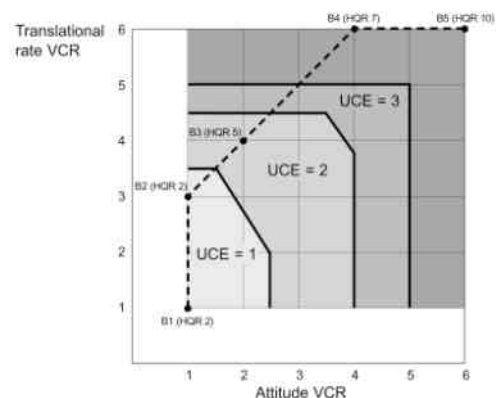


Fig 16 UCE Chart for Accel-decel flown on HELIFLIGHT; 5 levels of cueing

The visual perception research is being extended at Liverpool in an EPSRC-funded project to develop simulation fidelity criteria based on the concept of the Adaptive Pilot Model. Basically the pilot-vehicle combination is modelled as a variable parameter, low order model representing the overall task goal. For the accel-decel manoeuvre, the task variable is the distance to stop. It can be shown that a second order model for the manoeuvre range exhibits simple variations in frequency and damping as the range is closed to zero, based on the optical ? theory. Comparison with flight test data for the same manoeuvres offers the opportunity to make judgements about the control strategies used by pilots in the simulator compared with real flight. This research forms part of an ongoing effort to develop validation techniques and fidelity assessment criteria for flight simulators. Details will be reported at a later date.

Looking to the future, the HELIFLIGHT facility will be extensively utilised in its second year of service. A major new activity with the CAA involves developing an understanding of the requirements for simulating engine failure, flight in autorotation and engine-off landings. The number of accidents occurring in training is considerably greater than the number associated with actual engine failures. There is clearly scope for a greater utilisation of flight simulators in training but the cues have to be realistic to impart a positive training benefit. A number of new undergraduate projects have also been launched this year, including:

- (a) Develop hazard severity criteria for the response of helicopters to aircraft vortex wakes through piloted assessment
- (b) Design SCAS to augment stability of helicopters deliberately degraded to improve agility
- (c) Develop heave and yaw axis handling qualities criteria for helicopters
- (d) Design novel control functions to mitigate against the adverse handling caused by tail rotor failures
- (e) Develop improved aerodynamic model to enhance the simulation of flight in steep descent including vortex ring state and the application to tilt rotor aircraft
- (f) Effect of helmet-mounted-display field-of-view on a pilot's ability to fly manoeuvres at low speed
- (g) Impact of visual cues on approach profiles during decelerative descent to hover

Examples of fixed-wing projects are:

- (h) Develop improved modelling of the spin characteristics of the Grob 115 trainer
- (i) Develop simulation model of the Handling Page Jetstream in support of the Cranfield University Flight Test course at Liverpool
- (j) Develop simulation model of the X-29 research aircraft to provide the basis for research into aircraft-pilot couplings
- (k) Impact of visual cues on approach profiles during constant speed approaches with particular emphasis on the flare manoeuvre

A particularly exciting PhD project underway is entitled 'The Flying Qualities of the Wright Brothers Aircraft'. This centenary project involves the creation of high fidelity simulations of the Wright's 1901 glider, 1902 glider and the 1903 powered Flyer. The simulated 1901 glider flew for the first time in August 2001, 100 years after the Wrights were practising gliding over the Kill Devil Hills in North Carolina. The civil tilt rotor is, of course, a hybrid of helicopter and airplane and the creation of the FXV-15 and EURO TILT configurations has demonstrated the flexibility of FLIGHTLAB to combine components from different types of air vehicle. A new EU-funded programme, ACT-TILT, is scheduled to begin in late 2001. This critical technology project will develop a range of active control technologies applicable to a future CTR including those functions necessary to ensure Level 1 HQs throughout the operational flight envelope. HELIFLIGHT at the University of Liverpool is one of the key simulation facilities to be used in this programme.

5 Concluding Remarks

This paper has described the HELIFLIGHT simulation facility at the University of Liverpool and illustrated its capabilities by outlining a number of current activities. HELIFLIGHT, the primary facility within the University's Flight Simulation Laboratory, was commissioned in September 2000 and has enjoyed a year of trouble-free operation. At the time of writing, 6 funded research projects and 13 undergraduate projects are underway or secured all of which utilise the facility. A common theme is handling qualities and the associated flight technologies. The facility is also used extensively in the Aerospace Engineering teaching programmes. The first year of operation has seen the development of best practices for using simulation in an academic environment, based on extensive flight test and simulation experience. Students and researchers alike are required to work within a disciplined

approach that focuses on sound experimental design, communication protocols and purposeful data analysis and interpretation. A EU-funded project to develop handling qualities criteria for a future civil tilt rotor has been described and results presented to highlight the considerable potential of the HELIFLIGHT system in research. At the heart of HELIFLIGHT is FLIGHTLAB, a comprehensive modelling and simulation environment that provides tools for: (i) assembling aircraft models from existing or newly developed components, (ii) conducting detailed analysis with the models including linearisation and control law design, and (iii) running real time simulations. The combination of FLIGHTLAB and the Motionbase simulator has provided the University with high fidelity at relatively low cost and represents the first of a new generation of flight simulators designed to meet the challenges of a rapidly expanding domain.

6 Acknowledgements

The RHILP project is funded by the EU 5th framework Growth programme and the results presented in Section 3 were derived from a HQ-team simulation trial; the contribution from partners at DLR and ONERA, and the CAA and DGA test pilots is acknowledged. Post-Doc researcher on the RHILP project at Liverpool, Binoy Manimala, created the FXV-15 simulation. The support from undergraduates Helen Baker, Beth Davidson and Gary Clark in the analysis of the FXV-15 test data is gratefully acknowledged. The discussion on flight in degraded visibility in Section 4 has been informed by the research conducted for QinetiQ, technical monitor Malcolm Charlton; support from QinetiQ and MoD is acknowledged; thanks to the post-grad researcher on this project, Julia Tims, who ran the simulation trial and produced the UCE results in Fig 16. Special thanks to staff at Motionbase and Advanced Rotorcraft Technology for delivering HELIFLIGHT on schedule and meeting all performance targets in addition to the ongoing support throughout the first year. Numerous technical staff in the Department of Engineering at the University of Liverpool have provided excellent day-to-day support to research and teaching activities. Their commitment is appreciated. The authors' particularly wish to express their gratitude to senior management at the University of Liverpool for their commitment to Aerospace Engineering and to supporting the development of the Bibby Flight Simulation Laboratory. Finally, the authors would like to acknowledge the generosity of the late Dr Mason Bibby; his contribution to the Laboratory development fund made it possible to avoid any corner-cutting during development.

7 References

1. DuVal, R. W., A Real-Time Multi-Body Dynamics Architecture for Rotorcraft Simulation, The Challenge of Realistic Rotorcraft Simulation, RAeS Conference, November 2001, London
2. Maxcue 600 Series Technical Data Sheet, Motionbase, October 1998.
3. anon., Aeronautical Design Standard-33E-PRF, Performance Specification, Handling Qualities Requirements for Military Rotorcraft, US Army AMCOM, Redstone, Alabama, March 21, 2000.
4. Rollet, P., RHILP – A Major Step for European Knowledge for Tilt Rotor Aeromechanics and Flight Dynamics, Aeronautics Days 2001, Hamburg, Jan 2001
5. Harendra, P.B., et al., A Mathematical Model for Real-Time Flight Simulation of the Bell Model 301 Tilt Rotor Research Aircraft, Bell Helicopter Report No 301-099-001, April 1973
6. Schillings, J.J., Roberts, B.R., Wood, T.L., Wernicke, K.G., Manoeuvre Performance Comparison between the XV-15 and an Advanced Tiltrotor Design, J. American Helicopter Society, May 1980
7. McRuer, D T. et al, Understanding and preventing unfavourable pilot-vehicle interactions, Aviation Safety and Pilot Control, NRC, National Ac Press, Washington, 1997
8. Schroeder, J.A., Helicopter Flight Simulation Motion Platform Requirements, NASA/TP-1999-208766, July 1999
9. Padfield, G.D., Lee, D.N., Bradley, R., How Do Helicopter Pilots Know When to Stop, Turn or Pull Up? (*Developing guidelines for vision aids*), proceedings of the 57th Annual Forum of the American Helicopter Society, Washington DC, May 2001