# ACCEPTANCE TESTING OF A ROTORCRAFT FLIGHT SIMULATOR FOR RESEARCH AND TEACHING: THE IMPORTANCE OF UNIFIED METRICS

*Mark White, Philip Perfect, Gareth D Padfield*
The University of Liverpool
Liverpool
United Kingdom

*Arthur W Gubbels*
National Research Council
Ottawa
Canada

*Andrew Berryman*
Consultant Test Pilot
The University of Liverpool
United Kingdom

**Abstract**

The expanding requirements for rotorcraft operations in harsh environments along with the introduction of tilt-rotor aircraft into both civil and military service and the extensive replacement of large numbers of airframes dating from the 1960s and 1970s, are some of the challenges facing the rotorcraft industry today. Successful completion of the conception-design-build-test/qualification-production-operation cycle of helicopters is highly dependent on the use of modelling and simulation. In addition, flight simulators have become integral to the manufacturing, training and research communities and their utilisation is expanding rapidly. The quantification of simulation fidelity underpins the confidence required for the expanding use of flight simulation in design, to reduce real life testing, and to provide a safe environment for pilot training. Current simulator standards do not provide a fully quantitative method for assessing simulation fidelity, especially in a research environment. This paper details the commissioning and acceptance process of the new research flight simulation facility at the University of Liverpool, HELIFLIGHT-R and its subsequent use in a new research project aimed at developing new predicted and perceived measures of simulator fidelity. Some initial results from both piloted simulation and flight tests using the Bell 412 ASRA aircraft are reported within the context of the rotorcraft simulation fidelity project.

## 1. INTRODUCTION

Flight simulators (or synthetic training devices) are extensively used in engineering design and flight training, and are an essential tool in the conceive-design-build and qualification processes of rotorcraft. Indeed, the use of flight simulation has become integral to the rotorcraft manufacturing, training and research community. However, simulators have an inherent flaw: despite their complexity and the use of state of the art components, they are not able to provide an exact representation of reality and therefore rely on providing a 'sufficiently realistic' illusion of flight to the pilot. How strong that "illusion" is may act as an indicator of the "fitness for purpose" of a simulator for a given use.

The Department of Engineering at the University of Liverpool has operated a single seat, full motion flight simulator, HELIFLIGHT [1], since its commissioning in academic year 2000-2001. Based in the Flight Science and Technology Research Group (FS&T), the HELIFLIGHT facility has been successfully used both in research projects funded by EPSRC, European Commission and Industry and also as an interactive teaching tool for undergraduate projects, handling exercises and laboratory classes. It was built around a technical and functional specification that would allow research into flight handling qualities, flight mechanics, flight control system design, aircraft design concepts and cockpit technologies. The requirement specification for this simulator was to have a motion capability, a "reasonably" wide field of view, programmable force feel and a modelling environment compatible with the FLIGHTLAB modelling system [2], running on a PC-based architecture. In addition, the requirement to be able to simulate both rotary and fixed-wing aircraft was mandatory. The solution provided by Motionbase plc (now cueSim) and Advanced Rotorcraft Technology Inc. (ART), was selected as providing the best solution in terms of price and technical quality.

The use of HELIFLIGHT in piloted simulation was key in the success of research activities including, amongst others; development of handling qualities criteria and load alleviation concepts for a European civil tilt-rotor [3], [4] and the development of pilot guidance strategies and display concepts in fixed-wing and rotary wing flight [5], [6]. Whilst the majority of HELIFLIGHT's utilisation was accounted for with industry research, more than a third if its use has been in the support of undergraduate teaching activities. During the 4$^{th}$ year Aerospace Engineering masters module, Flight Handling Qualities (a problem-based-learning module for final year aerospace engineering students [7]), the simulation environment provides the "vehicle" for knowledge acquisition through the process of identifying handling deficiencies of an aircraft and the assessment of the efficacy of the subsequent aircraft upgrades. Central to all of the research and teaching activities undertaken using HELIFLIGHT was the notion that the level of fidelity of the system was high enough i.e. it was “fit for purpose” based on the subjective opinion of the test pilots using the system, ensuring the validity of the research and teaching outputs.

HELIFLIGHT has certain capability limitations e.g. a 135 x 40 degree field of view visual system with a single seat cockpit, which, when combined with approaching utilisation capacity limits (1000 hours of utilisation in 2005) meant that a new facility was required to continue the growth of FS&T’s research and teaching portfolio. In late 2005, the business case for the procurement of a new simulator was developed in order to allow a system to be delivered and installed during the £32M Engineering Restructuring Project that was due for completion in summer 2008.

Driving the requirement for a new simulator was the need for extra capacity and an enhancement in the existing simulation capabilities, whilst ensuring that the fidelity of the new system was “sufficiently” high to ensure it is “fit” to be used as a research tool. This paper will detail the simulator, HELIFLIGHT-R, chosen to meet the new requirements and describe its use in a new project, Lifting Standards: A Novel Approach to the Development of Fidelity Criteria for Rotorcraft Flight Simulators, which aims to bridge the gap between pilot subjective opinion and formal metrics in the acceptance testing of rotorcraft flight simulators.

Section 2 describes the technologies involved in the new simulator, HELIFLIGHT-R and the commissioning work undertaken prior to commencing the simulation fidelity research project. Section 3 discusses the simulation qualification process, the need for objective metrics and the limitations identified in the current simulator standards. Section 4 introduces FS&T’s new simulation fidelity research activity, Lifting Standards and details the initial set of flight and simulation tests carried out to date. An introduction to pilot perceived fidelity issues is presented in Section 5, prior to a discussion of initial simulation fidelity results in Section 6. The paper is drawn to a close in Section 7 with concluding remarks.

## 2. HELIFLIGHT-R

### 2.1. New Simulator Specification

The utilisation of FS&T’s original flight simulator, HELIFLIGHT, increased from 240 hours in 2001 to almost 1000 hours in 2005 and was expected to reach operational limit during 2006-7. This increase in utilisation reflected a growth in both the number and scope of simulator-related activities, which presented two problems for that system: operational availability and technical/functional capability to support continued growth in research diversity.

In order to encourage continued expansion in research and teaching capabilities, a new facility was envisaged to provide the functional capabilities that were lacking with the original simulator. HELIFLIGHT is limited in what it can do, in particular:

- There is limited capability, particularly with regard to cockpit layout and technology, to simulate fixed wing aircraft concepts, operations and problems.
- It features a single seat pod and hence cannot address multi-crew issues directly.
- The field of view (excluding LCD chin windows) is limited to 135° x 40°, whereas for some helicopter operations 210° x 60° is desirable
- No provision of ‘active’ tactile cueing through the pilot’s controls was present
- No distributed network capability existed in the basic system
- A single 15” LCD monitor is available for displaying primary flight instruments and there is very limited scope for navigation and radio operations to be carried out.

Drawing on these limitations, a Statement of Requirements (SoR) [8] was produced for the new simulator as follows:

> “The cockpit must be multi-person, with a flexible, re-configurable fixed wing or rotary wing cockpit layout (with sufficient hardware to provide a functioning navigation and procedural element to simulator missions). Programmable force-feedback control loading and preferably with a motion cueing capability (depending on cost, motion was not included as an essential item) was required. The facility must offer a visual record and playback facility, using data taken from the flight dynamics models and a direct video/DVD recording of a visual channel (out the window view or an external “mapping” view). In order to enable the network capability between HELIFLIGHT and the new device, communications should be provided to allow an engineer in either control room to speak to either simulator pilot. This communication process and an outside/external view should also be directed to the planned de-brief areas and lobby area which will contain display monitors. Any new system architecture must be compatible with the HELIFLIGHT system.”

### 2.2. HELIFLIGHT-R System Description

Following a tendering process during summer 2006, ART’s HELIFLIGHT-R simulator was selected as the best match in terms of the advertised SoR. A schematic of the HELIFLIGHT-R system is shown in Figure 1.

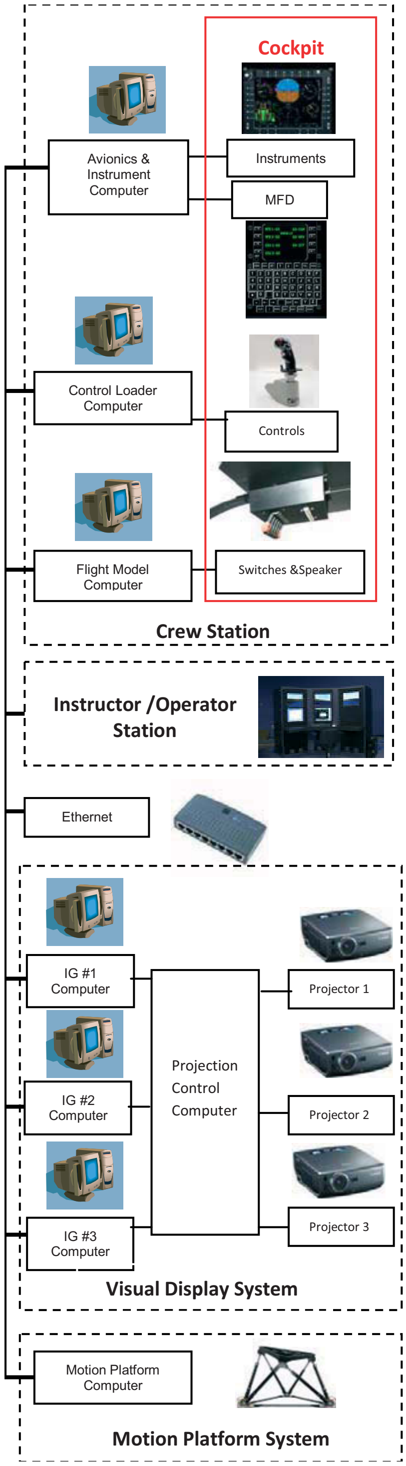


**Figure 1: HELIFLIGHT-R Schematic**

HELIFLIGHT-R (Figure 2) consists of a 12 ft visual dome mounted on a 6 degree of freedom motion platform. The system utilises general purpose Linux based computers to drive the simulator from a central Instructor-Operator Station (IOS) PC. The IOS PC is connected to a local network that allows communication with each of the other elements of the system – 3 Image Generation (IG) machines that produce the visual environment, one machine to run the reconfigurable instrument panel displays (left and right primary flight displays, backup analogue displays and Head Up Display), and a machine for the Instructor Station within the dome, which serves dual purpose by creating the audio environment. In addition, the network is connected to the control interfaces for the control loading and motion systems.

An interchangeable and reconfigurable cockpit, allowing one or two crew operations, (Figure 3) is equipped with two wide screen 19" LCDs to represent the primary flight information, engine information and navigation information. The configuration provides a glass cockpit layout of analogue instruments as well as simulation of Multi-Function Keyboards and Displays via touch sensitive transparent overlays. The two centre displays are 10" 4:3 touch screens. The upper centre screen displays generic backup instruments, whilst the lower centre screen displays a Control Display Unit multi-function keypad and message display area.

**Figure 2: HELIFLIGHT-R Simulator**

The Crew Station uses a 4-axis (longitudinal and lateral cyclic, collective and pedals) Moog FCS ECoL 8000 Q&C-Line electric control loading system that back-drives the pilots' controls and allows fully programmable force-feel characteristics. The conventional rotorcraft controls can be replaced with an F-16-style side stick and throttle for fixed wing operations. The dome is also equipped with an Instructor Station which can, for fixed-base operation, control all simulator functionality. A head-up-display unit is available and uses a 10" 4:3 LCD screen with a beam splitter and is mounted on the glare shield on the right hand side of the cockpit. An in-cockpit camera is installed on the left of the rear tower to provide a live display of the pilot and co-pilot to the IOS.

**Figure 3: HELIFLIGHT-R Cockpit Layout**

Motion cueing is provided by a Moog MB/E/6dof/24/1800kg electric motion system, consisting of six Moog electric actuators arranged in a hexapod structure to provide full 6 degree of freedom motion. Each actuator has a 600mm stroke, giving peak accelerations of >300°/s$^2$ in each rotational axis, 0.71g in surge and sway, and 1.02g in heave (see Table 1, note values are for single axis). The platform has a 1,800 kg loading capacity with the estimated weight of the cockpit being 900 kg.

**Table 1 HELIFLIGHT-R Motion Envelope**

| | Displacement | Velocity | Acceleration |
|---|---|---|---|
| **Pitch** | -23.3°/25.6° | ±34 °/s | 300 °/sec$^2$ |
| **Roll** | -23.2° | ±35 °/s | 300 °/sec$^2$ |
| **Yaw** | ±24.3° | ±36 °/s | 500 °/sec$^2$ |
| **Heave** | ±0.39 m | ±0. 7 m/s | +/- 1.02 g |
| **Surge** | -0.46 /+0.57 m | ±0. 7 m/s | +/- 0.71 g |
| **Sway** | ±0.47 m | ±0. 5 m/s | +/- 0.71 g |

Three high resolution Canon SX60 projectors, with a 1400 x 1050 resolution, equipped with wide angle lenses provide a wide field of view of 210° horizontally by +30°/-40° vertically. This results a 3.43 arc-min/pixel which is very close to the level-D visual requirement of 3 arc-min/pixels. The field of view represents a significant increase in capability compared with that available on the original HELIFLIGHT system (Figure 4). It should be noted that the field of view shown in Figure 4 is that available from the left hand seat. The Liquid Crystal on Silicon (LCoS) technology used in the projectors allows a high quality visual display without the pixel gridding seen with LCD projectors. A Silicon Optix Image AnyPlace Video Scaler box is used to warp and edge blend the 3 OTW images into one scene on a 12 foot diameter visual dome consisting of 12 carbon fibre composite panels.

The image generation is provided using Boeing's Multi-Purpose Viewer (MPV), an Open Scene Graph (OSG) based tool that supports rendering of any OpenFlight terrain or object database. In addition, a further integration activity was undertaken to allow the system to operate BAE's Landscape run-time [9], ensuring compatibility with the HELIFLIGHT system.

Whilst there is provision for the simulator to be operated from an IOS inside the cockpit, the standard modus operandi is to use the IOS in a separate control room. The control room is equipped with the simulator's primary Operator Station, and is also home to the PC-based processing capabilities of the simulator. A single Instructor-Operator Station (IOS) PC controls operations and also runs the high-fidelity FLIGHTLAB modelling, analysis and real-time simulation environments.

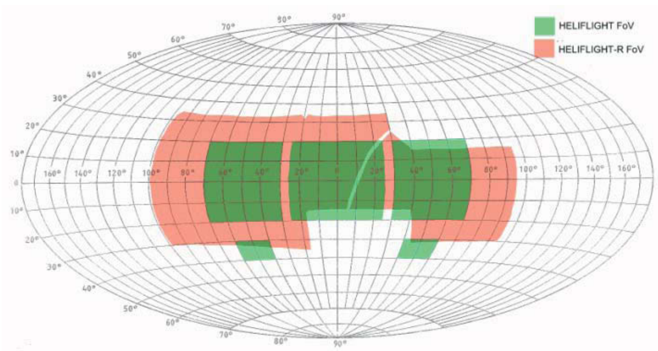


**Figure 4: Comparison of Outside World Field of View Between HELIFLIGHT-R (Left hand Seat) and HELIFLIGHT simulators.**

## 2.3. FLIGHTLAB Modelling

As with HELIFLIGHT, ART's FLIGHTLAB modelling and simulation software [2] is at the centre of operation of the new facility. FLIGHTLAB provides a modular approach to developing flight dynamics models, producing a complete vehicle systems model from a library of predefined components. A number of GUIs; Xanalysis, CSGE/GSCOPE and FLIGHTLAB Model Editor are available to aid in the generation and analysis of flight models.

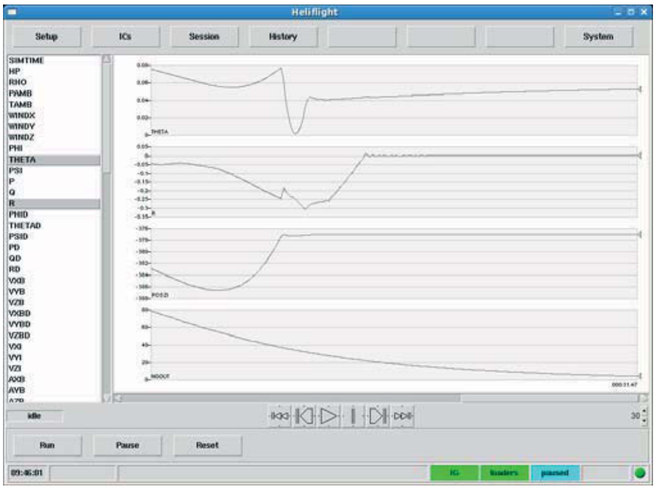


**Figure 5 HELIFLIGHT Run-Time Interface in Data Monitoring Mode**

A key difference with the new system compared with HELIFLIGHT is apparent during real-time operations. Instead of launching the PilotStation interface, a user now generates a FLIGHTLAB Code-generated Model (FCM) which is cycled at run-time. 2 new interfaces are available, FCMConsole and HELIFLIGHT (Figure 5) which support initialisation, trim, run/pause, malfunction insertion, system monitoring and recording of data for post-sortie analysis and debriefing purposes.

## 2.4. Commissioning and Acceptance Testing

### 2.4.1. Commissioning Process

Unlike commissioning of civil training simulators there are no defined standards for the acceptance or qualification of research simulators. Indeed the judgement of the suitability of the device in a research role is heavily reliant on the commissioning pilot having an intimate understanding of the needs of the researchers and the scope of the work undertaken. With this in mind the commissioning pilot assessed the fidelity of the simulator against Quantitative and Subjective criteria. The Quantitative criteria relate to the items that can be reproduced in the simulator as a direct match to the real aircraft (e.g. control configuration, cockpit layout, displays etc.) or in the case of HELIFLIGHT-R, matched against the SoR. Subjective assessment is the degree to which the pilot perceives the simulator to replicate real world operations with respect to physiological impressions in flight (and on the ground) in an operational task setting.

The acceptance process for HELIFLIGHT-R was undertaken in 3 phases. Two interim acceptance tests (December 2007 and April 2008) were carried out at ART's facility in the United States, to allow the end user to monitor the progress of the simulator development. These were system checks aimed at ensuring that the functionality detailed in the SoR was being delivered. The final acceptance test was undertaken following the completion of the installation process in the UK.

The HELIFLIGHT-R system was delivered to the University of Liverpool in July 2008. After its arrival, a period of 6 weeks was required to complete the finishing works to the laboratory area prior to its installation. The installation process commenced at the end of August 2008 and was completed within 4 weeks. During the latter phase of the installation process a commissioning test pilot was brought in to the laboratory to carry out a 2 day evaluation of the new simulator. The pilot used in the commissioning tests was one of the pilots used during the commissioning of the HELIFLIGHT system in 2000 and has acted as a consultant test pilot at UoL in the intervening period.

The commissioning pilot's brief was to carry out a combined test pilot and end-user evaluation. On day 1, the first part of this process involved an examination of the simulator suite infrastructure only. Starting with the control room, the pilot performed a walk-through of the facility examining potential Health and Safety and ergonomic issues with the operation of the simulator and its supporting hardware. Once completed, the functionality of the internal systems of the simulator was examined and cross-checked against those specified in the SoR and any deficiencies that were identified were subsequently corrected.

### 2.4.2. Motion Tuning

On the second day of evaluation, the pilot conducted a subjective pilots' assessment combining: traditional test manoeuvres; ADS-33E [10] manoeuvre profiles using natural references, and low level aggressive tasks replicating flight in a military environment. The stability augmentation system (SAS) was ON for all tests and the aircraft model used was the FLIGHTLAB generic rotorcraft. During this phase of the evaluation an assessment of the Flight Control Mechanical Characteristics (FCMC) and the motion platform was carried out and tuning of both systems was undertaken. The tuning processes were carried out using Moog's FCS Explorer software which is a Graphical User Interface to monitor, control and diagnose all individual components of the control loading and motion system.

Motion cueing is generated by Moog FCS Adaptive Motion Cueing and Advanced Platform Kinematics software. The HELIFLIGHT-R motion drive algorithm uses adaptive washout filters, which approximate to

3rd order filters in the translational axes (surge, sway and heave) and classical 3rd order linear filters in the rotational axes (roll, pitch and yaw). In equation 1 the input $\ddot{\phi}_{in}$ is the roll acceleration from the aircraft mathematical model and the output $\ddot{\phi}_{out}$ is the roll acceleration demand to the motion platform. The gain K scales the motion cues uniformly at all frequencies, $\zeta$ and $\omega$ are respectively the damping ratio and natural break-frequency of the second order filter, and $\omega_1$ sets the third order pole. The advantage of a third order high-pass filter over a second order filter is its return to neutral characteristic i.e. sustained accelerations at the input, will always results in the platform slowly returning or 'washing-out' to the neutral position [11].

(1) $$\frac{\ddot{\phi}_{out}}{\ddot{\phi}_{in}}(s) = \frac{Ks^2}{s^2 + 2\zeta\omega s + \omega^2}\frac{s}{s+\omega_1}$$

The initial motion tuning was undertaken with the assistance of a Moog engineer and an experienced simulation engineer, following the procedure indicated in Figure 6. During the tuning process values of the gain, the break frequency and the first order pole were varied but the damping, third order pole value and amplitude rates/limits were not changed. A series of single axis manoeuvres were flown by pilot to provide subject feedback on the "quality" of the motion cueing provided, allowing the engineers to tune the motion using the parameters in (1). Particular attention was paid to eliminating false cues e.g. a second false cue shortly after the initial motion cue produced by having too short a washout period and minimising the scope for reaching actuator travel limits.

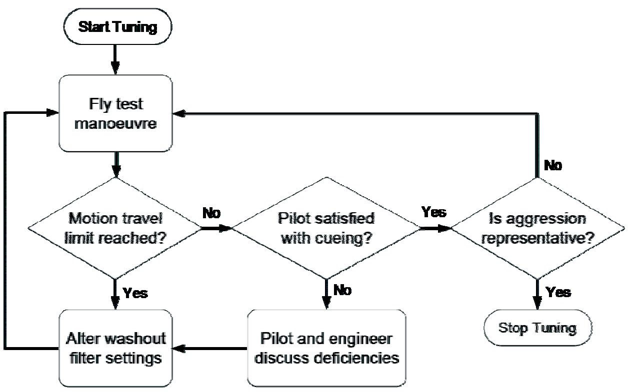


**Figure 6 Motion tuning flowchart for one motion axis/manoeuvre**

The motion tuning process is an iterative one and is best carried out on each axis in isolation, before moving onto multiple axes [12]. The approach taken here was to perform a limited set of representative flying tasks or Mission Task Elements (MTEs). In total four different manoeuvres were performed to exercise specific axes: pirouette (yaw), sidestep (roll/sway), bob-up (heave), acceleration-deceleration (pitch/surge), and a slalom followed by a hurdle-hop manoeuvre were performed to exercise multiple axes. Each manoeuvre was flown against a stylised test course, defined in [10], to enable the pilot to assess achieved levels of aggression and accuracy in the manoeuvre. The tasks were performed at varying levels of urgency to ensure that motion limits were not reached during high aggression manoeuvring.

The procedure in Figure 6 was repeated until the commissioning pilot was satisfied that a motion tuning set had been derived providing him with appropriate motion cues for the tasks flown, which are representative of the tasks flown in a variety of FS&T research activities.

### 2.4.3. Control Loading Tuning

The ECol 8000 control loading system in HELIFLIGHT-R was integrated by ART to allow pilot control movements to be read as inputs into the FLIGHTLAB model. The force-feedback system is operational on the helicopter cyclic and collective controls (which can be used for fixed wing and tilt rotor operations as centre stick and throttle respectively) and the pedals. The F-16 side stick and throttle do not have any force-feedback applied to them. The system was delivered with a generic control model already implemented.

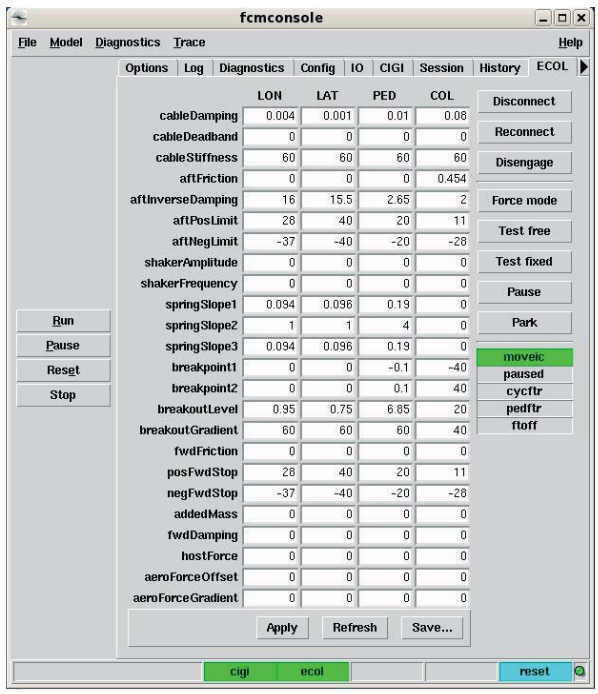


**Figure 7 Control Loading Tuning Parameters**

During the commissioning, feedback from the pilot allowed the simulation engineers to tune the control loaders to generate flight control mechanical characteristics (FCMC) that were representative of the test aircraft. To achieve the desired control characteristics, the properties (e.g. damping, spring stiffness, breakout force and breakout position as shown in Figure 7) for the different control channels were changed iteratively until the pilot approved of the settings based on his subjective opinion.

It should be noted that in lieu of FCMC data for a real aircraft, the pilot's subjective opinion was deemed acceptable for the commissioning process. What was most important was the assessment demonstrated that the system had the capability to allow a quantitative evaluation to be made once data was available.

It is clear from the Sections above that the successful acceptance of HELIFLIGHT-R (completed September 2008), was made possible based considerably on the commissioning pilot's subjective opinion and his previous experience not only with training and research simulators in general but also with the specific simulation requirements of FS&T. The need for objective quantification of simulator fidelity is discussed in the next section and is the focus of a new research activity reported later in this paper.

## 3. THE NEED FOR UNIFIED FIDELITY METRICS

### 3.1. Engineering and Research Simulators

The expanding requirements for rotorcraft operations in harsh environments, e.g. emergency medical/law enforcement services and maritime/coast guard, along with the introduction of tilt-rotor aircraft into both civil and military service and the extensive replacement of large numbers of airframes dating from the 1960s and 1970s, are some of the challenges facing the rotorcraft industry today. These challenges are being met within the context of new environmental and safety constraints [13]. Successful completion of the conception-design-build-test/qualification-production-operation cycle of helicopters is highly dependent on the use of modelling and simulation. In addition, flight simulators have become integral to the manufacturing, training and research communities and their utilisation is expanding rapidly. For example, the Joint Shipboard Helicopter Integration Process (JSHIP [14]), examined the benefits of maximising the use of simulation in defining the safe envelopes for rotorcraft offshore operations.

The simulation requirements for maritime operations have been the focus of other recent studies [15], [16] (collaboratively with BAE Systems), including the successful integration of CFD ship airwakes into a real-time helicopter flight simulation environment. Echoing the JSHIP findings, the results of the helicopter-ship interface research at UoL indicate how simulator motion, visual and airwake fidelity impact pilot workload in the development of Ship Helicopter Operational Limits.

Quantifying fidelity, using an engineering metrics approach, underpins the confidence required for the expanding use of flight simulation in design, to reduce real life testing, and to provide a safe environment for pilot training, yet has been neglected in the rotorcraft world. For fixed wing aircraft, the concept of zero flight time training using flight simulation is accepted and deemed necessary from a safety and cost standpoint. This must become the modus operandi for rotorcraft training, emphasised by the fact that the risk of an accident when flying in a helicopter is an order of magnitude greater than when flying in an airliner [17]. To achieve the goal of an 80% reduction in accidents, targeted by the International Helicopter Safety Team (IHST, [17]), new technologies and aircrew training solutions are required.

In the context of helicopter requirements capture and design, simulators are commonly used to assess handling qualities and crew-station technologies. Attempts to quantify overall simulation fidelity within the framework of handling qualities engineering have been presented in a number of forms in recent years. Hess and colleagues [18], [19], [20] have developed an approach based on pilot-aircraft modelling and introduced the handling qualities sensitivity function as the basis of a quality metric. Padfield et al., [21] and later McCallum and Charlton [22] proposed the use of the handling qualities standard, ADS-33, for deriving metrics; the rationale here being that if the simulator is to be used to optimise handling qualities, then what better parameters to judge fidelity than those defining the predicted handling. Within the JSHIP project, Advani and Wilkinson [14] and Roscoe and Thompson [23] presented an approach using comparative measures of performance and control activity, correlated with handling qualities ratings given for the same tasks flown in simulation and flight. In all these approaches, the philosophy has been to try to develop a rational and systematic approach to identifying differences between simulation and flight, hence directing attention to areas of deficiency. The partial success of these methods is encouraging, but only serves to highlight the importance of fidelity criteria for the use of simulation in design, development and product qualification. In these areas, flight simulation can be a primary source of data from which knowledge is derived, decisions are made and significant resources committed.

### 3.2. Flight Training Simulators

In the context of training simulators, regulatory authorities have produced functional performance standards, along with associated training credits, to provide a framework for the acceptance of a synthetic training device. Documents such as JAR-STD 1H [24] and FAA AC120-63 [25] describe the qualifying criteria and procedure for rotorcraft flight training simulators and detail the component fidelity required to achieve a “fit for purpose” approval. The qualification process serves two purposes: first, to indicate whether the training device provides a learning environment where a student can be trained to operate the aircraft safely and, secondly, to ensure the simulator replicates the aircraft and the environment in which it operates.

Both specify criteria for the cueing environment (motion, visuals, control loading system, audio etc) and the aircraft flight dynamics models. Such criteria are formulated by using “tolerances” defined as acceptable differences between the simulation results and flight test data, typically ±10% for flight model tolerances. What is not clear is whether meeting this standard will always guarantee a simulation sufficiently representative of the real world, such that the simulator is fit for purpose; there is simply no supporting data or analysis to judge one way or the other. JAR-STD 1H is still under development, with the philosophy that it “should be applied in practice and the lessons learned embodied in future amendments”.

To establish an engineering basis for civil simulator qualification standards, GARTEUR Action Group HC-AG12 [26], [27] recently conducted sensitivity analyses using the JAR training simulator standards [24], including correlation of handling qualities and fidelity metrics, revealing many shortcomings. In particular, the AG showed that the relationship between fidelity and the tolerances prescribed by JAR-STD 1H is sensitive to the nature and duration of the manoeuvre, and that models of the aircraft-pilot combined ‘system’ offer significant potential as a basis for overall fidelity metrics [28], [29].

Experience highlighted in the GARTEUR HC-AG12 study [26], [27], showed that, in most areas, 80% “fidelity” should be achievable with physical modelling and the remaining 20% requires artificial tuning, yet is critical for acceptance. While tuning may be able to correct problems in a specific flight condition, it often has an adverse affect in other parts of the flight envelope. Thus, to achieve an acceptable level of performance, modifications are implemented which are not physically realistic and difficult to justify from an engineering standpoint. What is clear is that there is limited understanding of the relationship between the settings of the simulator cueing environment and the behaviour of the pilot.

In Europe, there is a Royal Aeronautical Society [30] sponsored initiative underway to rationalise the various qualification standards; however, the rotary wing requirements will, once again, follow the new framework developed for fixed wing aircraft.

Rationalisation of the simulator standards, either fixed wing or rotary wing, does not address the underlying question of the suitability of the criteria for specifying each of the component parts, and particularly the definition of overall fidelity of the simulator. What is required is an objective means for assessing the overall fidelity of a simulator, to complement the perceived fidelity and the predicted component fidelity.

## 4. LIFTING STANDARDS: A NOVEL APPROACH TO THE DEVELOPMENT OF FIDELITY CRITERIA FOR ROTORCRAFT FLIGHT SIMULATORS

The quantification of simulation fidelity underpins the confidence required for the expanding use of flight simulation in design, to reduce real life testing, and to provide a safe environment for pilot training. Yet this has been seriously neglected in the rotorcraft world as, even for training simulators, there is no supporting data or analysis techniques available to show whether the current criteria always produce a simulator of sufficient quality for the required purpose. What is needed is a unified, metric based, engineering framework for the assessment of the fitness-for-purpose; this is the topic of a new research programme at the University of Liverpool (UoL). In a research environment, the purpose is often highly flexible, with a simulator being required to replicate many different aircraft which in turn operate in varied roles. The aim in quantifying the fidelity of the simulation then becomes one of understanding the effect that a change in the simulation environment will have upon the pilot’s perception of the task. A two stage approach for defining fidelity criteria for simulator qualification will be adopted in the new research project. Firstly, a quantitative basis for providing the predicted fidelity of a simulator is developed using new engineering metrics and, subsequently, a pilot fidelity rating scale used to assign the perceived fidelity of the simulator.

This project involves a collaborative effort between the UoL and the National Research Council of Canada’s Flight Research Laboratory and consists of two main parts. The first part involved the collection of flight test data of the Bell 412 ASRA for use as benchmark data. Using a FLIGHTLAB Bell 412 (F-B412) model [31] the predictive fidelity of the flight model was assessed against the benchmark data. One of the initial flight test manoeuvres was “re-run” within the simulation facilities at UoL in order to examine the fidelity of the overall simulation environment. The data from both the UoL simulation and NRC trials will then be used to derive a set of fidelity metrics for rotorcraft simulation.

During the second part of the program, the fidelity metrics derived in phase 1, will then be assessed via a second trial at the NRC towards the end of the UoL project. These metrics will be used to produce evidence based justification for requirements within existing and emerging simulator standards. The progress in these areas is reported in the following sections.

### 4.1. FLIGHTLAB Bell 412 Simulation model

Accurate modelling of the aircraft flight dynamics is one of the key elements in the creation of a realistic and believable simulation environment. In a previous collaboration with the NRC, UoL created a high fidelity FLIGHTLAB model of the Bell 412HP helicopter, with initial validation showing excellent on-axis predictions of the aircraft response across a wide range of airspeeds [30].

The model consists of a four-bladed rigid, articulated, blade element main rotor system with flap and lag degrees of freedom. Rotor inflow is modelled using the Peters-He finite-state dynamic inflow model [32]. The tail rotor is modelled using the Bailey method [33].

A table look-up method is used to model the Bell 412 fuselage, where force and moment coefficients for each of the degrees of freedom are supplied as functions of the angles of attack and sideslip.

The left-side and right-side horizontal stabilisers are modelled independently using lifting surface theory [34], with each stabiliser having independent initial incidence settings. Each stabiliser is attached to a spring-loaded tube, allowing the incidence to change in flight according to the aerodynamic pitching moment experienced by the surface. The vertical fin is likewise modelled using lifting surface theory.

Engine dynamics were derived from an NRC linear state-space model of the engine-governor-rotor system. The response of this linear model was used to tune the FLIGHTLAB ‘simple engine’ component to give a well-matched, second order response (Figure 8). The simple engine model acts as an engine governor, commanding torque to hold the rotor speed constant [35].

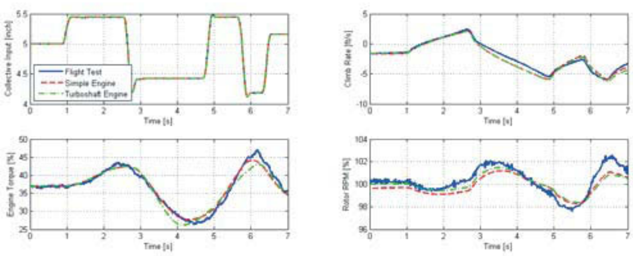


**Figure 8 FLIGHTLAB Engine Model Tuning**

#### 4.1.1. Bell 412 Simulator Integration

The new HELIFLIGHT-R simulator provides the capability to generate a more realistic audio environment than was possible with the HELIFLIGHT simulator. The audio environment is driven by a set of model ‘controls’. For the Bell 412 simulation, the main rotor speed, NR, and the gas generator speed, NG, were selected, in order to produce representative audio cueing of engine power output and rotor loading. The FLIGHTLAB simple engine modelling option described in the previous section does not provide as an output the gas generator speed. Thus, in order to provide accurate audio cueing for the pilot, and to enhance the instrumentation display, an alternate version of the Bell 412 model was generated using the FLIGHTLAB turboshaft engine modelling option.

The turboshaft engine modelling option represents a higher level of complexity than the simple engine, with full modelling of the nonlinear engine thermodynamics and fuel control systems associated with a typical turboshaft engine. The parameters within the turboshaft model were defined based upon the known properties of the Pratt & Whitney PT6T-3BE engine, as fitted to the Bell 412. The remaining parameters were tuned to provide the best match in the engine response to the FLIGHTLAB simple engine model and flight test data (Figure 8). The FLIGHTLAB turboshaft model provides a wide array of engine output values, including NG, power turbine speed NP and engine temperatures, enabling a much more comprehensive display of engine parameters to be made available to the pilot of the model.

One other addition was made to the model in order to support the “Lifting Standards” project. This was the incorporation of an attitude command/attitude hold (ACAH) controller in to the model. The controller was developed by the NRC to offer improved stabilisation and handling qualities over the unaugmented, bare airframe flight dynamics. The ability to assess aircraft dynamics and task performance with more than one set of handling qualities was considered to be important to the project, in that a broader view of rotary-wing operations could be considered. Multiple aircraft configurations would also allow investigation of the effect of configuration and response type on the required level of fidelity in a simulation environment.

As mentioned in section 2.4.3, the new simulator allows a user to tune the control loading system to produce a representative FCMC setup for a given aircraft. Using data supplied by the NRC for the Bell 412 ASRA aircraft, it was possible to replicate the stick forces in the simulator.

## 5. FLIGHT TESTS

The Bell 412 operated by the NRC has been heavily modified to create the “Advanced Systems Research Aircraft” (ASRA) [36] (Figure 9). The modifications to the aircraft have included the incorporation of a full authority digital fly-by-wire control system at one of the cockpit stations (flown by the Evaluation Pilot (EP)), enabling experimental control laws to be implemented and assessed whilst maintaining the safety of the original mechanical control system at the second cockpit station (flown by the Safety Pilot (SP)).

**Figure 9: NRC Bell 412 ASRA in Flight**

The second major modification to the ASRA is the instrumentation with which the aircraft has been equipped. This instrumentation includes inertial measurements based upon ring laser gyroscopes and force rebalanced accelerometers combined with GPS data, engine parameters and rotor activity. Aerodynamic data such as the angles of attack and sideslip are captured through a probe mounted on a boom extending ahead of the nose of the aircraft [37].

In a set of flight tests conducted on the Bell 412 ASRA, UoL gathered a database of in-flight data to support the “Lifting Standards” project. Several goals were set out in the planning of the flight testing:

1. To extend the range of data used for validation of the Bell 412 model, with clinical test inputs such as the 2-3-1-1 and frequency sweeps.
2. To generate a database of test points to allow the evaluation of the Bell 412 model against current ‘predictive’ criteria, such as JAR-STD 1H, and the quantitative component of ADS-33E-PRF.
3. To perform a series of piloting tasks to enable an assessment of the impact of the simulation environment on piloting strategies.

Two test pilots took part in ten sorties over a four day period. One of these pilots was UoL’s simulator commissioning pilot, who flew as the EP and was familiar with both the Bell 412 model and the test course layouts (from the piloted simulation), but had not previously flown the Bell 412 ASRA. The second pilot was provided by the NRC flying as the SP and was very familiar with both the Bell 412 ASRA and the test course layouts.

Flight testing was conducted using two aircraft configurations – "bare airframe“, with no control augmentation, and ACAH, using an attitude command controller. The UoL pilot was the primary test pilot during this flight trial and flew the majority of test points. A small number of the test points using an NRC test pilot were flown in order to allow comparisons to be made between different piloting techniques.

For the ADS-33-E-PRF tests, Cooper-Harper ratings [38] were given for each Mission Task Element and Visual Cue Ratings and Usable Cue Environment ratings were also taken. In addition, comments were invited regarding the cues (visual, aural, motion, controls etc.) that were being employed during the task.

In the JAR-STD 1H tests, the simulation model is compared to Performance and Trim Flight Control Positions (TFCP) allowing the simulation model’s trim characteristics to be assessed. Typical parameters include: engine torque, sideslip angle, pitch/roll attitudes, control positions etc.

### 5.1. Use of Piloted Simulation to Support Test Plan Development

The HELIFLIGHT-R simulator was used extensively as the test plan was being developed. With limited flying time available in Canada, the efficiency with which that time was used was important and the pre-flight test work-up in the simulator allowed the sortie priorities to be defined. This simulator utilisation focussed on three primary areas:

- Determination of realistic maximum amplitudes for control inputs and levels of aggression for each of the manoeuvres.
- Familiarisation with the environment around the Ottawa base of the Bell 412 ASRA, including the layout of the airport and the location/set up of each of the test courses for the handling qualities manoeuvres (Figure 10).
- Assessment of required timing for each manoeuvre, allowing the construction of a test plan that would be accurate and robust.

Table 2 provides details of the test manoeuvres flown in Phase 1 of the flight tests in Ottawa. Two non-standard ADS-33E-PRF manoeuvres were flown; roll-step and the hop-scotch. Due to lack of markings available on the runway at Ottawa airport, instead of flying a standard ADS-33E-PRF slalom, a roll step manoeuvre was flown based on one used in a project assessing the handling qualities criteria for a future European civil tilt-rotor aircraft [39] and was designed to provide some insight into the lateral agility/manoeuvrability of the test vehicle.

**Figure 10: In-Flight and Simulation Views of ADS-33 Test Course**

The hop-scotch manoeuvre was designed during the pre-flight test simulation trial to assess pilot control strategies when departing from and re-capturing stabilised hover at various angles. The task involved low-to-moderate aggression manoeuvres in which the aircraft is accelerated away from hover in the desired direction, and then brought back to a stabilised hover at a designated point, keeping height constant (less than 20 feet) throughout the manoeuvre. To introduce a time constraint into completing the MTE, the SP would begin a count of 2 seconds on arriving at a designated point prior to giving an instruction to the EP to continue along the course. Figure 11 illustrates the suggested route through the task which is as follows:

- Start at (1), looking towards (3). Traverse to (3). Angle 0°.
- Turn through 180° to look back at (1). Traverse to (6). Angle 90°.
- Continue looking ahead (now at (4)). Traverse to (7). Angle 44°.
- Continue looking ahead. Traverse to (8). Angle 180°.
- Continue looking ahead (now at (7)). Traverse to (4). Angle -44°.
- Turn left through 90° to look at (1). Traverse to (6). Angle -90°.

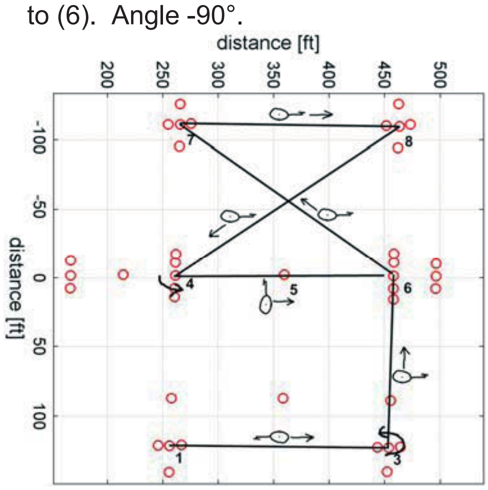


**Figure 11 Hop-scotch Manoeuvre**

The flight tests have generated a substantial new database, the analysis of which is still ongoing. The following sections provide detail of some of the initial analysis carried out on this data.

**Table 2 Flight Test Matrix**

| Test | Axes | Condition |
|---|---|---|
| ADS-33-E-PRF | | |
| 2-3-1-1 inputs | Lat/Log/Coll/Ped | Hover, 80kts, autorotation @ 70 kts |
| Frequency Sweeps | Lat/lon/ped | Hover |
| Quickness | Roll, pitch, yaw | Hover |
| Precision Hover<br>Accel-Decel<br>Sidestep<br>Pirouette<br>Roll Step<br>“Hop-Scotch” | | |
| JAR-STD 1H | | |
| Control Responses | Lat Lon Coll Ped | Hover, 80 knots |
| TFCP<br>Hover<br>Climb<br>Level flight<br>Vertical climb<br>Descent<br>Autorotation<br>Low Speed<br>Critical Azimuth | Left/right/back/forward* | (IGE/OGE)<br>70kts<br>70kts,105kts<br>70kts (1000fpm RoD)<br>50kts, 70kts 105kts<br>10/20/30/45kts* |
| Take-Off (AEO)<br>Approach to hover Landing (AEO)<br>Dynamic Stability:<br>Manoeuvring Stability<br>Static Stability<br>Response to Gusts<br>Entry to Autorotation<br>Autorotational Landing | Longitudinal, lateral directional<br>Longitudinal<br>Longitudinal, Directional, Lateral/directional | Hover, 80 kts<br>30° and 45° banked turns<br>80 kts,<br>80kts ±5° & ±10° β,<br>80kts – Turn on 1 control |

## 5.2. Simulation Model Validation Using ADS-33E-PRF Parameters

Results from flight test of the Bell 412 ASRA have been used to assess the fidelity of the simulation model in terms of accuracy of prediction of ADS-33E-PRF parameters, such as quickness, bandwidth and modal stability.

For each handling qualities measure, the result for the Bell 412 has been calculated from flight test data. For the simulation model, a range of results have been generated using different FLIGHTLAB modelling options. This has allowed an assessment of the sensitivity of each handling qualities measure to the various options available within FLIGHTLAB to be conducted, showing where the mathematical fidelity of the model can be improved. The models are defined in Table 3.

**Table 3: FLIGHTLAB Bell 412 Model Definitions**

| Model | Components |
|---|---|
| 01 | FLIGHTLAB Bell 412 simulation model with turboshaft engine |
| 02 | As 01 but with empirical inflow correction and rotor wake distortion |
| 03 | As 01 but with finite state interference modelling from main rotor to tail rotor; the fuselage; the vertical fin and the horizontal stabilisers |
| 04 | As 01 but with both inflow and interference effects applied |
| 05 | As 01 but with time lag of 100 ms in control path |
| 06 | As 03 but with time lag of 100 ms in control path |

For each assessment point, the configuration of the simulation model was set so as to precisely match the weight and c.g. location at which the aircraft was operating for the equivalent flight test point.

Pitch bandwidth in the hover is shown in Figure 12. The flight testing for this point was conducted from the SP cockpit station, meaning that the original mechanical systems were employed, thus bypassing any time lags that may be introduced by the FBW system. The models with the best match to the bandwidth are Model 03 and Model 04. However, the influence of the inflow modelling options, as seen with Model 02 appears to be to cause an increase in the phase delay, meaning that Model 03 gives the best match to the flight test data.

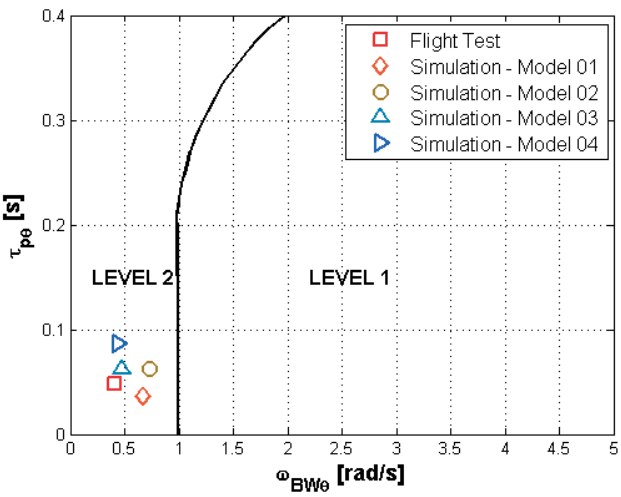


**Figure 12: Pitch Bandwidth in the Hover**

When the aircraft is being flown through the FBW system with the EP controls, the phase delay is generally higher, as is illustrated in Figure 13 for the yaw axis. In this case, none of the simulation models accurately match the flight test result, with the bandwidth being higher and the phase delay much less in every case. The modelling options appear to have minimal effect on the bandwidth, although it could be said that Model 02 and Model 04 move the result slightly in the correct direction.

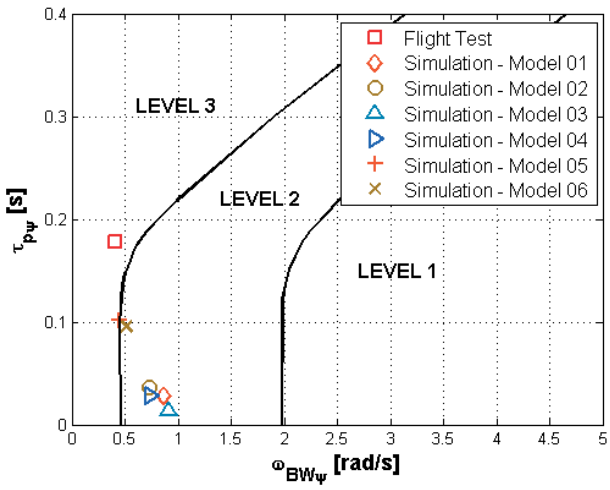


**Figure 13: Yaw Bandwidth in the Hover**

The primary cause of this large difference is the time delay in the FBW system, which is not captured in any of the simulation models discussed to this point – a change in inceptor position creates an immediate result at the swashplate.

Model 05 and Model 06 begin to address this modelling deficiency by incorporating a pure time lag of 100ms within the control path. They are otherwise identical to Model 01 and Model 03 respectively. It is clear that this time lag significantly improves the accuracy of the bandwidth prediction. For off-line analysis of a simulation model, the importance of accurately capturing the transport delays within a control system can be seen. However, for piloted simulation, the situation is somewhat less clear, as the simulator itself will be subject to its own time delays. Therefore In order to give the pilot the correct representation of the time delays of the aircraft, the delay in the mathematical model must be combined with the delay in the simulator to give the correct total delay, as experienced on the aircraft.

Turning from a closed loop stability measure in bandwidth to open loop stability, Figure 14 shows the stability of the Phugoid mode in the hover. While the flight test data shows the aircraft to be extremely unstable in this condition, with a time to double amplitude of the mode of just 2 seconds, the standard FLIGHTLAB model, Model 01, shows much better handling qualities, with a time to double amplitude as high as 5.7 seconds.

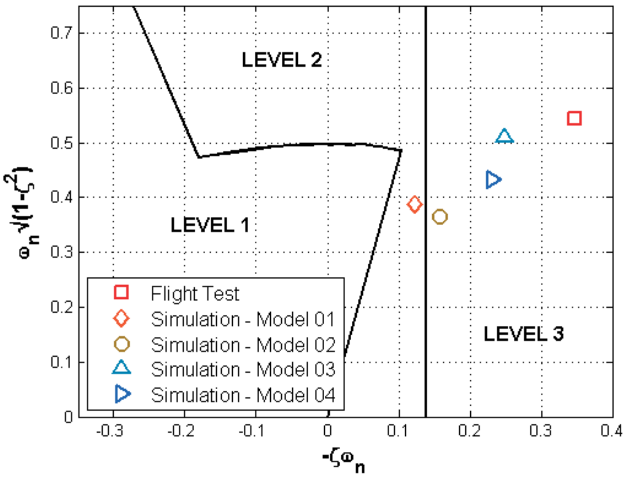


**Figure 14: Phugoid Stability in the Hover**

Each of the options that have been assessed improves the fidelity of modelling of the Phugoid mode, although it can be seen that by far and away the largest improvement comes from Model 03, which applies interference between the main rotor and the horizontal stabilisers. An interesting point to note is that, although Model 02 shows increased Phugoid mode instability over Model 01, when the same options are applied to Model 03 to create Model 04 the instability of the mode actually reduces.

The Dutch Roll in cruise at 80kts is poorly damped in flight, but the frequency is relatively low (Figure 15). The simulation model predicts similar Dutch Roll damping, but combined with a much higher natural frequency. None of the modelling options captures the Dutch Roll dynamics with excellent accuracy, although it can be seen that, once again, Model 03 produces the result that most closely approximates the flight test data.

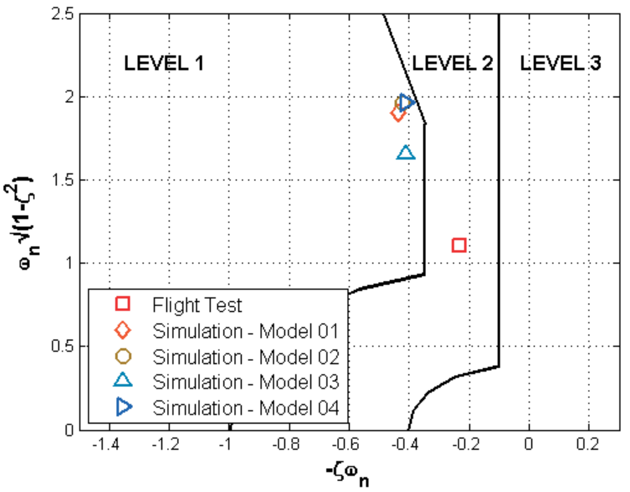


**Figure 15: Dutch Roll Stability at 80kts**

ADS-33E-PRF employs attitude quickness as a measure of the agility of an aircraft. Quickness is calculated by dividing the peak rate achieved following a sharp control input by the resulting attitude change.

Figure 16 shows results for positive and negative (not differentiated) control inputs in the pitch axis, in hover. Although the achieved attitude changes vary quite considerably between the various modelling options, it can be seen that all of the results fall on the same 'curve' of data, suggesting that the dynamics of the models are similar, even though the pitch rate that results from each of the control inputs is somewhat different.

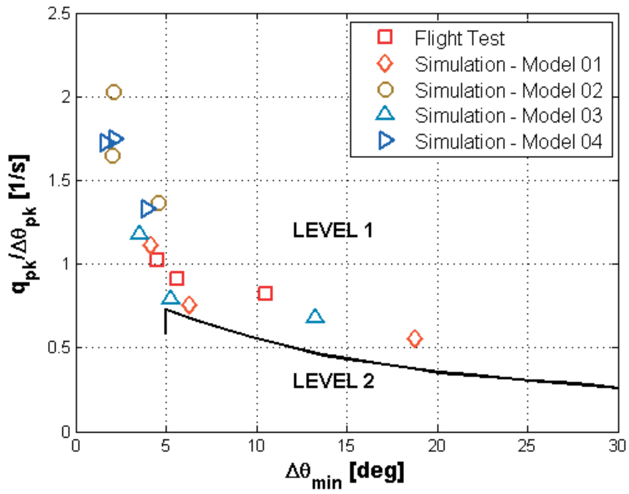


**Figure 16: Pitch Quickness in the Hover**

In terms of achieving the most accurate prediction of the flight test results, once again, Model 03 delivers the nearest attitude change for all three control inputs. Model 02 and Model 04 both produce attitude changes that are significantly smaller than the flight test data showed.

In summary, therefore, it has been shown that the prediction of the handling qualities level for each of the ADS-33E-PRF parameters is generally correct for all of the simulation models. An exception has been found in the natural frequency of the Dutch Roll in cruise at 80kts, where the higher frequency of the simulation models leads to a prediction of Level 1 performance, whereas the flight test data shows Level 2 performance.

The options that are selected within the FLIGHTLAB model can have a significant effect on the accuracy of the predictions. In particular, the inclusion of interference effects between the main rotor and the empennage/tail rotor has been shown to be of great significance to the accurate prediction of longitudinal handling qualities.

### 5.3. Flight Test Results – Potential Impact on Fidelity Requirements

The ADS-33E-PRF pirouette manoeuvre was flown, in which the task is to translate laterally along the circumference of a circle of 100ft radius, whilst keeping the nose of the aircraft pointing at the centre of the circle.

With the bare airframe configuration, both pilots found this task to be quite difficult (Figure 17), especially in terms of maintenance of longitudinal position. The workload required was very high in both cases, although as can be seen, the UoL pilot was generally applying larger amplitudes in his corrections. The frequencies at which corrective inputs were made were similar. In each case, the pilot found that the effort required to achieve this level of performance resulted in minimal spare capacity, especially at the half-way point in the manoeuvre when the wind was blowing from the rear of the aircraft.

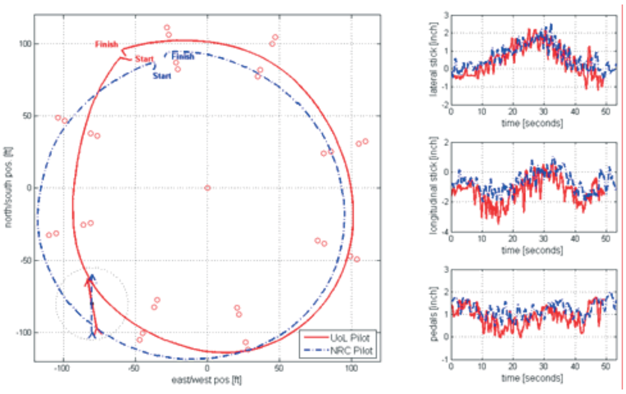


**Figure 17: Flight Test Results - Pirouette**

It is evident that the two pilots were applying similar, but at the same time different, control strategies as they navigated around the pirouette course. Despite this difference, both pilots considered the deficiencies to be similar and awarded the aircraft a Cooper-Harper HQR of 6. A key issue to be addressed in the development of simulation fidelity criteria is therefore; does the type of pilot affect the requirements? In this case, the more aggressive technique being applied by the UoL pilot would push the aircraft, and therefore the simulation model, closer to the limits of the flight envelope, potentially exposing deficiencies in the model that the NRC pilot would not observe.

A second manoeuvre was the acceleration-deceleration, in which the aircraft is accelerated longitudinally to 50kts, followed immediately by a symmetrical deceleration back to the hover. Due to the limited length of the test course available, the target airspeed was reduced to 40kts. This adjustment created a task that demanded a high level of aggression but that was achievable with the Bell 412.

Figure 18 shows the performance achieved by the UoL pilot with both bare airframe and ACAH aircraft configurations. In the primary task axis, performance and workload were similar, although the additional compensation that is being provided by the ACAH controller is evident.

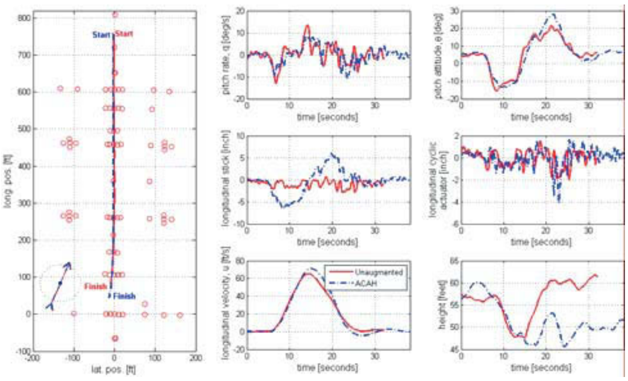


**Figure 18: Acceleration-Deceleration Results - On Axis Performance**

However the picture is very different when off-axis performance is examined, (Figure 19). Here, the benefits of the ACAH controller are evident, with the required pilot effort to suppress inter-axis couplings and instabilities being dramatically reduced.

The off-axis disturbances seen in Figure 19 were the primary deficiencies (bare airframe configuration), limiting the performance that could be achieved to adequate only, which, combined with the very high workload, resulted in a HQR of 6 in this task.

With the ACAH controller, task performance was within the desired limits for the duration of the manoeuvre. However, despite the elimination of inter-axis couplings, the workload remained high, leading to a HQR of 4 for this task.

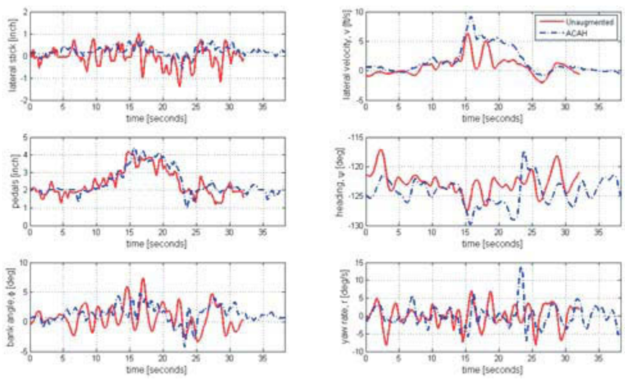


**Figure 19: Acceleration-Deceleration - Off Axis Performance**

The main driver for the workload with the ACAH controller was monitoring of the rotor torque. The Bell 412 suffers from an under-damped engine governor response, which produces oscillations in torque. Monitoring of these oscillations, and the taking of corrective action to prevent exceedance of the operational envelope for rotor torque, contributed significantly to the workload, and was a factor in limiting the aggression that could be applied.

Although the operational torque limit for the Bell 412 is 100%, a safety limit is imposed within the FBW system to allow the SP sufficient margin to recover in the event of an exceedance by the EP. This torque limitation, together with similar limitations in place on the other axes, constrains the envelope within which the EP can fly the aircraft to less than the operational limit of the aircraft itself. This highlighted the importance of accurately capturing all of the characteristics within the simulation model – the FBW limits had not been incorporated into the model prior to the flight testing, allowing the UoL pilot to be more aggressive in his work-up with the model than he would be able to be in flight.

A second important question can therefore be posed – to what extents do the characteristics of the aircraft itself affect the requirements for simulation fidelity? This example showed that it was essential to provide at least a representation of the FBW safety system within the simulation model in order to ensure that the correct aircraft limits are observed.

### 5.4. Effect of Simulation Environment on Task Performance

A series of piloted simulation tests have been performed using the Bell 412 model to generate comparison data between flight test and the equivalent manoeuvres performed in the simulator. The piloted simulation has been conducted using the same UoL pilot as participated in the flight testing and the initial simulator commissioning process.

A visual database that is representative of the environment around the international airport in Ottawa was used for all of the piloted assessments, giving the pilot similar near- and far-field visual cues to those experienced in flight.

One of the manoeuvres flown was the “roll step”. In this task, the aircraft approaches at an airspeed of 60kts along the left hand side of the runway. At a designated point, a sharp right jink is initiated to re-align the aircraft with the right hand side of the runway, again at a designated point. Following a stabilisation period, the manoeuvre is reversed to return the aircraft to the left hand side of the runway. This profile is illustrated in Figure 20, which shows ‘roll step’ task performance with the bare airframe configuration. For the simulation, Model 01 was employed.

The task flown by the pilot in the simulator, in terms of the route taken along the runway and the bank angle and heading changes applied during the transitions, was very similar to that flown in the real aircraft. The only significant difference is that, in the simulator, the pilot began the run slightly closer to the runway edge, leading to a larger lateral translation, and hence slightly delaying the roll reversal to capture the right hand runway edge.

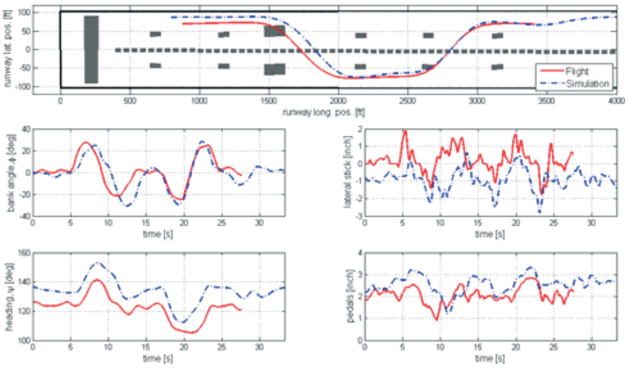


**Figure 20: Roll Step – Primary Task Performance**

The control inputs applied to the aircraft throughout the manoeuvre were very similar in terms of the amplitude and duration required to generate the course changes. A slightly higher frequency of stabilisation input is evident in the flight test data – possibly the result of the pilot having to apply a higher gain to his control inputs in flight to overcome the more deficient Dutch Roll handling qualities.

Away from the primary task of navigating across the runway, other differences can be seen (Figure 21). The first of these is the much higher amplitude and frequency of corrective input required in the longitudinal axis to maintain the target airspeed of 60kts with the simulation model.

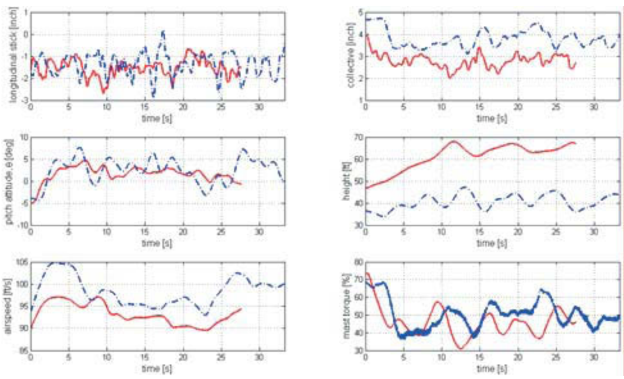

**Figure 21: Roll Step – Off-Axis Performance**

Model 01 exhibits a Short Period mode that has significantly greater damping at 60kts than was found in flight test, indicating that this is not the source of the difficulties experienced by the pilot. The Phugoid mode exhibits similar damping ratios in both flight test and Model 01. However, the natural frequency of the Phugoid in Model 01 is approximately 50% higher than the natural frequency in flight. This higher frequency would contribute to additional workload for the pilot. However, it likely cannot fully explain the much greater control activity observed with the simulation.

Model 03 was predicted to offer a greater level of fidelity than Model 01. How does piloted performance in the roll step manoeuvre differ between the two models?

Figure 22 shows the on-axis task performance of the UoL pilot in roll step manoeuvres performed using Models 01 and 03. As anticipated in the predictive analysis section, the degraded Dutch Roll HQs in Model 03 demand greater compensation from the pilot in order to accomplish a task of slightly lower accuracy.

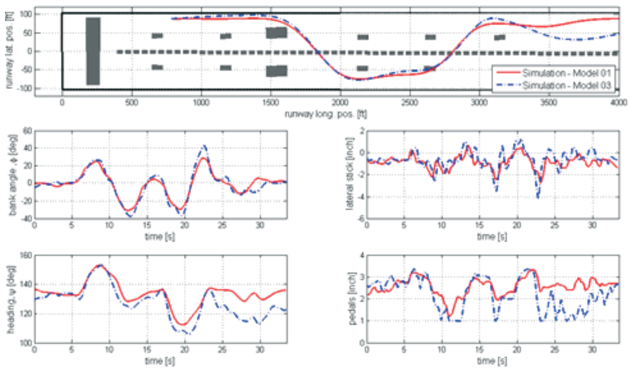


**Figure 22: Comparison of Roll Step Performance between Simulation Models**

Off-axis, the pattern is similar with both models, although it is possible to say that the magnitude of corrective inputs applied was slightly greater with Model 03 than with Model 01 (Figure 23). This is in apparent contrast to the predicted results, where it was expected that Model 03 would provide better longitudinal HQs than Model 01.

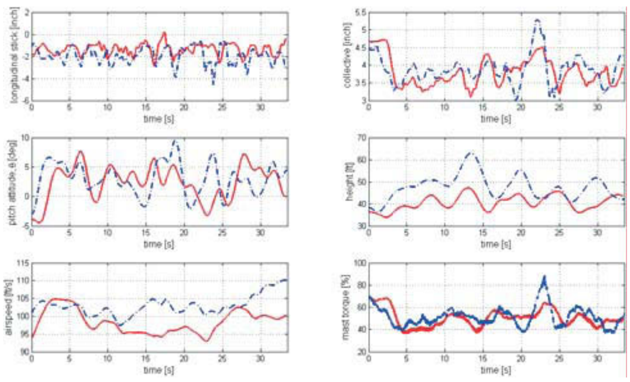


**Figure 23: Simulation Modelling Options - Off-Axis Roll Step Performance**

However, when the airspeed is taken into account, it can be seen that the greater level of effort that has been applied by the pilot to Model 03 has allowed him to achieve much better airspeed tracking performance. Height tracking is slightly worse however with Model 03.

These observed differences were backed up by the pilot's comments following each of the runs. He considered that Model 03 allowed him to achieve better pitch and airspeed control, but at the expense of degraded roll, yaw and height control.

If the predictive analysis presented above were to be used as a basis for identifying model differences that might impact on a pilot's ability to perform the task, a positive outcome has been observed. It was found that laterally, the predicted performance correlated closely with the achieved performance and workload. In contrast, the predicted change in performance longitudinally was not as immediately obvious in the data, especially in terms of longitudinal stick corrective inputs. Analysis of the pilot's comments following each of the runs did, however, reveal the expected changes in handling qualities.

Two other aspects of the simulation that may affect the pilot's ability to control the airspeed are the visual cueing that is being provided, and vestibular cues that are detected from the motion platform. The visual database contains a simplified representation of the terrain details around the runway on which the 'roll step' manoeuvres were flown. It is possible that one of the elements of the visual scene that the pilot uses to determine his translational rate is not present. Another indicator of deficient visual cues is the height at which the tasks were flown. The pilot was asked to perform the manoeuvre at a height which felt natural and comfortable to him. In flight, this resulted in the 'roll step' manoeuvre being flown at a height of approximately 65feet. However, in the simulator, this height was reduced to only 40feet, the pilot commenting on the need to go lower in order to be able to generate the immediacy of cueing that he felt was necessary in order to perform the task.

The cues from the motion platform were tuned for general helicopter operations. The 'roll step', however, is a very aggressive manoeuvre, demanding large lateral displacements from the platform. It is possible that the much more subtle surge cues are being obscured or masked by the other axes.

In flight, the pilot commented that the task required a considerable level of compensation, especially in the roll axis. However, his primary concern as far as task performance was concerned was height above the runway, where the maximum height of 68feet during the capture on the right hand side of the runway was only marginally within the adequate performance boundaries. A HQR of 5 was awarded.

Simulation of Model 01 resulted in considerably greater effort longitudinally, and a perception from the pilot that the task was harder than in flight. A HQR of 6 comes as no surprise. However, the pilot gave as the primary reason for the rating a very objectionable roll response, which is interesting given the lack of roll control activity relative to the flight test. Figure 20 shows a less 'smooth' flight path along the runway in the simulation data, which may have contributed to the pilot's perception of deficiencies in the roll response. Model 03 closed some of the gaps between the predicted performance of the simulation model and flight test. Although the changes in predicted performance were realised in the piloted simulation, the change in task performance and pilot workload was relatively minor in comparison to the differences between simulation and flight. HQRs of 6 were awarded for both of the simulated runs.

Overall, although it is likely that the mathematical modelling will have affected the task performance in the simulation environment, the differences cannot fully explain the increased difficulties experienced by the pilot in the simulator to those he experienced in flight. Other aspects, such as visual and motion cueing, are playing a part, and the influence of these parameters must be examined more fully to assess their true impact on the task.

## 6. PILOT PERCEIVED FIDELITY

Central to the operation of a simulator is the pilot who not only undertakes the training or research task at hand, but also provides feedback on the suitability of the simulator in that role. In the case of flight training, a rigorous process is followed to ensure that the component fidelity is of a defined standard for a given training task. This is subjectively assessed by an evaluation pilot who may make recommendations for modifications to the simulator environment based on their "sensing" of the simulator's "perceived" deficiencies. It is assumed that the deficiencies would also be an issue for other pilots undertaking the task and must be addressed.

In the research environment the question of perceived fidelity is just as valid with the pilot indicating whether or not overall fidelity of the simulator is high enough to ensure the validity of the research findings. The main characteristics may be considered to be Quantitative or Subjective for a number of sub-characteristics namely; visual, motion, audio, FCMC, displays, cockpit station, environment, aircraft model (flight, ground) and latency (visual and motion).

Quantitative measures cover components that can be reproduced in the simulator as a direct match of the real aircraft e.g. control configuration, forces and envelopes, cockpit layout, displays etc.

Subjective measure fidelity is the degree to which the pilot subjectively perceives the simulator to replicate real world operation with respect to physiological impressions in flight (and on ground) in an operational task setting.

The more robust the simulator is with respect to Quantitative measures the better but a compromise has to be made for a research simulator such as HELIFLIGHT-R since the cockpit will be generic. However FCMC and displays can still be accurate for the type being flown.

The sub-characteristics can be given descriptors according to the complexity of each task such that a fidelity level could be defined. The difficulty here lies in defining the required or expected realism for the sub-characteristics, their weightings in terms of importance to the overall system and what minimum combination equates to high fidelity as judged by the pilot.

Whilst components of the simulator system have been subjected to some calibration or validation, the pilot does not undergo any calibration, relying on previous flying experience to identify deficiencies and provide feedback on test conditions. As the pilot is acting as a sensor, giving a subjective opinion on test points, it is important to gain a baseline of what that sensor is doing and what tolerances are applicable.

Answering the open question "How do you calibrate a pilot?" compliments the lifting standards research activity and will be the focus of two Masters' projects at Liverpool commencing in September 2009. It is anticipated that the projects will develop fundamental tests to investigate a pilot's sensitivity to various stimuli and then to examine the relationship between these sensitivities and changes in the flight simulator environment.

## 7. CONCLUDING REMARKS

This paper has described the new simulator capability at the University of Liverpool, HELIFLIGHT-R, in the context of research into simulation fidelity. The new facility represents a significant capability upgrade from the existing HELIFLIGHT at Liverpool, including a wider field of view, larger motion envelope, force feedback system and interchangeable multi-crew cockpit layout. During its first year of operation, the simulator has been used to support the undergraduate/postgraduate Aerospace Engineering degree programmes and extensively in new and ongoing research projects. At the time of writing the new simulator has been used for over 700 hours and will surpass 800 hours by the end of its first year of utilisation.

The need for unified metrics in rotorcraft flight simulation has been discussed. For a flight training simulator, industry uses a physical modelling and non-physical tuning process (based on pilot subjective opinion) to determine the fidelity of a simulator. Standards such as JAR-STD 1H define the model tolerances required to satisfy fidelity requirements of a rotorcraft simulator. Previous studies have shown that the relationship between fidelity and these tolerances is sensitive to the nature of the manoeuvre performed and also the errors in the simulation model. The standards used to define fidelity levels for training simulators are not appropriate to assess the fidelity of simulators used in a highly flexible research environment, however. Subjective pilot opinion does play an important role in assessing a simulator's fitness for purpose, but there is a need to develop objective measures of fidelity in order to validate flight training standards and produce new research simulator requirements. The complementary use of predicted and pilot-assigned fidelity is seen as the way forward here.

The use of HELIFLIGHT-R in a new research project, Lifting Standards, aimed at developing objective measures of rotorcraft simulator fidelity, has been described in the paper. Lifting Standards includes a series of flight tests using the NRC's Bell 412 ASRA aircraft and the initial results from the first test campaign have been presented in this paper. Analysis of the flight test data has shown influences on the results from piloting strategy and aircraft response type.

Examination of the FLIGHTLAB Bell412 flight model indicates a good match between the model predictions and the flight test data using ADS-33E-PRF handling parameters, such as attitude quickness, bandwidth and modal stability. Incorporation of enhanced rotor wake effects into the flight model produced improvements in the prediction of the ADS-33E parameters when compared with flight test data.

Some preliminary piloted simulation tests have been reported in which the task performance whilst flying the roll-step manoeuvre was affected by changes in the flight model as predicted by the off-line analysis. Incorporation of rotor wake effects into the flight models resulted in a decrease in Dutch roll stability and an improvement in Phugoid stability, the latter allowed improved air speed control whilst directional control was more difficult. Whilst this change brings the simulation results closer to those found in flight, a discrepancy between them exists. This may be as a result of the simulation environment and will be investigated further.

The Lifting Standards project will continue the analysis and interpretation of the flight test data and comparison with simulation, developing fidelity measures based upon both subjective pilot opinion and objective metrics. In particular the following areas will be examined:

- Affect of simulation environment (e.g. motion tuning, field of view) on task performance
- "calibration" of pilots acting as a sensor
- Assessment of flight model fidelity on pilot control strategies
- Development of pilot-vehicle models to facilitate metric development
- Introduction of a subjective fidelity rating scale
- Development of new flight test manoeuvres for use in the assessment of fidelity criteria.

These will be supported by further flight trials at the NRC and the results reported in future publications.

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