PROGRESS IN THE DEVELOPMENT OF UNIFIED FIDELITY METRICS FOR ROTORCRAFT FLIGHT SIMULATORS

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Abstract

Flight simulators are integral to the design/development, testing/qualification, training and research communities and their utilisation is expanding rapidly. The quantification of simulation fidelity underpins the confidence required for the use of flight simulation in design, to reduce real life testing, and to provide a safe environment for pilot training. Whilst regulatory simulator standards exist and new standards are in development, previous research has shown that current standards do not provide a fully quantitative approach for assessing simulation fidelity, even in a research environment. This paper reports progress on developments of the HELFLIGHT-R flight simulator at the University of Liverpool, and its subsequent use in a research project (*Lifting Standards*) aimed at creating new predicted and perceived measures of simulator fidelity, derived from handling qualities engineering. Results from flight tests on the National Research Council (Canada) Bell 412 ASRA research aircraft and HELIFLIGHT-R piloted simulation trials are presented to show the strong connection between handling qualities engineering and fidelity assessment. The issue of (pilot) perceived fidelity is examined and the development of new metrics discussed.

NOTATION

CP_ϕ,CP_θ, CP_ψ	Roll, pitch yaw Control Power (°/s)
$\dot{h}$	Height rate (ft/s)
p, p_{pk}	Roll rate, peak roll rate (°/s)
Q_ϕ, Q_θ, Q_ψ	Roll, pitch, yaw quickness (/s)
q, q_{pk}	Pitch rate, peak pitch rate (°/s)
r, r_{pk}	Yaw rate, peak yaw rate (°/s)
$r_{(1)}$, $r_{(3)}$	Yaw rate at 1s, 3s (°/s)
T_{hdot}	Time constant (s)
Xa	Pilot lateral control (inch)
Xb	Pilot longitudinal control (inch)
Xc	Pilot collective control (inch)
Xp	Pilot pedal control (inch)
ζ	Damping
η	Pilot control deflection (nd)
θ, ϕ, ψ	Pitch, roll, yaw attitude (°)
τ_{hdot}	Response delay time (s)
$\tau_{p\phi}$,$\tau_{p\theta}$,τ_ψ	Roll, pitch, yaw phase delay (s)
$\omega_{p\phi}$,$\omega_{p\theta}$,ω_ψ	Roll, pitch, yaw bandwidth (rad/s)

ACRONYMS

ACAH	Attitude Command Attitude Hold
ADS	Aeronautical Design Standard
ASRA	Advanced Systems Research Aircraft
EPRSC	Engineering and Physical Sciences Research Council
FAA	Federal Aviation Authority
FBW	Fly by Wire
FS&T	Flight Science and Technology Research Group
FoV	Field of View
GARTEUR	Group for Aeronautical Research and Technology in Europe
HQR	Handling Qualities Rating
JAR	Joint Aviation Requirement
MTE	Mission Task Element
NRC	National Research Council (Canada)
OTW	Out-the-Window
UCE	Usable Cue Environment
UoL	University of Liverpool
SoR	Statement of Requirements
STD	Synthetic Training Device
VCR	Visual Cue Rating

INTRODUCTION

Flight simulators are extensively used in engineering design, development and flight training, and are an essential tool in the conceive-design-build and qualification processes of rotorcraft. However, simulators have an inherent flaw: despite their complexity and the use of state of the art components, they are not able to provide a fully coherent representation of reality and 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. 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 [1] and FAA AC120-63 [2] describe the qualifying criteria and procedure for rotorcraft flight training simulators and detail the component fidelity required to achieve a “fit for purpose” approval. Whilst these standards serve a vital role in the regulatory process, the influence of the cueing environment on pilot opinion during qualification needs to be understood better. Currently there are no quantitative methods used to assess the fidelity of the overall system, with the pilot performing a task. The current development philosophy of the European JAR-STD 1H specification is that simulator requirements “*should be applied in practice and the lessons learned embodied in future amendments*”, providing an opportunity to incorporate new fidelity criteria when appropriate. It is the need to have objective measures of predicted fidelity, supplemented by subjective measures of perceived fidelity, that is main focus of an EPSRC funded project “*Lifting Standards: A Novel Approach to the Development of Fidelity Criteria for Rotorcraft Flight Simulators*” [3]. The approach follows the fundamental constructs of handling qualities engineering.

In 2000, a single seat, full motion flight simulator, HELIFLIGHT [4][3] was commissioned in the Department of Engineering at the University of Liverpool (UoL). The facility has been operated by the Flight Science and Technology Research Group (FS&T), and successfully used both in research projects funded by the Engineering and Physical Sciences Research Council (EPSRC), European Commission, Ministry of Defence and Industry and in the teaching curricula. Based in an academic environment, HELIFLIGHT has been utilised as an interactive teaching tool for undergraduate and postgraduate projects, flight handling exercises and laboratory classes [5] . 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 crew station technologies. The requirement specification for this simulator was, broadly, to have a motion capability, a “reasonably” wide field of view, programmable force feel and a modelling environment compatible with the FLIGHTLAB modelling system [6], running on a PC-based architecture. In addition, the requirement to be able to simulate both rotary and fixed-wing aircraft was mandatory.

The use of HELIFLIGHT in research projects was key to a number of achievements including; development of handling qualities criteria and load alleviation concepts for a European civil tilt-rotor [7],[8], the development of pilot guidance strategies and display concepts in fixed-wing and rotary wing flight [9],[10] [9]and the prediction of simulator-based ship-helicopter operational limits [11-15].

HELIFLIGHT has capability limitations however, e.g. a limited 135 x 40 degree field of view visual system with a single seat crew station, 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 to allow a system to be developed, delivered and installed during the wide-ranging Engineering Restructuring Project at the University.

Driving the requirement [16] for a new simulator was the need for extra capacity and capability enhancement, whilst ensuring that fidelity was “sufficiently” high to ensure it was “fit” to be used as a research tool.

This paper initially reviews the commissioning work undertaken prior to commencing research activities. We then provide an overview of the current simulation qualification process and highlight the need for objective metrics and the limitations identified in the current simulator standards. The main body of the paper presents initial results from the fidelity research and discusses the importance of complementary predicted and perceived fidelity.

HELIFLIGHT-R SIMULATION FACILITY

In 2006, a specification for a new flight simulator was developed and put out to tender. The main driver for the new specification was to address some of the shortcomings of HELIFIGHT e.g. limited field of view, lack of programmable tactile cueing functions, single seat crew station. The facility would not only enhance FS&T’s capability but would also increase the level of simulator capacity within the research group which was limiting operational availability. A statement of Requirements (SoR) [16] was produced and, following a tendering process during summer 2006, ART’s HELIFLIGHT-R simulator (**Error! Reference source not found.**) was selected as the best match with the SoR.

Figure 1 HELIFLIGHT-R Simulator

Features of HELIFLIGHT-R (Fig.1) include:

- 12 ft visual dome with 3 x LCoS HD projectors on gimballed mounts to provide up to 210x70 deg. (field of view) FoV
- Interchangeable crew stations with front pilot and co-pilot seats and a rear engineer seat
- Moog FCS ECoL 8000 Q&C-Line electric control loading system four-axis control loading
- Moog MB/E/6dof/24/1800kg electric motion system
- Instructor-Operator Station PC
- Reconfigurable instrument panel displays (left and right primary flight displays, backup analogue displays and Head Up Display)
- the selective fidelity FLIGHTLAB multi-body flight dynamics modelling environment

Commissioning and Acceptance Testing

HELIFLIGHT-R was delivered to the University of Liverpool in July 2008. During the installation process a commissioning test pilot carried out a 2-day evaluation. The commissioning process determines both the suitability of the simulator for the role and identifies any deficiencies, enhancing features and areas of potential development.

Initial areas of investigation included safety, operability and functional specification compliance, both in terms of applicable civil/military standards and contractual compliance. This latter point provides the baseline against which the commissioning process is measured since the performance of the simulator must, as a minimum, meet user specifications.

In the research role a flight simulator is not a replica of a specific aircraft, but rather must be capable of representing a wide range of aircraft types, and this challenging task sets research simulators apart from their more traditional counterparts. Consequently the crew station, inceptors, visual and motion systems must engender sufficient cueing to ensure a high degree of immersion in the task such that the quality of research output is not in question. It was this characteristic which was investigated in depth as part of the commissioning process and also its flexibility as a research facility when establishing whether it was fit for purpose. In parallel with the evaluation, a portfolio of operating procedures were compiled to optimise the research process, and to ensure safe and efficient operation of the facility.

HELIFLIGHT-R Features

Visuals: As delivered, the visual system used three Silicon Optix Image AnyPlace Video Scaler boxes to warp and edge blend the 3 out-the-window (OTW) images into one scene on a 12 foot diameter visual dome. The image generation was provided using Boeing’s Multi-Purpose Viewer, an Open Scene Graph based tool that supports rendering of any OpenFlight terrain or object database. A further integration activity was undertaken to allow the system to operate BAE’s Landscape run-time [17], ensuring compatibility with the HELIFLIGHT system. Whilst this combination of hardware and software provided a strong visual cueing environment, there was scope for further enhancement of the system in the areas of image resolution, image warping, pilot eye-point and instrument panel layout.

The resolution of the image generation system was limited to 1024 x 768 pixels per channel whilst the projectors themselves were capable of running at a higher 1400 x 1050 resolution. With the existing system, in order to run at the higher resolution it would be necessary to produce a new image map of the dome requiring new development software and hardware and the extraction of the crew station.

The image warping system provided a continuous 180° horizontal FoV which did not fully utilise the viewing area of the projection dome. In the upper and lower regions of the OTW scene the image was non linear, producing a slightly unrealistic viewing window. The three images were blended together in 2 blend regions and whilst the “static” image was aligned well, some blurring and latency deficiencies were observed during real-time operations.

The reference eye-point for the image generation was located in the centre of the crew station between the pilot and co-pilot seats. Whilst this meets the requirements for fixed wing simulators it was preferable for the rotary wing projects to have the ability to locate the pilot’s eye-point to either the left or right hand seat.

Figure 2 OTW Scene from HELIFLIGHT-R

In collaboration with the Flight Simulation group at BAE (Warton), integration of a Rockwell Collins Mercator III distortion correction system into HELIFLIGHT-R was achieved. Replacing the Image AnyPlace scalers, Mercator allows fixed matrix projectors to be used in curved screen applications. This system was installed in August 2009, allowing the resolution of the visual system to run at the full 1400 x 1050 provided by the projectors. During the image warping setup, the pilot reference eye-point was relocated to the left hand seat as this was the operational requirement for the research project *Lifting Standards* (evaluation pilot flies from left seat in the National Research Council (NRC) of Canada's Bell 412 Advanced Systems Research Aircraft (ASRA)). The new image map allowed the horizontal range of the image to cover a 210° horizontal section of the dome and the upper and lower image edges were warped to produce a more realistic letterbox OTW image was produced (**Error! Reference source not found.**).

Instrument Panel: HELIFLIGHT-R was delivered with a generic instrument panel (Figure 3) which provides the pilot with essential flight information including radar altimeter, barometric altimeter, airspeed, ADI, vertical speed, and slip ball.

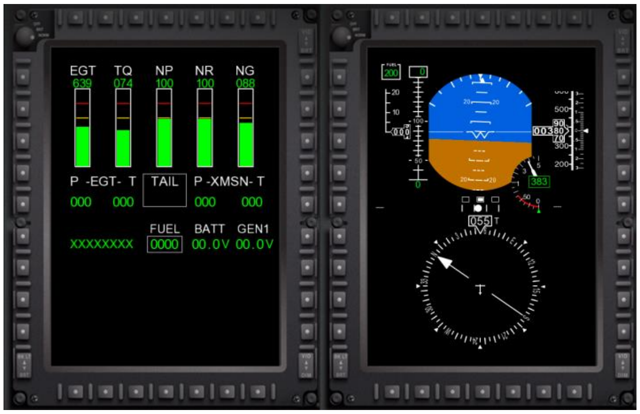


Figure 3 HELIFLIGHT-R Instrument Panel

An important aspect of high fidelity piloted simulation is to try to ensure that the pilot undertakes the flying tasks in the same manner that they would in the real aircraft. In the SoR there was no requirement for type specific instrumentation in the simulator. Instrument scan plays an important role in maintaining real world flying techniques and to this end the default HELIFLIGHT-R instrument panel environment was replaced with panels developed using Presagis' Human Machine Interface development software, VAPs. Using the VAPs software a replica of any instrument panel can be developed using photo-realistic textures for the dials and instruments, driven by variables from the flight model. Following the flight trials at the NRC, time was spent photographing the Bell 412 instrument layout and a new type-specific instrument panel was produced (Figure 4).

Figure 4 VAPs Bell 412 Instrument Panel

THE NEED FOR UNIFIED FIDELITY METRICS

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 [18]. Successful completion of the conception-design-build-test / qualification-production-operation cycle of helicopters is highly dependent on the use of modelling and simulation, but fidelity is critical to confidence at early stages of the life cycle.

Quantifying fidelity, using an engineering metrics approach, underpins this confidence, 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 [19]. To achieve the goal of an 80% reduction in accidents, targeted by the International Helicopter Safety Team [19], new technologies and aircrew training solutions, alongside enhanced safety practices, are required.

In the context of rotorcraft requirements capture and design, simulators are commonly used to assess handling qualities and develop 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 [20], [21], [22] 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., [23] and later McCallum and Charlton [24] proposed the use of the handling qualities standard, ADS-33E [25], 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 [26] and Roscoe and Thompson [27] 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 need for fidelity criteria for use 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; similar arguments can be tabled for the development of flight training.

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 [1] and FAA AC120-63 [2] describe the qualifying criteria and procedures 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, but only applied to a limited range of aircraft responses. 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 [28], [29], conducted sensitivity analyses using the JAR training simulator standards [1], including correlation of handling qualities and fidelity metrics, and revealing several 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 [30], [31].

Experience highlighted in the GARTEUR HC-AG12 study [28], [29], showed that, in most areas, 80% "fidelity" should be achievable with physical model tuning with the remaining 20% requiring artificial tuning. While this may be able to correct problems in a specific flight condition, it often has an adverse affect in other parts of the flight envelope. To achieve an acceptable level of performance, modifications are often 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.

A Royal Aeronautical Society [32] sponsored initiative is underway to rationalise the various qualification standards; however, the rotary wing requirements are likely, once again, to follow the framework developed for fixed wing aircraft.

Rationalisation of simulator standards, either fixed 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. This is the theme of research underway at Liverpool.

LIFTING STANDARDS: THE DEVELOPMENT OF FIDELITY CRITERIA FOR ROTORCRAFT FLIGHT SIMULATORS

As discussed, the quantification of simulation fidelity underpins the confidence in the expanding use of flight simulation in design, in qualification support, and to provide safe and realistic environments for pilot training. The aim in quantifying the fidelity of the simulator then becomes one of understanding the effect that a change in the simulation environment will have upon the pilot's ability to perform the task. A two stage approach for defining fidelity criteria for simulator qualification is being developed. Firstly, a quantitative basis for predicting fidelity using metrics, derived in part from handling qualities engineering. Secondly, perceived fidelity metrics supplemented by a pilot fidelity rating scale, used to assign the perceived fidelity of the simulator.

This project involves collaboration with the NRC's Flight Research Laboratory and consists of two main phases. The first involves the collection of 'benchmark' test data from the NRC's ASRA (Figure 5) test aircraft and Liverpool's HELIFLIGHT-R. During the second phase of the programme, handling qualities fidelity metrics derived in phase 1 will be tested in comparative exercises with varying levels of fidelity. The metrics will be used to produce evidence-based validation for requirements within existing and emerging simulator standards.

Using a FLIGHTLAB Bell 412 (F-B412) model [33] a number of simulator 'work-up' trials were conducted to support the development of the test plan for the flight tests in Canada. The aim of the simulator work-up exercise was to determine realistic maximum amplitudes for control inputs and levels of aggression for each of the manoeuvres; also, to familiarise with the environment around the Ottawa base of the Bell 412 ASRA, including the layout of the airport and the location/set up/timings of each of the HQ mission task element (MTE) courses.

Figure 5 NRC's ASRA in the closing stages of an acceleration deceleration manoeuvre

F-B412 Fly by Wire System Integration

The NRC's ASRA is fitted with a full authority experimental fly-by-wire (FBW) control system [34]. It contains a number of safety trip points that cause the experimental fly-by-wire system to disengage and control to be reverted to the safety pilot. During testing the safety pilot flies the helicopter using the standard mechanical control system, and is responsible for taking control in the event of a disengagement, or if a potentially dangerous situation arises. The evaluation pilot's controls, when engaged by the safety pilot, control ASRA through a fully programmable, full authority digital control system. During flight testing, the safety system restricts the level of aggression that the evaluation pilot is able to use. Experience from the flight test campaign in February 2009 showed the importance of incorporating the FBW trip limits into the flight model to ensure that the evaluation pilot approaches the flying task with the equivalent control and safety limits in the simulator as in the flight tests. Table 1 shows the FBW trip limits that were used during the flight and simulation trials.

Table 1 FBW Safety Trip Limits

Parameter	Limitation
Torque	Below 105kts: 92% Mast Torque Above 105kts: 85% Mast Torque
Roll Attitude/Rate (above 25 ft)	Above 45 kts: ±65°, ±60°/s 30 – 45 kts: ±45°, ±40°/s Below 30 kts: ±35°, ±35°/s
Roll Attitude/Rate (below 25 ft)	Above 45 kts: ±45°, ±60°/s 30 – 45 kts: ±35°, ±40°/s Below 30 kts: ±25°, ±35°/s
Pitch Attitude/Rate (above 25 ft)	All speeds: ±32°, ±25°/s
Pitch Attitude/Rate (below 25 ft)	Above 30 kts: ±25°, ±25°/s Below 30 kts: ±15°, ±25°/s
Yaw Rate	Above 45 kts: ±25°/s 30 – 45 kts: ±30°/s Below 30 kts: ±40°/s Additional yaw limitation - ±10°/s when height is < 10ft

Visual Database Development

At the time of the initial simulator work-up, a visual database of the Ottawa International Airport area, the base of operations during the flight tests, was in the early stages of development. A virtual model of the airport and surrounding test areas was created and used for MTE familiarisation in the simulator. However the database was deficient in terms of texture detail and macro-texture elements e.g. prominent trees in the MTE area. Following the flight tests, GPS co-ordinate measurements for all of the cones used to define the MTE test courses were taken along with the positions of key database features to update the visual database. Figure 6 shows an example of the visual database used in the simulator for the hover point in the precision hover MTE and the pilot eye view from the Ottawa flight tests. The roll step MTE was flown on one of the runways at the main airport and an improved level of texture resolution has been included in the visual database.

Figure 6 Comparison of the Visual Database and Real World Precision Hover Course

Flight and Simulator Test Campaigns

In February 2009 two test pilots took part in ten sorties over a four day period [3]. One of these pilots was UoL's simulator commissioning pilot, who was familiar with both the Bell 412 model and the test course layouts, but had not previously flown the ASRA. The second pilot was the NRC safety pilot, 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 an ACAH configuration, with an attitude command/attitude hold system, implemented using the ASRA FBW system architecture. 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 were flown by the NRC test pilot.

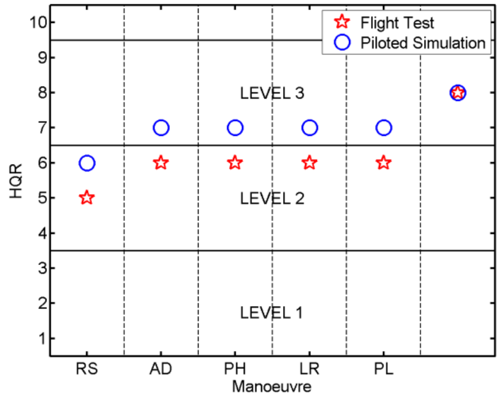
The aim of the flight test campaign was threefold:

1. To extend the range of data used for validation of the Bell 412 model, with clinical test inputs such as the multi-step 2-3-1-1 and frequency sweep.
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 [25].
3. To perform a series of MTEs to assess the impact of the simulation environment on piloting strategies.

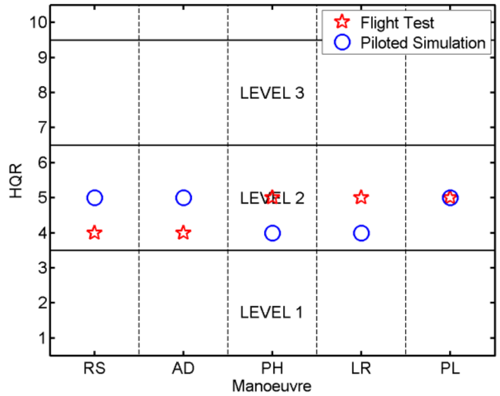
The repeat simulation trial focussed primarily on the ADS-33 MTEs flown in Ottawa. In both the flight and simulation trials, Handling Qualities Ratings (HQRs) [34] were given for each MTE and Visual Cue Ratings (VCRs) [25] were also taken. In addition, pilot impressions of the cues (visual, aural, motion, controls etc.) employed during the task were recorded.

HANDLING QUALITIES SUMMARY

The HQRs awarded by UoL's pilot are summarised in **Error! Reference source not found.** for the bare airframe (7 (a)) and ACAH (7 (b)) tests.



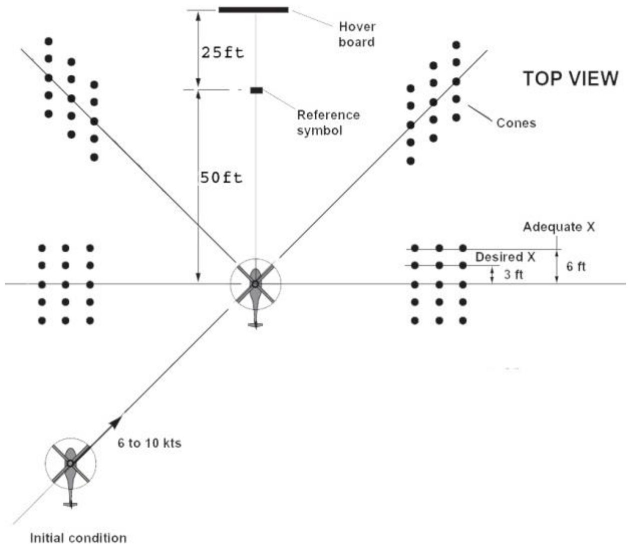
(a) bare airframe



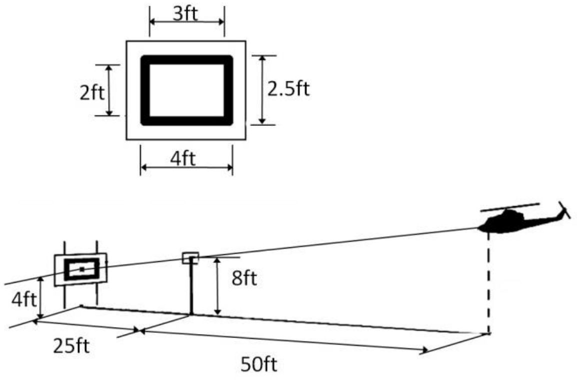
(b) ACAH

Figure 7 HQR summary for all MTEs

The MTEs included hover/low speed tasks (Precision Hover (PH), Pirouette, (PL (left), PR right)), Lateral Reposition (LR)), and forward flight tasks (Roll Step (RS), Acceleration-Deceleration (AD)). In general, a difference of one HQR between flight and simulation is observed. The bare airframe was experienced as a borderline Level 2-3 aircraft, due primarily to poor low speed stability, pitch/roll/pitch and collective to yaw couplings exacerbated by a rotor-speed governor that gave rise to large torque fluctuations. All the MTEs required maximum tolerable compensation and in most of the HELIFLIGHT-R runs with the bare airframe the pilot was not able to achieve the adequate performance standards. The ACAH system was designed to give Level 1 handling qualities based on the ADS-33 metrics although, as we shall see later, this was not the case for all dynamic response criteria. In both flight and simulator, Level 2 ratings were awarded by the pilots. The specific reasons for these ratings will be discussed in the section on perceived fidelity. The focus of attention in this paper will be on the fidelity assessments for the ACAH system flown in the low-speed MTEs – precision hover and pirouette - the layouts and performance standards are shown in Figures 8 and 9 and Tables 2 and 3.



(a) plan view



(b) side view

Figure 8 Precision Hover MTE

Table 2 Performance Requirements for the Precision Hover MTE

Requirement	Desired	Adequate
Attain stabilised hover within X seconds of initiation of deceleration	5	8
Maintain a stabilised hover for at least X seconds	30	30
Maintain the longitudinal and lateral position within ±X ft on the ground	3	6
Maintain altitude ±X ft	2	4
Maintain heading within ±X °	5	10
There shall be no objectionable oscillations during the transition to hover or during the stabilised hover	Applies	n/a

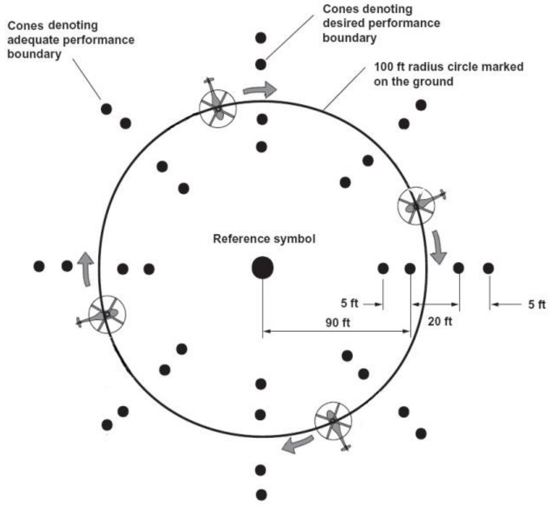


Figure 9 Plan view of the Pirouette MTE

Table 3 Performance Requirements for the Pirouette MTE

Requirement	Desired	Adequate
Maintain a selected reference point on the rotorcraft within ±X ft of the circumference of the circle	10	15
Maintain altitude within ±X ft	3	10
Maintain heading so that the nose of the rotorcraft points at the centre of the circle within ±X °	10	15
Complete the circuit and arrive back over the starting point within X seconds	45	60
Achieve a stabilised hover within X seconds after returning to the starting point	5	10
Maintain the stabilised hover for X seconds	5	5

In the case of the PH the pilot was able to achieve desired performance in the simulator (HQR 4) but not in flight (HQR 5). For the Pirouette, the pilot awarded an HQR 5 in both flight and simulator, only able to achieve the adequate performance standard. The step between the HQR 4 and HQR 5 is an important one, both in terms of performance and workload (Table 4).

Table 4 Comparative aspects of Level 2 HQRs

	System characteristics	Performance and Workload
HQR 4	Minor annoying deficiencies	Desired requires moderate compensation
HQR 5	Moderately objectionable deficiencies	Adequate requires considerable compensation
HQR 6	Very objectionable but tolerable deficiencies	Adequate requires extensive compensation

In awarding an HQR 5, not only is the pilot no longer able to achieve the desired standard, but he also has to apply considerable compensation to achieve the adequate standard. Harper and Cooper later [35] explore this large step in more detail and advocated the use of the 4.5 rating for situations where adequate performance was achievable with less than considerable compensation. Strictly from a safety standpoint, a pilot's ability to achieve the desired performance standard with no more than moderate compensation is considered to be important. Equivalence here between flight and simulator is therefore also important and we use the two low-speed MTE test cases to develop an integrated approach to predicted and perceived fidelity.

PREDICTED FIDELITY

Comparisons of the ACAH response type characteristics between flight and simulator are shown in Figures 10 and 11.

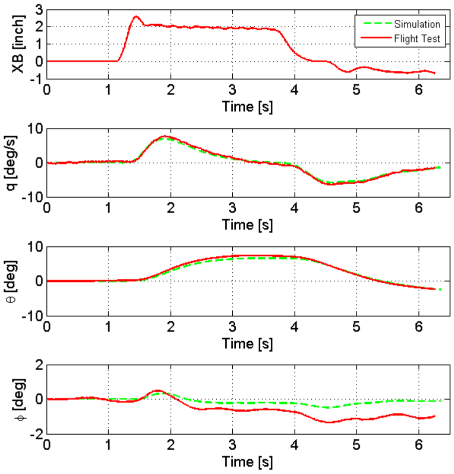


Figure 10 Comparison of Pitch and Roll Responses to Longitudinal Cyclic Control Input

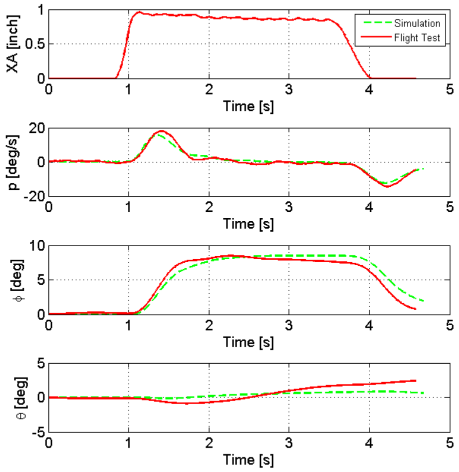


Figure 11 Comparison of Roll and Pitch Responses to Lateral Cyclic Control Input

The use of Handling Qualities metrics

The dynamic response criteria in the handling qualities standard, ADS-33, cover both agility and stability characteristics as well as cross-coupling effects. They define the level of performance required of an aircraft to be able to achieve Level 1 standards of performance and workload consistently in a mission. ADS-33 contains a mix of time and frequency domain parameters covering short-long term response and over small-large amplitudes. Dynamic response criteria are often displayed in two-parameter charts, for example damping and frequency or bandwidth and phase delay, with boundary lines demarking regions of Level 1, 2 and 3 performance. As measures of dynamic performance, these metrics also provide a basis for quantifying simulation fidelity, since they are referenced to missions and pilot control strategies in MTEs. The parameters relevant to the low speed precision hover and pirouette MTEs, and investigated in the current research, are summarised below;

a) Attitude quickness, Q, provides a measure of the ability to attain moderate amplitude attitude changes during a manoeuvre. It is defined as the ratio of peak attitude rate to the peak attitude change, hence for pitch quickness,

$$Q_\theta = \frac{q_{pk}}{\Delta\theta_{pk}}$$

b) Bandwidth, ω_{bw} is a stability measure that defines the range of control input frequencies over which a pilot can apply closed-loop control without threatening the stability of the aircraft. ADS-33E provides two definitions of bandwidth, depending upon the response type of the aircraft. For a rate response type, it is the lesser of the gain bandwidth (the frequency corresponding to a gain margin of 6 dB) and the phase bandwidth (the frequency corresponding to a phase margin of 45° relative to the 180° attitude response phase). For an attitude response type, it is equal to the phase bandwidth.

c) Phase Delay, τ_p, is a measure of the equivalent time delay between pilot control input and aircraft attitude response. The phase delay parameter assesses the quality of the phase response at frequencies higher than the crossover frequency (when response phase is 180°). As such, it is proportional to the slope of the phase response between the crossover frequency, ω_{180}, and twice that frequency, $2\omega_{180}$, and is defined as

$$\tau_p = \frac{\Delta\Phi_{2\omega 180}}{57.3 \text{ x } 2\omega_{180}}$$

where $\Delta\Phi_{2\omega 180}$ is the phase change between ω_{180} and $2\omega_{180}$.

d) Control Power, CP, is defined as the maximum response achievable by applying full control from a trim condition. When it is not desired to apply a full control input, the CP can be determined based upon smaller inputs by extrapolating the aircraft response.

e) Open-loop stability is quantified in terms of the frequency, ω_n, and damping, ζ, of the aircraft's natural modes, such as the Dutch Roll and Phugoid.

f) Roll/Pitch Couplings: The acceptable limit on coupling between the pitch and roll axes is derived from the peak off-axis response to the desired on-axis response, after 4 seconds, following a sharp cyclic step input.

g) The yaw due to collective cross coupling is determined from the first peak in yaw rate response, r_1 (or if no peak is found it is the yaw rate at 1s), the difference between r_1 and the yaw rate at 3s, r_3, and the height rate, $\dot{h}$ after 3s, following a sharp collective input. This is quantified by the collective to yaw couple at 1s,

$$\text{r from Xc @ 1s} = \left|\frac{r_1}{\dot{h}(3)}\right|$$

and the collective to yaw couple at 3s,

$$\text{r from Xc @ 3s} = \frac{r_3}{|\dot{h}(3)|}$$

h) Heave response: The ADS-33E requirements on vertical axis response characteristics are based on the assumption that the height rate response, $\dot{h}$, to a collective input, X_c, exhibits a first order response in the transfer function form:

$$\frac{\dot{h}}{X_c} = \frac{K e^{-\tau_{hdot} s}}{T_{hdot} s + 1}$$

where T_{hdot} is the time constant and τ_{hdot} represents the response time delay. ADS-33E has an additional requirement that the torque displayed to the pilot (as a measure of the maximum allowable power that can be commanded without exceeding engine or transmission limits) shall have characteristics that fall within the limits shown in A3 (b). The Level is determined from the ratio of the first torque peak value/first torque minimum value and the time to first peak following a step collective input.

Hover/Low-speed Metrics

A comprehensive comparison of ADS-33 metrics for the ASRA and F-B412 simulation model is given in Appendix A and summarised in Table 5. The Table includes the % difference between simulation and flight and also the comparative margins to the Level 1-2 HQ boundary.

A key question is - how close should be the match between the simulator and flight? If the acceptable match was 20%, then only two primary response metrics, the yaw quickness and control power, would fail the fidelity test. The fidelity assessment would also fail with respect to all cross-coupling and heave response parameters. If the acceptable margin were 10%, then the roll bandwidth and pitch control power would also fail the fidelity test.

What do the predicted fidelity metrics suggest?

The precision hover and pirouette MTEs are low-moderate aggression tasks flown with strong reference to outside world visual cues. Pitch and roll attitude demands and excursions are likely to remain within 10 degrees and, while the yaw excursions in the pirouette are large, the mean yaw rate should be less than 10 deg/sec for a 45 second circuit. The Level 2 (predicted) yaw response characteristics are likely to feature in this respect. Stability should be a critical aspect in the pilot's ability to maintain the nominally steady transitions and also capturing the final hover. The cross coupling appears to be significantly worse in flight compared with the simulator, particularly pitch from roll (Level 2 compared with Level 1) and collective to yaw (Level 3 compared with Level 1). The ACAH controller was designed to remove these effects, but clearly was more effective in the simulator, although the bare airframe cross coupling is also greater in flight. In summary, the fidelity metrics for the yaw response suggests that the simulator will be more difficult to fly than the aircraft while the reverse is true when considering cross-couplings.

Table 5 Predicted Fidelity; Hover and Lower Speed

Fidelity Parameter	Flight (Sim)	HQL	%Δ F-S	Margin to Level 1-2 Boundary	% Margin to Level 1-2 Boundary
Quickness					
Average Q_{Φ} ($10° < \Phi < 20°$)	1.98 (1.87)	1 (1)	-5.81	0.82 (0.70)	70 (60)
Average Q_{θ} ($5° < \theta < 10°$)	1.05 (1.05)	1 (1)	0.0	0.41 (0.41)	64 (64)
Average Q_{ψ} ($10° < \psi < 20°$)	0.41 (0.22)	2 (3)	-44.9	-0.79 (-0.97)	-66 (-81)
Bandwidth					
ω_{φ}	5.38 (6.21)	1 (1)	15.5	3.4 (4.24)	172 (215)
$\tau_{p\varphi}$	0.15 (0.18)	1 (1)	18.7	n/a	n/a
ω_{θ}	2.79 (2.71)	1 (1)	-2.9	1.79 (1.71)	179 (171)
$\tau_{p\theta}$	0.18 (0.17)	1 (1)	-5.5	n/a	n/a
ω_{ψ}	1.18 (1.23)	2 (2)	4.5	-0.82 (-0.79)	-41 (-39)
$\tau_{p\psi}$	0.13 (0.14)	2 (2)	7.7	n/a	n/a
Control Power					
CP_{φ}	56 (59)	2 (2)	5.4	-4 (-1)	-7 (-2)
CP_{θ}	24 (21)	2 (2)	-12.5	-6 (-9)	-20 (-30)
CP_{r}	28.2 (21.7)	2 (3)	-23.0	-31.8 (-38.3)	-53 (-64)
Stability					
ω_{n}	TBD	TBD			
ζ	TBD	TBD			
Couplings					
p from q	0.24 (0.11)	1 (1)	-56.1	0.01 (0.14)	2 (57)
q from p	0.25 (0.07)	2 (1)	-70.7	-0.01 (0.18)	-4 (72)
Collective to Yaw @ 1s	0.41 (0.23)	1 (1)	-44.7	0.24 (0.42)	36 (65)
Collective to Yaw @ 3s	-0.79 (-0.11)	3 (1)	-86.1	-0.64 (0.04)	-427 (27)
Heave Response					
T_{hdot}	3.61 (2.21)	1 (1)	-38.7	1.39 (2.79)	28 (56)
τ_{hdot}	0.14 (0.08)	1 (1)	-42.9	0.06 (0.12)	30 (60)
Torque Overshoot Ratio	1.28 (2.11)	1 (2)	65.7	0.06 (-0.78)	5 (-58)
Time to First Torque Peak	2.44 (1.65)	1 (2)	-32.5	n/a (-1.52)	n/a (-1226)

PERCEIVED FIDELITY

Following the flight tests with the ASRA, the UoL pilot undertook a subjective assessment of the HELIFLIGHT-R configuration.

The control forces and displacements in HELIFLIGHT-R were tailored to emulate the ASRA 412. However, the actual configuration of flight controls and their physical location in the aircraft were different in the simulator, creating a perception of differing control forces and displacements during manoeuvres.

The simulator is equipped with a large FoV outside world display, unimpeded in all areas except below and behind the instrument panel. In contrast, the ASRA has a reduced FoV in many areas, due to the location of the airframe structure and instrument panels (Figure 12 and 13). The reduction in available FoV in the ASRA was a key factor in driving piloting strategy during manoeuvres where the required visual references were obscured, whereas in the simulator no such compromise on piloting strategy was apparent.

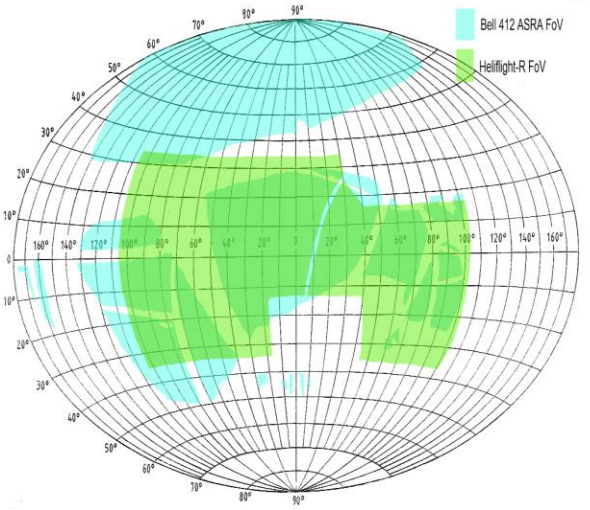


Figure 12 FoV Comparison for HELIFLIGHT-R and ASRA

Both the surface micro and macro textures and scene content were extensively developed within the simulator work-up phase. However, the available resolution of the visual system coupled to the reduced scene content in comparison with the rich textural environment of the real world airfield, even covered in snow, was obvious to the pilot. Visual cueing from the surface texture and scene content provided at Ottawa could not be replicated in the simulator and thus the perceived fidelity was reduced slightly.

Figure 13 Crew station framing limitations on pilot FoV in ASRA

The audio cueing environment of the ASRA 412 was complex with engine, rotor, communications and environment cueing providing a rich audio stimulus to the pilot. In comparison the simulator, whilst significant steps have been made, was lacking in fidelity in this area, particularly during aggressive tasks when the pilot was able to respond to audio cues in the ASRA.

Perceived Fidelity in the MTEs

The perceived fidelity metrics relate to the task performance and pilot compensation. Definitions of the perceived fidelity parameters used are as follows:

a) Handling Quality Rating (HQRs): HQRS were awarded based on task performance and pilot workload.

b) Visual Cue Ratings (VCR) and Usable Cue Environment (UCE): for each MTE the worst of the attitude and translational rate VCRs awarded by the pilot are used to derive the UCE.

Performance:

c) Total task time – the time taken to complete the manoeuvre, from start to end.
    a. For the pirouette manoeuvre, the manoeuvre begins (for the purposes of measuring the task performance) in a stable hover at the start point, and is complete when the aircraft has been in a stable hover for 5 seconds following its return to the start point.
    b. For the precision hover manoeuvre, the manoeuvre begins at the point that the aircraft first enters the desired performance 'box', within which the goal is for it to stay. The end point of the manoeuvre is when a stable hover has been maintained for 30 seconds.

d) Time spent within desired performance – this is the percentage of the total manoeuvre time that was spent with the aircraft within the desired performance tolerance for a given requirement.

e) Time spent within adequate performance – this is the percentage of the total manoeuvre time that was spent with the aircraft within the adequate performance tolerance for a given requirement. Note that this time includes all of the time that was spent within the, more restrictive, desired performance region.

f) Time spent beyond adequate performance – this is the percentage of the total manoeuvre time that was spent with the aircraft beyond the adequate performance tolerance for a given requirement.

Compensation:

g) Control attack is a parameter which measures the size and rapidity of a pilot's control inputs during a manoeuvre [36]. It is defined as:

$$attack = \frac{\eta_{pk}}{\Delta\eta},$$

where η is the pilot's control deflection. The control attack is summarised using the following parameters:

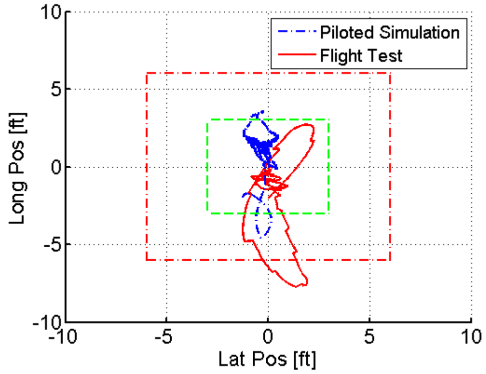
   a. Attack number – this is the total number of times that the pilot moves a particular control by more than 0.5% of full travel. It is recognised that this is a very small level but stick movements of this size are detected by the attack filter.
   b. Attack number per second – this is the attack number expressed in terms of the average number of control movements per second.
   c. Mean attack rate – this is the mean rate at which the pilot is moving his control, and is expressed in terms of the % control travel per second.
   d. Mean control displacement – this is the mean of the control displacements measured for each of the attack points.

h) Quickness can be applied to assess closed loop control in addition to open loop agility (see the predicted metrics section for definition of the quickness parameter). The closed loop quickness, Q_{CL}, can be summarised using equivalents of the parameters described above for the control attack. They are:

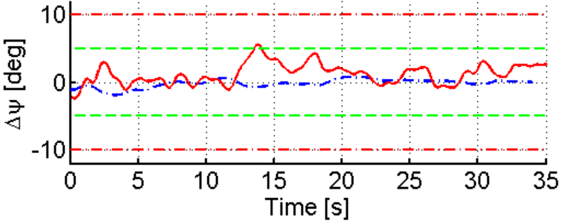
   a. Number of quickness points – the total number of attitude changes measured as being larger than 0.5° during the manoeuvre.
   b. Quickness points per second – the number of quickness points divided by the total manoeuvre time.
   c. Mean quickness,
   d. Mean attitude change

The Precision Hover

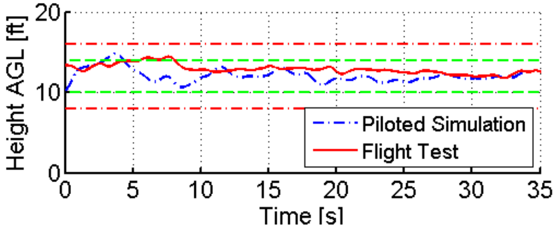
The task performance in the PH MTE is shown in Figure 14, and the fidelity metrics collected in **Error! Reference source not found.** (a)-(e). The HQR 5–4 (flight–sim) comparison is contrasted by the UCE 1–2 comparison. The excursion into the adequate region and beyond (12% of time) for longitudinal position in flight, along with the considerably higher level of compensation, led the pilot to return the HQR 5. Apart from this excursion, the pilot maintained position within the desired region for nearly 80% of the time and held the desired lateral position, height and heading for more than 90% of the time.



(a) plan position



(b) heading



(c) height

Figure 14 Task Performance in the Precision Hover MTE – Comparison of Flight and Simulation

The control attack shows the pilot using more than double the number of cyclic inputs in flight compared with the simulator, at an average rate of 1.60/1.25 Hz (pitch/roll) compared with 0.7/0.8 Hz. The reduced number of quickness events, compared with attack events, suggests that much of the pilot activity is ineffective, particularly in pitch. For example the average quickness rate is about 0.30 Hz in pitch and 0.65 Hz in roll. Increasing the threshold of attack detection will remove the smaller control inputs. Figure 15 shows how this filter reduces the number of control attacks detected. The trends indicate that in both flight and simulator, the reduction is relatively uniform; if the features in flight had been artefacts then a more nonlinear variation would be expected with stronger convergence of the fit lines.

Table 6 Precision Hover Perceived Fidelity

(a) ratings

Fidelity parameter	Flight	Simulator	Δ%
HQR	5	4	
UCE	1	2	
• VCR(TR)	3.0	3.0	
• VCR(A)	1.5	2.0	
Total task time	30	30	0

(b) longitudinal axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Long. Position % time			
• Inside desired	79.2	76.2	-3.0
• inside adequate	88.5	100	11.5
• outside adequate	11.5	0	-11.5
Pitch Axis – Attack			
• attack number	173	72	-58.4
• attack number per sec. (/s)	3.21	1.36	-57.6
• mean attack rate (%/s)	25	10	-60.0
• mean control displ. (%)	7.8	4.7	-39.7
$Q_{\theta CL}$			
• no of quickness points	32	18	-43.8
• quickness points per sec. (/s)	0.59	0.34	-42.4
• mean quickness (/s)	2.45	0.81	-66.9
• mean att. change (°)	1.48	1.86	-25.7

(c) lateral axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Lateral Position % time in			
• desired	100	100	0
• adequate	100	100	0
• inadequate	0	0	0
Roll Axis – Attack			
• attack number	133	83	-37.6
• attack number per sec. (/s)	2.47	1.57	-36.4
• mean attack rate (%/s)	13	8	-38.5
• mean control displ. (%)	4.5	3.8	-15.6
$Q_{\Phi CL}$			
• no of quickness points	72	36	-50.0
• quickness points per sec. (/s)	1.34	0.68	-49.3
• mean quickness (/s)	3.1	1.6	-48.4
• mean att. change (°)	2.2	2.8	27.3

(d) yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Heading % time in			
• desired	99	100	1
• adequate	100	100	0
• inadequate	0	0	0
Yaw Axis – Attack			
• attack number	130	38	-70.8
• attack number per sec. (/s)	2.4	0.7	-70.8
• mean attack rate (%/s)	22	7	-68.2
• mean control displ. (%)	8.2	2.8	-65.9
$Q_{\Psi cl}$			
• no of quickness points	34	12	-64.7
• quickness points per sec. (/s)	0.63	0.23	-63.5
• mean quickness (/s)	1.7	0.6	-64.7
• mean att. change (°)	2.6	1.7	-34.6

(e) vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Height % time in			
• desired	93	96	3
• adequate	100	100	0
• inadequate	0	0	0
Heave Axis - Attack			
• attack number	96	82	-14.6
• attack number per sec. (/s)	1.78	1.55	-12.9
• mean attack rate (%/s)	20	10	-50
• mean att. change (°)	9.0	5.4	-40

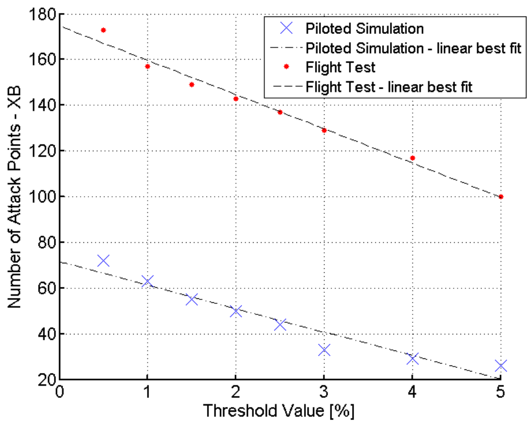


Figure 15 Number of control movements (attack parameters) in the PH as a function of threshold filter

The major features in flight that the pilot did not experience in the simulator with the Precision Hover were;

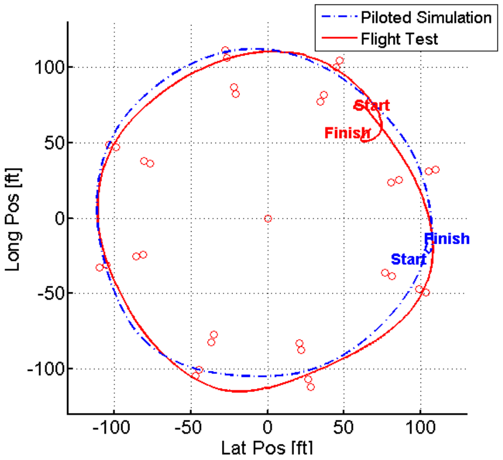
a) a noticeably more unsteady (“gravelly”) ride resulting in attitude disturbances that required the ‘extensive compensation’ to achieve the adequate standard,

b) the need for larger collective inputs to maintain height and consequent heading and torque fluctuations (note Level 3 collective to yaw Predicted HQs in flight, Level 1 in the simulator).

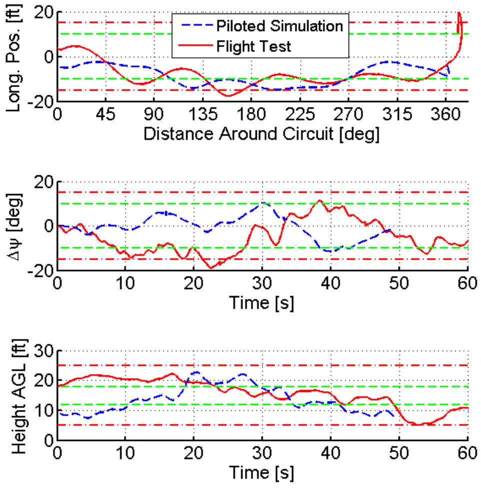
c) during the stabilised hover phase, the crew station framing obscured the pilot's view of the cones positioned at -45 degrees (Figure 8).

The Pirouette

The task performance for the Pirouette MTE is shown in Figure 16**Error! Reference source not found.Error! Reference source not found.**, and the fidelity metrics in Table 7 (a - e).



(a) plan position



(b) longitudinal pos., heading and height

Figure 16 Task Performance in the Pirouette MTE - Comparison of Flight and Simulation

HQRs of 5 were returned in both flight and the simulator; UCE for both was 2. The aircraft was held on the desired track for about 60% of the time, drifting into adequate for 30% in both flight and simulator but drifting outside the adequate boundary for >10% in flight. The pilot could only hold the desired height for 40% of the time, the rest of the time in the adequate region. Within about 10%, Flight and Simulator were similar, in terms of task performance. As with the PH, the pilot is working harder in flight, with nearly double the number of attack events in pitch and more than that in roll and yaw, albeit over a 20% longer manoeuvre time.

The major features in flight that the pilot did not experience in the simulator with the Pirouette MTE were;

a) similar rough ride as experienced in the PH, leading to pilot's perceived need for increased pitch and roll compensation,

b) significantly greater right pedal required to maintain the turn,

c) the door frame obstructed the pilot's view of his direction of travel,

d) the view of the cone marking the centre of the course was not obscured. This was not the case in the simulator.

Table 7 Pirouette Perceived Fidelity

(a) ratings

Fidelity parameter	Flight	Simulator	Δ%
HQR	5	5	
UCE	2	2	
• VCR(TR)	3	3	
• VCR(A)	2	3	
Total task time	55	46	-16.4

(b) longitudinal axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Longitudinal Position % time			
• Inside desired	55.3	68.5	-3.0
• inside adequate	85.6	100	14.4
• outside adequate	14.4	0	-14.4
Pitch Axis – Attack			
• attack number	190	100	-47.4
• attack number per sec. (/s)	3.1	2.0	-35.5
• mean attack rate (%/s)	30	13	-56.7
• mean control displ. (%)	9.9	7.2	-27.3
$Q_{\theta CL}$			
• no of quickness points	48	22	-54.2
• quickness points per sec (/s)	0.8	0.4	-50.0
• mean quickness (/s)	2.5	0.92	-63.2
• mean attitude change (°)	2.1	2.74	30.5

(c) lateral axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Roll Axis – Attack			
• attack number	160	65	-59.4
• attack number per sec. (/s)	2.6	1.3	-50.0

• mean attack rate (%/s)	13	8.6	-33.8
• mean control displ. (%)	4.7	4.6	-2.1
$Q_{\Phi CL}$			
• no of quickness points	84	31	-63.1
• quickness points per sec (/s)	1.4	0.6	-57.1
• mean quickness (/s)	3.9	1.4	-64.1
• mean attitude change (°)	2.1	3.4	61.9

(d) yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Heading % time in			
• desired	69.0	91.6	22.6
• adequate	94.3	100	5.7
• inadequate	5.7	0	-5.7
Yaw Axis - Attack			
• attack number	168	63	-62.5
• attack number per sec. (/s)	2.8	1.3	-53.6
• mean attack rate (%/s)	30	11	-63.3
• mean control displ. (%)	11.7	5.7	-51.3
$Q_{\Psi cl}$			
• no of quickness points	9	2	-77.8
• quickness points per sec (/s)	0.1	0.04	-60.0
• mean quickness (/s)	-----	-----	-----
• mean attitude change (°)	-----	-----	-----

(e) vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Height % time in			
• desired	42.1	36.9	-5.2
• adequate	100	100	0
• inadequate	0	0	0
Heave Axis - Attack			
• attack number	86	58	-32.6
• attack number per sec (/s)	1.4	1.2	-14.3
• mean attack rate (%/s)	15	6	-60.0
• mean control displ. (%)	7.8	4.4	-43.6

DISCUSSION

Based on the handling qualities metrics, the combined predicted and perceived fidelity analysis tells a reasonably consistent, if complex, fidelity story. However, the HQR has proven to be a rather insensitive measure of fidelity. For the Precision Hover MTE, similar performance was achieved in flight and simulator, but the pilot was pushed into awarding an HQR 5 in flight, compared with HQR 4 in the simulator, because of the considerably higher levels of compensation required in all axes. The single HQR point difference 'hides' a multitude of fidelity issues, but the predicted fidelity parameters appear to capture most of these. The same is broadly true for the Pirouette MTE, where the awarded HQR was 5 in both flight and simulator.

The significantly higher number and rate of application of control movements in flight have been captured by the control attack parameter in both MTEs. The level of compensation associated with essentially stabilisation activity at a rate of 1-2 control movements per second (in PH and PL in flight) did not draw the pilot to award an HQR 6, again suggesting an insensitivity of the HQR as a fidelity measure, at least in the Level 2 range. Equivalence in HQRs, and associated VCRs, between simulation and flight are considered to be necessary but not sufficient to guarantee high fidelity. For a Level 2 aircraft like the ASRA ACAH configuration, the pilot may well remain on the HQR 5 'plateau' for a wide range of performance/workload conditions; he may be reluctant to rise to the HQR 4, on the one hand, as he cannot achieve desired standards without extensive compensation or, on the other hand, to degrade to HQR 6 as this is the edge of Level 2 and tolerable workload (Table 4).

If a 10-20% tolerance was set for the attack metric, then the simulator would certainly fail a fidelity test. The pilot appears to be working with about double the 'gain' in flight, although considering the response quickness values, it appears that most of this activity is actually ineffective, a point discussed in detail in [38]. In flight, the pilot was experiencing a higher disturbance level, due to wind effects not fully modelled in the simulator. This will almost certainly account for some of the additional compensation. The system time delay in the ASRA, estimated to be about 100ms, will also increase the level of pilot compensation. Both these aspects will be investigated in the continuing research.

Different aircraft configurations will also be assessed, including rate and attitude configurations having 'solid' Level 1 HQ characteristics in flight. Detailed analysis of the other MTEs tested in phase 1 of the research is also underway and will be reported, including the results with the bare airframe configuration.

The *Lifting Standards* research is also applying system identification techniques to quantify simulation fidelity using models of both the open-loop aircraft system and closed-loop pilot-aircraft system. Fidelity then relates to the level of equivalence of model parameters. Such methods are valuable diagnostic tools used to identify the source of fidelity shortcomings.

The pilot is a complex sensor and motivator, able to close the loop on several variables at the same time in the performance of a typical helicopter re-positioning task. This performance is achieved through basic training and countless hours of re-current training; a very expensive business. For hazardous operations there is also a high safety risk. For simulation to be truly representative of the real world, cueing and aircraft behaviour need to be sufficiently good that training is effective at skill development and retention. The flight simulation community has engaged with the concept of 'fit for purpose' for many decades and needs to continue to do so as technologies advance and the user aspirations of what can be achieved increase. Fidelity metrics, based on fundamental engineering science, need to advance ahead of the utilisation so that qualification standards development is properly supported. The continuing research at Liverpool will include the development of a (pilot) fidelity rating scale drawing on the HQ and VC rating scale structures, and combine with the fidelity metrics discussed in this paper to propose fidelity levels.

CONCLUDING REMARKS

The paper has addressed the topic of simulator fidelity within a framework of handling qualities engineering – drawing on the predicted and assigned HQ concepts to develop Fidelity metrics. The HELIFLIGHT-R ground-based facility has been described, along with the companion research aircraft, the NRC's Bell 412 ASRA in-flight simulator; complementary use of these research facilities underpins the *Lifting Standards* research project at Liverpool.

A set of predicted fidelity metrics has been proposed and results compared for hover/low speed manoeuvres for both bare airframe and ACAH configuration. MTEs flown using the ASRA airborne simulator have been replicated in HELIFLIGHT-R and results for the Precision Hover and Pirouette re-positioning tasks have been reported in detail.

Analysis of the predicted HQs of the aircraft showed that the results were expected to fall around the Level 2-3 boundary for the bare airframe and the Level 1-2 boundary for the ACAH configuration. The assigned HQ results were consistent with this expectation for both the simulation and flight tests.

A new set of fidelity metrics, based on the HQ parameters has been defined and used in a comparative assessment between flight and simulator. This fidelity analysis tells a reasonably consistent, if complex, fidelity story. Control activity, task performance and temporal metrics have been presented and their efficacies discussed. The *Handling Qualities Rating* itself has proven to be a rather insensitive measure of fidelity. It is a necessary but not sufficient perceived metric; differences in HQR may arise due to many different influencing factors. The same HQR can reflect a multitude of fidelity aspects. As such, a more rigorous methodology for analysis of the HQ results is required, alongside the development of a fidelity-based rating scale; these are the subjects of ongoing research in the *Lifting Standards* project.

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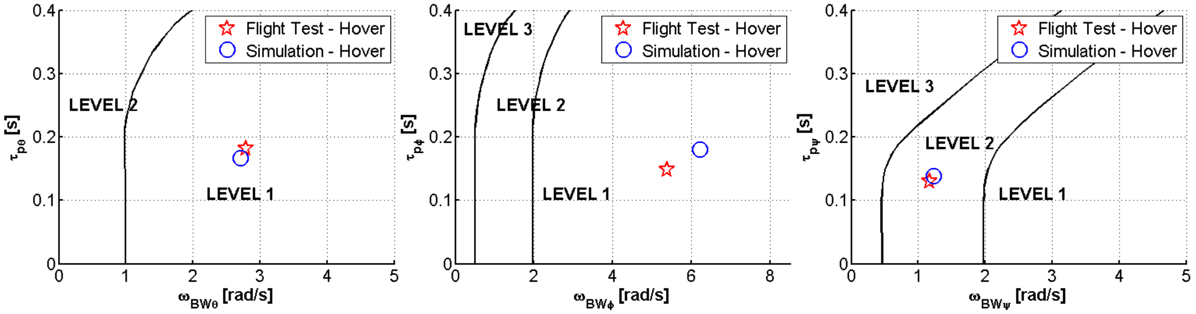
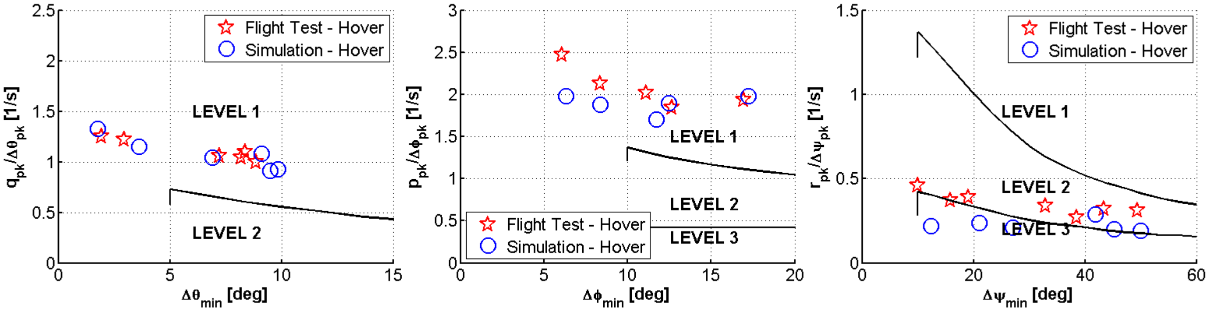
Appendix A – Hover Predicted HQ/Fidelity



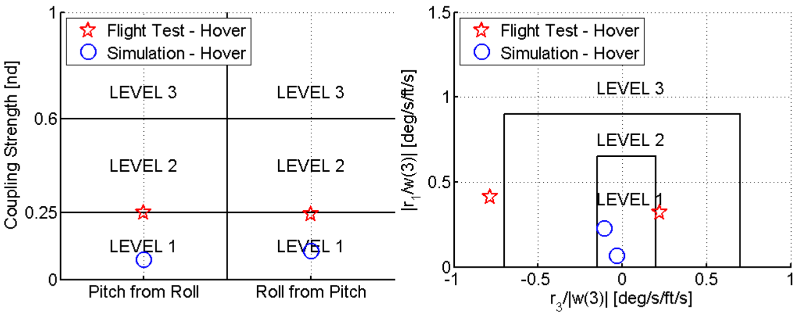
(a) Pitch Axis (b) Roll Axis (c) Yaw Axis

Figure A1 Attitude Bandwidth



(a) Pitch Axis (b) Roll Axis (c) Yaw axis

Figure A2 Attitude Quickness



(a) Roll/Pitch (b) Collective to Yaw

Figure A3 Cross Couplings

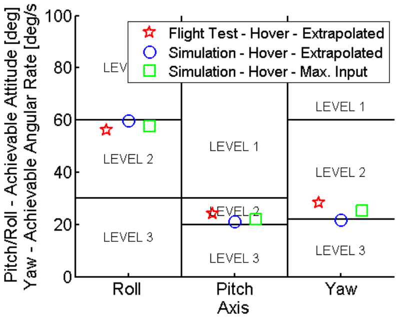
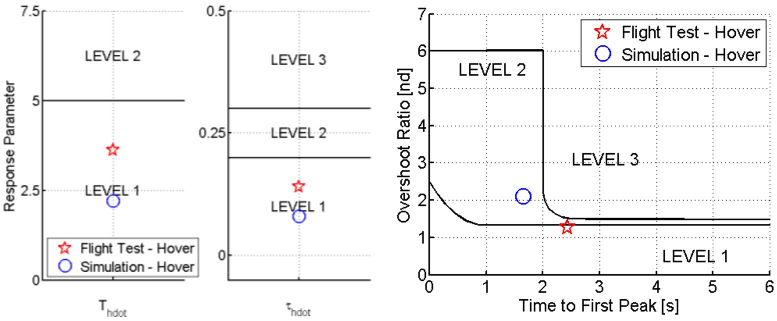


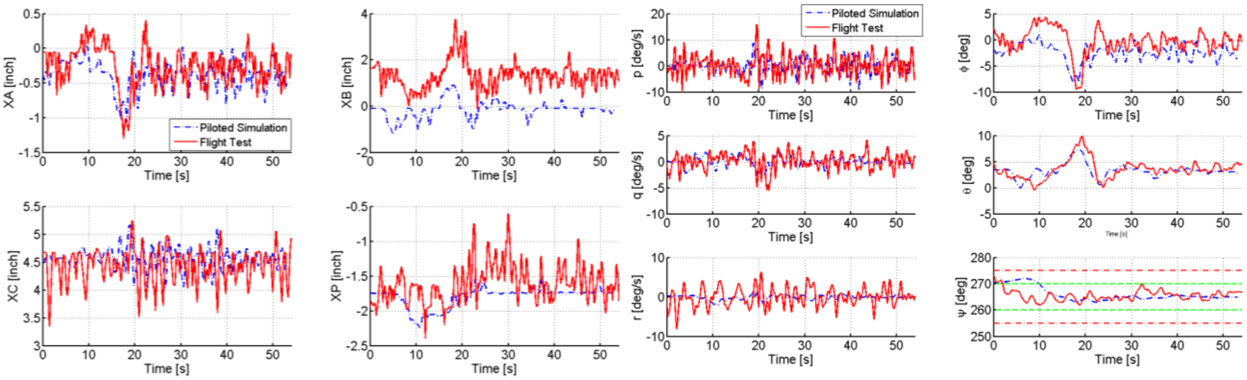
Figure A4 Control Power



(a) Height Response (b) Torque Response

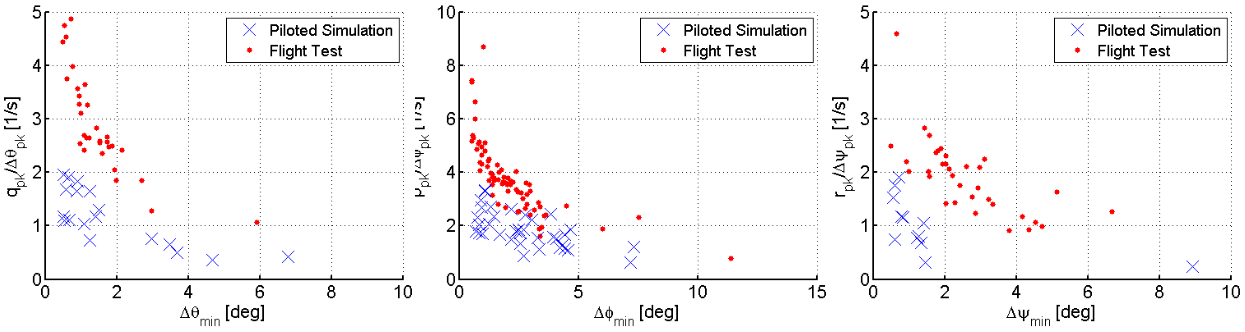
Figure A5 Heave Response Characteristics

Appendix B – MTE Pilot Controls and Aircraft Attitudes and Rates



(a) Pilot Controls (b) Rates (c) Attitudes

Figure B1 Precision Hover Control Inputs and Aircraft Responses



(a) Pitch (b) Roll (c) Yaw

Figure B2 Closed Loop Quickness for the Precision Hover

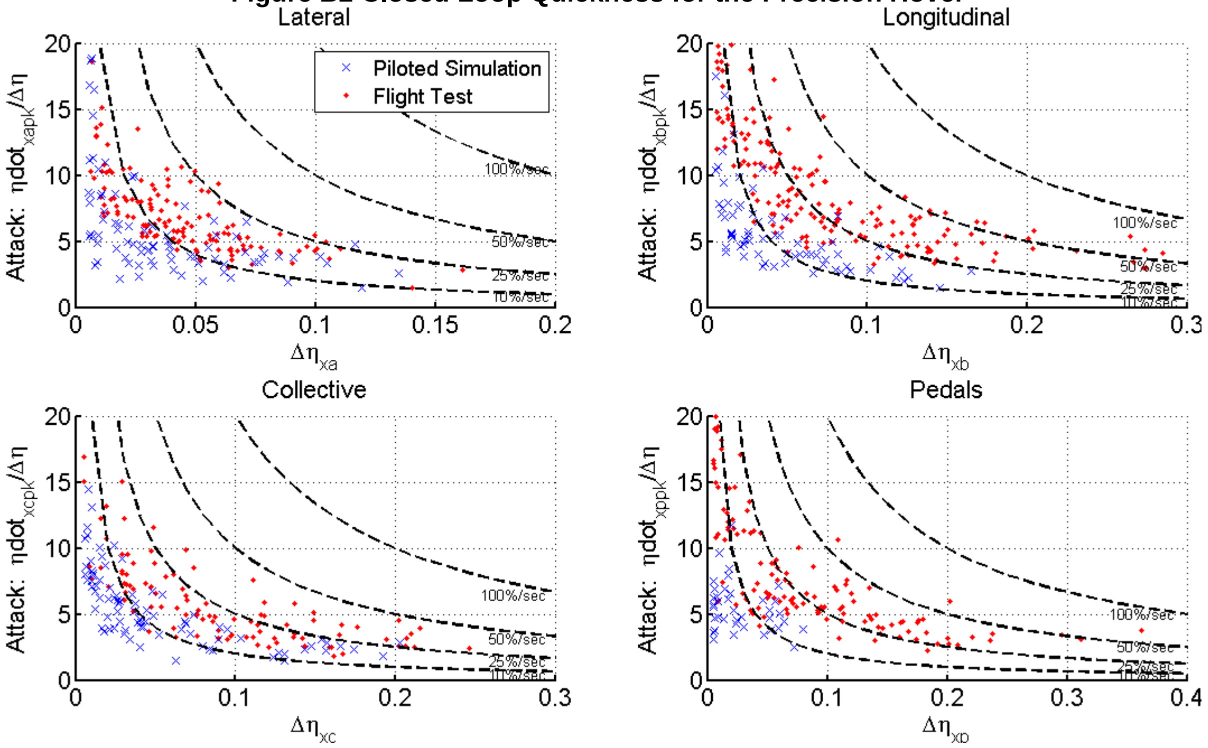
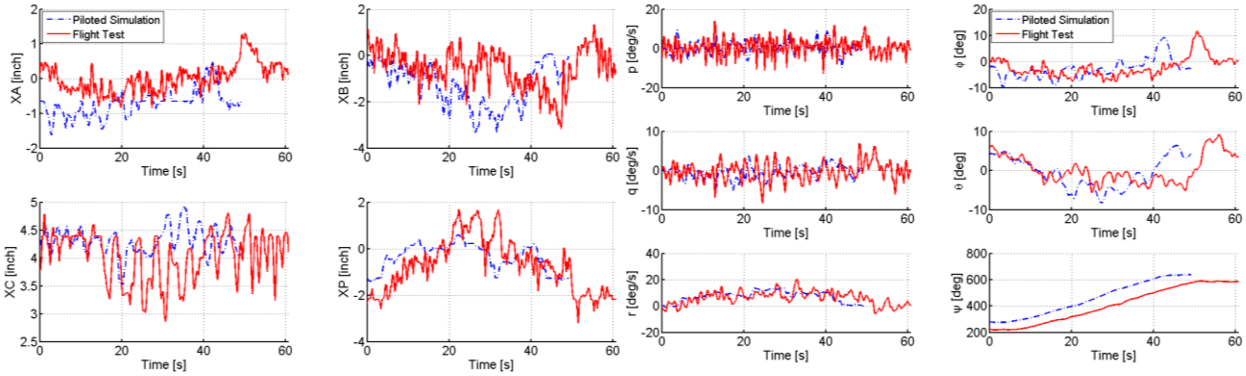
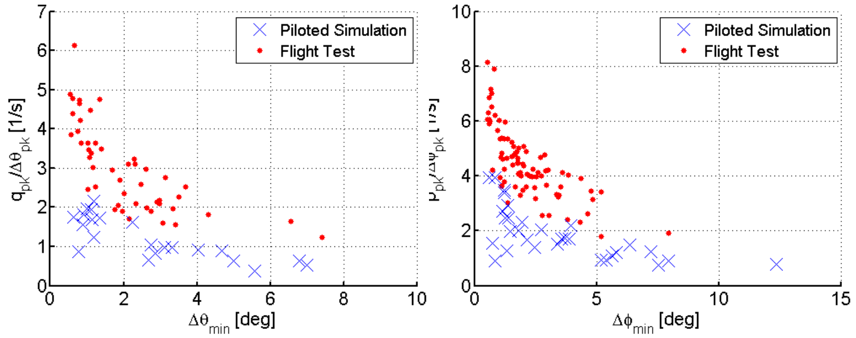


Figure B3 Control Attack for Precision Hover



(a) Pilot Controls (b) Rates (c) Attitudes

Figure B4 Pirouette Control Inputs and Aircraft Responses



(a) Pitch (b) Roll

Figure B5 Closed Loop Quickness for the Pirouette

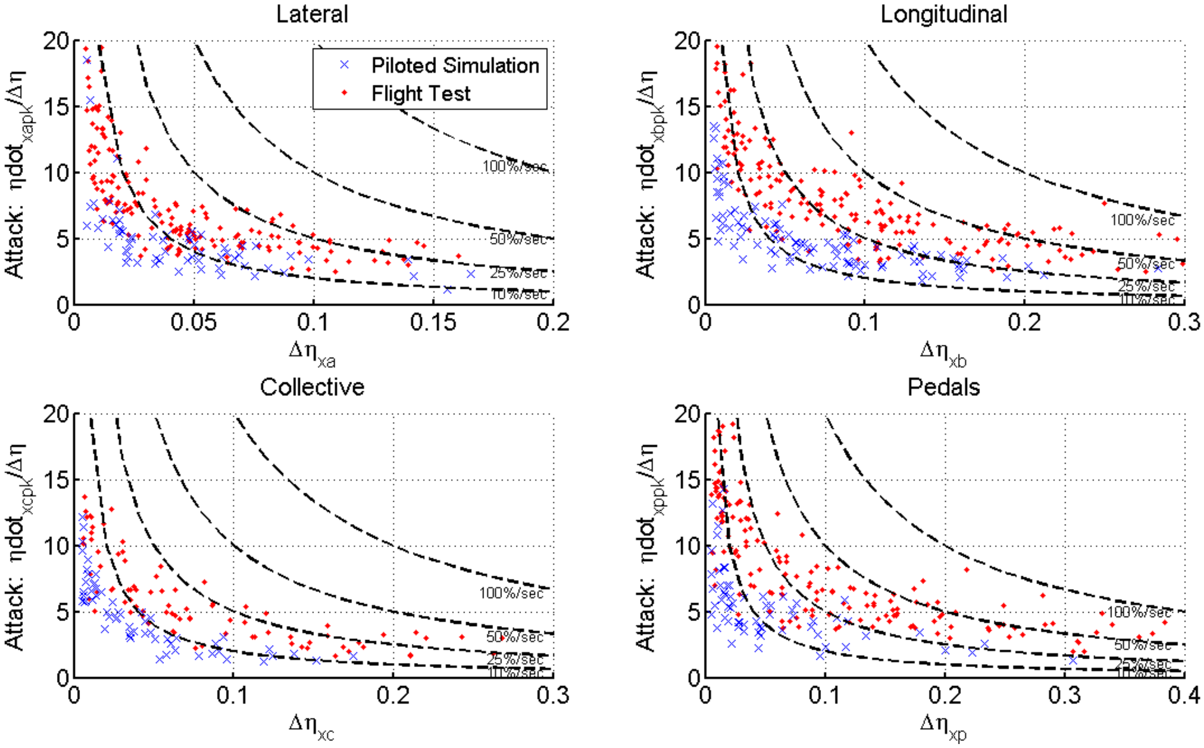


Figure B6 Control Attack for Pirouette