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INTEGRATING PREDICTED AND PERCEIVED FIDELITY FOR 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 ever expanding. 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 for flight training simulators and new standards are in development, previous research has shown that current standards do not provide a fully quantitative approach for assessing simulation fidelity, especially in a research environment. This paper reports on progress made in a research project at the University of Liverpool (*Lifting Standards*), in which new predicted and perceived measures of simulator fidelity are being developed. The proposed new metrics are being derived from handling qualities engineering practice. Results from flight tests on the National Research Council (Canada) Bell 412 ASRA research aircraft and piloted simulation trials using the HELIFLIGHT-R simulator at Liverpool are presented to show the efficacy of adopting a handling qualities approach for fidelity assessment. Analysis of the proposed metrics has shown the control attack parameter to be appropriately sensitive to differences between flight and simulation. Equivalence of handling qualities ratings is necessary but not sufficient to judge fidelity, highlighting the importance of establishing a new perceived fidelity rating scale to capture pilot perceptions.

NOTATION & ACRONYMS

CP_ϕ, CP_θ, CP_ψ	Roll, pitch yaw Control Power (°/s)
$\dot{h}$	Height rate (ft/s)
n_z	Normal acceleration (ft/s^2)
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)
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 (°)
$\tau_{p\phi}$, $\tau_{p\theta}$, $\tau_{p\psi}$	Roll, pitch, yaw phase delay (s)
$\omega_{p\phi}$, $\omega_{p\theta}$, $\omega_{p\psi}$	Roll, pitch, yaw bandwidth (rad/s)
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
FoV	Field of View
FS&T	Flight Science & Technology
HQR	Handling Qualities Rating
JAR	Joint Aviation Requirement
MTE	Mission Task Element
NRC	National Research Council (Canada)
OTW	Out-the-Window
PSD	Power Spectral Density
RMS	Root-Mean-Square
UCE	Usable Cue Environment
UoL	University of Liverpool
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. There is, however, a fundamental flaw with any simulation device: despite the complexity and the use of state of the art components in modern simulators, they are not yet able to provide a fully coherent representation of reality. The reliance is placed instead on providing a "sufficiently realistic" illusion of flight to the pilot. The strength of this "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 to provide a framework for the acceptance of a synthetic training device. 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. Currently, however, there are no quantitative methods used to assess the fidelity of the overall system. Further, the quantification of fidelity, using an engineering metrics approach, must underpin the confidence required to employ flight simulators for research and development. This however, has as yet been largely neglected in the rotorcraft world.

In order to develop effective metrics of simulator fidelity, the influence of the cueing environment on pilot opinion needs to be understood better. This will allow the identification of the minimum set of cues required by a pilot for a task (those that must be provided by a simulator) and facilitate the development of methods for the effective assessment of a pilot's perception of the fidelity of a simulator, such as a fidelity rating scale.

To establish an engineering basis for civil simulator qualification standards, GARTEUR Action Group (AG) HC-AG12 [3], [4], conducted sensitivity analyses using the JAR-

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STD 1H training simulator standard, including correlation of handling qualities and fidelity metrics. The work revealed 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 developing overall fidelity metrics [5], [6].

Simulators are extensively used in research and development, especially in the assessment of handling qualities and development of 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 [7], [8], [9] 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., [10] and later McCallum and Charlton [11] proposed the use of the handling qualities standard, ADS-33E-PRF "Handling Qualities Requirements for Military Rotorcraft" [12], for deriving metrics. If the simulator is to be used to optimise handling qualities, then what better parameters to judge fidelity than those defining the predicted handling qualities? Within the JSHIP project, Advani and Wilkinson [13] and Roscoe and Thompson [14] 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 simulators.

A New Approach – Lifting Standards

It is this need to have objective measures of predicted fidelity, complemented by subjective measures of perceived fidelity, that is main focus of a UK Engineering and Physical Sciences Research Council (EPSRC) funded project "*Lifting Standards: A Novel Approach to the Development of Fidelity Criteria for Rotorcraft Flight Simulators*" [15], [16].

A two stage approach for defining fidelity criteria for simulator qualification is being developed. The first stage involves the development of a quantitative basis for prediction of fidelity using metrics, derived in part from handling qualities (HQ) engineering. The second stage consists of perceived fidelity metrics supplemented by a pilot fidelity rating scale, used to assign the perceived fidelity of the simulator.

The *Lifting Standards* project involves collaboration with the National Research Council's (NRC) Flight Research Laboratory and consists of three main phases. The first involved the collection of "benchmark" test data from the NRC's Advanced System Research Aircraft (ASRA) Bell 412 helicopter and Liverpool's HELIFLIGHT-R flight simulator. During the second phase of the programme, fidelity metrics are being derived, which will be validated in comparative exercises between flight test and simulations with varying levels of fidelity during the third phase. The metrics will be used to produce evidence-based validation for requirements within existing and emerging simulator standards.

The research described in this paper is complementing the work on Verification and Validation (V&V) techniques currently being undertaken by the University's Virtual Engineering Centre (VEC). Virtual engineering is concerned with integrated product and process modelling and the creation of virtual prototypes. Accuracy, robustness and quality are critical in VE and are captured by the V&V processes. Whilst the VEC is examining issues related to V&V generally for all virtual processes, the work of the *Lifting Standards* project is focussed on the application to rotorcraft simulation. The methodologies and metrics developed in *Lifting Standards* will feed across into the VEC, where their applicability to the wider aspects of V&V for virtual prototypes is being addressed.

This paper examines the development of complementary metrics for the prediction of simulator fidelity, using ADS-33E HQ metrics and for assessing the pilot's perception of fidelity. A range of results from *Lifting Standards'* flight and simulation trial programmes are presented to support the development of the proposed fidelity metrics.

The paper describes the research facilities employed in the *Lifting Standards* project, followed by a description of the HQ-based methodology developed to support the new fidelity metrics. A selection of results from the flight and simulation tests is then presented, focussing on a pair of ADS-33E flight test manoeuvres – the acceleration-deceleration, and the lateral reposition. The paper is drawn to a close with a discussion of the significant findings from the research to date and concluding remarks.

RESEARCH FACILITIES

The Flight Science & Technology (FS&T) research group at the University of Liverpool (UoL) has been operating its HELIFLIGHT full motion flight simulator [17] since 2000. The simulator has been successfully used both in research projects funded by the EPSRC, the European Commission, UK 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 [18].

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 [19], [20], the development of pilot guidance strategies and display concepts in fixed-wing and rotary wing flight [21], [22] and the prediction of simulator-based ship-helicopter operational limits [23], [24].

HELIFLIGHT has certain capability limitations however, e.g. a limited 135 x 40 degree field of view visual system with a single seat crew station; combined with approaching utilisation capacity limits (1000 hours of utilisation in 2005). A new facility (HELIFLIGHT-R) was required to continue the growth of FS&T's research and teaching portfolio. In 2006, 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.

HELIFLIGHT-R

The HELIFLIGHT-R full motion flight simulator (Figure 1) was commissioned in the Department of Engineering at UoL during the summer of 2008. The key features of the simulator are as follows:

- 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 [25].

Figure 1: HELIFLIGHT-R Simulator at UoL

Over the course of the two years following the delivery of the HELIFLIGHT-R simulator, a number of enhancements to the simulation environment have been made, including:

- Upgrade of the visual system, to deliver higher resolution (1400x1050 pixel) outside world displays and a variable reference eye-point.
- Development of a visual database replicating the Ottawa airport operating area of the NRC Bell 412 ASRA aircraft.
- Development of simulation features to more accurately replicate the Bell 412 ASRA aircraft within the HELIFLIGHT-R simulator, such as:
    - Engine and rotor audio effects appropriate to a Bell 412 helicopter.
    - Bell 412 instrument panel display.
    - ASRA safety limit implementation (see next section).

The FLIGHTLAB model of the Bell 412 ASRA aircraft (designated F-B412) was developed during a previous collaboration with the NRC [26], and features a blade element articulated main rotor with finite state dynamic inflow modelling; Bailey tail rotor model and interference effects between the rotors and aerodynamic surfaces (fin, horizontal stabiliser and fuselage).

NRC Bell 412 Advanced Systems Research Aircraft (ASRA)

The Bell 412 ASRA (Figure 2) complements the experimental work being undertaken using the UoL flight simulators with two key features – extensive flight data recording and a fly-by-wire (FBW) flight control system, allowing the aircraft to be operated as an in-flight simulator.

Figure 2: NRC Bell 412 ASRA at the Flight Research Laboratory

The Bell 412 ASRA aircraft is fitted with a comprehensive range of monitoring and measurement equipment [27] to facilitate analysis of pilot control activity and aircraft performance following a flight. Data recording includes:

- Ring Laser Gyro Inertial Reference System, providing measurements of body attitudes, rates and accelerations
- GPS high-precision differential mode positioning
- Static and dynamic pressures
- Radio and laser altitude
- Control inputs (lateral cyclic, longitudinal cyclic, pedals and collective positions)
- Actuator positions

- Air data - true air speed, angles of attack and sideslip
- Engine parameters
- Head tracker

The ASRA is fitted with a full authority experimental FBW control system. The FBW system allows for the rapid implementation and testing of new control laws. More directly applicable to the *Lifting Standards* research, the FBW system allows the response configuration of the aircraft to be modified during the course of a sortie. Flight test data were gathered from two Bell 412 configurations – "bare airframe", with no control augmentation (i.e. a direct drive from the pilot's inceptors to the rotor cyclic and collective controls); and an Attitude Command, Attitude Hold (ACAH) configuration. It is the ACAH configuration that is the focus of the work being reported in this paper.

The ASRA system contains a number of safety limits that cause the experimental fly-by-wire system to disengage and control to revert to the safety pilot. 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 the digital flight control system.

During flight testing, the safety system restricts the level of aggressiveness 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 FLIGHTLAB model to ensure that the evaluation pilot approaches the flying task with an equivalent control strategy in the simulator as in the flight tests. Table 1 shows the FBW safety limits that were used during the trials.

Table 1: ASRA FBW Safety 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 ±10°/s when height is < 10ft

METHODOLOGY FOR SIMULATION FIDELITY BASED ON HANDLING QUALITIES ENGINEERING

In the area of Handling Qualities (HQ) engineering, two assessment processes, *prediction* and *assignment*, are conducted, which combine to give the overall HQs of an aircraft. The practices adopted in the *Lifting Standards* project draw on these processes and the HQ performance specification, ADS-33E-PRF [12].

For both processes, the test aircraft is assessed to be in one of three handling qualities "levels". Level 1 HQs indicate that there is no requirement for improvement to the aircraft and that tasks can be accomplished with low workload. In level 2, the workload will be higher and the level of precision reduced, but the safety of the aircraft is not significantly at risk. If level 3 HQs are found then the level of workload has increased to the extent that task performance is no longer achievable. At the higher end of Level 3 (sometimes defined as level 4), flight safety is compromised as the risk of loss of control increases.

Predicted Handling Qualities

The first assessment process analyses the *predicted HQs* of the test aircraft, with dynamic response criteria drawn from the response to clinical tests such as pulse, step, doublet and frequency sweep control inputs. HQ metrics have been developed to assess the full range of aircraft response, from low to high frequency and from small to large amplitude (Figure 3).

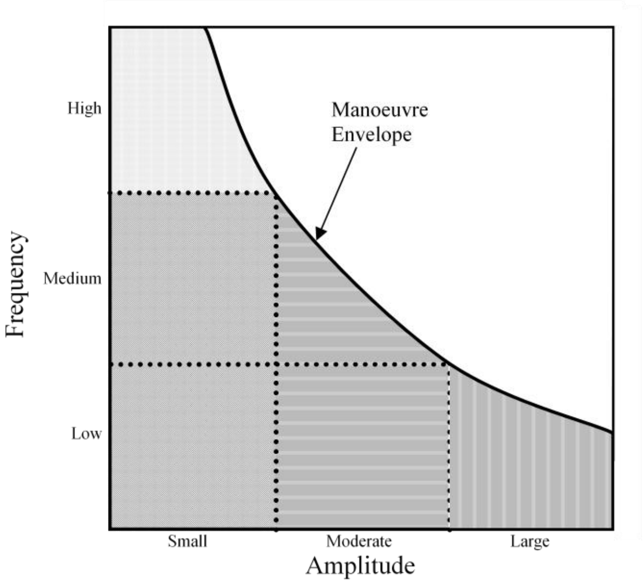

Figure 3: Dynamo Construct for Dynamic Response Criteria

Moving through the dynamo construct, the stability and agility criteria adopted in ADS-33E to assess each region are:

a) Small amplitude, high frequency – bandwidth and phase delay. 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. The phase delay, τ_p, is a measure of the slope of the phase response beyond 180° phase, 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 $2\omega_{180}$.

b) Small amplitude, low to medium frequency – open-loop stability. Stability is quantified in terms of the natural frequency, $\boldsymbol{\omega_n}$, and damping, ζ, of the aircraft's natural modes, such as the Dutch Roll and Phugoid.

c) Moderate amplitudes – quickness. Attitude quickness (Q) provides a measure of the ability to attain moderate amplitude attitude change. It is defined as the ratio of peak attitude rate to the attitude change, hence for pitch quickness,

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

d) Large amplitudes – control power. Control Power (CP) is defined as the maximum response achievable by applying full control from a trim condition.

A further set of HQ metrics is required that specify the required level of handling for the cross-coupled, off axis responses, e.g. pitch response to roll control inputs (and vice versa) and the yaw response to collective control inputs. Additionally for forward flight, the magnitude of the pitch response to a collective input is assessed:

a) 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.

b) 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,

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

a) The pitch due to collective coupling is calculated as the ratio of the peak pitch attitude change in the first three seconds following a step collective control input to the peak incremental normal acceleration:

$$\theta \text{ from Xc} = \left|\frac{\Delta\theta_{pk}}{\Delta n_{zpk}}\right|$$

Assigned Handling Qualities

Once the predicted HQ levels have been computed, the assessment can proceed to *assigned HQs*. In this stage, the test aircraft is flown in a range of manoeuvres that are representative of those that would be expected in the aircraft's operational role, the Mission Task Elements (MTEs).

Prior to the initiation of the MTE flying, expected results based on the predicted HQs can be developed. For example, a precision hover manoeuvre predominantly requires small amplitude corrective inputs, and so the bandwidth and open-loop stability of the aircraft will be of primary importance. The accel-decel, in contrast, requires moderate to large pitch attitude changes, increasing the importance of the quickness and control power.

Test pilots fly each of the MTEs and rate the performance of the aircraft using the Cooper-Harper Handling Qualities Rating (HQR) Scale [28]. The HQR scale requires the test pilot to award his rating based upon both the level of workload experienced during the task and also the achievable level of precision and aggressiveness. Precision is judged relative to a set of "adequate" tolerances, which represent safe flight in the Level 2 region, and more stringent "desired" tolerances which represent low workload flight in the Level 1 region.

HQ Methodology for the Assessment of Simulator Fidelity

Much of the methodology described in the previous section can be directly applied to the fidelity assessment of a flight simulator – both are intimately related to pilot control strategy. Here, however, the goal is to establish the quality of the simulator in replicating the behaviour of the real aircraft.

In the case of each of the prediction metrics, the fidelity assessment is focussed on the simulator components, in this case the simulation model of the test aircraft. For the assignments the pilot's impression of the behavioural accuracy of the model is closely linked with the experienced cues. The primary generators of task cues within the simulator are the visual, motion, audio and inceptor force-feel systems. In fidelity, we describe the pilot's experience as the perceived fidelity.

As in the HQ assessment process, a comparison of the predicted and perceived fidelity results forms a key component of the overall fidelity assessment process. This stage is required to establish that the predicted and perceived results are consistent, and for the same reasons in the simulator as they are in the flight test data.

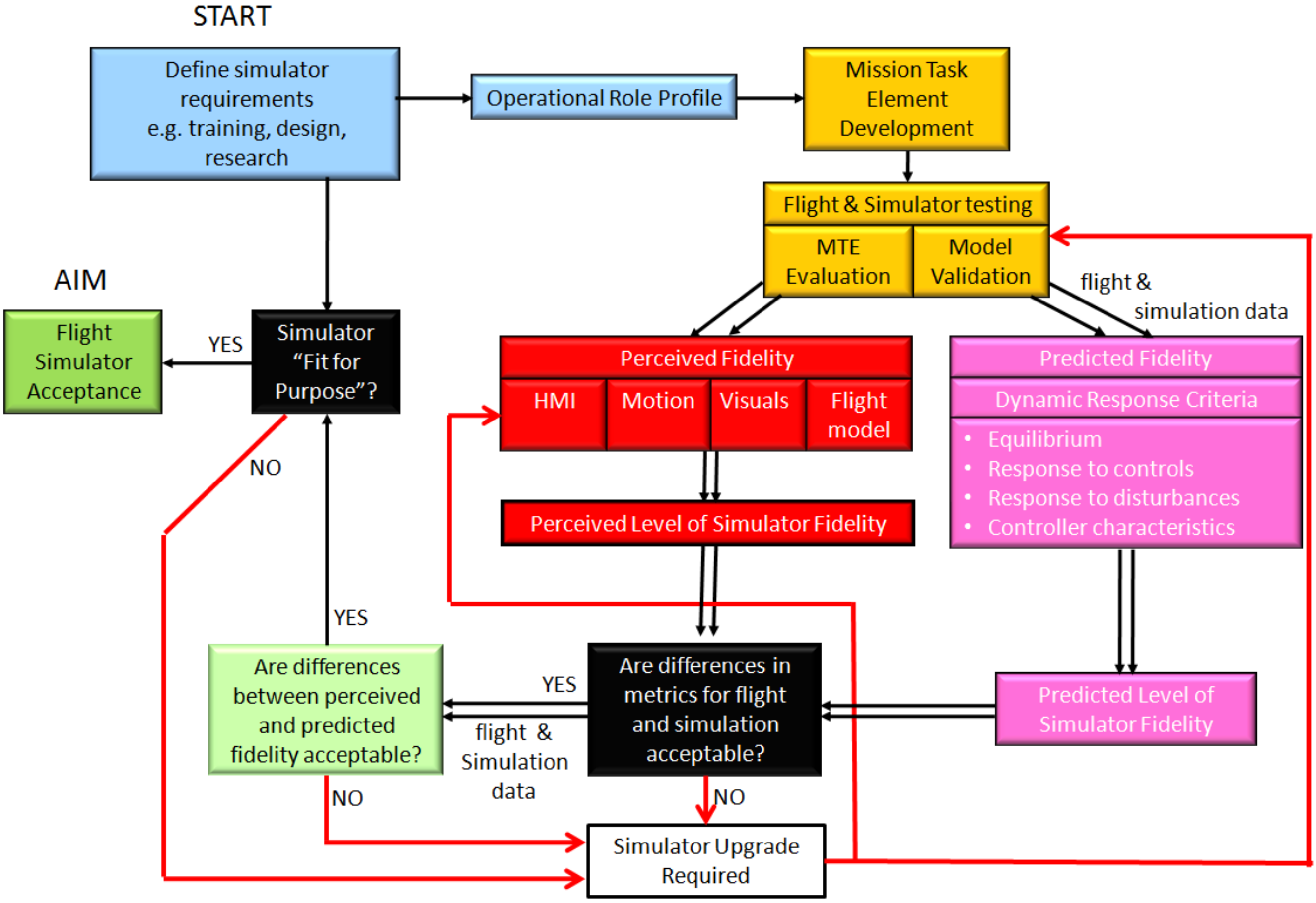

Figure 4: Methodology for Integrated Predicted and Perceived Simulator Fidelity Assessment

A flow diagram representing the process for the assessment of predicted and perceived simulator fidelity is shown in Figure 4. As with the assessment of an aircraft's HQs, the process begins with a definition of the required purpose of the flight simulator, which will set the required level of fidelity. Once the purpose of the simulator has been defined, the predicted and perceived fidelity can be computed using a set of metrics such as those described in this paper.

The results from these tests feed into two decision points. The first question is; do the individual predicted and perceived fidelity metrics show a good match between flight and simulation? This is a key stage in the overall fidelity assessment process, as it highlights the overall quality of the simulation. The second question is related to the comparisons between predicted and perceived fidelity. In addition to verifying the overall fidelity of the simulator, the analysis at this point provides a further indicator as to the source of discrepancies between flight and simulation. If the predicted metrics show a good match, while the perceived metrics do not, then the indication is that the fidelity issues lie within the generation of the task cues and not the model.

If both questions can be answered positively then a decision can be made that the simulator is fit for its designed purpose and can be accepted for service. If, however, one of the fidelity requirements is not met, this would be an indicator that the simulator is not fit for purpose, and an upgrade, either to the cueing or the flight model or both, is required before the simulator can be accepted.

As shown in [16], the HQR is a necessary but insufficient measure of fidelity. To complement the HQR, the test pilot was asked to rate the effect of the visual cues on vehicle control through the Visual Cue Rating (VCR) [12], from which a Usable Cue Environment (UCE) can be derived. As with HQ assessments, task performance and workload metrics are useful for quantifying differences between flight and simulator. For task performance, these are:

a) Total task time. The time taken to complete the manoeuvre.
b) Time spent within desired performance. Percentage of the total manoeuvre time spent within the desired performance tolerance.
c) Time spent within adequate performance. Percentage of the total manoeuvre time within the adequate performance tolerance (including the desired performance region).
d) Time spent beyond adequate performance. Percentage of the total manoeuvre time spent beyond the adequate performance tolerance.

For the pilot's control compensation, the following metrics are used:

a) Control attack which measures the size and rapidity of a pilot's control inputs [29], defined as:

$$attack = \frac{\dot{\eta}_{pk}}{\Delta\eta}$$

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

   i. Attack number. This is the total number of times that the pilot moves a particular control by more than 0.5% of full travel.
   ii. Attack number per second. This is the attack number expressed in terms of the average number of control movements per second.
   iii. 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.
   iv. Mean control displacement. This is the mean of the control displacements measured for each of the attack points.

b) Quickness can be applied to assess closed loop, in addition to open loop, agility. The closed loop quickness, Q_{CL}, can be summarised using equivalents of the parameters described above for the control attack. They are:
   i. Number of quickness points (number of attitude changes).
   ii. Quickness points per second.
   iii. Mean quickness.
   iv. Mean attitude change.

c) In the frequency domain, we can assess [30]:
   i. Root-Mean-Square (RMS) of the power spectral density in each control axis.
   ii. Cut-off frequency where 70% of the PSD has accumulated.

   The RMS value and cut-off frequency are calculated over the interval 0.2Hz>f>2Hz, with the lower limit removing the guidance element of the control activity from the analysis, and the upper limit signal noise.

The fidelity assessment methodology was reported in [16] and a selection of results was presented for hover and low speed MTEs (precision hover and pirouette). There was close agreement between the predicted HQ metrics and the assigned HQR. However, a significant difference emerged in terms of the control techniques in flight and in the simulator. For both MTEs, it was found that the pilot made a greater number of corrective control inputs during the flight test than he did in the comparable simulation run. The presence of atmospheric disturbances in flight, not modelled in the simulator will contribute to at least some of the additional pilot effort. However, the ability of the pilot to achieve similar or better performance in flight (e.g. HQR=5 for both flight and simulator in the pirouette MTE) suggests that atmospheric disturbances do not tell the complete story. The sources of these differences are a focus of continuing research at Liverpool.

Continuing the analysis, the next section will present results for two further MTEs, the acceleration-deceleration (often shortened to accel-decel), examining the longitudinal response of the aircraft, and the lateral reposition, examining the lateral response of the aircraft.

TRIAL RESULTS

Predicted Model Fidelity

Table 2 summarises the predicted HQs from flight and simulation testing of the ACAH configuration. A graphical presentation of the results is contained in Appendix A.

Table 2(a): Predicted Fidelity of the FLIGHTLAB Bell 412 Model in ACAH Configuration using ADS-33E HQ Metrics: Bandwidth, Stability and Control Power

Fidelity Parameter	**Flight (Sim)**	**HQL**	**%ΔF-S**	**Margin to Level 1-2 Boundary**	**% Margin to Level 1-2 Boundary**
Bandwidth (hover)					
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
Stability (hover)					
ω_n	TBD				
ζ	TBD				
Control Power (hover)					
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)

Table 2(b): Predicted Fidelity of the FLIGHTLAB Bell 412 Model in ACAH Configuration using ADS-33E HQ Metrics (cont.): Quickness and Cross-Couplings

Fidelity Parameter	Flight (Sim)	HQL	%ΔF-S	Margin to Level 1-2 Boundary	% Margin to Level 1-2 Boundary
Quickness (hover)					
Average Q_Φ (10°<Φ<20°)	1.98 (1.87)	1 (1)	-5.81	0.82 (0.70)	70 (60)
Average Q_θ (5°<θ<10°)	1.05 (1.05)	1 (1)	0.0	0.41 (0.41)	64 (64)
Average Q_ψ (10°<ψ<20°)	0.41 (0.22)	2 (3)	-44.9	-0.79 (-0.97)	-66 (-81)
Cross-Couplings (hover and forward flight)					
p from q [hover]	0.24 (0.11)	1 (1)	-56.1	0.01 (0.14)	2 (57)
q from p [hover]	0.25 (0.07)	2 (1)	-70.7	-0.01 (0.18)	-4 (72)
p from q [75kts]	0.32 (0.32)	2 (2)	0	-0.07 (-0.07)	-28 (-28)
q from p [75kts]	0.14 (0.05)	1 (1)	-66.4	0.11 (0.2)	44 (80)
Collective to Yaw @ 1s [hover]	0.41 (0.23)	1 (1)	-44.7	0.24 (0.42)	36 (65)
Collective to Yaw @ 3s [hover]	-0.79 (-0.11)	3 (1)	-86.1	-0.64 (0.04)	-427 (27)
Collective to Pitch @ +20% [75kts]	0.2 (0.09)	P (P)	-56.5	0.3 (0.41)	60 (82)
Collective to Pitch @ -25% [75kts]	0.15 (0.13)	P (P)	-13.3	0.1 (0.12)	40 (48)

Work to identify the stability of the natural modes of the Bell 412 ASRA using system identification techniques is ongoing as part of the *Lifting Standards* project. While this is not yet complete analysis of the response of the aircraft indicates that level 1 damping is expected for each of the Dutch Roll and Phugoid modes for the ACAH configuration under investigation in this paper.

It can be seen in Table 2 that the majority of the predicted metrics for the F-B412 are in the level 1 region. The only exceptions to this are in the yaw axis bandwidth and quickness, and the control powers, which are predicted to be level 2 or level 3. This is a different scenario to that depicted for the ASRA, where, in addition, many of the inter-axis coupling effects are of greater magnitude. In hover, the pitch due to roll and yaw due to collective degrade into level 2 and level 3 respectively, while in forward flight the roll due to pitch coupling is predicted to be a level 2 effect.

In terms of fidelity, 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 many of the cross-coupling parameters. If the acceptable margin were 10%, then the roll bandwidth and pitch control power would also fail the fidelity test.

While the primary response parameters (bandwidth, quickness) in pitch and roll are predicted as conferring level 1 HQs, the level 2 yaw axis bandwidth will demand additional effort from the pilot in maintaining a constant heading during both the accel-decel and lateral reposition MTEs. Furthermore, it would be anticipated that in flight, the level 2-3 coupling effects (especially roll due to pitch and pitch/yaw due to collective for the accel-decel; and pitch due to roll for the lateral reposition) would reduce the level of precision achievable and increase the workload compared with the simulator. Overall, from the predicted HQ analysis, it might be expected that the simulator would be able to achieve level 1-2 boundary performance (depending on the required number and severity of corrective heading control inputs), while in the flight test the level might be lower in the level 2 region, tending towards level 3.

Perceived Fidelity

The accel-decel and lateral reposition are a pair of complementary MTEs for assessing longitudinal and lateral HQs of an aircraft respectively. While the accel-decel is designed in ADS-33E as a maximum aggression manoeuvre, the constraints of the ASRA FBW system (Table 1) reduce this to a “high” level of aggression. The lateral reposition was flown to the ADS-33E specification, making it also a high aggression manoeuvre.

For both MTEs, the task is to accelerate the aircraft to a target airspeed. This is 40kts for the accel-decel, and an airspeed that allows the lateral reposition to be completed within the target time of 18s. The second phase of each MTE requires deceleration back to a stabilised hover at a marked end point (700 feet from the start for the accel-decel and 450 feet for the lateral reposition).

The test course for the accel-decel and lateral reposition MTEs is illustrated in Figure 5 (note that for clarity the track for the lateral MTE has not been shown in its actual location over the centre-line of the course). The adapted performance requirements for the accel-decel MTE are listed in Table 3 and the performance requirements for the lateral reposition MTE are shown in Table 4.

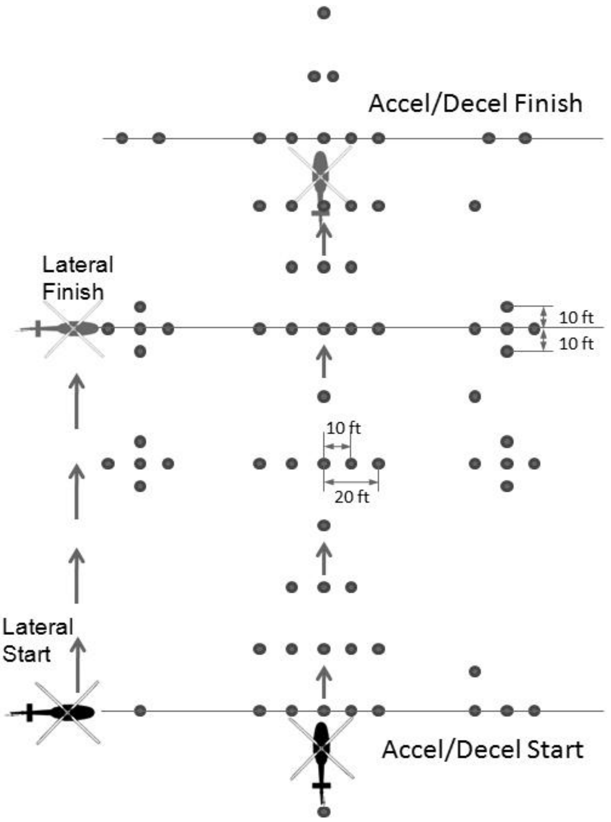

Figure 5: Accel-decel and Lateral Reposition Combined Test Course

Table 3: Accel-Decel MTE Performance Requirements

Requirement	Desired	Adequate
Maintain altitude below X feet	70	100
Maintain lateral track within ±X feet	10	20
Maintain heading within ±X °	10	20

Table 4: Lateral Reposition MTE Performance Requirements

Requirement	Desired	Adequate
Maintain altitude within ±X feet	10	15
Maintain lateral track within ±X feet	10	20
Maintain heading within ±X °	10	15
Complete manoeuvre within X sec	18	22

As the MTEs share many commonalities, it is expected that the critical HQs for each MTE will be similar, albeit in different axes. Open loop stability and bandwidth performance will be important in acquiring and maintaining the stabilised hover at the end point of the MTE. The attitude changes required to accomplish the aggressive acceleration and deceleration will heighten the importance of the vehicle's attitude quickness and the cross couplings. The power changes required to maintain altitude during these MTEs will exercise the collective to yaw coupling.

Before examining the results from the MTEs, it is useful to consider the test pilot's perception of the differences flying the ASRA 412 and the UoL F-B412 simulation.

- The test pilot noted that the control forces and displacements in HELIFLIGHT-R were different to those experienced in flight. Although the inceptors were tailored to emulate the ASRA 412, the actual configuration of flight controls and their physical location in the crew station were different in the simulator.
- A difference in field of view (FoV) was noted. The framing of the cockpit of the ASRA 412 reduced the FoV in a number of key areas during the manoeuvres. In contrast, the HELIFLIGHT-R OTW display is unimpeded except below and behind the instrument panel.
- The detail rendered in the simulator OTW display was noted as being less than that experienced in flight. This was a function of the available resolution of the HELIFLIGHT-R visual system, coupled to reduced scene content in comparison with the rich textural environment of the real world airfield, even covered in snow.
- The simulator was considered to be lacking in fidelity in terms of the generation of appropriate audio cues, particularly during more aggressive tasks when the pilot felt that he was able to respond to audio cues in the ASRA which were not detected as being so powerful in the simulator.

The Acceleration-Deceleration MTE

The performance achieved in this task is shown in Figure 6. The fidelity metrics are presented in Table 5. Further details, including time histories of the aircraft rates and attitudes, and analysis of the pilot's control activity is included in Appendix B. Although the pilot awarded a HQR=4 for the flight test (contrasting with HQR=5 for the simulator), the data show that desired performance was not achieved for the complete MTE either in flight or in the simulator. The pilot perceived a different level of performance to that achieved.

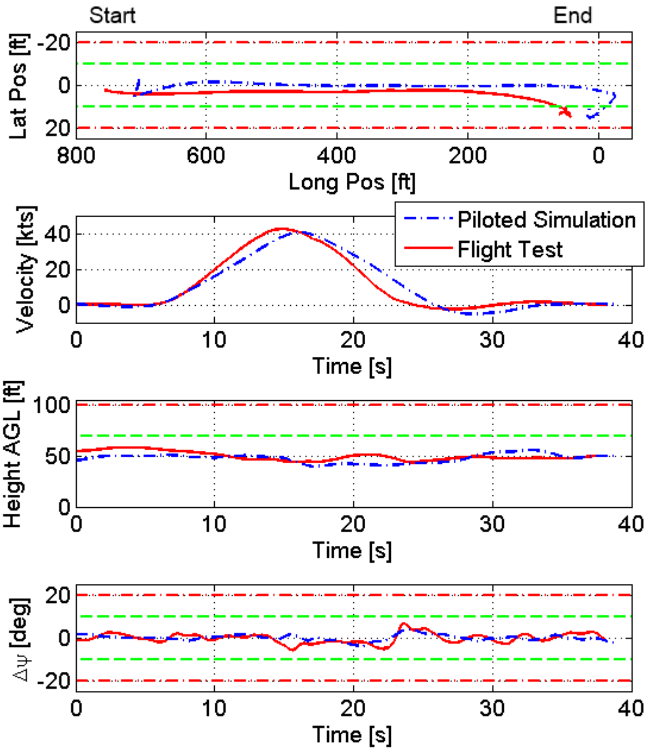

Figure 6: Task Performance in the Accel-Decel MTE

Table 5: Fidelity Metrics for Accel-Decel MTE

(a) ratings

Fidelity parameter	**Flight**	**Simulator**	**Δ%**
HQR	4	5	
UCE	1	2	
• VCR(TR)	2.0	3.0	
• VCR(A)	1.5	2.0	
Total task time (s)	38	38.5	1.3

(b) longitudinal axis parameters

Fidelity parameter	**Flight**	**Simulator**	**Δ%**
• attack number	117	77	-34
• attack number per sec. (/s)	3.07	1.97	-36
• mean attack rate (%/s)	28.8	13.0	-55
• mean control displ. (%)	10.6	7.8	-26
• no of quickness points	20	10	-50
• quickness points per sec. (/s)	0.52	0.26	-50
• mean quickness (/s)	1.26	0.54	-57
• mean att. change (°)	5.1	7.9	55
• PSD RMS	0.088	0.058	-34
• cut-off frequency (Hz)	0.97	0.81	-16

(c) lateral axis parameters

Fidelity parameter	**Flight**	**Simulator**	**Δ%**
Lateral Position % time in			
• desired	56.7	72.3	15.6
• adequate	100	100	0
• inadequate	0	0	0
• attack number	82	59	-28
• attack number per sec. (/s)	2.15	1.51	-30
• mean attack rate (%/s)	11.0	6.7	-39
• mean control displ. (%)	3.5	2.5	-29
• no of quickness points	51	26	-49
• quickness points per sec. (/s)	1.34	0.67	-50
• mean quickness (/s)	3.9	2.0	-49
• mean att. change (°)	1.8	1.6	-11
• PSD RMS	0.022	0.016	-27
• cut-off frequency (Hz)	0.96	1.01	5.2

(d) yaw axis parameters

Fidelity parameter	**Flight**	**Simulator**	**Δ%**
Heading % time in			
• desired	100	100	0
• adequate	100	100	0
• inadequate	0	0	0
• attack number	107	66	-38
• attack number per sec. (/s)	2.81	1.69	-40
• mean attack rate (%/s)	18.2	15.4	-15
• mean control displ. (%)	6.3	7.1	13
• no of quickness points	26	22	-15
• quickness points per sec. (/s)	0.68	0.56	-18
• mean quickness (/s)	1.7	1.2	-29
• mean att. change (°)	3.0	2.0	-33
• PSD RMS	0.097	0.028	-71
• cut-off frequency (Hz)	0.91	0.844	-7

(e) vertical axis parameters

Fidelity parameter	**Flight**	**Simulator**	**Δ%**
Height % time in			
• desired	100	100	0
• adequate	100	100	0
• inadequate	0	0	0
• attack number	41	53	29
• attack number per sec. (/s)	1.08	1.36	26
• mean attack rate (%/s)	17.8	8.7	-51
• mean control displ. (%)	12.1	5.5	-55
• PSD RMS	0.051	0.028	-45
• cut-off frequency (Hz)	0.92	0.97	5

Neither in simulation or flight did the pilot consider the desired lateral positioning requirement had been exceeded. It can be seen in Figure 6 that in both cases, the aircraft moves to the right during the very final stages of the MTE. It is during this time that the provided task cues are least visible to the pilot – either the nose has been raised to decelerate the aircraft, or, having reached the final hover point, no more sets of task markers are available ahead of the aircraft (this was due to limited space in the Ottawa test environment).

The pilot's primary comment was that the dynamics of the response to the collective lever required more compensation than he would typically expect for this MTE. The reason for this was twofold. Firstly, the FBW safety limit for mast torque (Table 1) required continuous monitoring during the acceleration, and during the final hover capture phase of the MTE, and secondly, the poor damping of the engine-rotor governor system prevented the pilot from rapidly setting a desired torque value.

The data show that the collective control technique (Figure B1) differed between flight and simulator, with collective inputs being made rather less frequently, but more sharply and with a larger amplitude in flight.

The time histories from the MTE (Figure 6) show that, as expected from the predicted HQ analysis, the aircraft's heading was disturbed more frequently, and more severely in flight than in the simulator, due to the more adverse collective to yaw coupling (level 3 in flight; level 1 in the simulator). This effect did not, however, prove to be so degrading as to result in the heading exceeding even the desired performance requirement. The pilot was able to achieve a greater proportion of time within the desired lateral position requirement in the simulator, the more benign couplings reducing lateral disturbances during this longitudinal MTE.

With the exception of the collective axis, the perceived fidelity metrics show that the pilot applied a significantly higher level of compensation during flight. The notable exception to this pattern is the cut-off frequency, for which there is no clear trend. This topic will be returned to in the discussion section.

The Lateral Reposition MTE

The performance achieved in this task is shown in Figure 7. The fidelity metrics are presented in Table 6. Further details can be found in Appendix B. The pilot awarded a HQR of 4 in the simulator and 5 in flight. Again, the data show that desired performance was not attained for the complete manoeuvre. The aircraft moved beyond the adequate requirement for longitudinal position for the final 22% of the run in the simulator. As with the accel-decel, it is thought that this discrepancy between the pilot's perception of his performance and that recorded is due to limitations in the task cues provided.

From the fidelity metrics in Table 6, it can be seen that the number of attack points and the mean attack rate are significantly higher in flight than in the simulator, with the exception of collective control. In terms of quickness, the mean attitude change is significantly larger in the simulator. While in the lateral axis this will partly be explained by the much smaller total number of quickness points (raising the prominence of the three primary bank angle changes required to complete the lateral reposition MTE), a difference of 121% in the longitudinal axis is more significant. Coupled with the lower mean quickness value (59% lower longitudinally in the simulator), a picture emerges of the pilot making coarser and less precise attitude corrections at a lower intervention frequency in the simulator. This is supported by the VCRs given by the pilot (1.5 in flight and 3.0 in the simulator for the ability to make attitude corrections).

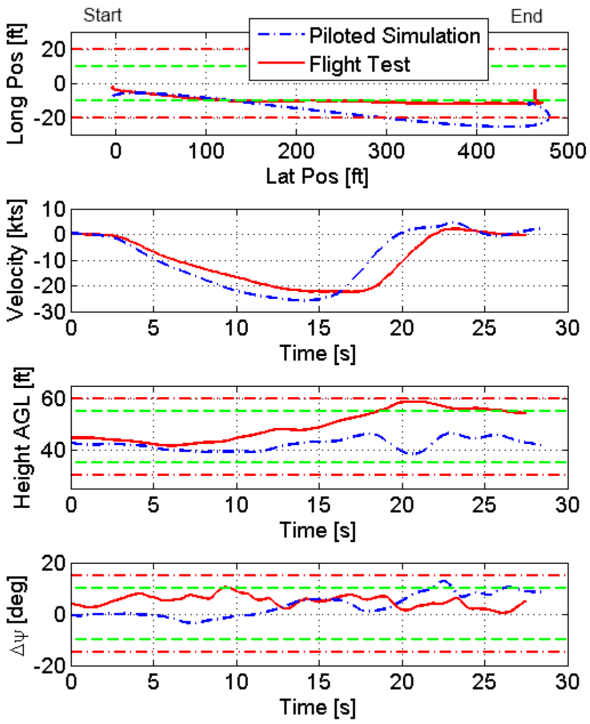

Figure 7: Task Performance in the Lateral Reposition MTE

Table 6: Fidelity Metrics for the Lateral Reposition MTE

(a) ratings

Fidelity parameter	Flight	Simulator	Δ%
HQR	5	4	
UCE	1	2	
• VCR(TR)	3.0	2.5	
• VCR(A)	1.5	3.0	
Total task time (s)	27.5	28.5	3.6
Time to complete translation (s)	20	19	-5

(b) longitudinal axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Longitudinal Position % time in			
• desired	50	32	-18
• adequate	100	78	-22
• inadequate	0	22	22
• attack number	71	46	-35
• attack number per sec. (/s)	2.6	1.6	-38
• mean attack rate (%/s)	20.6	10.6	-48
• mean control displ. (%)	6.6	5.4	-18
• no of quickness points	14	10	-29
• quickness points per sec. (/s)	0.51	0.35	-51
• mean quickness (/s)	2.2	0.9	-59
• mean att. change (°)	1.4	3.1	121
• PSD RMS	0.058	0.058	0
• cut-off frequency (Hz)	1.06	0.81	-24

(d) lateral axis parameters

Fidelity parameter	Flight	Simulator	Δ%
• attack number	60	41	-32
• attack number per sec. (/s)	2.2	1.4	-36
• mean attack rate (%/s)	12.4	10.3	-17
• mean control displ. (%)	4.9	6.4	31
• no of quickness points	36	15	-58
• quickness points per sec. (/s)	1.31	0.53	-59
• mean quickness (/s)	2.2	1.0	-55
• mean att. change (°)	2.8	7.3	161
• PSD RMS	0.035	0.046	31
• cut-off frequency (Hz)	1.09	0.78	-28

(e) yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Heading % time in			
• desired	98	93	-5
• adequate	100	100	0
• inadequate	0	0	0
• attack number	64	38	-41
• attack number per sec. (/s)	2.3	1.3	-43
• mean attack rate (%/s)	20.2	13.0	-36
• mean control displ. (%)	7.8	7.9	1.3
• no of quickness points	18	11	-39
• quickness points per sec. (/s)	0.65	0.39	-40
• mean quickness (/s)	1.5	0.86	-43
• mean att. change (°)	2.9	3.9	34
• PSD RMS	0.119	0.037	-69
• cut-off frequency (Hz)	1.0	0.56	-44

(f) vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Height % time in			
• desired	72	100	28
• adequate	100	100	0
• inadequate	0	0	0
• attack number	31	30	-3.2
• attack number per sec. (/s)	1.1	1.1	0
• mean attack rate (%/s)	11.3	6.4	-43
• mean control displ. (%)	6.5	5.1	-22
• PSD RMS	0.06	0.032	-47
• cut-off frequency (Hz)	0.94	0.94	0

DISCUSSION

As with the pirouette and precision hover MTEs discussed in [16], the adequacy of the HQR as a measure of simulator fidelity is questionable. For the accel-decel, although the pilot gave a HQR of 4 in flight, the proportion of time spent in the adequate performance region for lateral position suggests that HQRs of 5 for both flight and simulator would be appropriate. Applying the same argument to the lateral reposition MTE, the HQR of 4 awarded in the simulator does not fully reflect the achieved level of performance. The differences between the pilot's perception of the achieved task performance and that recorded complicate matters and question the validity of the HQRs. However, it may be assumed that, provided with knowledge of the adequate performance achieved for both flight and simulator tests, the pilot would have awarded HQR=5 for all runs. In this scenario, it can be seen that the HQR does not show good sensitivity to fidelity issues in the level 2 region, even though the data shows that there is a significant difference between the control strategies required to complete the MTEs in flight and those employed in the simulator.

The HQR is an essential element in the assessment of HQs of the aircraft and should find its way into the set of necessary fidelity metrics for a flight simulation. As the most direct qualitative measure of the pilot's perception of the aircraft in flight and simulator, it is important that the HQR is matched between the two environments. However, the HQR by itself is far from sufficient, and must be supported by other metrics through which fidelity can be assessed, such as those presented in this paper.

The HQR results highlight the importance of the introduction of a rating scale designed for the assessment of simulator fidelity. Such a *perceived fidelity rating scale* would allow a pilot to directly express his opinion on the differences experienced between flight and simulator. The use of a six-point scale in the assessment of the fidelity of linear models derived from system identification techniques has been described by Zivan and Tischler [31]. In this system, the evaluating pilot was required to rate the fidelity of a wide range of detailed comparisons, such as "ability to correct undesirable secondary effects". These detailed questions on the pilot's perception of the vehicle's characteristics are a differentiator between this scale and the HQR scale.

The control attack metric captured a significantly greater number and frequency of corrective control inputs in flight. This apparent difference in workload did not, however, result in the pilot moving from HQR=5 to HQR=6 for those cases where adequate performance had been perceived.

The frequency domain metrics (RMS value and cut-off frequency) did not show the same degree of consistency in terms of their sensitivity to the difference in control activity between the flight and simulator data. It would be expected that the RMS value would increase with the size of control movement (higher mean control displacement). The cut-off frequency would in contrast be expected to increase with a greater number of attack points per second. Although these trends can be seen in some of the data presented in Table 5 and Table 6 (e.g. lateral axis in the lateral reposition MTE), they were not observed for all axes in the two MTES under investigation.

In the majority of cases the RMS values from the PSDs of control activity matched the patterns seen in the attack data, but there were cases where this was not the case – for example longitudinal cyclic during the lateral reposition (Table 6b). In this case, the simulator data showed 35% fewer control inputs at an average displacement 18% less than that in flight, but the RMS value was identical for both sets of data. For this example, a difference between flight and simulator in the frequency domain is captured by the cut-off frequency analysis, with the simulator cut-off frequency 24% lower than that calculated from the flight test data (with the number of attack points per second 38% lower in the simulator).

The opposite pattern can be seen in the data for lateral cyclic activity during the accel-decel MTE. The attack data again shows a significantly lower number (28%) and average displacement (29%) from the control inputs. In this case, the cut-off frequencies are very similar (simulator 5% higher than flight) with a significant difference in RMS value (simulator 27% lower). The source of the higher cut-off frequency in the simulator in this example is the peak in the PSD (Figure 8) at 1.55Hz. Reducing the upper frequency limit in the cut-off calculation to 1.5Hz (from 2Hz) removes this effect and leaves a higher cut-off frequency in flight, matching the attack number analysis. Although the source of the mis-match between the attack and cut-off data is not fully understood, and is a subject of the continuing research at Liverpool, this result is being treated as anomalous, as it is isolated amongst the many other test points in which the attack number and cut-off data correlate strongly.

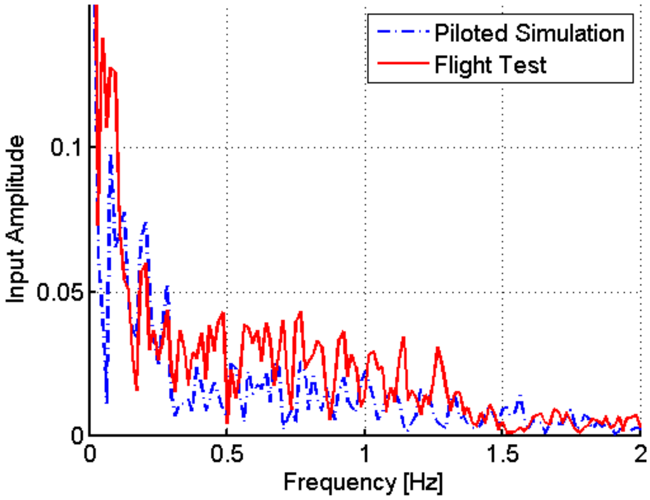

Figure 8: PSD of Control Activity (Lateral Axis) for Accel-Decel MTE

While these results indicate that neither of the frequency domain parameters always captures a difference in control activity between flight and simulator (as measured through the control attack), a combined metric (possible forms for the comparison are illustrated in Figure 9 and Figure 10) employing both an amplitude measure (such as mean control displacement) and a frequency measure (such as cut-off frequency) could accurately portray differences in a pilot's control strategy. For this scenario, both parameters must be matched in order to ensure similarity in control strategy for flight and simulation, and therefore good fidelity.

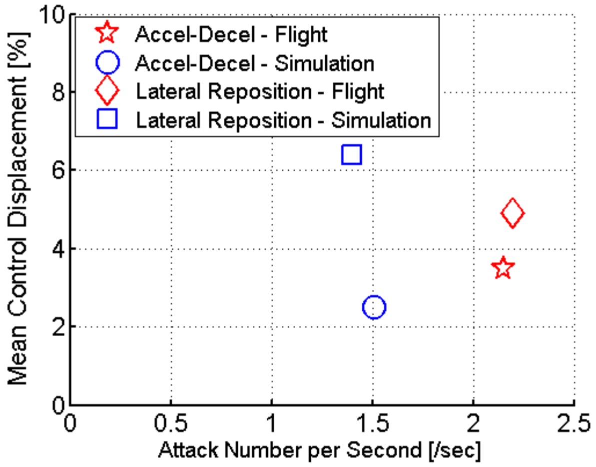

Figure 9: Chart Combining Temporal Metrics – Lateral Axis

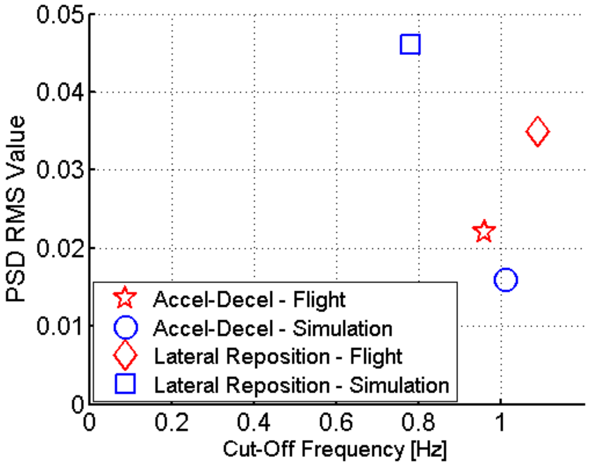

Figure 10: Chart Combining Frequency Metrics – Lateral Axis

While two possible forms for a simulator fidelity metric have been presented in Figure 9 and Figure 10, it is highly desirable for the fidelity process to be kept as simple as possible, requiring the minimum number of metrics to be assessed. Thus, a key focus in the ongoing research at Liverpool is the assessment of the efficacy of each of the possible fidelity metrics and the identification of a single metric for perceived fidelity to be recommended for adoption in the rotorcraft flight simulator certification process.

While the points discussed above hold true for the accel-decel and lateral reposition MTEs, it is also important to look back at the precision hover and pirouette MTEs from [16]. Generally, the trends can also be observed in the hover MTEs, as illustrated through the lateral axis analysis of the pirouette MTE shown in Table 7. Although the mean control displacement is lower in the simulator than in flight, the RMS value is returned as being somewhat higher in the analysis of the simulator data. The cut-off frequency is significantly lower in the simulator than in flight, as would be expected from the lower number of attack points per second.

Table 7: Fidelity Parameters for Lateral Axis in Pirouette MTE

Fidelity parameter	Flight	Simulator	Δ%
• attack number	160	65	-59
• attack number per sec. (/s)	2.6	1.3	-50
• mean attack rate (%/s)	13	8.6	-34
• mean control displ. (%)	4.7	4.6	-2.1
• no of quickness points	84	31	-63
• quickness points per sec (/s)	1.4	0.6	-57
• mean quickness (/s)	3.9	1.4	-64
• mean attitude change (°)	2.1	3.4	62
• PSD RMS	0.024	0.026	8.3
• Cut-off frequency (Hz)	1.11	0.844	-24

Based on the predicted fidelity, it was expected that level 2 ratings would be awarded in both flight and simulator, and so it proved to be. However, the additional deficiencies predicted in flight from the cross-coupling parameters did not appear to play a significant part in the MTEs under investigation, although heading control was a little less precise during the accel-decel MTE in flight. It would, however, be expected that the more severe cross-couplings will have contributed to the additional compensation recorded in the flight tests, as the pilot worked to suppress off-axis responses.

In the continuing research at UoL, the contribution to the additional pilot effort in flight from atmospheric turbulence and unsteady interactional aerodynamic effects not captured in the simulation model will be examined. Also under investigation is the sensitivity of each of the proposed fidelity metrics to changes in the simulation model and the other simulator sub-system fidelity (motion, visuals etc.). The focus here is to attempt to answer the question: how close does the match between flight and simulator need to be for the simulator to be fit for purpose?

The effect of changing the aircraft configuration on the fidelity metrics will also be assessed. This will include bare airframe flight dynamics and rate and attitude configurations having predicted and assigned Level 1 HQs in flight.

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 [32]. 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.

CONCLUDING REMARKS

This 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 full motion flight simulator has been described and utilised, 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 drawing on the ADS-33E HQ dynamic response criteria and results compared for an ACAH configuration. MTEs flown using the ASRA airborne simulator have been replicated in HELIFLIGHT-R and results for the acceleration-deceleration and lateral reposition 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 1-2 boundary for the ACAH configuration, with the ASRA aircraft exhibiting slightly poorer HQs than the F-B412, especially in terms of cross coupling effects. The assigned HQ results were broadly consistent with these predictions from both simulation and flight, although the predicted borderline level 2-3 coupling effects did not appear to affect task performance in flight as expected.

For the assessment of perceived fidelity, control activity, task performance, temporal and frequency domain metrics have been presented and their efficacies discussed. The HQR itself has proved to be a necessary but insufficient measure of fidelity, not least because differences in HQR may arise due to many different influencing factors. The same HQR can reflect a multitude of fidelity aspects. This highlights the need for a rating scale specifically addressing fidelity issues.

The control attack and closed-loop quickness metrics have been shown to be sensitive to differences between flight and simulator. In particular, both the number of attack points and the mean attack rate exhibit a large difference between flight and simulation for almost all test points. It is hypothesised that un-modelled atmospheric disturbances and unsteady interactional aerodynamics contribute to the reduced activity in the simulator.

The frequency domain metrics, cut-off frequency and RMS value for the PSD of control activity, do not individually show consistency with the temporal fidelity metrics (number of attack points per second and mean control displacement). Further, the individual metrics do not capture both the amplitude and frequency characteristics of a pilot's control activity. It can therefore be recommended that for the accurate assessment of control activity, a combined metric bringing together frequency and amplitude analysis is required. This may take a form similar to that illustrated in Figure 9 or Figure 10.

This paper has described progress in the identification of parameters that are sensitive to differences between flight and simulation, and are therefore suitable for use as metrics of fidelity. Work is, however, still required to fully establish cause and effect and to quantify the allowable discrepancies between flight and simulator; these are the subjects of ongoing research in the *Lifting Standards* project at Liverpool, together with the identification of a single, simple metric for fidelity assessment and the development of a perceived fidelity rating scale.

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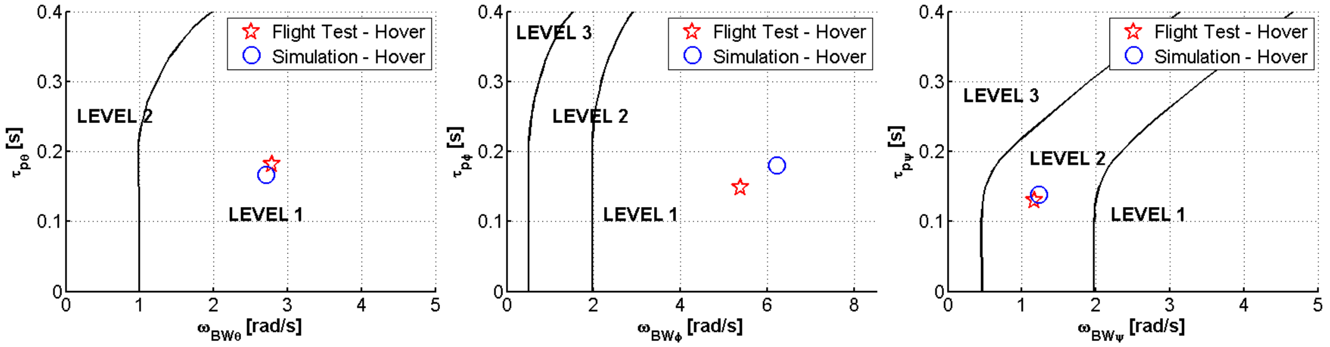
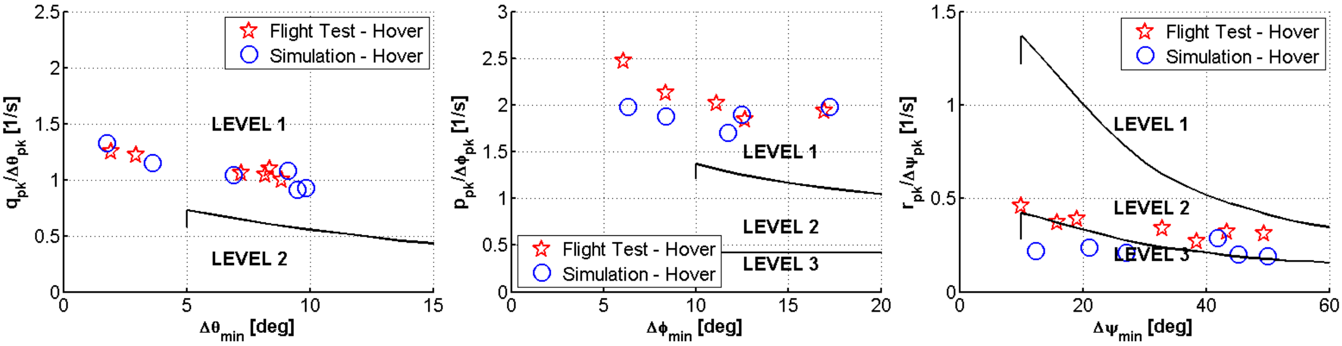
APPENDIX A – PREDICTED MODEL FIDELITY



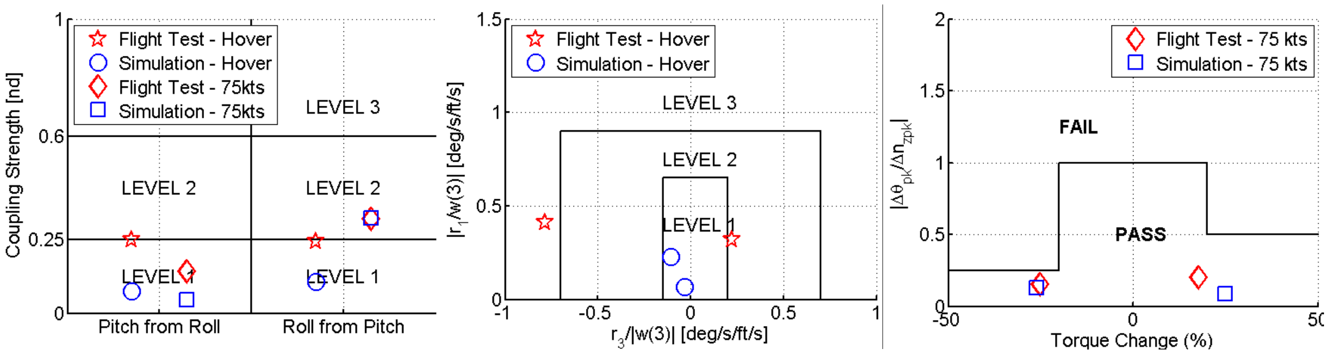
(a) Pitch Axis (b) Roll Axis (c) Yaw Axis

Figure A1: Attitude Bandwidth



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

Figure A2: Attitude Quickness



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

Figure A3: Cross Couplings

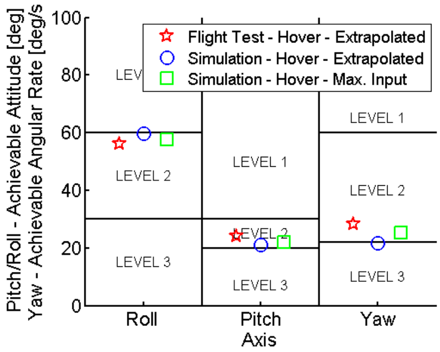
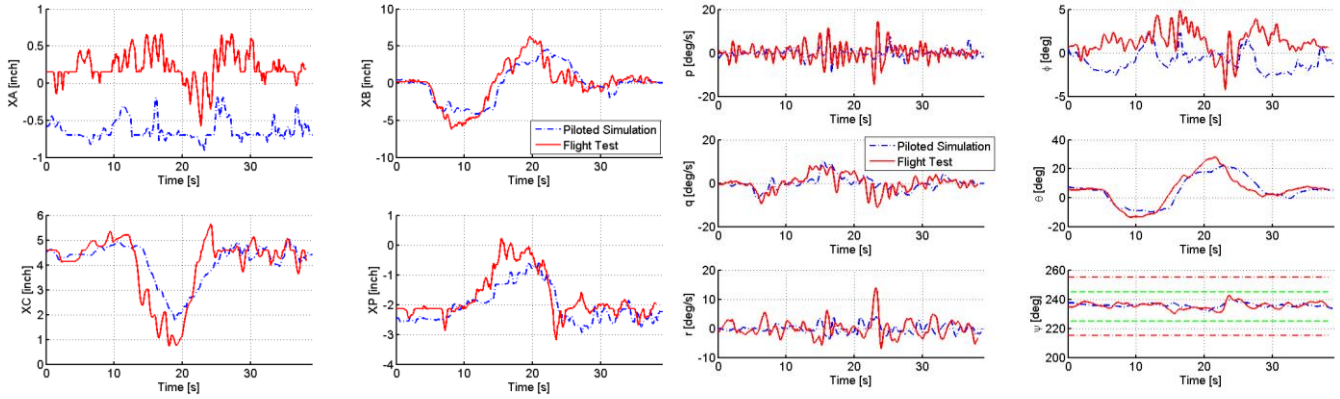


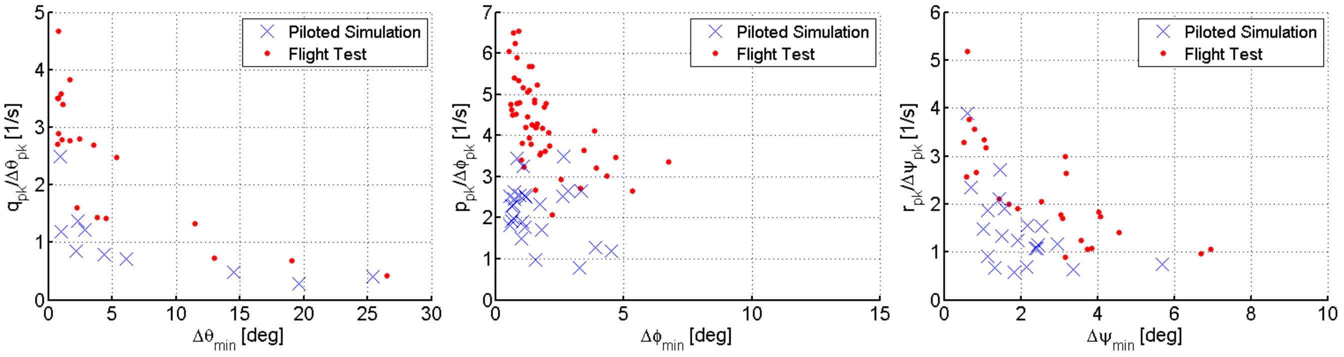
Figure A4: Control Power

APPENDIX B – MTE PILOT CONTROLS AND AIRCRAFT ATTITUDES AND RATES



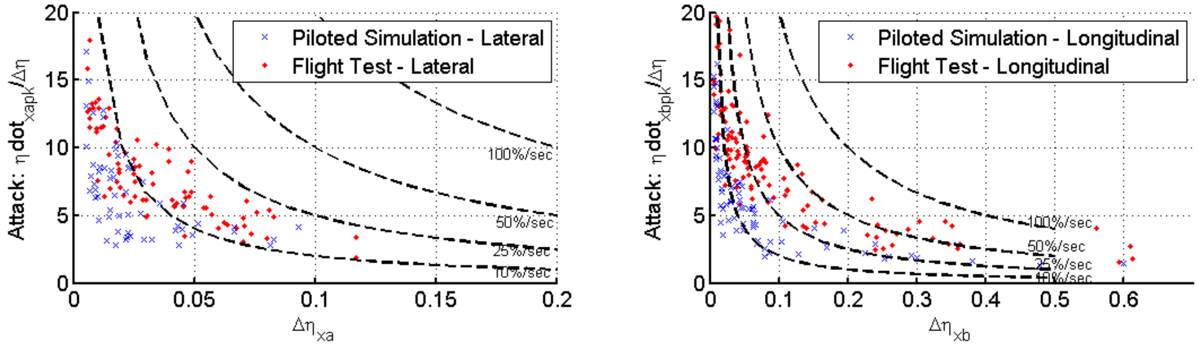
(a) Pilot Controls (b) Rates (c) Attitudes

Figure B1: Acceleration-Deceleration Control Inputs and Aircraft Responses

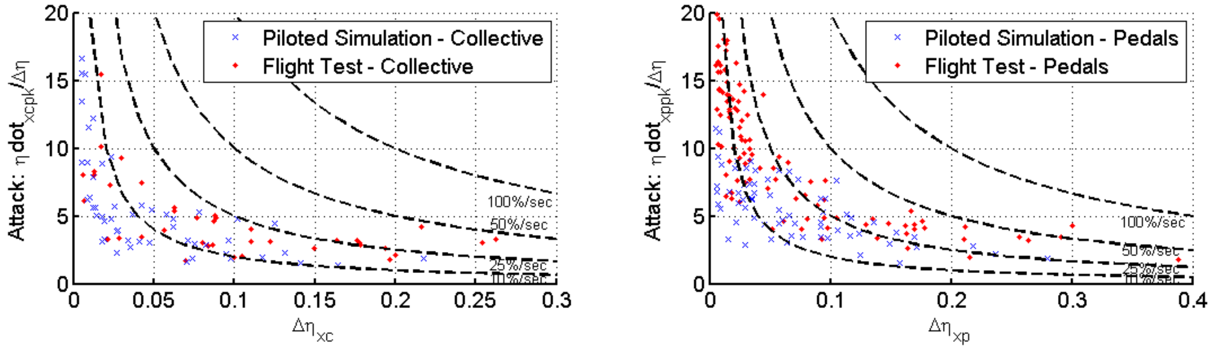


(a) Pitch (b) Roll (c) Yaw

Figure B2: Closed Loop Quickness for the Acceleration-Deceleration

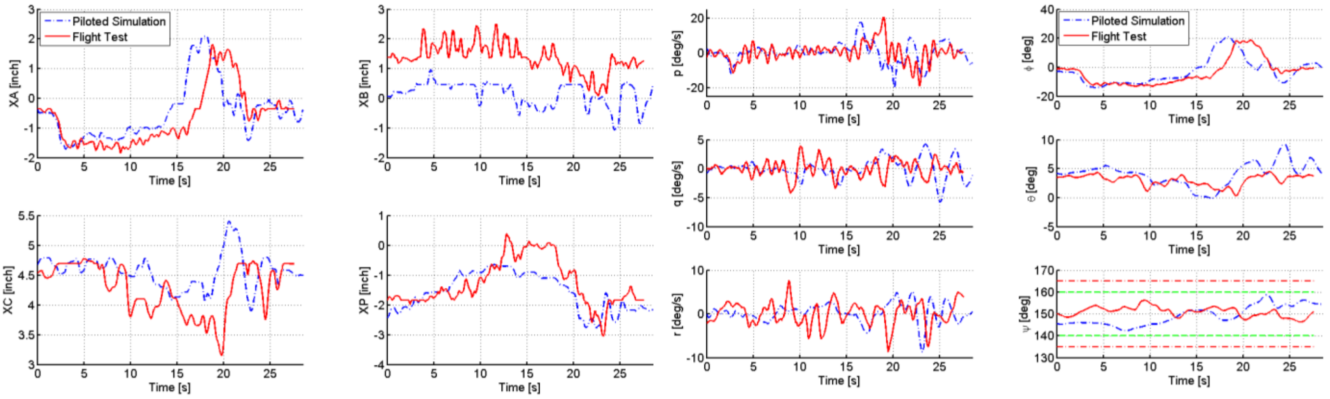


(a) Lateral (b) Longitudinal



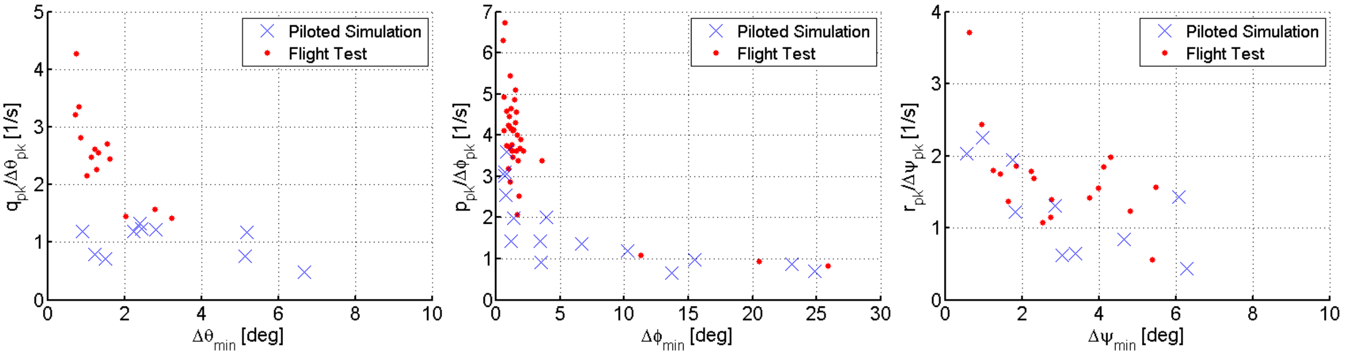
(c) Collective (d) Pedals

Figure B3: Control Attack for the Acceleration-Deceleration



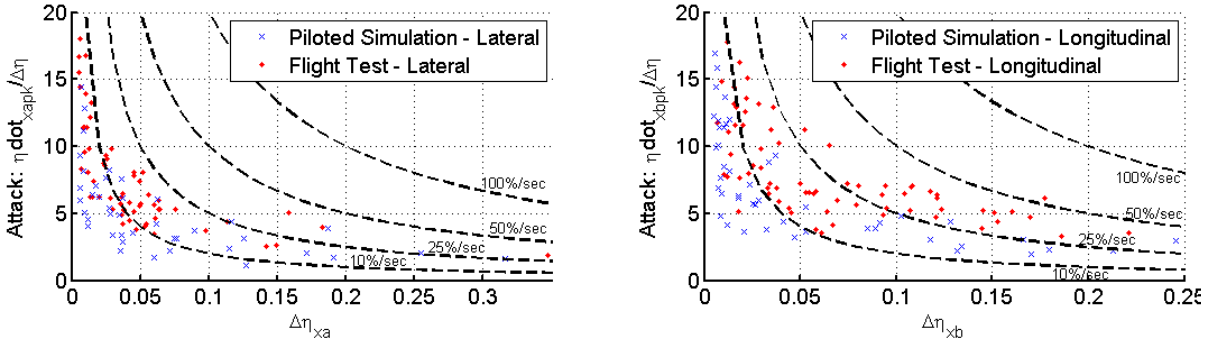
(a) Pilot Controls (b) Rates (c) Attitudes

Figure B4: Lateral Reposition Control Inputs and Aircraft Responses

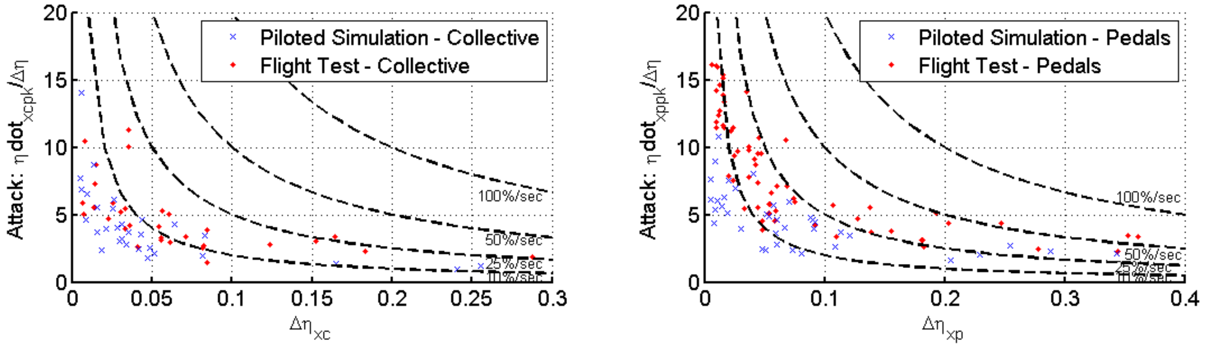


(a) Pitch (b) Roll (c) Yaw

Figure B5: Closed Loop Quickness for the Lateral Reposition



(a) Lateral (b) Longitudinal



(c) Collective (d) Pedals

Figure B6: Control Attack for the Lateral Reposition