Rotorcraft simulation fidelity: new methods for quantification and assessment

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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 use of flight simulation to provide a safe environment for pilot training, and in research and development, must be underpinned by quantification of simulator fidelity. While 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 perceptual measures of simulator fidelity have been developed. The new metrics have been 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 new metrics has shown an appropriate degree of sensitivity to differences between flight and simulation.

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NOMENCLATURE

$\dot{h}$	height rate (ft/s)
MR_ϕ, MR_θ, MR_ψ	roll, pitch, yaw max. response (°/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 ratio
η	pilot control deflection (nd)
ϕ, θ, ψ	pitch, roll, yaw attitude (°)
$\tau_{p\phi}$, $\tau_{p\theta}$,$\tau_{p\psi}$	roll, pitch, yaw phase delay (s)
ω_ϕ, ω_θ, ω_ψ	roll, pitch, yaw bandwidth (rad/s)

Acronyms

ACAH	attitude command, attitude hold
ADS	Aeronautical Design Standard
AG	Action Group
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
HQs	handling qualities
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
SFR	simulation fidelity rating
STD	synthetic training device
VCR	visual cue rating

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1.0 INTRODUCTION

Flight simulators are used extensively in support of engineering design, qualification and crew training. However, simulators are not able to provide a fully coherent illusion of flight to pilots, and the strength of this 'illusion' can act as an indicator of the simulator's 'fitness for purpose'.

CS-FSTD(H)[1] and FAA AC120-63[2] describe the criteria, tolerances and procedures for the qualification of rotorcraft flight training simulators and also 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. Furthermore, the quantification of fidelity, using an engineering metrics approach, must underpin the confidence required to employ flight simulators for research and development. These substantial challenges have not, as yet, been fully addressed in the rotorcraft world.

In support of establishing an engineering basis for civil simulator qualification standards, GARTEUR Action Group (AG) HC-AG12 was formed to conduct a critical examination[3,4] of the existing simulator standard, JAR-STD 1H[5], (consolidated along with JAR-STD 2H[6] and JAR-STD 3H[7] into JAR-FSTD H[8] in 2008, and subsequently adopted as EASA CS-FSTD(H) in 2012), including correlation of handling qualities and fidelity metrics. The work revealed a range of shortcomings. For example, the AG showed that the relationship between fidelity and the JAR-STD 1H tolerances is sensitive to the nature of the manoeuvre being flown and, more significantly, that matching tolerances does not always lead to matching handling qualities.

Simulators are extensively used in research and development, especially in the assessment of handling qualities (HQs) and the development of crew-station systems. The use of handling qualities engineering as a framework within which to quantify overall simulation fidelity has developed in a number of forms. Hess and colleagues[9-11], introduced the handling qualities sensitivity function as a quality metric. Padfield *et al*[12], and McCallum and Charlton[13] first proposed the handling qualities standard, ADS-33E-PRF 'Handling Qualities Requirements for Military Rotorcraft'[14], as the basis for deriving metrics; since the HQ parameters define the flying characteristics, they ought also to be suitable to judge the fidelity. Within the JSHIP project, Advani and Wilkinson[15] and Roscoe and Thompson[16] used comparative performance and control activity, and handling qualities ratings given for the same tasks flown in simulation and flight.

In each of these approaches, the adopted philosophy has been to develop a rational and systematic approach to the identification of differences between simulation and flight, and hence the areas where the simulator is deficient. These methods have met with partial success, but this only highlights the need for new fidelity criteria for use in design, development and product qualification.

1.1 A new approach to fidelity

It is this need to have objective measures of predicted fidelity, complemented by subjective measures of perceptual fidelity, that is the main focus of a UK Engineering and Physical Sciences Research Council (EPSRC) funded project at the University of Liverpool (UoL) – 'Lifting Standards: A Novel Approach to the Development of Fidelity Criteria for Rotorcraft Flight Simulators'[17-19].

A two-stage approach for defining fidelity criteria for simulator qualification has been developed in Lifting Standards. The first stage involves the development of a quantitative basis for prediction of fidelity using metrics, derived in part from HQ engineering. The second stage consists of perceptual fidelity metrics supplemented by a simulator fidelity rating scale, used to assign the perceptual fidelity of the simulator.

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The Lifting Standards project has involved collaboration with the National Research Council's (NRC) Flight Research Laboratory and consisted of three main phases. The first involved the collection of 'benchmark' test data from the NRC's Advanced Systems Research Aircraft (ASRA) Bell 412 helicopter and Liverpool's HELIFLIGHT-R flight simulator [17] configured with the FLIGHTLAB [20] F-B412 flight model. During the second phase of the programme, fidelity metrics have been derived, which have been validated in comparative exercises between flight test and simulations with varying levels of fidelity during the third phase. The metrics are being used to produce evidence-based validation for requirements within existing and emerging simulator standards, such as CS-FSTD(H)[1] and ICAO 9625 Volume 1, 3rd Edition[21] (for fixed wing aircraft; Volume 2 for rotary wing aircraft is currently in development).

This paper presents the development of this methodology for the quantification and assessment of the overall fidelity of a flight simulator. Metrics for the prediction of simulator fidelity, using ADS-33E-PRF[14], and for assessing the pilot's perception of fidelity are introduced. A selection of results from Lifting Standards' flight and simulation trial programmes are presented to support the development of the proposed fidelity metrics. The paper is drawn to a close with a discussion of the significant findings from the research to date and concluding remarks.

2.0 METHODOLOGY FOR SIMULATION FIDELITY BASED ON HANDLING QUALITIES ENGINEERING

In the area of HQ engineering, two assessment processes, prediction and assignment, are integrated, and combine to give the overall HQs of an aircraft. The practices adopted in the Lifting Standards project draw on this integrative process and the HQ performance specification, ADS-33E-PRF[14].

For both processes, the test aircraft is assessed to be in one of three handling qualities 'levels'. Level 1 HQs (HQ ratings of 1, 2, 3) indicate that there is no requirement for improvement to the aircraft, and that all operational tasks can be accomplished with low workload. In Level 2 (with HQRs of 4, 5, 6), 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 (HQRs > 6) then the level of workload has increased to the extent that task performance is no longer achievable. At the higher end of level 3 (HQRs 9, 10; sometimes defined as Level 4), flight safety is compromised as the risk of loss of control increases.

2.1 HQ Methodology adapted for the assessment of simulator fidelity

Much of this methodology can be directly applied to the fidelity assessment of a flight simulator – both handling qualities and fidelity are intimately related to pilot control strategy and task performance. If a pilot makes the same control inputs in the simulator as he is required to in flight, then correct behavioural patterns have been learned, and the simulator training will have been effective; meaning that the pilot will have benefitted from their time in the simulator. The goal in fidelity assessment is to establish the 'quality' of the simulator in replicating the behaviour of the real aircraft and its pilot, rather than purely to assess the handling qualities of the simulated aircraft.

In the case of the prediction metrics, the fidelity assessment is focussed on the simulator components, e.g. the flight model, the image generation system and so forth, with the fidelity predictions for each component contributing towards a prediction for the overall simulation. 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 perceptual fidelity.

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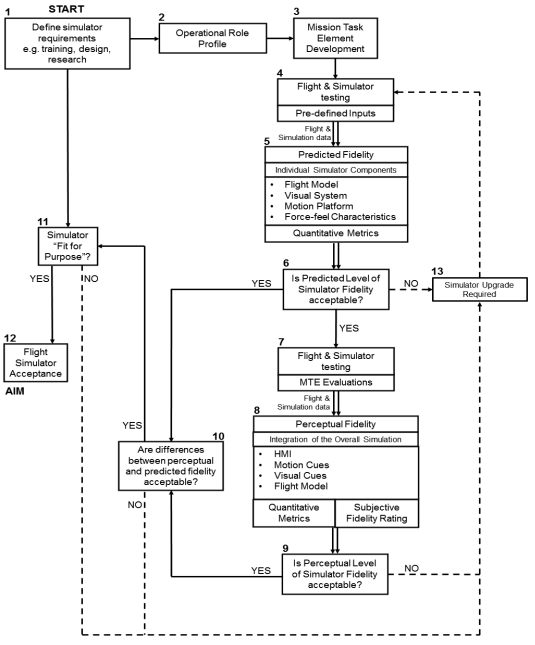


Figure 1. Methodology for integrated predicted and perceptual simulator fidelity assessment.

As in the HQ assessment process, a comparison of results from predicted and perceptual assessments forms a key component of the overall fidelity assessment process. This is required to establish that the predicted and perceptual results are consistent; for the same reasons in the simulator as they are in flight; and to understand better any differences.

A flow diagram representing the process for the assessment of predicted and perceptual simulator fidelity is shown in Fig. 1. The process begins with a definition of the required purpose of the flight simulator, and hence the tasks that will be trained (Blocks 1-3 in Fig. 1), which will set the required level of fidelity. Once the purpose of the simulator has been defined, testing on the simulator and the simulated aircraft can be conducted (Block 4). This leads to the computation of the predicted fidelity (Block 5), using a set of metrics such as those described in this paper. The results for each simulator component in the predicted fidelity stage can then be analysed to arrive at an overall level of predicted fidelity for a particular task.

The results from these tests feed into the first decision point. The question is; do the individual predicted fidelity metrics show a sufficiently good match between flight and simulation? (Block 6). This stage highlights the quality of individual components of the simulation. Subject to a satisfactory result at this stage, further flight and simulator testing can be conducted to examine the perceptual fidelity of the simulation (Block 7). As with the predicted fidelity, metrics are computed for each test point (Block 8), and a decision made as to the suitability of the resultant Level of perceptual fidelity for the intended purpose (Block 9).

A third decision point addresses the acceptability of the comparison between predicted and perceptual fidelity (Block 10). This stage is analogous to the comparison between predicted and assigned HQs, as an assessment of the validity of the testing. If the test results are valid, it would be expected that the predicted level of fidelity for the simulator would be in agreement with that from the perceptual assessment processes. In addition, the analysis at this point provides a further indicator as to the source of discrepancies between flight and simulation. For example, if the

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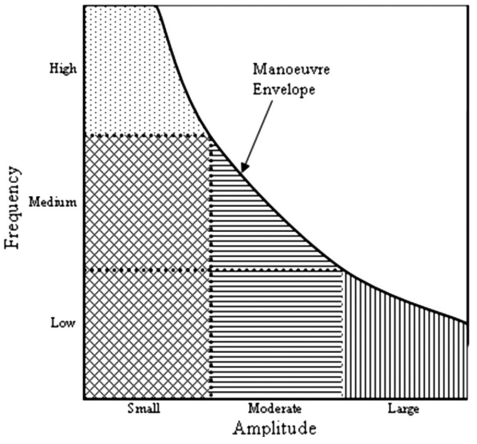


Figure 2. Dynamo construct for dynamic response criteria[23].

predicted metrics for the flight model show a good match, while the perceptual metrics do not, then the indication is that the fidelity issues lie within the generation of the task cues and not the flight model.

If all questions (Blocks 6, 9 and 10) 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 (Blocks 11 and 12). 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 (Block 13). It should be recognised that a simulator may be fit for some purposes but not others and thus have limited fidelity; the ongoing research at Liverpool is detailing this aspect of the qualification process[22-24].

2.2 Predicted fidelity

The first part of the fidelity assessment process involves analysis of the individual simulator components. For the flight model, the predicted HQs of the test aircraft and flight model are computed, with dynamic response criteria drawn from the response to clinical tests such as pulse, zstep, doublet and frequency sweep control inputs. HQ metrics define the level of performance/workload achievable/required to fly the defined missions. Metrics have been developed in both the time and frequency domains, to assess the full range of aircraft response, from low to high frequency and from small to large amplitude (Fig. 2).

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 provide a sound basis for quantifying predicted simulation fidelity, since they are referenced to missions and pilot control strategies in operational tasks. The fidelity of the simulated flight model is defined as the goodness of the match between flight and simulation for each of the predicted HQ metrics.

Moving through the so-called dynamo construct[25], the stability and agility criteria adopted in the predicted HQs section of ADS-33E-PRF to assess each region are:

1. 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-PRF provides

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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 6dB) 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:

$$\tau_p = \frac{\Delta\Phi_{2\omega 180}}{57 \cdot 3 \times 2\omega_{180}}$$

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

2. Small amplitude, low to medium frequency – open-loop stability. Stability is quantified in terms of the natural frequency, ω_n, and damping, ζ, of the aircraft's natural modes, such as the Dutch Roll and Phugoid.
3. Moderate amplitudes – quickness. Attitude quickness (Q) provides a measure of the ability to attain a moderate amplitude attitude change. It is defined as the ratio of peak attitude rate to the attitude change, hence for pitch quickness,

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

4. Large amplitudes – maximum response. Maximum response (MR) is defined as the maximum achievable rate or attitude, 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:

1. Roll/pitch couplings: The acceptable limit on coupling between the pitch and roll axes is derived from the ratio of peak off-axis response to the desired on-axis response, after four seconds, following a sharp cyclic step input.
2. 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,

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

and the collective to yaw couple at 3s,

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

3. 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:

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

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In addition to quantification of the flight model fidelity, prediction of the fidelity of the other simulator components would also be performed at this stage. Techniques such as those described by Hodge *et al*[26] for motion platform response would be used. The predicted fidelity of these other components will not be considered in this paper.

2.3 Perceptual fidelity

Once the predicted fidelity levels have been computed, the assessment can proceed to perceptual fidelity, computed through the process of assigning handling qualities ratings (HQRs) and simulator fidelity ratings (SFRs)[23]. 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 MTE predominantly requires small amplitude corrective inputs, and so the bandwidth and open-loop stability of the aircraft will be of primary importance. The acceleration-deceleration MTE, in contrast, requires moderate to large pitch attitude changes, increasing the importance of the quickness and maximum response amplitude.

Test pilots fly each of the MTEs and rate the performance of the aircraft using the Cooper-Harper HQR scale[27]. This scale requires the test pilot to award a rating based on both the level of compensation needed to fly 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.

The HQR is considered to be an important element in the perceptual fidelity process. If a match is not achieved here then a flaw must exist in the simulation. However, the HQR by itself is insufficient to quantify differences between flight and simulation fully; the same HQR can be given for very different aircraft. To complement the HQR, the test pilot is asked to rate the effect of the visual cues on vehicle control through the visual cue rating (VCR)[14], from which a usable cue environment (UCE) can be derived. As with the HQR, it is desirable for a match between flight and simulation VCRs and UCEs to be demonstrated. The VCR, as a measure of the precision achievable and aggressiveness of control inputs that can be applied by the pilot, provides a subjective assessment of not just the differences in visual cues, but also any differences in the control strategies adopted in flight and simulation. The authors acknowledge that the UCE concept was developed within ADS-33 for specific purposes and this extension to simulation fidelity will need further refinement.

As a new addition to the subjective rating process, the SFR scale provides a method for an evaluating pilot to directly rate the suitability of the overall simulation for a specified task[21]. The pilot is asked to compare the level of performance attained in flight and simulator, and to judge the level of adaptation of task strategy that must be made to convert from one environment to the other. The use of the SFR scale in the assessment of simulator fidelity is described in detail elsewhere[23], and the scale will not be further discussed in this paper.

As with HQ assessments, task performance and compensation metrics are fundamental for quantifying differences between flight and simulator. For task performance, these are:

1. Task time. The time taken to move from the start point to the end point of the manoeuvre. This is less than the total time spent performing the task, which additionally includes stabilisation time prior to, and after the manoeuvre.

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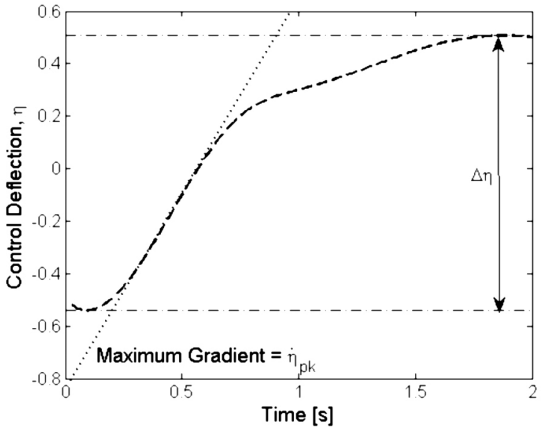


Figure 3. Attack point parameters.

2. Time spent within desired performance. Percentage of the total manoeuvre time spent within the desired performance tolerance.
3. Time spent within adequate performance. Percentage of the total manoeuvre time within the adequate performance tolerance (including the desired performance region).
4. Time spent beyond adequate performance. Percentage of the total manoeuvre time spent beyond the adequate performance tolerance.
5. Quickness can be applied to assess closed loop, in addition to open loop, agility. The closed loop quickness, Q_{CL}, can be summarised using the following parameters:
   (a) Number of quickness points (the total number of discrete attitude changes of greater than 0·5° occurring during an MTE).
   (b) Quickness points per second. This is the number of quickness points expressed in terms of the average number of attitude changes per second.
   (c) Mean quickness. This is the mean quickness measured for each of the individual attitude changes.
   (d) Mean attitude change. This is the mean attitude change measured for each of the individual quickness points.

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

1. Control attack[28] which measures the size and rapidity of a pilot's control inputs, defined as:

$$\text{attack} = \left| \frac{\dot{\eta}_{pk}}{\Delta\eta} \right|$$

   where η is the pilot's control deflection (Fig. 3). The control attack is summarised using the following parameters, which are analogous to those described above for closed loop attitude quickness:
   (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.

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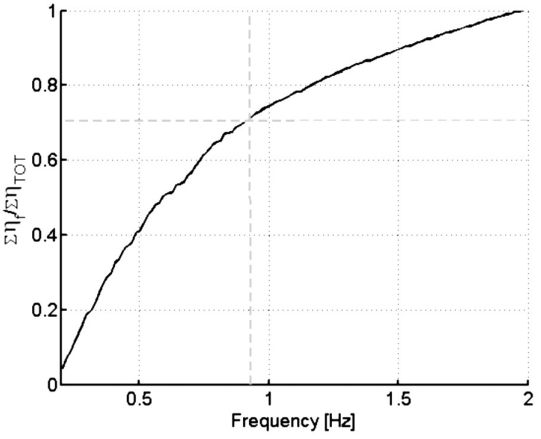


Figure 4. Calculation of cut-off frequency.

(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.

Further discussion on the appropriate attack thresholds comes later in the paper.

2. In the frequency domain, we can assess[29]:

(a) Root-mean-square (RMS) of the power spectral density (PSD) in each control axis.

(b) Cut-off frequency, where 70% of the control displacement signal has accumulated. Figure 4 illustrates the method, with a ratio between the control input amplitudes summed up to the current frequency ($\Sigma\eta$)and the amplitudes summed over the full frequency range ($\Sigma\eta_{TOT}$) plotted. The cut-off frequency is the frequency at which this ratio reaches 0·7.

The RMS value and cut-off frequency are calculated over the interval 0·2Hz > f > 2Hz, with the lower limit largely removing the lower frequency guidance element of the control activity from the analysis, and the upper limit removing artefacts introduced in the time-frequency domain transformation.

3.0 RESEARCH FACILITIES

The metrics development work in the Lifting Standards project has been underpinned by a series of simulation trials undertaken using the HELIFLIGHT-R simulator at UoL, and flight trials using the NRC's Bell 412 Advanced Systems Research Aircraft (ASRA).

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Figure 5 (left). HELIFLIGHT-R Simulator at UoL. Figure 6 (right). NRC Bell 412 ASRA at the Flight Research Laboratory.

3.1 HELIFLIGHT-R

The HELIFLIGHT-R full motion flight simulator (Fig. 5)[17] was commissioned in the School of Engineering at UoL during the summer of 2008. The key features of the simulator are as follows:

1. 12ft visual dome with 3 × LCoS HD projectors on gimballed mounts to provide up to 210 × 70° field of view (FoV).
2. Interchangeable crew stations with front pilot and co-pilot seats and a rear engineer seat.
3. Moog FCS ECoL 8000 Q&C-Line electric control loading system four-axis control loading.
4. Moog MB/E/6dof/24/1,800kg electric motion system
5. Instructor-operator station PC.
6. Reconfigurable instrument panel displays (left and right primary flight displays, backup analogue displays and head-up display).
7. The selective fidelity FLIGHTLAB multi-body flight dynamics modelling environment[8].

The FLIGHTLAB model of the Bell 412 ASRA aircraft (designated F-B412) was developed during a previous research project[30], and features a blade element 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).

3.2 NRC Bell 412 Advanced Systems Research Aircraft (ASRA)

The Bell 412 ASRA (Fig. 6) 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.

The Bell 412 ASRA aircraft is fitted with a comprehensive range of monitoring and measurement equipment[31] to facilitate analysis of pilot control activity and aircraft performance following a flight. Data recording includes:

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Table 1
ASRA FBW safety limits

Parameter	Limitation
Torque	Below 105kt: 92% mast torque Above 105kt: 81.5% mast torque
Roll attitude/rate (above 25ft)	Above 45kt: ±65°, ±60°/s 30-45kt: ±45°, ±40°/s Below 30kt: ±35°, ±35°/s
Roll attitude/rate (below 25ft)	Above 45kt: ±45°, ±60°/s 30-45kt: ±35°, ±40°/s Below 30kt: ±25°, ±35°/s
Pitch attitude/rate (above 25ft)	All speeds: ±32°, ±25°/s
Pitch attitude/rate (below 25ft)	Above 30kt: ±25°, ±25°/s Below 30kt: ±15°, ±25°/s
Yaw rate	Above 45kt: ±25°/s 30-45kt: ±30°/s Below 30kt: ±40°/s ±10°/s when height is < 10ft

1. Ring laser gyro inertial reference system, providing measurements of body attitudes, rates and accelerations
2. GPS high-precision differential mode positioning
3. Static and dynamic pressures
4. Radar and laser altitude
5. Control inputs (lateral cyclic, longitudinal cyclic, pedals and collective positions)
6. Actuator positions
7. Air data – true air speed, angles of attack and sideslip
8. Engine parameters
9. 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.

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, following engagement by the safety pilot, controls ASRA through the digital flight control system.

During flight testing, the safety system restricts the level of aggressiveness the evaluation pilot is able to apply. Experience from the first phase of flight testing showed the importance of

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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.

4.0 FLIGHT AND SIMULATION TESTING

In February 2009 two test pilots took part in ten flight test sorties over a four day period[17]. One of these pilots was UoL's consultant test pilot, who was familiar with both the F-B412 model and the test course layouts, but had not previously flown the ASRA. The second pilot was an NRC test 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. Results from the ACAH configuration will form the focus of this paper. 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 F-B412 model against current 'predictive' criteria, such as JAR-STD 1H[5], and the quantitative component of ADS-33E-PRF[14].
3. To perform a series of MTEs to assess the impact of the flight model fidelity and simulation environment on piloting strategies.

A repeat simulation trial was conducted in HELIFLIGHT-R with the UoL pilot. The focus here was repeating the MTEs; the predicted metrics for the F-B412 had been computed prior to the flight tests.

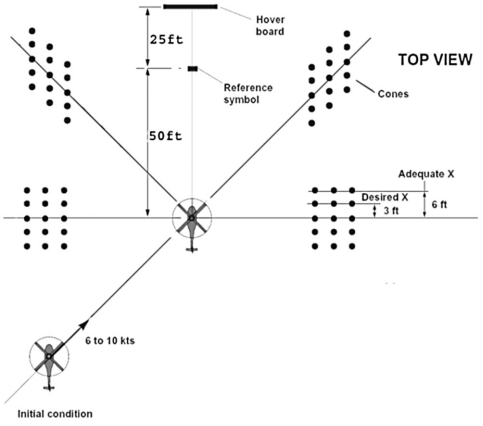
The MTEs chosen for the fidelity assessment focussed on the hover and low speed flight regime, with precision hover, pirouette, acceleration-deceleration and lateral reposition ADS-33E-PRF MTEs being performed. In some cases, restrictions due to the FBW safety limits (Table 1), or the test course layouts meant that manoeuvres were modified slightly from the ADS-33E-PRF templates. For example, the acceleration-deceleration was flown to a target airspeed of 40kt, rather than the 50kt specified in ADS-33E-PRF.

Following each of the MTEs, a number of responses were collected from the test pilot. In both the flight and simulation trials, handling qualities ratings (HQRs)[27] were given for each MTE and visual cue ratings (VCRs)[14] were also taken, allowing the usable cue environment to be determined. In addition, pilot impressions of the cues (visual, aural, motion, controls etc.) employed during the task were recorded, along with subjective impressions regarding differences between the flight and simulation environments.

4.1 Mission task element descriptions

For each of the MTEs, the desired flight profile is specified (generally according to ADS-33E-PRF, although as noted above, with occasional modifications), along with tolerances for 'desired' and 'adequate' performance. Summaries for the precision hover MTE are given in Fig.

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(a) Plan view (b) Side view

Figure 7. Precision hover test course.

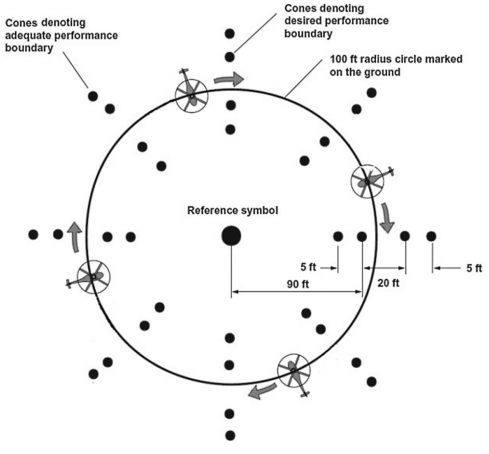


Figure 8. Pirouette test course.

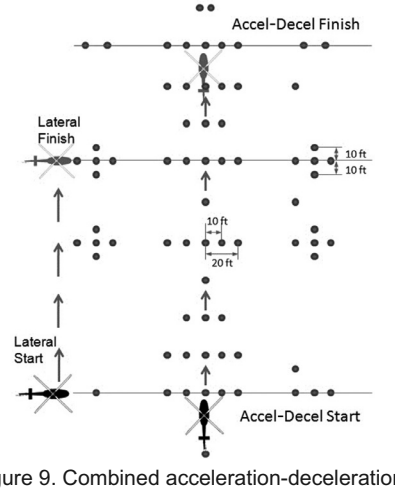


Figure 9. Combined acceleration-deceleration and lateral reposition test course.

7 and Table 2, and for the pirouette MTE in Fig. 8 and Table 3. The acceleration-deceleration (abbreviated to accel-decel) and lateral reposition MTEs were performed using the same set of ground markings – shown in Fig. 9. The performance standards for these two MTEs are given in Tables 4 and 5 respectively.

5.0 RESULTS

5.1 Predicted fidelity

Handling qualities predictions for the ACAH configuration ASRA and F-B412 are summarised in Table 6, with full details provided in Appendix A. The Table includes the percentage difference between simulation and flight, and also the comparative margins to the Level 1-2 HQ

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Table 2
Precision hover MTE performance standards

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

Table 3
Pirouette MTE performance standards

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

Table 4
Acceleration-deceleration MTE performance standards

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

Table 5
Lateral reposition MTE performance standards

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

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Table 6
ACAH predicted fidelity – Differences between flight test and simulation in the hover

Fidelity parameter	Flight (sim)	HQL	%ΔF-S
	Bandwidth		
ω_φ	5·38 (6·21)	1 (1)	15·5
$\tau_{p\varphi}$	0·15 (0·18)	1 (1)	18·7
ω_θ	2·79 (2·71)	1 (1)	–2·9
$\tau_{p\theta}$	0·18 (0·17)	1 (1)	–5·5
ω_ψ	1·18 (1·23)	2 (2)	4·5
$\tau_{p\psi}$	0·13 (0·14)	2 (2)	7·7
	Stability		
ω_n	n/a – No oscillatory modes identified with ACAH		
ζ	configuration in hover for flight or simulation		
	Maximum response		
MR_φ	56 (59)	2 (2)	5·4
MR_θ	24 (21)	2 (2)	–12·5
MR_r	28·2 (21·7)	2 (3)	–23·0
	Quickness		
Average Q_ϕ ($10°<\phi<20°$)	1·98 (1·87)	1 (1)	–5·81
Average Q_θ ($5°<\theta<10°$)	1·05 (1·05)	1 (1)	0·0
Average Q_ψ ($10°<\psi<20°$)	0·41 (0·22)	2 (3)	–44·9
	Cross-couplings		
p from q	0·24 (0·11)	1 (1)	–56·1
q from p	0·25 (0·07)	2 (1)	–70·7
Collective to yaw @ 1s	0·41 (0·23)	1 (1)	–44·7
Collective to yaw @ 3s	–0·79 (–0·11)	3 (1)	–86·1

boundary. It can be seen in Table 6 that the majority of the predicted metrics for the F-B412 are in the level 1 HQ region. The 'not applicable' label associated with the stability arises because the heavily augmented ACAH configuration does not feature such modes. The only exceptions to the Level 1 HQ results are in the yaw axis bandwidth and quickness, and the maximum response amplitudes, 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? For example, if the acceptable match was 20%, then only two primary response metrics, the yaw quickness and maximum response amplitude, 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 maximum response amplitude would also fail the fidelity test. At this stage, there is insufficient evidence for defining an acceptable tolerance, but this must be an important aspect of ongoing research.

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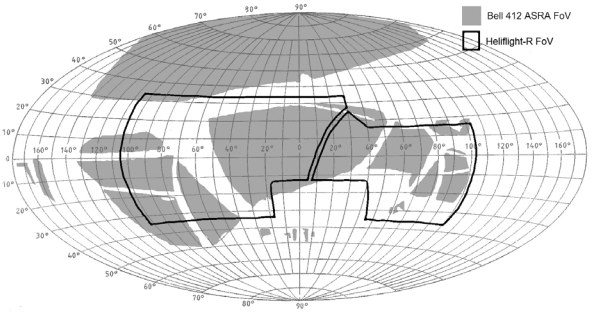


Figure 10. ASRA and HELIFLIGHT-R FoV comparison.

The precision hover and pirouette MTEs are complex 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° and, while the yaw excursions in the pirouette are large, the mean yaw rate should be less than 10deg/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.

The accel-decel and lateral reposition MTEs, in contrast, are moderate-high aggression tasks. Again, outside visual cues dominate the pilot's task strategy. While stability and bandwidth continue to play an important role in the overall tasks, particularly so in the capture and stabilisation of the final hover, attitude quickness (predicted Level 1) and maximum response amplitude (predicted Level 2) now have a greater relevance to the expected results. Differences between flight and simulation in terms of yaw response and couplings will be emphasised here by the increased magnitude of the expected control inputs.

Overall, the fidelity metrics in the yaw axis suggest that the simulator will be more difficult to fly than the aircraft, while the reverse is true when considering cross-couplings, with better HQs predicted for the F-B412 than for flight.

5.2 Perceptual fidelity

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 relative to the pilot's seat 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 out-of-the-window (OTW) display is unimpeded except immediately below the aircraft and behind the instrument panel (Fig. 10).

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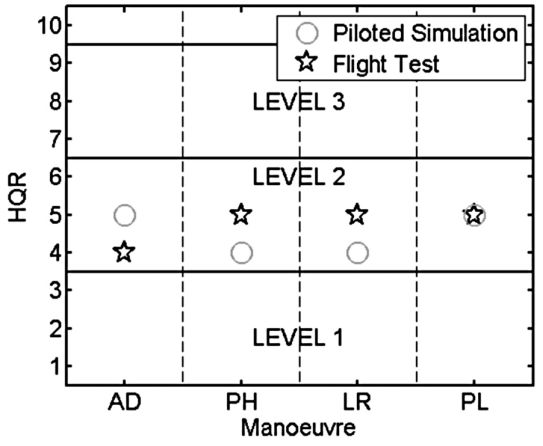


Figure 11. Summary of HQRs from ACAH configuration.

- The surface 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 with 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.

5.3 Handling qualities summary

The HQRs awarded to the Bell 412 ASRA and F-B412 by the UoL pilot during the flight and simulator trials are summarised in Fig. 11 for the ACAH mode. The MTEs are abbreviated as follows:

AD – Acceleration-deceleration
PH – Precision hover
LR – Lateral reposition
PL – Pirouette, translating to the left

In general, a difference of one HQR between flight and simulation is observed. In both flight and simulator, Level 2 ratings were awarded by the pilots. The ACAH system was designed to give Level 1 handling qualities based on the ADS-33 metrics although, as was seen in Table 6, this was not the case for all dynamic response criteria. The specific reasons for these ratings will be discussed later. For a majority of the MTEs, the ratings for flight and simulator bridged the HQR 4-5 gap, a very important step both in terms of performance and workload, as illustrated in Table 7.

In awarding an HQR 5, not only is the pilot unable to achieve the desired standard, but he also has to apply considerable compensation to achieve the adequate standard. Harper and Cooper later[32] explored this large step in more detail and advocated the use of the 4·5 rating for situations

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Table 7
Comparison of Level 2 HQR characteristics

	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

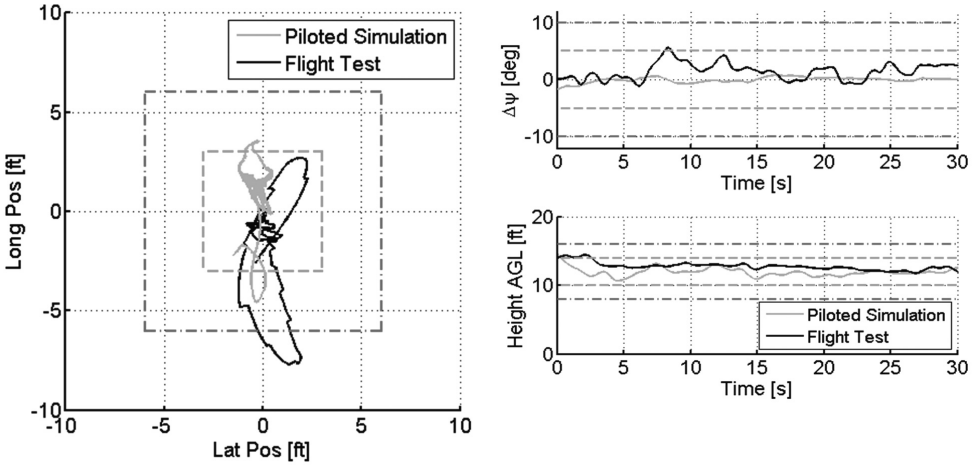


Figure 12. Precision hover MTE task performance.

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 for accurate and beneficial simulation.

In the following sections, the manoeuvres will be addressed in turn, and comparisons will be made between the performance and compensation metrics recorded from the UoL pilot's flight and simulator trials.

5.4 The precision hover MTE

The task performance in the precision hover MTE is shown in Fig. 12, and the fidelity metrics collected in Table 8 (a)-(e). Further details are contained in Appendix B. The HQR 5–4 (flight–simulator) comparison is contrasted by the UCE 1–2 comparison. In flight, the excursion into the adequate region and beyond (12% of time) for longitudinal position, during the initial capture of the hover, led the pilot to award 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.

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Table 8
Precision hover MTE metrics

(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%
Longitudinal position % time			
• inside desired	79·2	76·2	–3
• inside adequate	88·5	100	12
• outside adequate	11·5	0	–12
• attack number	173	72	–58
• attack number per sec (/s)	3·21	1·36	–58
• mean attack rate (%/s)	25	10	–60
• mean control displ (%)	7·8	4·7	–40
• no of quickness points	32	18	–44
• quickness points per sec· (/s)	0·59	0·34	–42
• mean quickness (/s)	2·45	0·81	–67
• mean att change (°)	1·48	1·86	–26
• PSD RMS	0·050	0·022	–56
• cut-off frequency (Hz)	0·705	0·340	–52

(c) Lateral axis parameters

Fidelity parameter	Flight	Simulator	Δ%
Lateral position % time			
• inside desired	100	100	0
• inside adequate	100	100	0
• outside adequate	0	0	0
• attack number	133	83	–38
• attack number per sec (/s)	2·47	1·57	–36
• mean attack rate (%/s)	13	8	–39
• mean control displ (%)	4·5	3·8	–16
• no of quickness points	72	36	–50
• quickness points per sec· (/s)	1·34	0·68	–49
• mean quickness (/s)	3·1	1·6	–48
• mean att change (°)	2·2	2·8	27
• PSD RMS	0·023	0·022	–4
• cut-off frequency (Hz)	0·389	0·378	–3

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(d) Yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
heading % time			
• inside desired	99	100	1
• inside adequate	100	100	0
• outside adequate	0	0	0
• attack number	130	38	–71
• attack number per sec (/s)	2·4	0·7	–71
• mean attack rate (%/s)	22	7	–68
• mean control displ (%)	8·2	2·8	–66
• no of quickness points	34	12	–65
• quickness points per sec (/s)	0·63	0·23	–64
• mean quickness (/s)	1·7	0·6	–65
• mean att· change (°)	2·6	1·7	–35
• PSD RMS	0·071	0·028	–63
• cut-off frequency (Hz)	0·538	0·453	–16

(e) Vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
height % time			
• inside desired	93	96	3
• inside adequate	100	100	0
• outside adequate	0	0	0
• attack number	96	82	–15
• attack number per sec (/s)	1·78	1·55	–13
• mean attack rate (%/s)	20	10	–50
• mean control displ (%)	9·0	5·4	–40
• PSD RMS	0·036	0·005	–86
• cut-off frequency (Hz)	0·519	0·472	–9

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 1·60/1·25Hz (pitch/roll) compared with 0·7/0·8Hz. In comparison the cut-off frequencies are only about 20% greater in flight. This apparent anomaly will be returned to in the discussion section of this paper.

The pilot commented on a noticeably more unsteady (‘gravelly’) ride during flight, in comparison to the simulation, resulting in attitude disturbances that required the ‘extensive compensation’ to achieve the adequate standard.

In addition, the pilot noted a need for larger collective inputs in flight to maintain height, leading to heading and torque fluctuations (note Level 3 collective to yaw predicted HQs in flight, Level 1 in the simulator).

Finally, the pilot commented that the cockpit framing in the aircraft obscured the view of the cones at the –45 degrees position (Fig. 7) in flight. This was not an issue in the simulator due to the uninterrupted FoV (Fig. 10).

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5.5 The pirouette MTE

The task performance for the pirouette MTE (with translation to the left) is shown in Fig. 13, and the fidelity metrics presented in Table 9 (a-e), with further details in Appendix B.

HQRs of 5 were returned in both flight and the simulator; UCE for both was 2. The degradation in UCE for the pirouette manoeuvre in flight, compared to the other tasks, was due to impingement of the cockpit framing on the pilot's field of vision (Fig. 10) as the aircraft translated to the left. At the roll attitude required to hold the desired translational rate, the framing obscured the pilot's view of the ground markings for the task. This limitation required the pilot to oscillate the aircraft in roll (see Fig. B4) to maintain view of the ground markings and sustain the correct average translational rate. The impact of this was the perception of a reduction in ability to accurately command the roll attitude of the aircraft, hence the degradation in VCR reported in Table 9.

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. As with the precision hover MTE, the pilot is working harder in flight, with nearly 50% more attack events per second in pitch, and nearly 60% more than in roll.

Table 9
Pirouette MTE metrics

(a) Ratings

Fidelity parameter	Flight	Simulator	Δ%
HQR	5	5	
UCE	2	2	
• VCR(TR)	3·0	3·0	
• VCR(A)	2·0	3·0	
Total task time	55	46	–16

(b) Longitudinal axis parameters

Fidelity parameter	Flight	Simulator	Δ%
longitudinal position % time			
• inside desired	55·3	68·5	–3
• inside adequate	85·6	100	14
• outside adequate	14·4	0	–14
• attack number	190	100	–47
• attack number per sec (/s)	3·1	2·0	–36
• mean attack rate (%/s)	30	13	–57
• mean control displ (%)	9·9	7·2	–27
• no of quickness points	48	22	–54
• quickness points per sec (/s)	0·8	0·4	–50
• mean quickness (/s)	2·5	0·92	–63
• mean attitude change (°)	2·1	2·74	31
• PSD RMS	0·060	0·044	–27
• cut-off frequency (Hz)	0·528	0·285	–46

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(c) Lateral axis parameters

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
• 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
• cut-off frequency (Hz)	0·660	0·244	–63

(d) Yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
heading % time			
• inside desired	69·0	91·6	23
• inside adequate	94·3	100	6
• outside adequate	5·7	0	–6
• attack number	168	63	–63
• attack number per sec (/s)	2·8	1·3	–54
• mean attack rate (%/s)	30	11	–63
• mean control displ· (%)	11·7	5·7	–51
• no of quickness points	9	2	–78
• quickness points per sec (/s)	0·1	0·04	–60
• mean quickness (/s)	-----	-----	-----
• mean attitude change (°)	-----	-----	-----
• PSD RMS	0·065	0·027	–58
• cut-off frequency (Hz)	0·231	0·244	6

(e) Vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
height % time			
• inside desired	42·1	36·9	–5
• inside adequate	100	100	0
• outside adequate	0	0	0
• attack number	86	58	–33
• attack number per sec (/s)	1·4	1·2	–14
• mean attack rate (%/s)	15	6	–60
• mean control displ (%)	7·8	4·4	–44
• PSD RMS	0·057	0·017	–70
• cut-off frequency (Hz)	0·231	0·244	6

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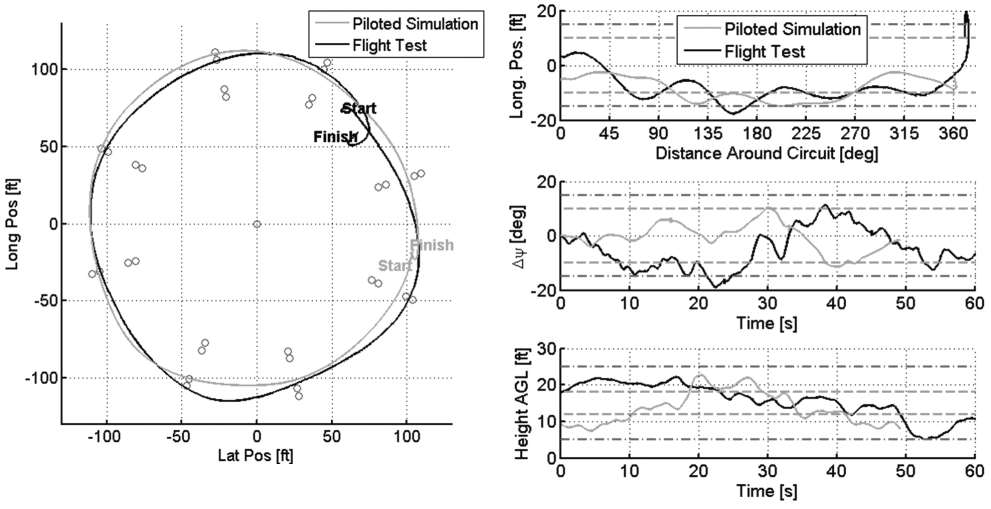


Figure 13. Pirouette MTE task performance.

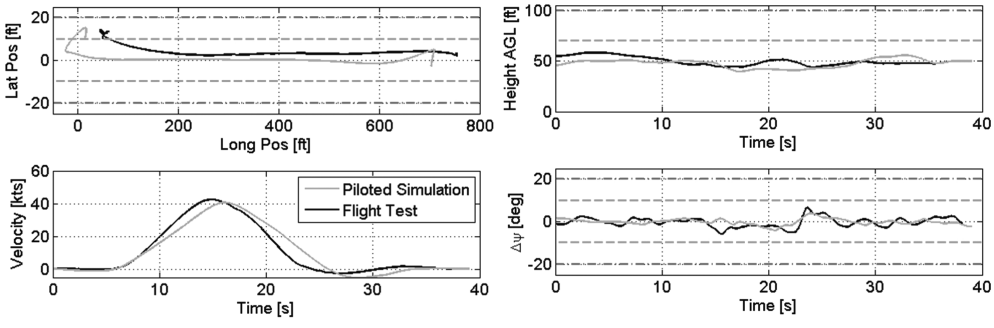


Figure 14. Acceleration-deceleration MTE task performance.

The contrast in manoeuvre times (55sec–46sec, flight–simulator) is of note. Where adequate performance cannot be achieved within the 45sec desired performance time limit, the pilot is allowed to relax his applied level of aggression to determine if a better level of performance is achievable within the 60sec adequate performance time limit. Conducting this test in flight showed that it was not possible to regain desired performance in any of the performance requirements. The pilot did not attempt this in the simulator, as adequate performance had already been achieved for each requirement. It is important to note that, while the application of differing strategies led to the award of the same HQR for flight and simulator, the effect of the lower aggression control strategy will have affected the metrics comparison, with reductions in the attack number per second and cut-off frequency for the flight run.

The demand to complete the manoeuvre in a shorter time leads to a higher translational rate around the pirouette circuit. The rate of corrective inputs depends on the aircraft's natural frequencies, and also on the pilot's perceived need to apply corrections to the flight path. Typically, the natural frequencies will not change significantly between the translational velocities used in flight and simulator (averaging 11ft/sec and 13ft/sec respectively), and so the

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pilot's perceived compensation requirements will dominate.

As with the precision hover MTE, the pilot commented on a notably rougher ride in flight, leading to a perceived need for increased pitch and roll attitude compensation during the flight task.

The pilot noted the significantly greater right pedal displacement required to sustain the yaw rate in flight (Table 9 (d), 11·7%–5·7%).

Field of view restrictions were apparent both in flight and the simulator. In flight, the door frame obstructed the pilot's view in his direction of travel; while in the simulator, the instrument panel obstructed the view of the cone marking the centre of the course.

5.6 The acceleration-deceleration MTE

The performance achieved in this task is shown in Fig. 14. The fidelity metrics are presented in Table 10 (a-e) (additional details can be found in Appendix B). Although the pilot awarded a HQR = 4 in flight (contrasting with HQR = 5 for the simulator), the data show that desired performance was not achieved for the MTE either in flight (only 56·7% of time within desired performance for lateral position) or in the simulator (72·3%). It can be seen in Fig. 14 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 task markers are available ahead of the aircraft (this was due to limited ground space in the Ottawa test environment).

Table 10
Acceleration-deceleration MTE metrics

(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

(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)	0·341	0·308	–10

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(c) Lateral axis parameters

Fidelity parameter	Flight	Simulator	Δ%
lateral position % time			
• inside desired	56·7	72·3	15·6
• inside adequate	100	100	0
• outside adequate	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)	0·603	0·282	–53

(d) Yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
heading % time			
• inside desired	100	100	0
• inside adequate	100	100	0
• outside adequate	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)	0·315	0·410	30

(e) Vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
height % time			
• inside desired	100	100	0
• inside adequate	100	100	0
• outside adequate	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)	0·341	0·282	–17

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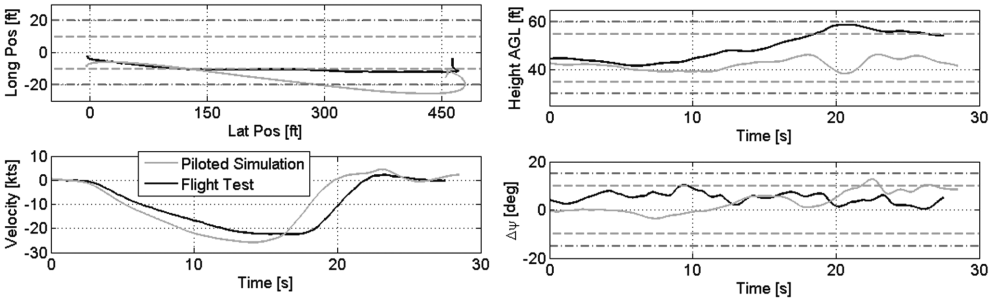


Figure 15. Lateral reposition MTE task performance.

The pilot commented that the response to collective 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. Secondly, 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 (Table 10 (e)) 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 (Fig. 14) 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 predominantly longitudinal MTE.

With the exception of the collective axis, the perceptual fidelity metrics show that the pilot applied a significantly higher level of compensation during flight.

5.7 The lateral reposition MTE

The performance achieved in this task is shown in Fig. 15. The fidelity metrics are presented in Table 11 (a-e). As with the other MTEs, additional details are to 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 throughout the manoeuvre. The aircraft moved beyond the adequate requirement for longitudinal position for the final 22% of the run in the simulator. As with the acceleration-deceleration, 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 – during the deceleration phase of the manoeuvre with a high bank angle, visibility of immediate near-field longitudinal track markers is significantly restricted, in the aircraft, and even more so in the simulator.

From the fidelity metrics in Table 11, it can be seen that the number of attack points and the mean attack rate are, once again, 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

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Table 11
Lateral reposition MTE metrics

(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	4
Time to complete translation (s)	20	19	–5

(b) Longitudinal axis parameters

Fidelity parameter	Flight	Simulator	Δ%
longitudinal position % time			
• inside desired	50	32	–18
• inside adequate	100	78	–22
• outside adequate	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)	0·800	0·351	–56

(c) 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)	0·364	0·281	–23

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(d) Yaw axis parameters

Fidelity parameter	Flight	Simulator	Δ%
• heading % time			
• inside desired	98	93	–5
• inside adequate	100	100	0
• outside adequate	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
• 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)	0·436	0·492	12

(e) Vertical axis parameters

Fidelity parameter	Flight	Simulator	Δ%
height % time			
• inside desired	72	100	28
• inside adequate	100	100	0
• outside adequate	0	0	0
• attack number	31	30	–3
• 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	0·060	0·032	–47
• cut-off frequency (Hz)	0·327	0·246	–25

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).

6.0 DISCUSSION

Based on the handling qualities metrics, the combined predicted and perceptual fidelity analysis tells a reasonably consistent, if complex, fidelity story. 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

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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.

For the acceleration-deceleration MTE, 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, if it can 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 acceleration-deceleration and lateral reposition runs, a more consistent picture of task performance and workload emerges.

In each of these cases, it has been seen that the HQR does not show good sensitivity to the fidelity issues in the Level 2 region. This highlights the importance of the introduction of new metrics (such as the control attack) that do capture the (sometimes significant) differences between the control strategy in flight and that in the simulator.

The significantly higher number and rate of application of control movements in flight have been captured by the control attack parameter in all MTEs. The level of compensation associated with essentially stabilisation activity at a rate of 1-2 control movements per second (in the flight MTEs) 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. 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 7).

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 perceptual simulator 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[32]. 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. An effort to develop a new, internationally accepted, fidelity rating scale is underway[20-22].

6.1 Flight and simulation comparisons

Across the MTEs, a picture of lower control activity in the simulator for all axes emerges. Examples are shown below for the number of attack points per second (Fig. 16) and the cut-

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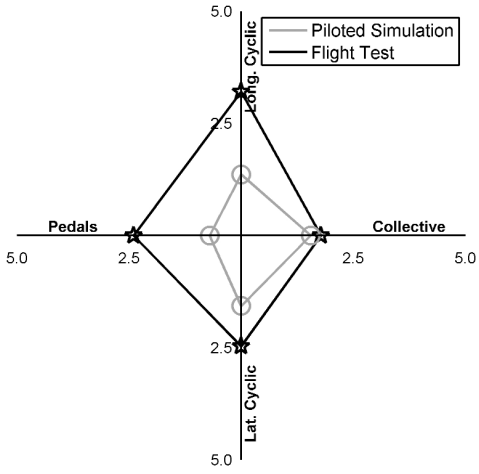


Figure 16. Number of attack points per second for flight and simulation – precision hover.

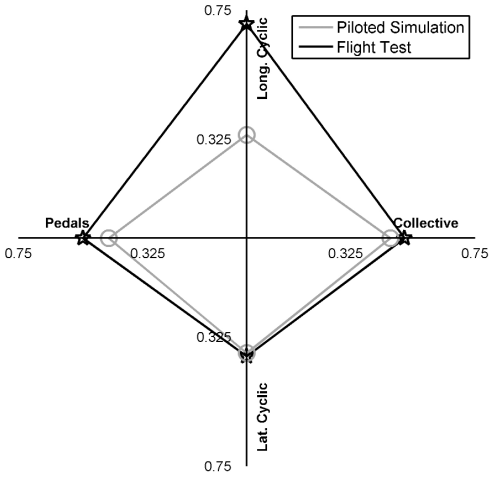


Figure 17. Cut-off frequency for flight and simulation – precision hover.

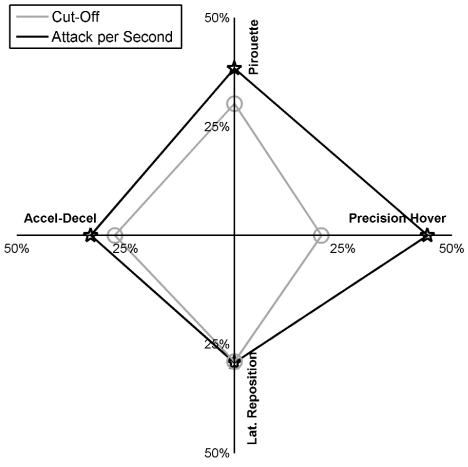


Figure 18. Sensitivity of attack and cut-off metrics.

off frequency (Fig. 17) in the precision hover MTE. Larger percentage differences between flight and simulator are typically recorded by the attack analysis than by the cut-off frequency analysis.

The different sensitivities are highlighted in Fig. 18, which shows the average percentage difference in number of attack points per second and cut-off frequency, between flight and simulation, across all four control axes for each manoeuvre. These metric sensitivities will be further discussed later in this section; here we focus on the flight-simulator comparisons.

The test pilot's compensation (as measured through the number of attack points per second) was between 30% and 60% lower in the simulator than in flight in every MTE. A number of factors are considered to contribute to this difference.

The first is an absence of atmospheric and unsteady aerodynamic disturbances around the

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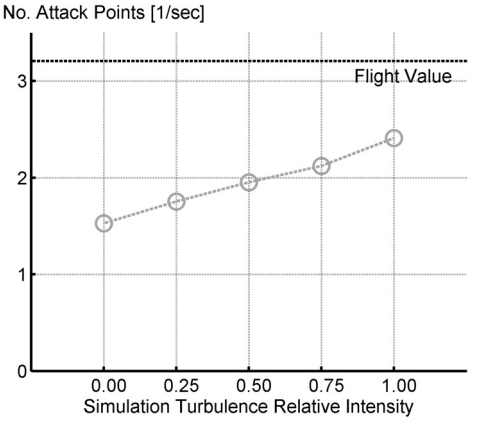


Figure 19. Effect of atmospheric disturbances on pilot compensation.

simulated helicopter. These effects cause attitude and velocity perturbations away from the desired flight path, requiring compensation from the pilot to correct. An investigation was carried out by creating a disturbance model using a sum-of-sinusoids series to generate un-commanded pitch and roll attitude changes, the magnitude of which could be varied. Figure 19 shows the effect of these disturbances on the number of attack points recorded per second, in the longitudinal axis, for precision hover tasks. The strength of the disturbances was varied from 0 (no un-commanded disturbances) to 1 (a level rated through a Turbulence Rating Scale[33] as representing the upper limit of light turbulence, with occasional moderate chop). This was, however, considered by the evaluating pilot to be in excess of that experienced during the flight testing.

It is clear from Fig. 19 that increased levels of disturbance have a well-defined effect on the pilot compensation to maintain performance – which did not degrade significantly across the five sets of simulation data. Comparing with the equivalent result from flight test, it can be seen that the compensation applied to the longitudinal axis during the precision hover task remained beyond that seen for any of the simulated disturbance cases. It therefore seems likely that, although the lack of atmospheric disturbance modelling in the simulation contributes to the recorded difference between flight and simulation, other factors also contribute to the gap.

Motion platform response is another area where the simulator does not fully replicate the experience of real flight. In each of the six degrees of freedom of a hexapod Stewart platform such as that of the HELIFLIGHT-R simulator, the response to a vehicle stimulus (such as a pitch attitude change) will consist of two phases. The first phase is a command for a platform displacement that follows the vehicle model displacement. The commanded platform acceleration, and thus displacement, is scaled according to a prescribed motion gain. In the second phase, the platform is returned to its central reference point at a rate which is, in theory, below the detection threshold of the simulator occupants. The rapidity of the return motion is specified through a washout filter[24]. There are thus three contributors to differences in vestibular motion cues between flight and simulation:

1, Motion gains are generally less than one, particularly so for translational motions
2. Washout filters will reduce the effect of the commanded motion
3. Physical limitations of the motion platform prevent it from responding as rapidly as the aircraft does

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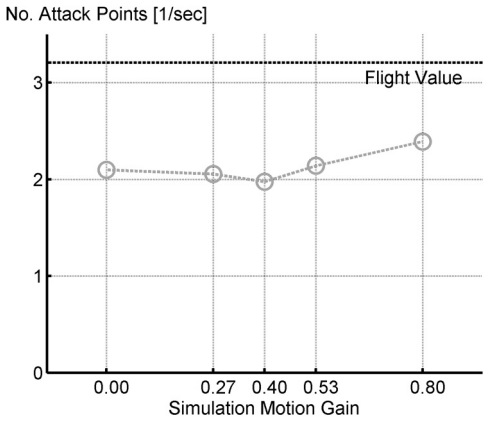


Figure 20. Effect of motion gain on pilot compensation.

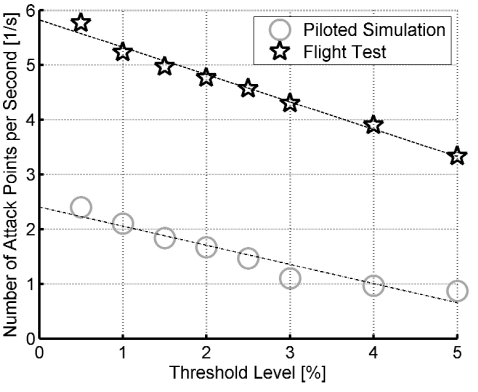


Figure 21. Effect of attack threshold on measured data – longitudinal axis for precision hover.

The motion gain and washout filter settings for the HELIFLIGHT-R simulator have been tuned to prevent the generation of adverse cueing across the low speed flight envelope required for typical ADS-33E-PRF-style manoeuvres.

An investigation of the impact of motion response on compensation in the precision hover MTE was conducted. Figure 20 shows how the number of attack points measured per second in the longitudinal axis changed with motion gain (motion gains for all axes reduced proportionately). The default gain (for pitching motion) at which all other tests described in this paper were conducted is 0·8, and it should be noted that these tests were conducted with the atmospheric disturbance model described above active (at level = 1·0 from Fig. 19), hence why a higher number of attack points is recorded in every case here than are seen in Table 8.

While there is an initial trend for a small reduction in compensatory activity as motion begins to be experienced, beyond a certain level of motion gain, the pilot's control activity begins to increase. If this trend were to continue to a gain of 1·0 (equivalent onset motion cue to flight) then the gap between flight and simulation would conceivably be closed.

A factor which has not been quantified, but which will certainly affect the pilot's workload, is the cueing that the pilot can extract from the visual scene. The VCRs suggest that the simulator's re-creation of the Ottawa test environment restricted the pilot's ability to apply both attitude and translational rate corrections. While this might lead to a reduction in accuracy, which would require additional control activity from the pilot to correct, it is generally seen in Tables 8-11 that the achieved task performance was similar both in flight and simulator. An alternative explaination is that the limitations of the visual cues prevented the pilot from working at a higher rate to deliver the improved level of performance that might have been expected based on the better HQs predicted for the F-B412 in Table 6.

One further factor that was considered as a potential cause of the measured difference between flight and simulation was the method of calculating the attack points. A lower threshold of 0·5% of full range travel was applied before an attack point would be registered. However, with significant numbers of small amplitude attack points being recorded in both flight and simulation, consideration of the threshold level was merited. Figure 21 shows a linear relationship between threshold level and change in number of attack points measured for both flight and simulation. Importantly, the ratio between flight and simulation attack points remains

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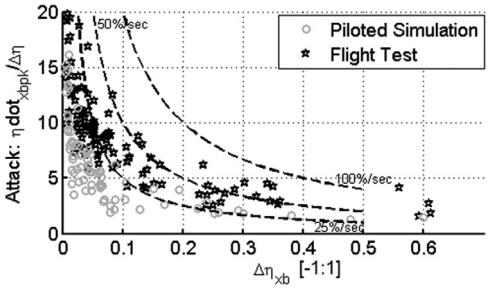


Figure 22. Typical attack portrait; longitudinal cyclic in the accel-decel MTE.

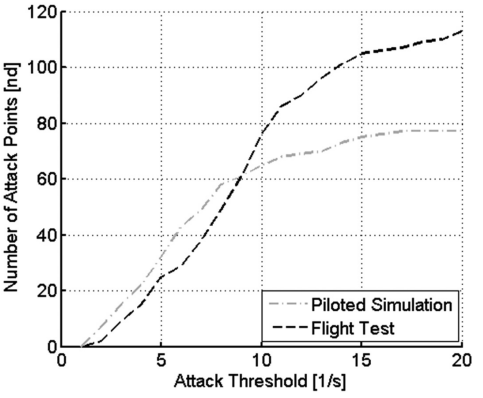


Figure 23. Typical growth of attack with upper threshold; longitudinal cyclic in the accel-decel MTE.

essentially unchanged across the threshold limits investigated. This result gave confidence that the analysis method was providing a fair reflection of the true differences between the levels of compensation in flight and simulation, and as such, was rejected as a cause of measured differences between flight and simulation.

6.2 Sensitivity of time and frequency domain metrics

Figure 18 highlighted the differing sensitivity of the time domain attack parameter and the frequency domain cut-off frequency to fidelity gaps. While, to a certain extent, the two metrics are sensitive to differing aspects of a pilot's control activity, the calculation methods for the metrics do not lend themselves to direct comparisons. To better understand the comparison, the attack data are converted into a form similar to that of the cut-off frequency. Figure 22 shows the longitudinal cyclic attack chart for the accel-decel manoeuvre, highlighting the difference between flight and simulator. Each attack point represents a discrete control movement by the pilot. This dataset will be used to exemplify the transformation process.

Figure 23 shows the growth in number of attack points as an upper attack threshold is increased, and Fig. 24 shows the same data normalised by the total number of attack points. To place the attack metric in frequency context, a single sine wave (one oscillation) would contain three attack points. However, pilot inputs are normally sharper and more discrete than a sine wave; a double movement of the stick leading to four attack points.

The lower end of the frequency range used in the cut-off frequency computation was 0·2Hz. Assuming a triangular-wave control input (Fig. 25), this would correspond to attack values less than unity. For each of the discrete inputs (η changed from –1 to 0, 0 to +1 etc), the rate of displacement of the control is given by $\dot{\eta} \approx 4f\Delta\eta$, where f is the primary frequency of the signal: 0·2Hz in Fig. 25. As the attack is given by the rate of displacement divided by the magnitude of the displacement, it can be seen that attack $\approx 4f$ for this signal.

Figure 22 shows that there are no attack points below about 1·5 – the lower frequency guidance component being lost within the stabilisation inputs. The upper frequency for cut-off computation was 2Hz, corresponding to attack values less than about eight; Fig. 24 suggests that this attack threshold corresponds to about 50% of the flight control movements and about 75% of the movements in the simulator.

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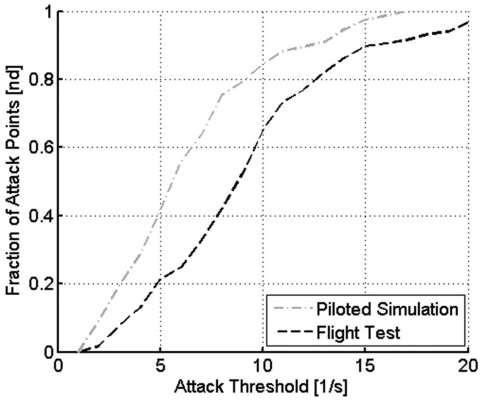


Figure 24. Typical growth in normalised attack with upper threshold; longitudinal cyclic in the accel-decel MTE.

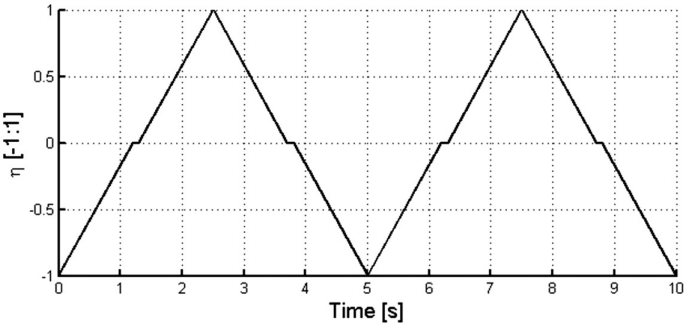


Figure 25. Development of attack – cut-off analogy using triangular wave.

Drawing an analogy with the cut-off frequency, the difference between flight and simulation at the 70% threshold (i.e. the attack value when 70% of the activity, according to this metric, is accounted for) is about 30% compared with 50% difference for the number of attack points per second given in Table 10. Also from Table 10, we see a difference in cut-off frequency between flight and simulation of 10%. This interpretation of the attack metric therefore correlates more closely with the frequency domain version. Whether it is a 'better' measure of pilot compensation than the number of attack points per second is still open to question however, which brings us to the final section of the paper.

6.3 Development of formal metric requirements

The metrics discussed have been shown to provide effective methods of quantifying the difference between a pilot's control strategy in flight, and that adopted in the simulator. However, the required closeness of matching between the flight and simulator, to allow qualification of a flight simulator – the tolerances – has not, as yet, been determined.

This process has begun, in conjunction with the development and validation of a new simulator fidelity rating scale, at UoL[22-24]. A process of implementing changes to a baseline simulation environment, followed by the assignment of fidelity levels using the new scale is being adopted. The change in the pilots' control strategies following a change in the simulation

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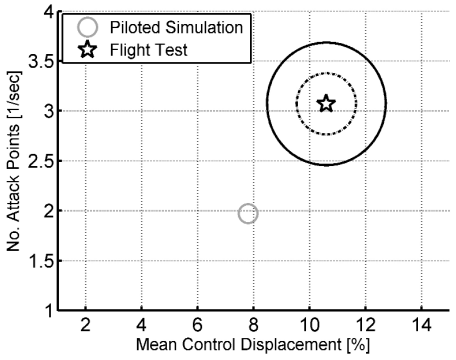


Figure 26. Potential form for fidelity metric based on attack.

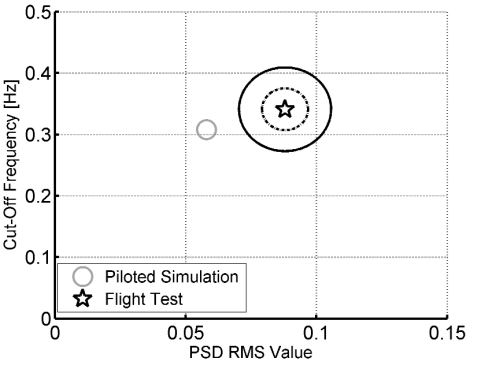


Figure 27. Complementary fidelity metric based on power spectrum.

will be correlated with the assigned fidelity, and conclusions drawn on the degree to which the pilot can adapt control strategy (as measured through the percentage change in each of the metrics), relative to the assigned fidelity level.

Reflecting back to the handling qualities requirements, in many cases ADS-33E-PRF captures requirements on two-dimensional charts. Examples of this are the quickness (quickness *vs* attitude change), stability (frequency *vs* damping) and bandwidth (phase delay *vs* bandwidth) requirements. These two dimensional requirements allow more complex relationships between the handling parameters to be captured than, say, by stating maximum or minimum requirements for each individual metric.

It is anticipated that the same will develop with the fidelity metrics. In this case, a combination of metrics should include an amplitude measure (such as the mean control displacement or RMS) and a frequency measure (such as the number of attack points per second or cut-off frequency), and could take a form similar to that illustrated in Figs 26 and 27, where the closed contours indicate nominal tolerances of 10% and 20% between the measured flight data and what might be allowable, for example, for Level 1 and Level 2 fidelity. In both cases the simulator is outside the 20% boundary and we might expect some subjective expression of this in pilot ratings. The results of such experiments will be reported in the very near future.

7.0 CONCLUSIONS

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 has underpinned the Lifting Standards research project at Liverpool.

A set of predicted fidelity metrics for flight dynamics modelling has been proposed, drawing on the ADS-33E-PRF 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 four hover/low speed tasks have been reported in detail.

Analysis of the predicted HQs of the aircraft showed that the results were expected to fall

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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 much as expected.

For the assessment of perceptual 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 can result from 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; early activity on the development of such a scale has been highlighted.

The attack, quickness and frequency domain 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, alongside visual and vestibular cueing gaps, contribute to the reduced activity in the simulator. A closer correlation between time and frequency domain metrics has been achieved by selecting similar thresholds in both domains; notably the 70% of activity level.

This paper has described the identification of parameters that are sensitive to differences between flight and simulation, and are therefore suitable for use as metrics of fidelity. Further research is ongoing in the Lifting Standards project to fully establish cause and effect, and to quantify the allowable discrepancies between flight and simulator – the all-important tolerances. Together with the identification of simple metrics for fidelity assessment, the development of a perceptual simulator fidelity rating scale is also being undertaken.

ACKNOWLEDGEMENTS

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The use of the Bell 412 ASRA facility is gratefully acknowledged, along with the flying expertise of NRC test pilots Rob Erdos and Stephan Carignan. The authors would like to thank Steven Hodge of BAE Systems for his ongoing assistance with the motion tuning and visual upgrade work undertaken on HELIFLIGHT-R.

The work of UoL Consultant Test Pilot Andrew Berryman has been invaluable throughout the Lifting Standards project.

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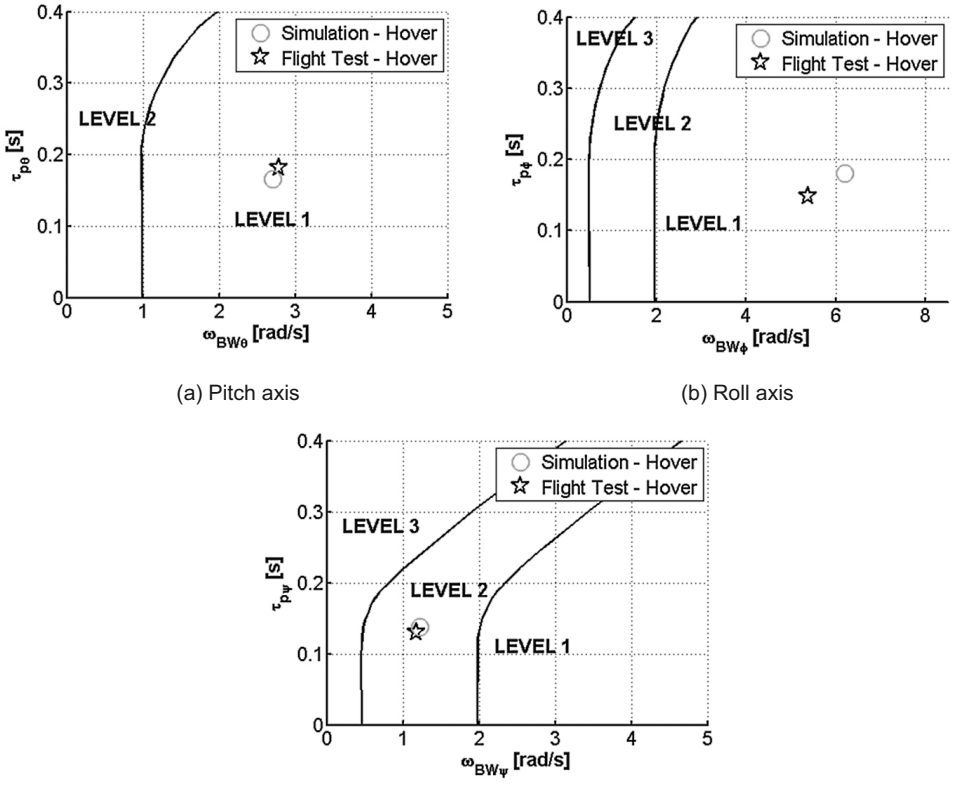
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APPENDIX A – PREDICTED FIDELITY



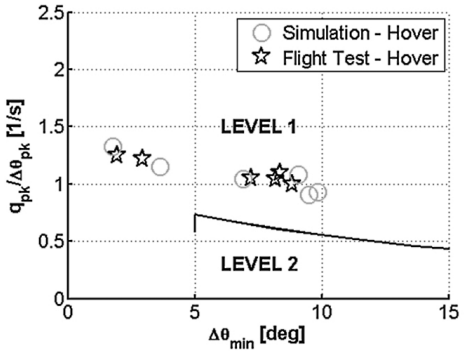
(a) Pitch axis

(b) Roll axis

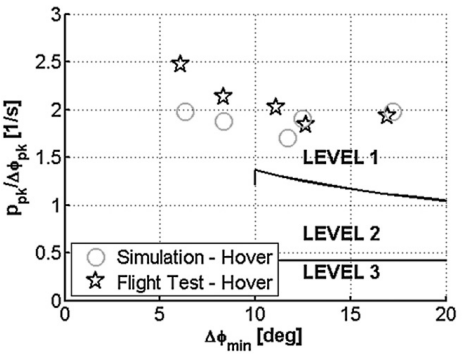
(c) Yaw axis

Figure A1. Attitude bandwidth – hover.

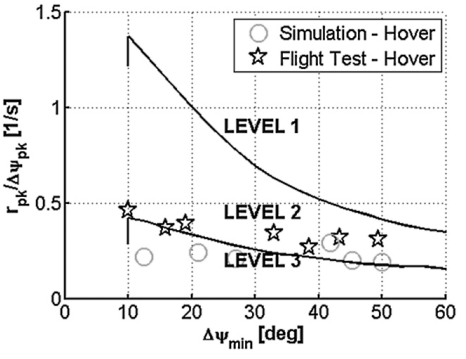
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(a) Pitch axis

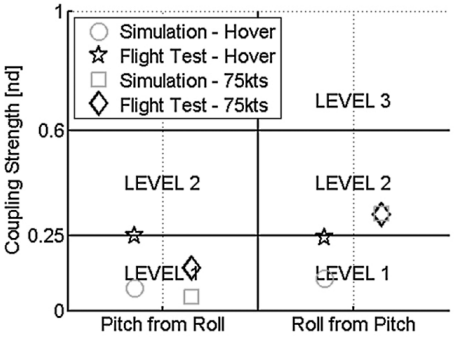


(b) Roll axis

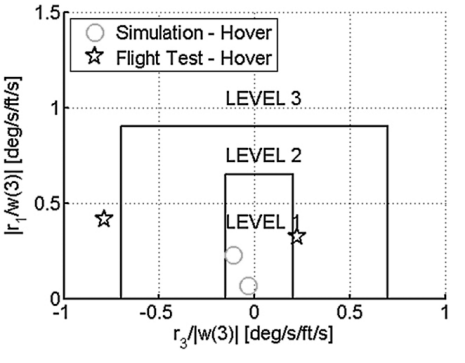


(c) Yaw axis

Figure A2. Attitude quickness – Hover.



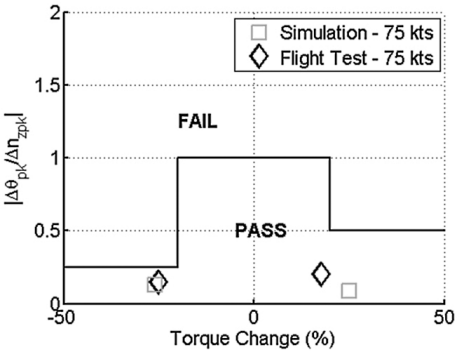
(a) Roll/pitch



(b) Collective to yaw

Figure A3 (a-b). Cross couplings – hover and forward flight.

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(c) Collective to pitch

Figure A3 (c). Cross couplings – hover and forward flight.

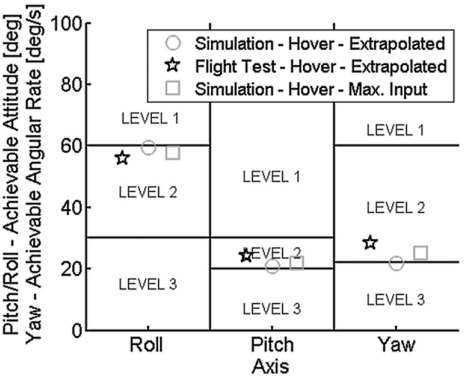
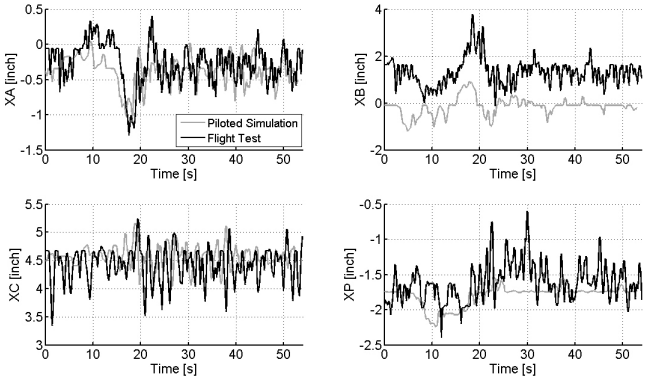
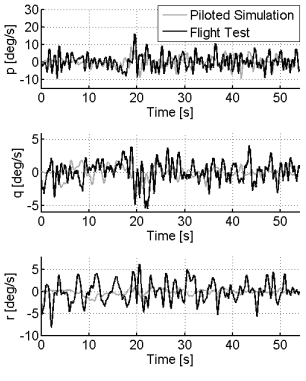


Figure A4. Maximum response – hover.

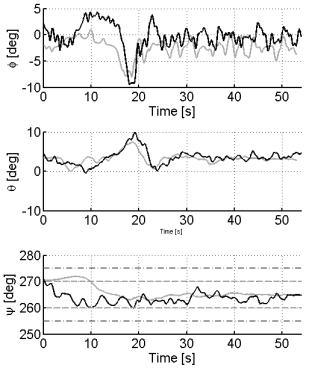
APPENDIX B – PERCEPTUAL FIDELITY



(a) Pilot controls



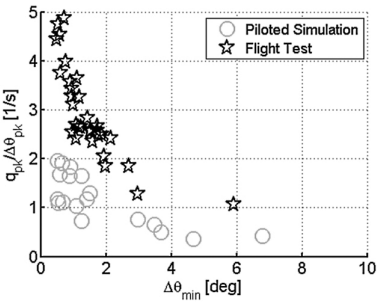
(b) Rates



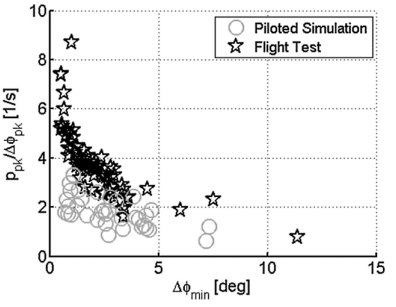
(c) Attitudes

Figure B1. Precision hover control inputs and aircraft responses.

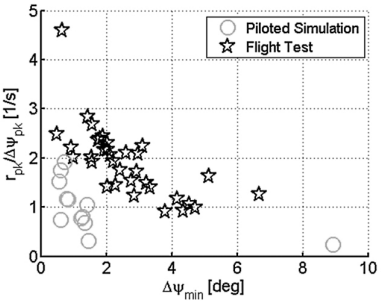
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(a) Pitch

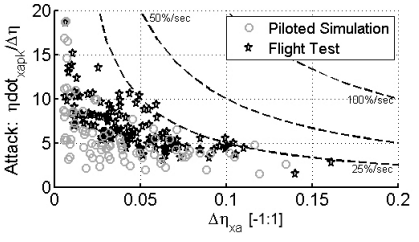


(b) Roll

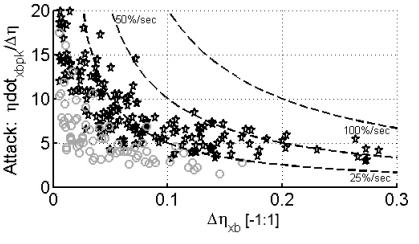


(c) Yaw

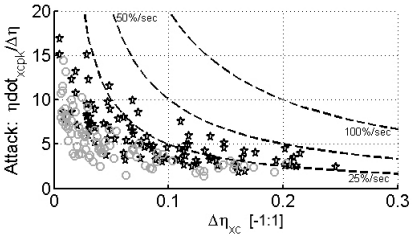
Figure B2. Closed loop quickness for the precision hover.



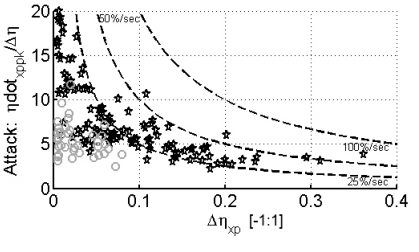
(a) Lateral



(b) Longitudinal



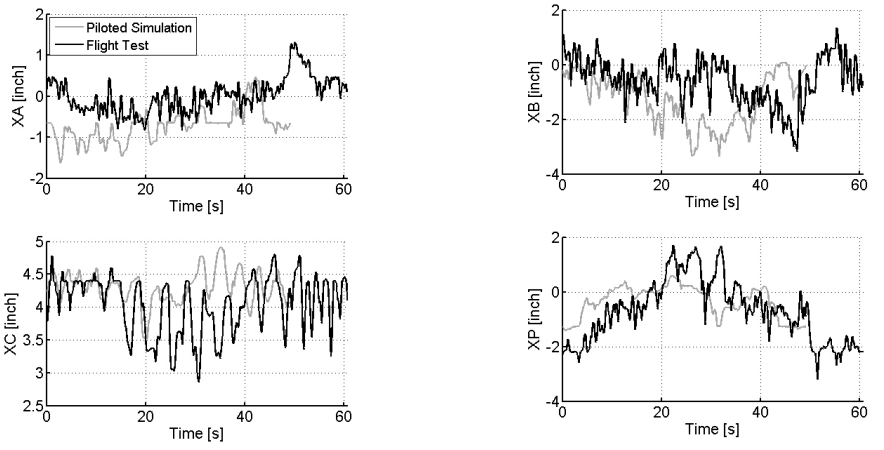
(c) Collective



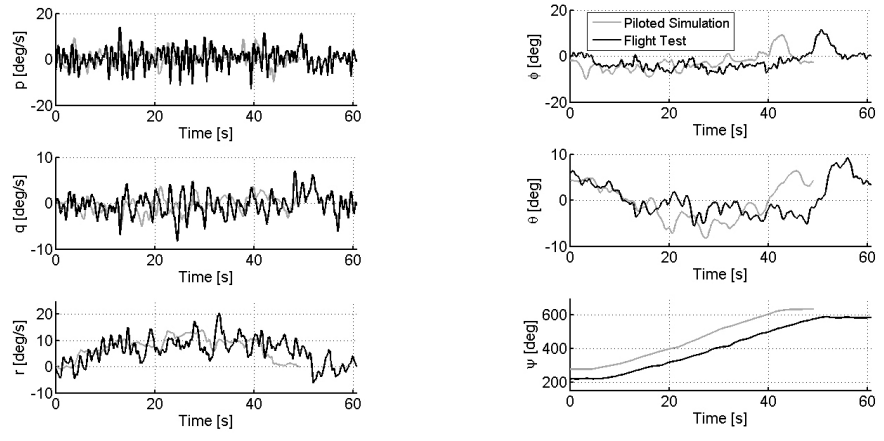
(d) Pedals

Figure B3. Control attack for the precision hover.

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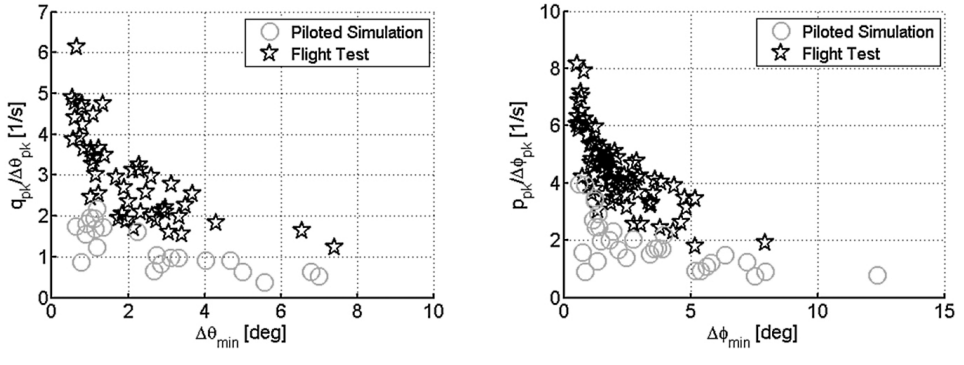


(a) Pilot controls



(b) Rates (c) Attitudes

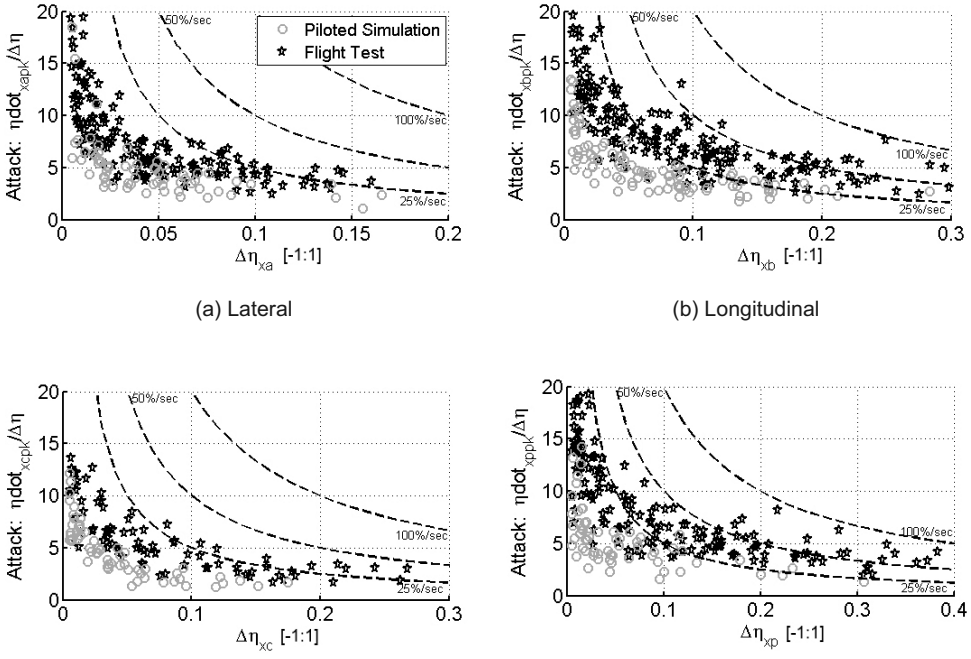
Figure B4. Pirouette control inputs and aircraft responses.



(a) Pitch (b) Roll

Figure B5. Closed loop quickness for the pirouette.

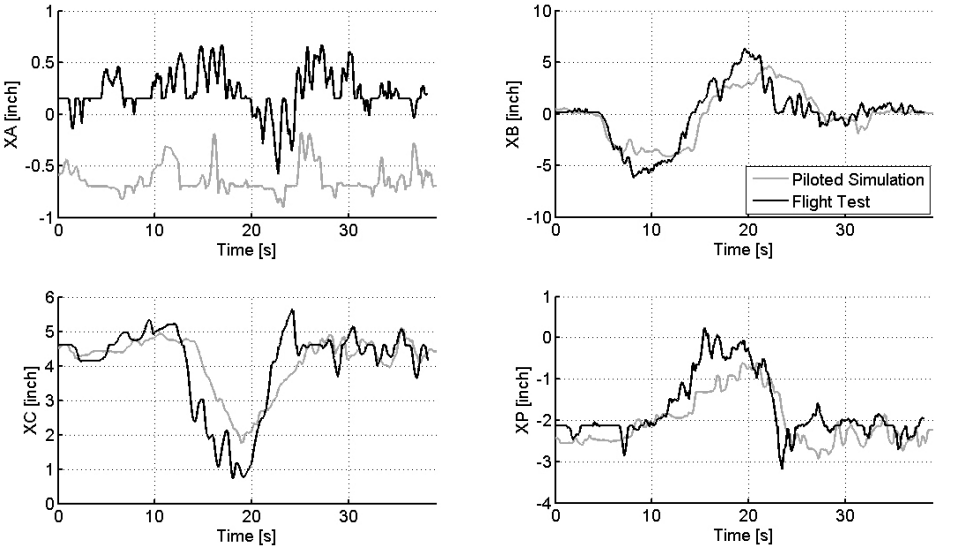
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(a) Lateral (b) Longitudinal

(c) Collective (d) Pedals

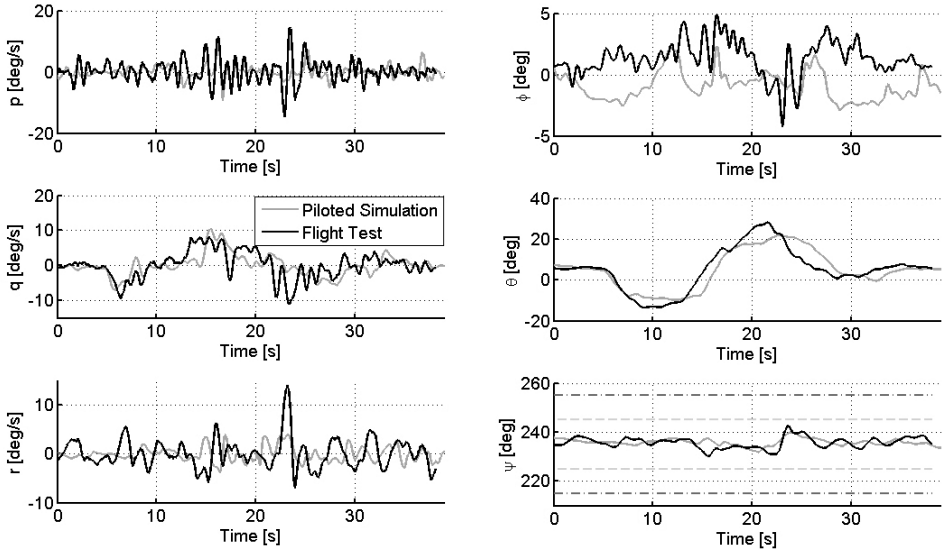
Figure B6. Control attack for the pirouette.



(a) Pilot controls

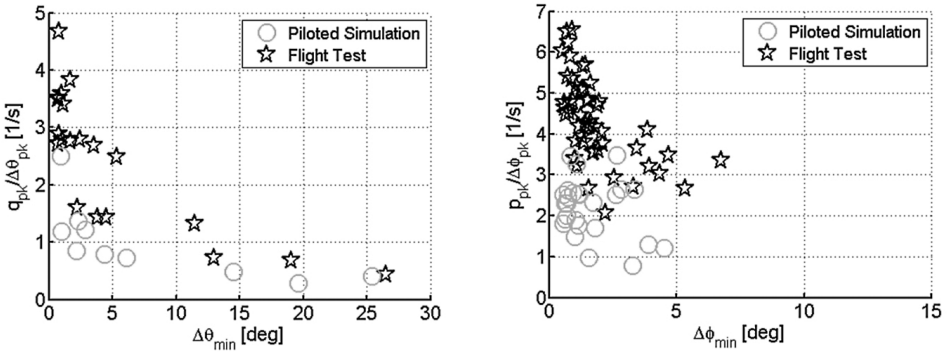
Figure B7 (a). Acceleration-deceleration control inputs and aircraft responses.

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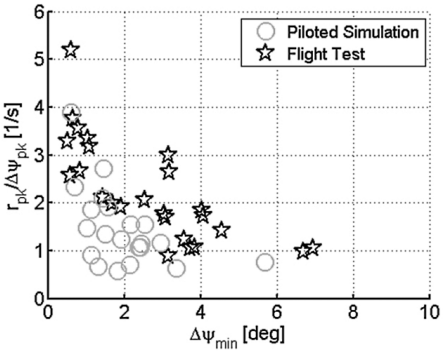


(b) Rates (c) Attitudes

Figure B7 (b-c). Acceleration-deceleration control inputs and aircraft responses.



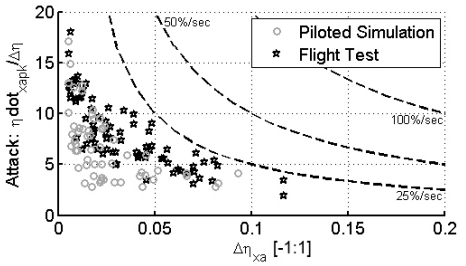
(a) Pitch (b) Roll



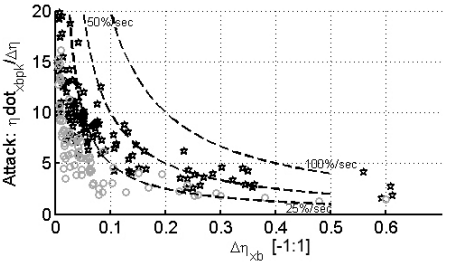
(c) Yaw

Figure B8. Closed loop quickness for the acceleration-deceleration.

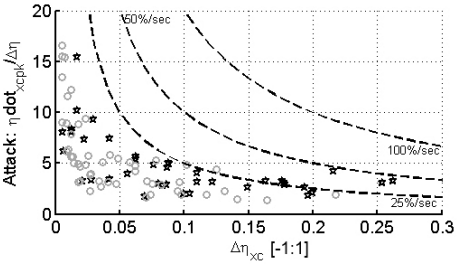
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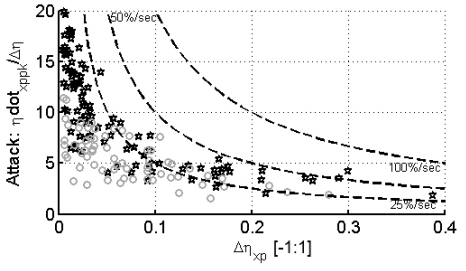
(a) Lateral



(b) Longitudinal

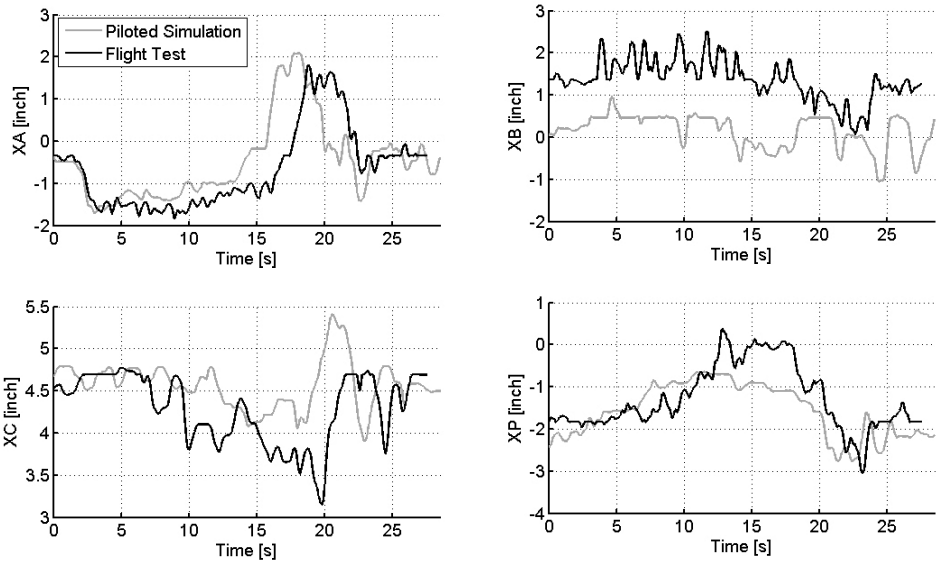


(c) Collective



(d) Pedals

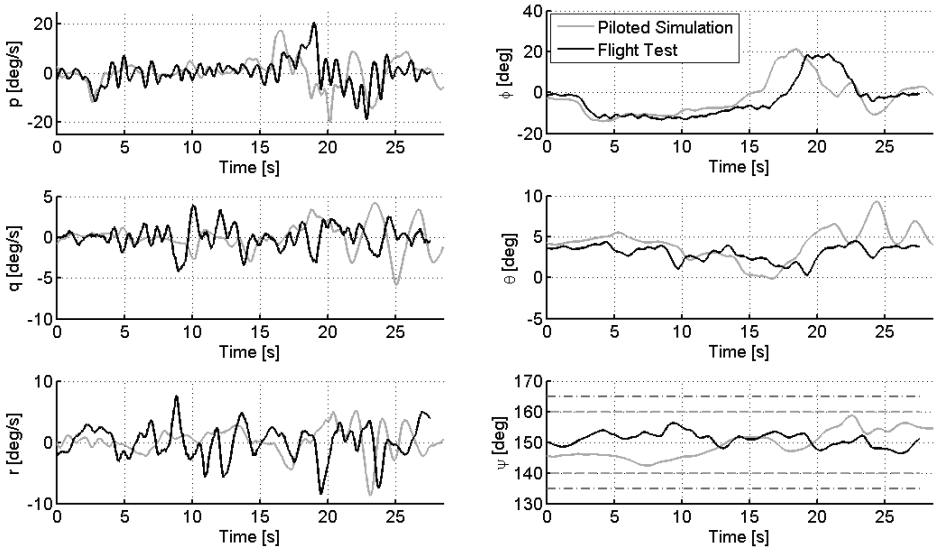
Figure B9. Control attack for the acceleration-deceleration.



(a) Pilot controls

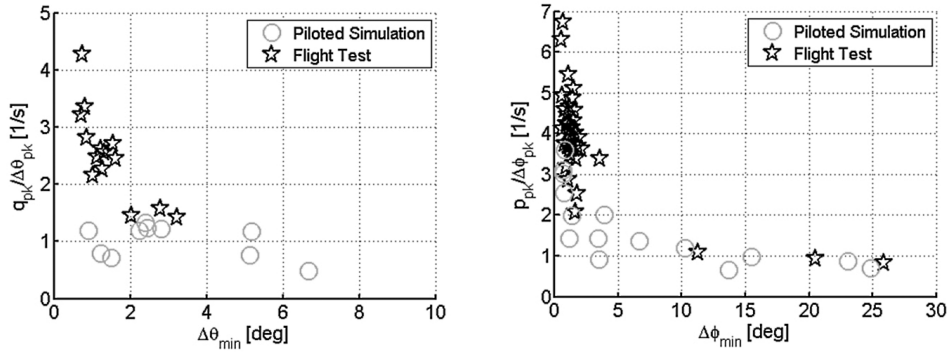
Figure B10 (a). Lateral reposition control inputs and aircraft responses.

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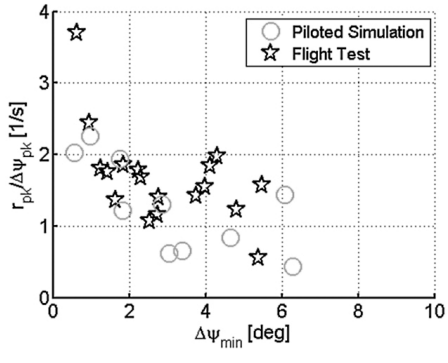


(b) Rates (c) Attitudes

Figure B10 (a). Lateral reposition control inputs and aircraft responses.



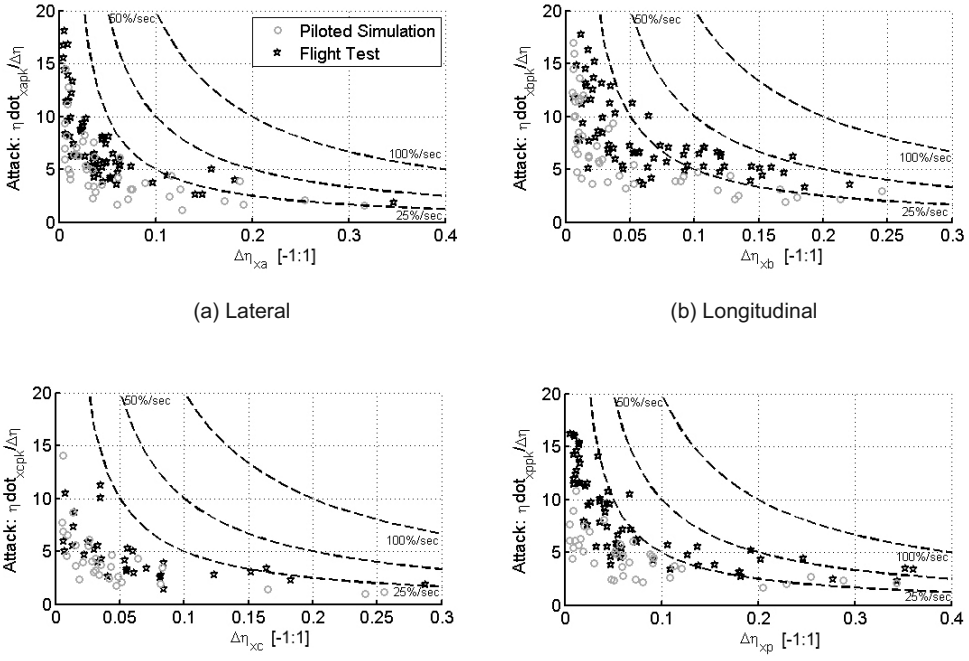
(a) Pitch (b) Roll



(c) Yaw

Figure B11. Closed loop quickness for the lateral reposition.

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(a) Lateral

(b) Longitudinal

(c) Collective

(d) Pedals

Figure B12. Control attack for the lateral reposition.

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