An Investigation of Task Specific Motion Cues for Rotorcraft Simulators

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The relevance of motion cueing in flight simulation is a widely debated topic. The aim of this paper is to present the results from a preliminary investigation of the effect of motion cueing on the perceived training effectiveness of a rotorcraft flight simulator. The paper shows the results from a series of simulator experiments that examined the effect of motion cueing on task performance and workload for a range of test maneuvers. Three test pilots flew three different rotorcraft models, with different levels of handling qualities, through test maneuvers which required different levels of task aggressiveness. The pilots used the Simulator Fidelity and Motion Fidelity rating scales, developed at the University of Liverpool, to make subjective assessments of simulator fidelity together with the Cooper Harper Handling Qualities scale. Results show that simulator fidelity requirements are not only tasked based, but are also dependent on the handling qualities of the aircraft being flown.

Abbreviations

ACAH	Attitude Command with Attitude Hold
ADS-33E	Aeronautical Design Standard 33, Version E
ART	Advanced Rotorcraft Technology
ASRA	Advanced Systems Research Aircraft
DSTO	Defence Science and Technology Organisation, Australia
ETPS	Empire Test Pilot School, UK
HQR	Handling Qualities Rating
IWG	International Working Group
MDA	Motion Drive Algorithm
MTE	Mission Task Element
NRC	National Research Council, Canada
OMCT	Objective Motion Cueing Test
RCAH	Rate Command with Attitude Hold
RWTES	Rotary Wing Test and Evaluation Squadron, UK
SFR	Simulator Fidelity Rating
UCE	Useable Cue Environment

I. Introduction

Flight simulators play an important role in the flight training process, providing a safe, reliable and effective environment to both acquire new skills and maintain proficiency. Simulators are particularly important for pilot assessment during emergency scenarios, where live training is simply not feasible. Key to the efficacy of the training device is the transfer of skills acquired in the simulator to the "real-world", referred to as transfer of training. The overall fidelity of a simulator, and hence its effectiveness in this process, is a function of the fidelity of its major components including the visual system, motion cueing and flight model. Qualification standards such as CS-

FSTD(H) Helicopter Flight Simulation Training Devices[1] and its predecessors define the component fidelity required to satisfy different fidelity levels, but these requirements are not tailored to individual training tasks. Developments in technology and training needs led to revision of the qualification standards, but did not fundamentally change the underlying structure they contained. The Royal Aeronautical Society Flight Simulation Group established an International Working Group (IWG) to review the technical criteria contained within the standards. The IWG produced a new document, ICAO 9625, "Manual of Criteria for the Qualification of Flight Simulation Training Devices" [2] to address the need to establish the simulation fidelity levels required to support the range of training tasks carried out for different pilot licenses and ratings. Whilst ICAO 9625 recognizes the need for task specific fidelity requirements and defines four fidelity levels for training devices (none, generic, representative and specific) it does not provide any new fidelity criteria. Pavel et al [3] examined the current standards and reported that "it is still not clear whether meeting the standards will guarantee a simulation sufficiently representative of the real world, such that the simulator is fit for purpose". Whilst the paper focused on flight model fidelity, it was recognized that simulator visuals and motion characteristics all contribute to the pilot's perception of the fidelity of the simulator and that the subjective assessment process needed further refinement to identify and correct deficiencies in the overall fidelity of the simulator.

The topic of motion fidelity requirements has received significant attention over the years. Under existing regulations the qualification of a flight simulator motion cueing system is largely achieved using objective, or automated tests, which measure the open-loop mechanical performance of the motion system hardware; including tests for frequency response, leg balance and turn-around[2]. However, the most recent revision of ICAO 9625 [2] does include details of a new objective motion cueing test, which measures the performance of the complete motion system, including the motion drive algorithm[4]. With specific reference to the fidelity of motion cues presented to the pilot, the only guidance currently stipulated by Ref. 2 is contained in the following requirement: "the flight simulator motion cueing system should have a high tilt co-ordination gain, high rotational gain and high correlation with respect to the aeroplane simulation model". Whilst there have been a number of studies examining the effect of motion on single axis tasks [5,6,7,8], there is still the need to examine the motion requirements for multi-axis tasks, taking into account aircraft with different levels of handling qualities undergoing a range of different dynamic maneuvers. This paper presents the results from a set of flight simulation trials that were undertaken to assess the influence of motion cues on task based simulator fidelity.

II. Comprehensive Fidelity Assessment

Fidelity may be defined as "the degree of exactness with which something is copied or reproduced". With reference to a flight simulator, fidelity is dependent on the context in which the comparison is made to the actual aircraft and the task required of the simulator. Training simulators, by definition, should have well specified requirements for the tasks pilots are expected to perform. To validate and assess the fidelity of a Human-in-the-Loop training simulator, two general approaches can be defined from the civil regulatory environment; objective and subjective tests. Objective tests being defined as quantitative processes where the pilot is not in the loop, and subjective tests defined as qualitative processes that require a pilot to assess the simulator as a whole. Through standards such as CS FSTD(H), each training task has specific objective tests with specified tolerances for flight data, audio, and visual comparisons. Conversely, industry standards for subjective tests rely on the pilot providing a Satisfactory or Unsatisfactory rating after flying a number of scenarios. No specific evaluation methods are provided, yet results of these subjective tests guide the overall rating of the simulator.

A more comprehensive definition of fidelity types in the aircraft simulator environment, and one that will be referred to throughout this investigation, is that of Figure 1 (Ref. 9). Here, objective fidelity is defined as per the previously noted industry standards. Similarly, perceptual fidelity is synonymous to the subjective fidelity, where fidelity is defined by the pilot's perception of the environment and their opinion of their own actions, strategy and performance compared to prior experience in the relevant aircraft. The additional concepts of behavioral and error fidelity are essentially an objective assessment of the pilot's subjective view. Behavioral fidelity is an assessment of the pilot's actions in control of the aircraft and use of external cues. Typically this could involve comparison of control input, head and eye movement strategy with that of flying the actual aircraft. Finally, error fidelity is an assessment of the overall performance of the aircraft system during the task. This may simply involve comparison of the simulated and real life aircraft trajectory during the task.

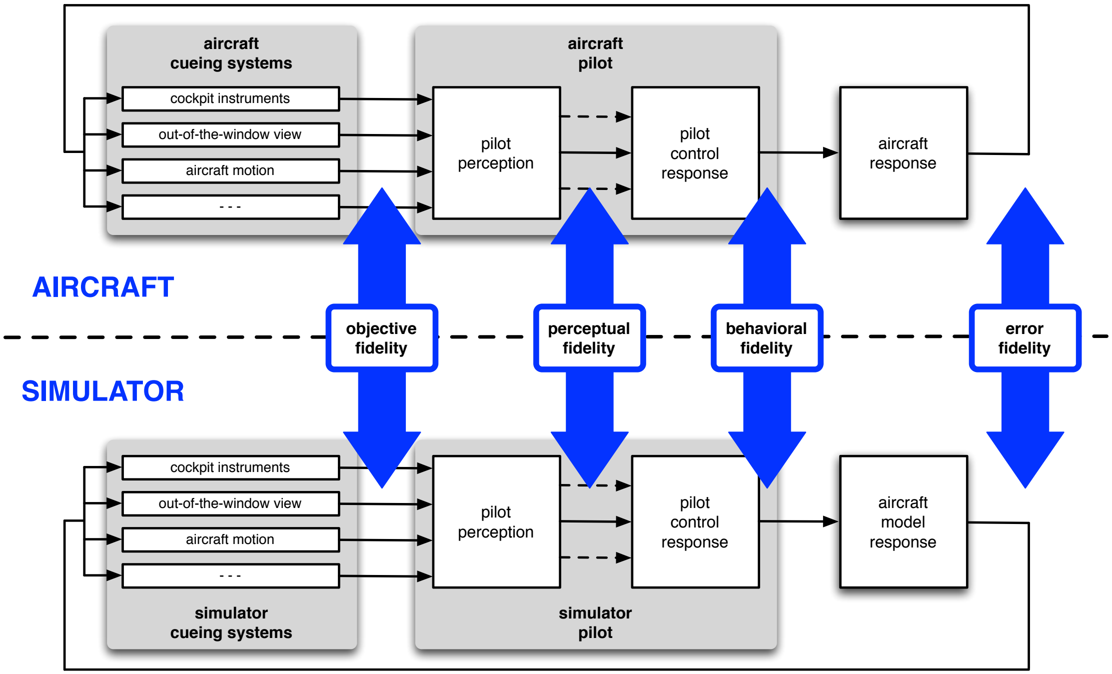


Figure 1. Comprehensive Fidelity Assessment of a Human-In-the-Loop Aircraft Simulator[9].

A. Simulator Fidelity Rating Scale

Although current effort is underway toward technical criteria to remove the need for subjective "pilot" assessment (ICAO), it is impossible to avoid the overriding requirement to appropriately identify "transfer of training" in the assessment of a training simulator. Transfer of training refers to the knowledge or abilities acquired through the simulation task being applicable to the real world, which is inherently subjective in nature. The use of a scale such as the Simulator Fidelity Rating (SFR) scale (Figure 2), developed at the University of Liverpool[10], can provide a repeatable method to subjectively measure simulator fidelity where requirements exist for "transfer of training".

The SFR scale is a comparative scale and applied on a task-by-task basis. Its structure is based on that of the Cooper-Harper Handling Qualities Rating (HQR) scale. Fidelity is determined by comparison of the achieved task performance and the adaptation of the pilot task strategy in the simulator with reference to the same specific task in the actual aircraft. The scale leads the assessor through a decision-tree process, the output of which determines whether or not the simulator is fit for purpose. A Level 1 rating indicates a full transfer of training, Level 2 offers only a limited transfer of training and Level 3 specifies a negative transfer of training. Whilst a fidelity Level 2 rated task may still be found fit for purpose, a negative transfer of training means task strategy differs significantly from the actual aircraft and therefore the simulator should not be used to train that particular task. Acceptable task performance and limits must be defined prior to the task assessment. The key questions to be addressed as part of task performance during the rating include:

- Can the task be undertaken in the simulator?
- Can the task be completed within acceptable task limits?
- Can the task be undertaken in the same manner as for the actual aircraft?

Pilots are required to also consider their adaptation of task strategy in the simulator. This requires pilots to have sufficient experience to identify variation in their behavior, including:

- Control activity (in each axis) compared with typical strategy and effort in the aircraft
- The availability and use of the useable cue environment, or lack thereof
- The comparative workload, both physical and cognitive

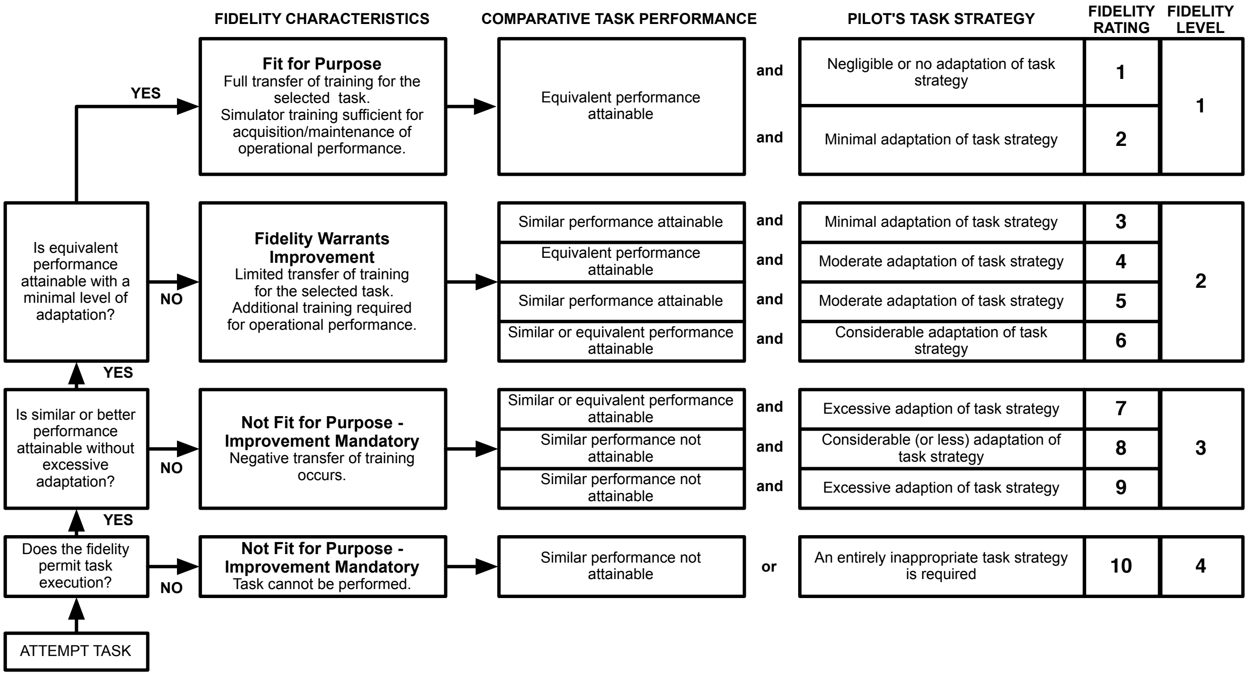


Figure 2. Simulator Fidelity Rating Scale.

B. The Importance of Motion

The perception of low frequency motion and steady-state orientation is dominated by visual cues; but the human visual system is slow to respond to the onset of motion. On the other hand, the body's other motion sensors, including the vestibular system, responds rapidly to the onset of motion. The human vestibular system contains two important motion sensors, both located in the inner ear – the semicircular canals and the otoliths. The otoliths are translational motion sensors that detect specific forces acting on the head. The semicircular canals are stimulated by angular acceleration, but have evolved to primarily sense angular velocity over the frequency-range typical of human motion[2]. Each semicircular canal consists of three fluid-filled rings which lie approximately orthogonal to each other, sensing rotational motion in the roll, pitch and yaw axes.

The ultimate aim of a flight simulator motion platform is to stimulate these sensors to provide the pilot with a sensation faithful to that of real flight. Invariably, this aim is never fully realized, largely due to the inherent limitations of ground-based motion platforms. Nevertheless, simulator motion feedback still provides important cues, which are used by pilots to stabilize and control the aircraft; and which enhance the pilot's perception of simulator fidelity. A number of factors influence the pilot's perception of motion cues, including the performance of the motion platform hardware, the configuration of the motion drive software and, to an extent, the experience of the pilot. To assess the quality of motion, a Motion Fidelity Rating scale was used. The scale was developed at the University of Liverpool[5] (Figure 3) and incorporates a 10-point scale devised to have a similar structure as the SFR scale and the established Cooper-Harper HQR scale[11]. Similarly, the decision tree leads the pilot first to descriptors, and then to numerical ratings.

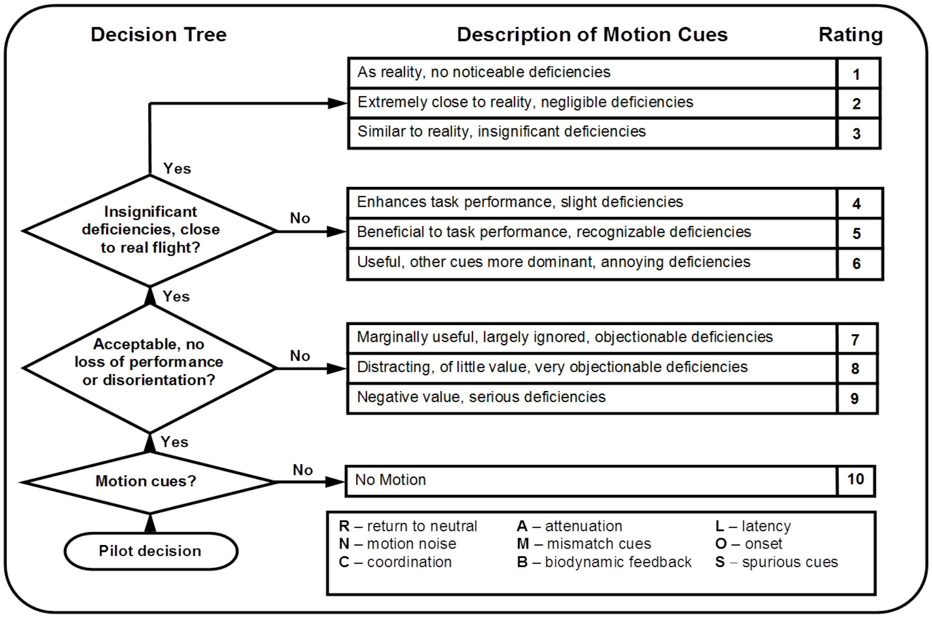
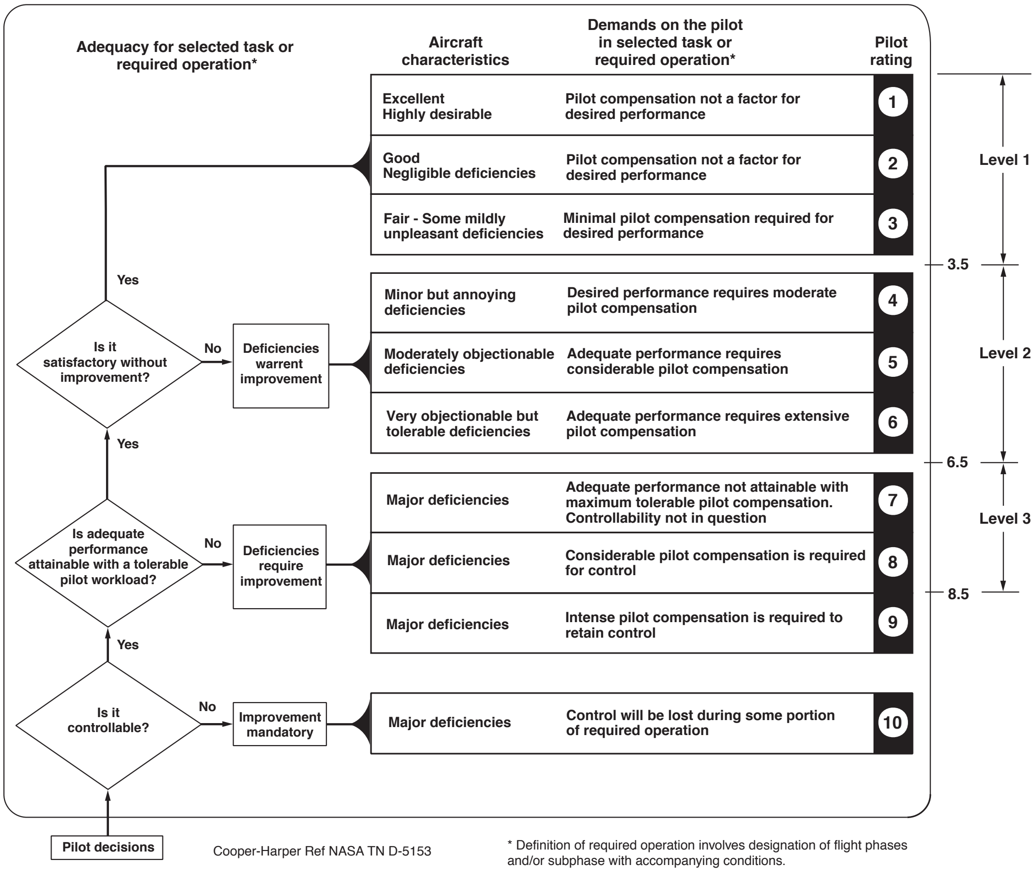


Figure 3. Motion Fidelity Rating Scale.



Cooper-Harper Ref NASA TN D-5153

* Definition of required operation involves designation of flight phases and/or subphase with accompanying conditions.

Figure 4. Cooper Harper Handling Qualities Rating (HQR) scale[11].

C. ADS-33E PRF Mission Task Elements & Handling Quality Assessment

The requirement of well-defined task and performance limits for completing a fidelity assessment has led to the use of the Aeronautical Design Standard 33 (ADS-33), Version E, Mission Task Elements (MTEs) [11] in this investigation. ADS-33 is a performance specification for military rotorcraft that includes a comprehensive set of handling qualities requirements. The handling qualities criteria and metrics of ADS-33 depend primarily on the mission and role of the helicopter. ADS-33 includes definitions of aircraft response characteristics dependent on the visible cues of the environment, quantitative criteria in both the frequency and time domains, and qualitative criteria based on pilot ratings. The qualitative criteria, in the form of demonstration maneuvers, assure a comprehensive and independent assessment of the handling qualities of the helicopter during certain well defined tasks. These tasks are representative of actual tasks which are likely to occur during operations.

Subjective pilot ratings are given on the Cooper-Harper scale (Figure 4) as Handling Qualities Ratings (HQR). The HQR can be used as an indicative measure of fidelity through comparison of pilot ratings between aircraft and/or flight models. For flight within the operational flight envelope, Level 1 handling qualities are desired, Level 2 is acceptable in the case of failed and emergency situations, but Level 3 is considered unacceptable. To assess handling qualities, ADS-33 requires that the specifications of the MTE, the Usable Cue Environment (UCE) and the response type are defined. UCEs, rated on a three level scale, relate to the need for different flying qualities in different visual conditions. A UCE of 1 corresponds to very good visual cues that support the aircraft control of attitude and translational rates, whereas a UCE of 3 relates to a deficiency in visual cues such that significant augmentation in aircraft control is required for safe flight

III. Task Specific Motion Cues - Experimental Arrangement

The aim of this experiment was to produce a dataset to enable investigation into how motion cues influence the fidelity of rotorcraft simulators undertaking specific tasks. The dataset was first used to identify pilot performance and control strategy adaptation between motion and non-motion cueing when performing well defined maneuvers. Analysis was then completed to identify whether and/or how rotorcraft response types affect the fidelity and requirements of motion cueing. Well defined tasks and performance limits were desired for the investigation, therefore the following set of ADS-33E Mission Task Elements (MTE) were chosen. This selection offers a range of tasks requiring different levels of maneuver aggressiveness:

1) Hover MTE.
2) Lateral Maneuver MTE.
3) Bob-Up Maneuver MTE.
4) Pirouette MTE.
5) Acceleration/Deceleration MTE.

The investigation was carried out using the University of Liverpool's HELIFLIGHT-R flight simulator[12], shown in Figure 5. HELIFLIGHT-R is a re-configurable simulator, with a 6 Degree of Freedom motion platform, 4 axis control loading and a 210º x 70º field of view. Flight models are developed for real-time operation using either Advanced Rotorcraft Technology's (ART) multi-body flight dynamics modeling environment, FLIGHTLAB[13], or Matlab/Simulink.

Motion cueing is generated by Moog Force Control System Adaptive Motion Cueing and Advanced Platform Kinematics software. The Moog Motion Drive Algorithm (MDA) uses adaptive washout filters, which approximate to third-order filters in the translational axes (surge, sway and heave) and classical third-order linear filters in the rotational axes (roll, pitch and yaw). To avoid the non-consistency of an adaptive system, where motion generated is dependent on the movement and location of the platform, a traditional wash-out MDA was developed to directly drive the Moog platform. The MDA allowed independent tuning and selection of filters for all axes of motion.

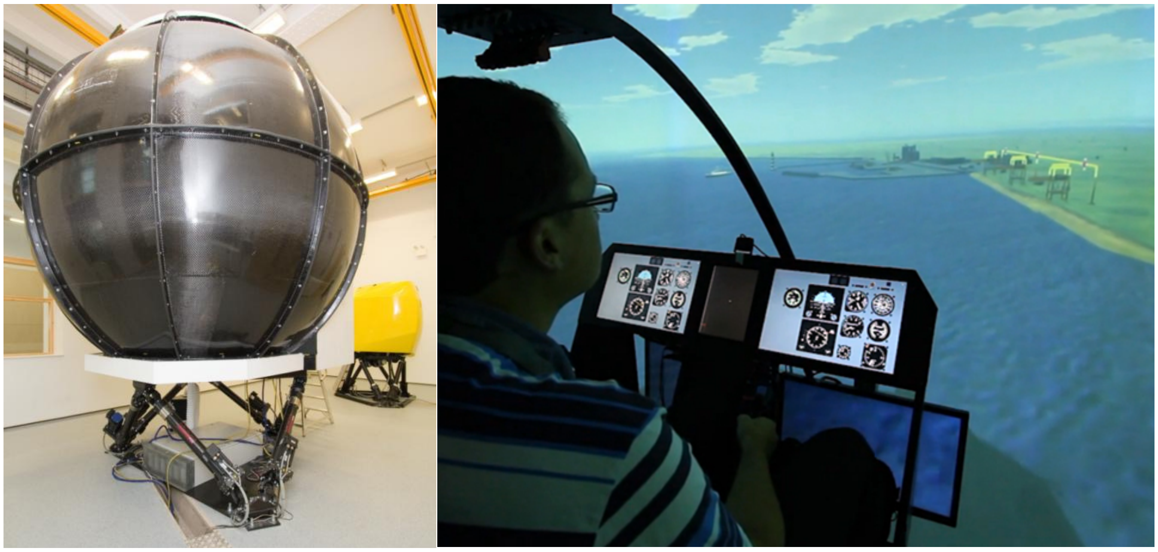


Figure 5. HELIFLIGHT-R Full Motion Flight Simulator.

A key goal of this investigation is to identify how an aircraft's response type affects the motion cue requirements to achieve good fidelity. Response type can typically be related to the potential handling qualities of the aircraft. The rotorcraft that has been modeled for this work is the National Research Council of Canada (NRC), Flight Research Laboratory's Bell 412 Advanced Systems Research Aircraft (ASRA)[14]. The aircraft can be configured to produce a range of response types, which for this investigation included a bare airframe (i.e. acceleration command), rate command with attitude hold (RCAH) and attitude command with attitude hold (ACAH). These models theoretically reflect Level 3, Level 2, and Level 1 handling qualities respectively[10]. The flight model was developed in FLIGHTLAB and validated against flight test data gathered in collaboration with the NRC Flight Research Laboratory in Ottawa[12]. FLIGHTLAB is a commercial tool developed by ART for rotorcraft modeling and analysis. Multi-body dynamics are used to simulate real-time models, where simulation components are assigned specific values and parameters defining the aircraft. Each component is a self-contained dynamic entity that is interconnected to all other components through a child and parent structure. Solution components then take care of the kinematic and force interactions throughout the model.

Three pilots were available to participate in the investigation, including two test pilots from the UK's Rotary Wing Test and Evaluation Squadron (RWTES), and one former test pilot at the Empire Test Pilot School (ETPS). The test programme was developed and completed over three trials:

Trial 1 – *Motion performance classification of the University of Liverpool HELIFLIGHT-R flight simulator.*
Trial 2 – *Pilot specific motion fidelity assessment.*
Trial 3 – *Task specific simulator fidelity assessment.*

In Trial 1, a motion performance classification of the University of Liverpool HELIFLIGHT-R simulator was undertaken (Figure 5.) This involved completing a frequency response of the motion platform to allow subsequent system identification. An offline model of the platform was then developed to allow simulation of the ICAO 9625 Objective Motion Cueing Test (OMCT) using a range of developmental motion drive algorithms.

Trial 2 involved the two RWTES pilots undertaking subjective motion tuning. Individual motion axes were tuned by varying the gain and break frequencies of a traditional wash-out algorithm, and the effect of the changes was assessed by the pilots. The combined axes were rated for its motion fidelity while performing the set of ADS-33E tasks. Pilots were asked to award Motion Fidelity Ratings for the different mission task elements.

The best performing motion drive algorithm was then used for Trial 3, task specific simulator fidelity assessment. The simulator fidelity was individually assessed for each ADS-33 MTE with each Bell 412 ASRA response type. Using the comprehensive view of simulator fidelity as guidance (Figure 1), rather than comparing fidelity between simulator and aircraft, the pilots were assessing fidelity between two simulation tasks. Firstly, the pilots would undertake a selected MTE in the simulator with the 6-axis motion cueing turned "on", and award an HQR. Following this, the MTE was repeated in the simulator with the motion cueing turned "off". The pilots then awarded an HQR and provided an SFR with comparison to the baseline "motion" case. Each MTE was repeated three times prior to assessment, to allow for any training effects. Additionally, UCE was assessed in the simulator for each MTE with the ACAH response type model prior to the fidelity assessment.

IV. Task Specific Motion Cues - Results & Discussion

Preliminary results and analysis are presented here from Trial 3. Figure 6 to Figure 9 display the subjective results obtained for the set of ADS-33 flight test maneuvers. HQRs and SFRs were awarded for the different response types of the Bell 412 ASRA. During the trial, a performance limitation of the ACAH response Bell 412 ASRA model was identified. The available cyclic control range limited the attitude rate response of the aircraft and subsequently decreased the handling performance during certain ADS-33 maneuvers. This is evident in the results for the lateral and pirouette maneuvers, and is the reason behind the unsuccessful completion of the acceleration/deceleration maneuver.

The hover MTE subjective ratings are shown in Figure 6. In the baseline motion "on" case, the perception of handling quality decreased in line with the degradation of the control response. The pilots identified a similar reduction in handling qualities without motion cues, though with a greater deficiency in handling qualities for the bare airframe response. When the pilots were asked to rate their perception of fidelity with the absence of motion cues, the decline in perceived fidelity follows that of the HQR awarded.

Similar correlation between the HQR and the SFR was observed for the subjective results in the lateral maneuver (Figure 7), the bob-up maneuver (Figure 8), and the pirouette (Figure 9). It can be surmised that good handling qualities of an aircraft may reduce the importance of motion cues by the pilot to aid in control and stabilization of the aircraft response. Although Level 1 handling qualities may reduce the requirement for motion cues, it is evident from the pirouette maneuver that Level 1 SFR is not guaranteed

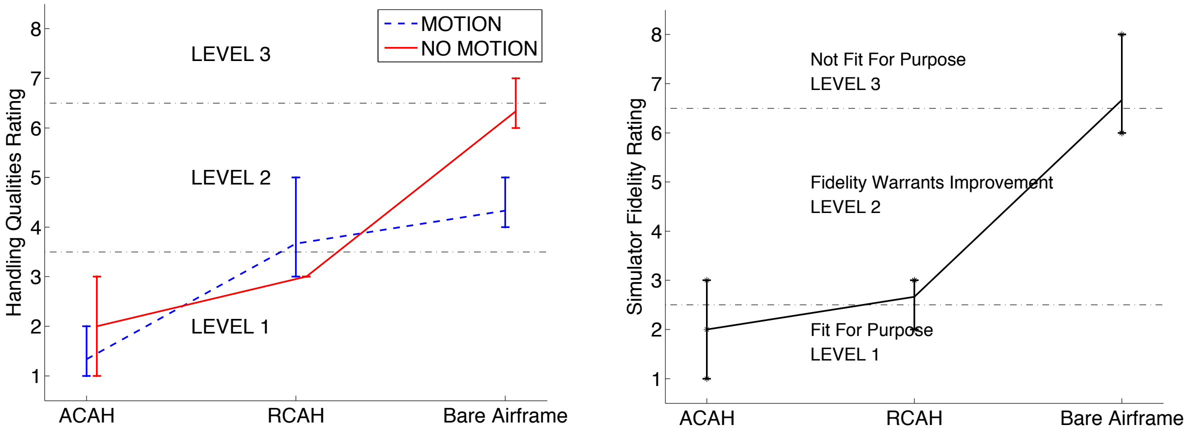


Figure 6. Hover Mission Task Element. *Handling Qualities and Simulator Fidelity Ratings awarded for the Hover Mission Task Element.*

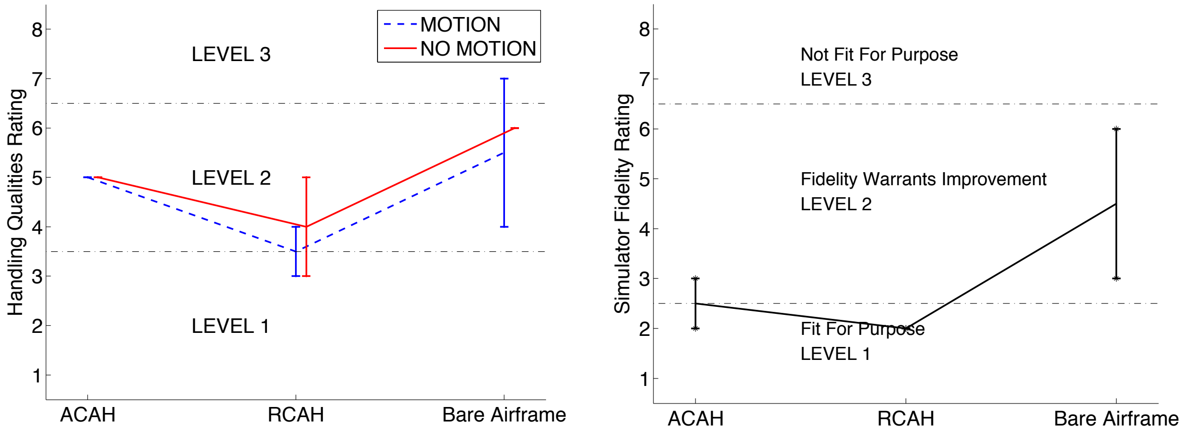


Figure 7. Lateral Maneuver Mission Task Element. *Handling Qualities and Simulator Fidelity Ratings awarded for the Lateral Maneuver Mission Task Element.*

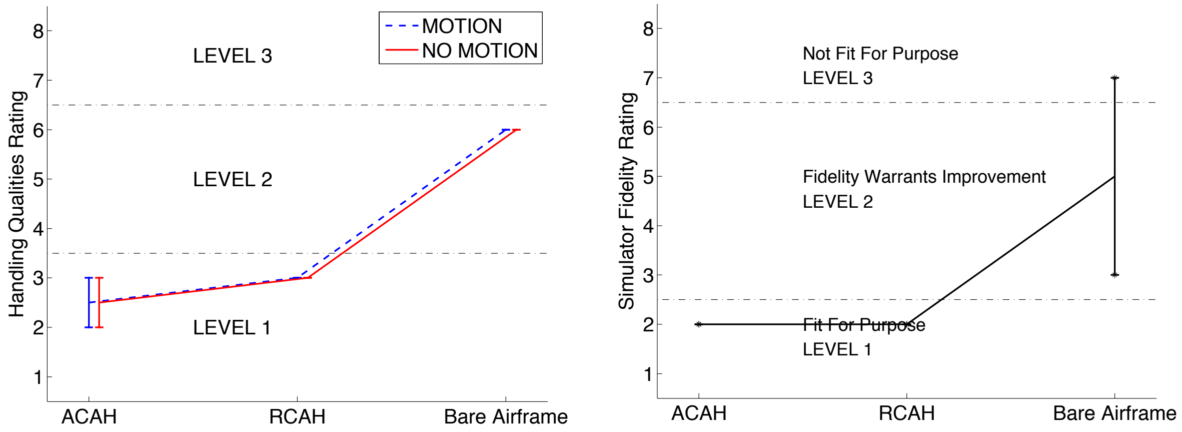


Figure 8. Bob-Up Maneuver Mission Task Element. *Handling Qualities and Simulator Fidelity Ratings awarded for the Bob-Up Maneuver Mission Task Element.*

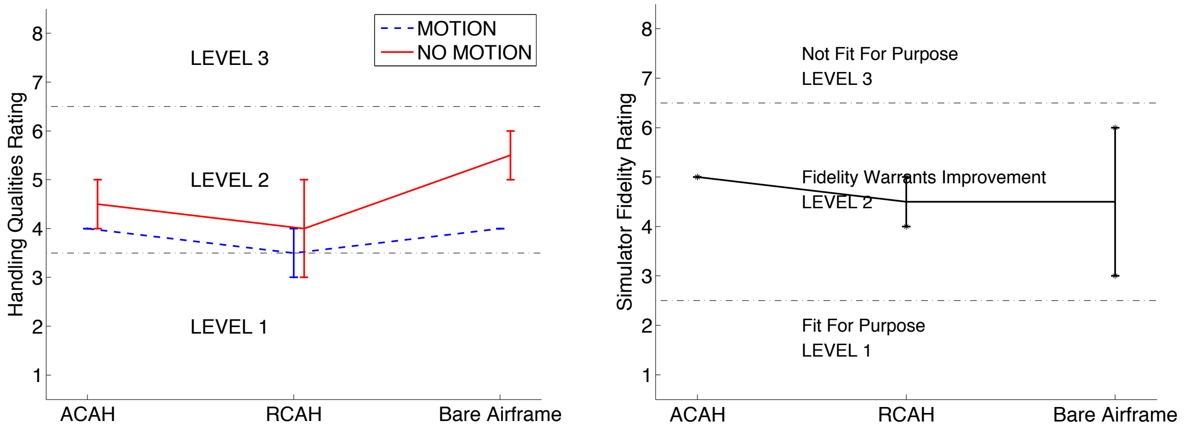


Figure 9. Pirouette Mission Task Element. *Handling Qualities and Simulator Fidelity Ratings awarded for the Pirouette Mission Task Element.*

To complement the subjective assessments presented, objective metrics were used to quantify the effect of motion on task performance and pilot task strategy adaptation. Analysis of the hover MTE for Pilot 3 is used as an example here. Figure 10 shows the hover test course as replicated in the simulation environment. The task of the pilot was to approach a ground referenced point at a ground speed of between 6 and 10 knots. The pilot was required to arrive over the reference point and hold a stable hover for a minimum of 30 seconds. The position and orientation of the cones, and the provision of a "ball on stick", allow visual reference points to achieve desired hover performance. The ADS-33 performance standard defines the requirement of a calm to moderate wind, but this was not modeled in an effort to reduce variability in the tasks and allow easier comparison with previous trials undertaken at the Defence Science & Technology Organisation[15].

An assessment of behavioral fidelity and error fidelity for the hover MTE can be undertaken with a pilot control amplitude frequency spectrum comparison and aircraft position comparison respectively. The results displayed in Figure 11 and Figure 12 are for the ACAH response type during the final 30 second hover position hold. The pilot provided an SFR rating of 2 (fit for purpose) for the motion "off" case. The results shown are an overlap of the two best performing maneuvers for each repeated set of MTE runs. Also highlighted in Figure 12 are the position limits defined by ADS-33 for desired (green) and adequate (yellow) aircraft drift from the ground reference hover point. It is evident for the ACAH case that pilot control frequency and aircraft positional performance are relatively similar between the motion "on" and motion "off" cueing tasks. The RCAH response comparisons are shown in Figure 13 and Figure 14. Here the location of the peaks in the control frequencies are similar, but there is more variation in the amplitude on control. The positional performance is similar, both showing a greater amount of drift than the ACAH tasks. This perceptual fidelity comparison was rated an SFR of 3 (fidelity warrants improvement). Finally, Figure 15 and Figure 16 are an objective view of the bare airframe response comparison. The pilot's decision to deliver an SFR of 8 (not fit for purpose) is corroborated by the significant amplitude difference in the control responses and the positional drift.

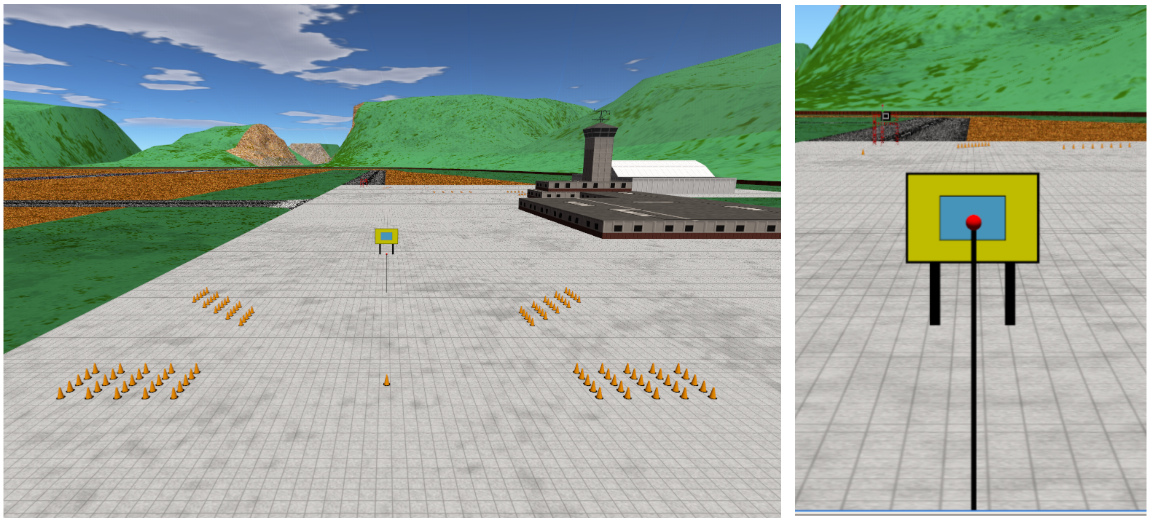


Figure 10. ADS-33E Precision Hover Mission Task Element Course.

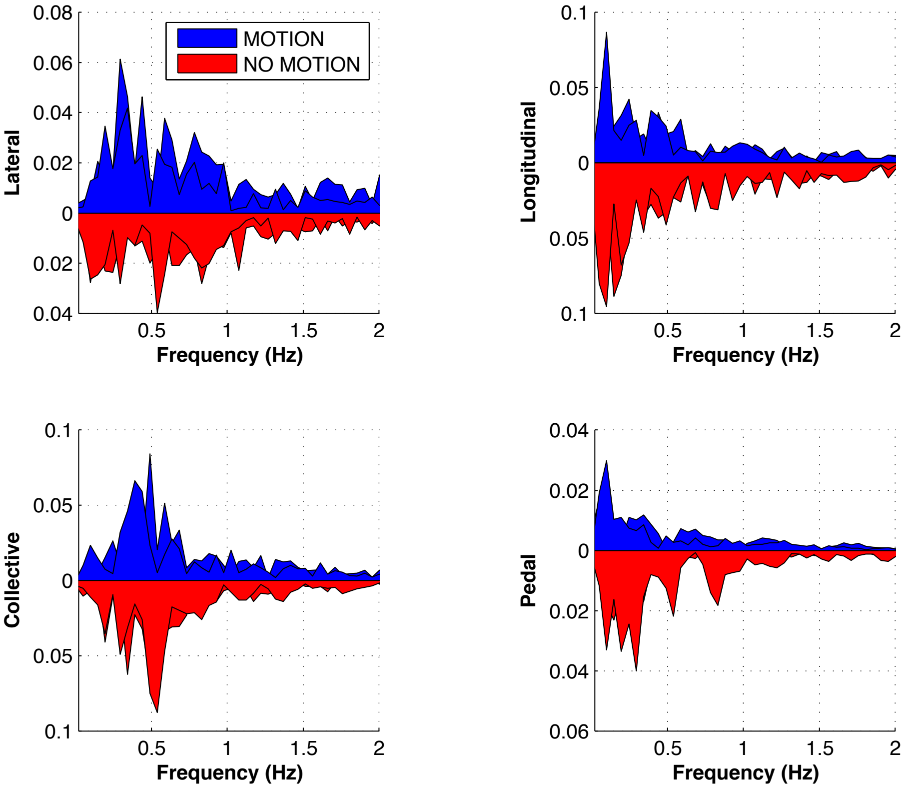


Figure 11. Pilot 3, ACAH response Bell 412 ASRA, Single Sided Control Amplitude Spectrum comparison for Hover MTE.

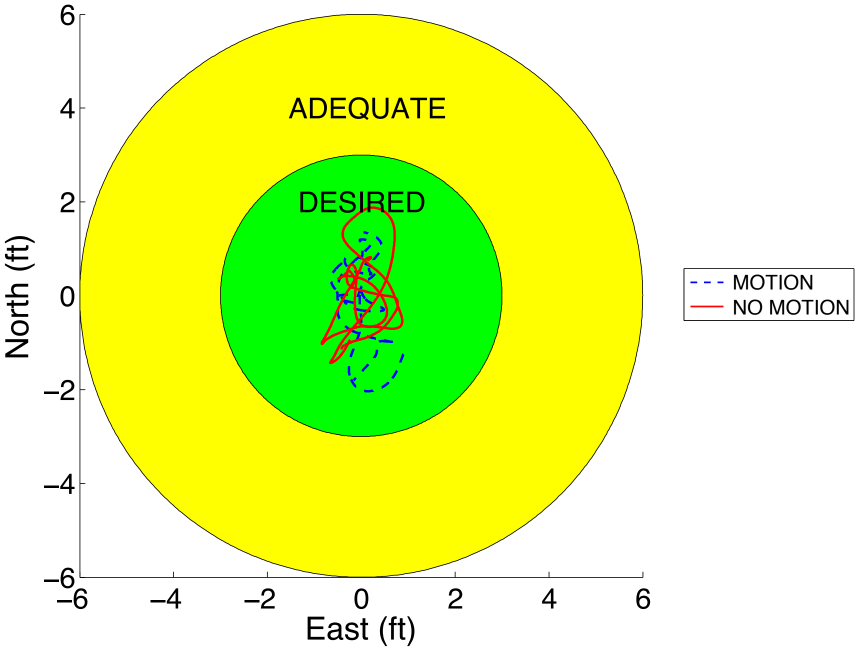


Figure 12. Pilot 3, ACAH response Bell 412 ASRA, Hover MTE positional performance.

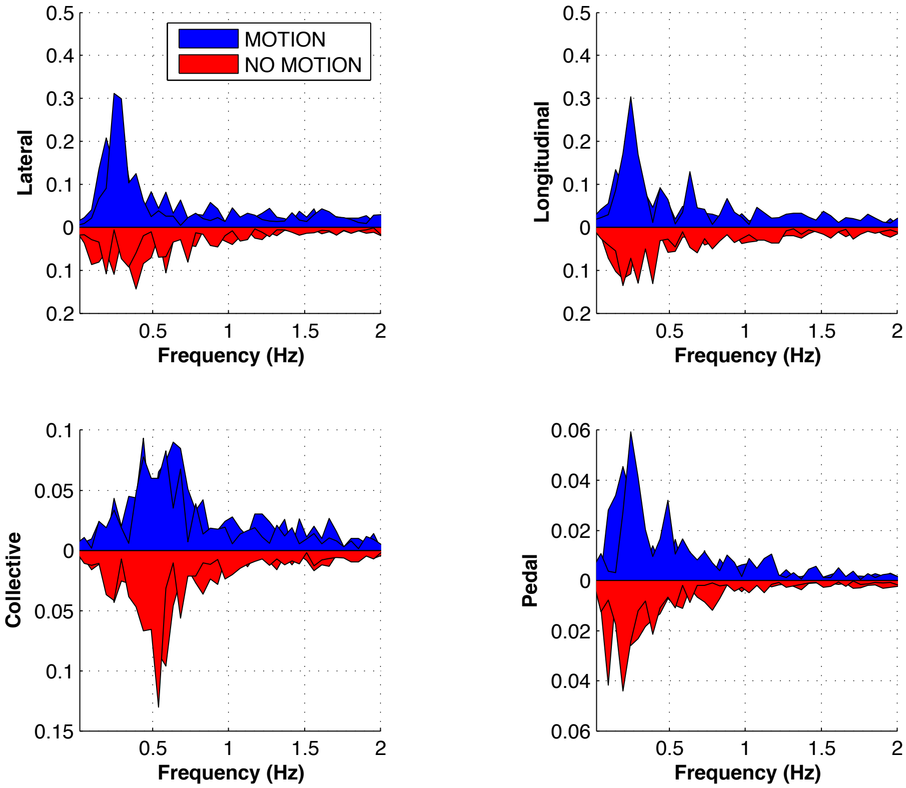


Figure 13. Pilot 3, RCAH response Bell 412 ASRA, Single Sided Control Amplitude Spectrum comparison for Hover MTE.

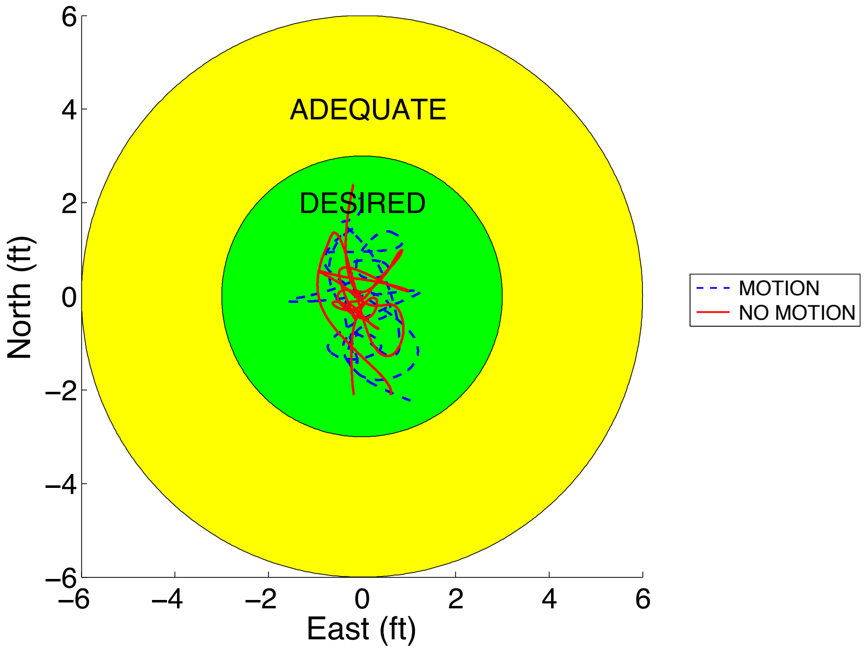


Figure 14. Pilot 3, RCAH response Bell 412 ASRA, Hover MTE positional performance.

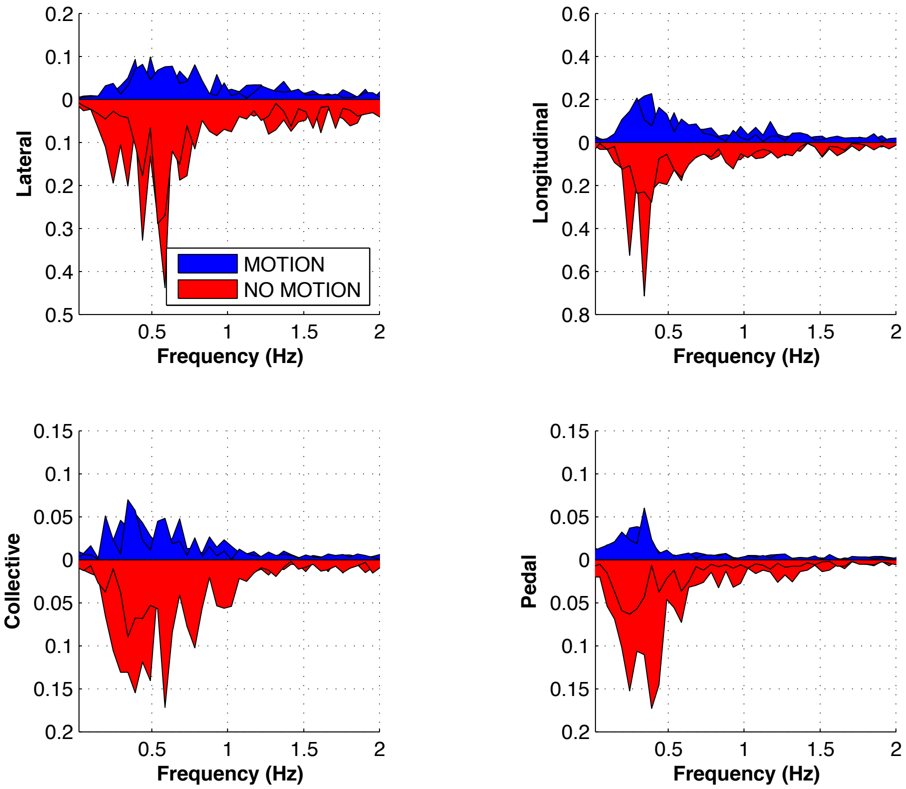


Figure 15. **Pilot 3, bare airframe response Bell 412 ASRA, Single Sided Control Amplitude Spectrum comparison for Hover MTE.**

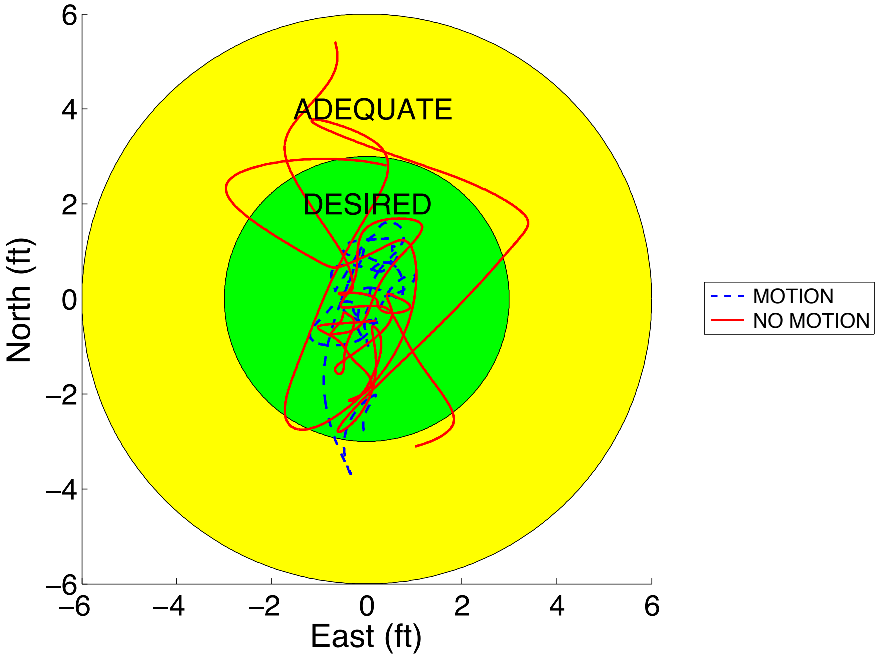


Figure 16. **Pilot 3, bare airframe response Bell 412 ASRA, Hover MTE positional performance.**

V. Conclusion

Full motion training simulators are an expensive outlay for many organizations, but current simulator accreditation practices do not guarantee the required fidelity, and therefore training quality, due to limitations in the subjective assessment process. A comprehensive simulator fidelity process was proposed with the use of the Simulator Fidelity and Motion Fidelity rating scales, developed at the University of Liverpool, as an improved method of subjective assessment. A preliminary analysis of the effect of motion cueing on the perceived fidelity, and hence training effectiveness, of a rotorcraft flight simulator was conducted using a set of test maneuvers from the ADS-33E performance standard. Three test pilots flew three different rotorcraft models, with different levels of handling qualities, assessing simulator fidelity in the absence of motion cues. Results show that simulator fidelity requirements are not only task based, but are also dependent on the handling qualities of the aircraft being flown. Consequently, dependent on the qualities of the aircraft being simulated, a fixed simulator platform without motion cues may be appropriate for specific training tasks.

VI. Acknowledgments

The authors would like to thank the Technical Co-operation Programme, in particular Bryan Finlay (Dstl, UK) and Jeremy Blackwell (DSTO Australia) for enabling the exchange of research staff for this project. The contribution of the test pilots from the UK's Rotary Wing Test and Evaluation Squadron and former pilot from the Empire Test Pilot School is acknowledged; without their professionalism and curiosity the tests would not have been such a success. The work is contributing to GARTEUR HC/AG-21, Rotorcraft Simulation Fidelity Assessment: Predicted and Perceived Measures of Fidelity.

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