Optimising the yaw motion cues available from a short stroke hexapod motion platform

S. J. Hodge
steve.hodge@baesystems.com
Simulation Department,
BAE Systems
Preston
UK

P. Perfect, G. D. Padfield and M. D. White
Department of Engineering
University of Liverpool
Liverpool
UK

ABSTRACT

This paper presents findings from research conducted at the University of Liverpool aimed at optimising the motion cues available from a short-stroke hexapod motion platform. Piloted simulation experiments were conducted to gather both objective and subjective measures of pilot performance and motion fidelity for a typical helicopter low-speed yaw axis capture task. These measures included subjective ratings taken for the first time using a new motion fidelity rating scale. During the experiment four baseline configurations were presented to the pilot; – No motion, Rotational-only motion, Translational-only motion and Rotational + Translational motion, and within these baseline configurations various values of motion filter gains were examined. The key findings from the experiment show that the most acceptable motion fidelity was obtained when congruent cues were presented in both the rotational and translational axes. A possible explanation for this result is postulated to lie within the relative motion perception thresholds of the human semicircular canals. These results contrast with previous research which suggested that yaw axis motion cues were of less importance than translational motion cues.

Paper No. 4013. Manuscript received 4 June 2013, revised version received 28 April 2014, accepted 17 July 2014.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

NOMENCLATURE

f_x surge specific force at the pilot seat in aircraft body frame, ft/sec^2
f_y sway specific force at the pilot seat in aircraft body frame, ft/sec^2
H_{oto} otolith dynamics
$HP_$ high-pass filter
H_{scc} semicircular canal dynamics
H_{vis} visual system time delay
$K_$ motion filter gain, non-dimensional
N_r normalised vehicle yaw damping derivative, 1/sec
N_δ vehicle yaw sensitivity derivative, rad/sec^2/inch
r vehicle yaw rate, rad /sec
s Laplace operator
T simulator reference frame to inertial frame transform
x_p longitudinal pilot offset from centre of gravity, ft
x_s simulator longitudinal displacement in inertial frame, ft
y_s simulator lateral displacement in inertial frame, ft
δ_{ped} pedal position, inches
$\tau_{1,2}$ semicircular canal lag time constants, sec
τ_3 otolith lag time constant, sec
τ_a visual attractor time constant, sec
τ_L semicircular canal neural lead term, sec
τ_n otolith neural lead term, sec
ψ vehicle yaw angle, rad
ψ_s simulator yaw angle, rad
$\omega_{b_}$ first-order high-pass break frequency, rad/sec
$\omega_{hp_}$ second-order high-pass break frequency, rad/sec
$\zeta_{hp_}$ second-order damping ratio, non-dimensional

1.0 INTRODUCTION

In a recent revision of the international standards for the design and qualification of flight training simulators, recognition has been made of the potential role of short stroke motion platforms in Flight Simulator Training Devices (FSTDs)[1]. Short stroke platforms typically have a stroke (maximum actuator leg travel) of around 24 to 36 inches. Under existing regulations 'high' fidelity pilot training simulators, designated Full Flight Simulators (FFS), must typically have an actuator stroke of 60 inches or more[2]. The use of smaller motion systems is not a new idea; short stroke platforms have been successfully used in research and development simulators, in both industry and academia for several years[3-4]. However, the subject of fidelity criteria and standards for small motion simulators has, thus far, received little attention in the open literature, where the focus has been on very large and often unique motion research simulators (e.g. Ref. 5). To enable the aforementioned potential to be fulfilled, research is urgently needed to understand the implications of using short stroke motion systems for pilot training, and to determine how the cues from such devices might be optimised. The Flight Science and Technology (FS&T) research group at the University of Liverpool operates such a flight simulator facility, the HELFLIGHT-R[6], for the purposes of flight handling qualities and control, human factors and simulation fidelity research. This facility incorporates a short stroke (24 inch) hexapod motion platform shown in Fig. 1.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press



Figure 1. The HELIFLIGHT-R simulator.

2.0 BACKGROUND

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 force 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

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

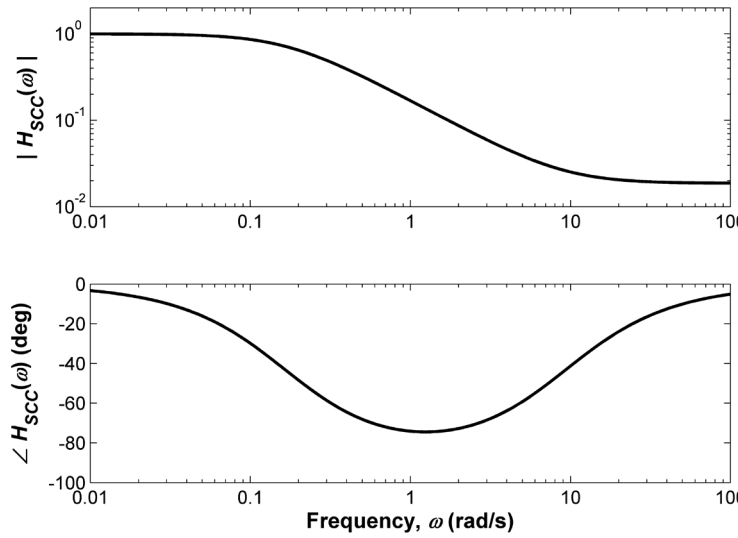


Figure 2. Semicircular canal frequency response.

motion, as made evident by the approximately 90º phase lag in their frequency response[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 realised, 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 stabilise 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. A number of studies have sought to identify relationships between these factors, in an attempt to develop systematic methodologies for optimising the motion cues available from flight simulators[7]. Of all the motion axes examined in these studies, the yaw axis has received relatively little attention but from the limited work conclusions regarding the importance of yaw motion vary considerably[8-14]. An early study by Meiry[8] concluded that the introduction of yaw motion had a beneficial impact on pilot performance, reducing pilot reaction time by 0·1 seconds in a yaw axis disturbance rejection task. In contrast, a study by Schroeder[9], conducted on the NASA Ames Vertical Motion Simulator (VMS), found no benefit, of the provision of yaw motion cues, during a yaw capture task. Schroeder's study involved three pilots who each evaluated four different motion filter configurations including full motion (1:1) and no motion (fixed-base) configurations. Schroeder found that the addition of yaw motion cues had no impact on pilots' performance or opinion of simulation fidelity; and some pilots could not even discern when yaw axis motion was present. However, both of these studies were performed with the pilot located at the centre of gravity of the aircraft. Therefore, the translational motion cues which normally accompany yaw motion were absent.

A follow-on study by Schroeder[10-11] aimed to determine which motion cues were important to reproduce in a flight simulator. In this study Schroeder investigated the relative importance

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

of yaw rotational motion cues and the corresponding translational motion cues, resulting from yawing around a point 4·5ft behind the pilot, for three tasks – (*i*) a 15º yaw capture task; (*ii*) a 180º hover turn; and (*iii*) a yaw regulation task. The results supported the conclusions of Schroeder's earlier study[9] and indicated that for all three tasks the addition of translational motion improved pilot performance, reduced workload and improved pilots' subjective impression of simulator fidelity. However, no significant benefit was found by the addition of rotational motion cues, leading Schroeder to conclude that the yaw motion degree-of-freedom may not be necessary for simulating hovering manoeuvres.

A study by Groen *et al*[12] investigated pilot motion perception during a simulated 'decrab' manoeuvre in a fixed-wing twin-engine passenger aircraft. This manoeuvre is used during crosswind landings to align the aircraft's heading with the runway prior to touchdown. Simulator roll, sway and yaw motion was varied independently to examine their relative contributions to pilots' perceptions. In Groen's experiment the pilot subjects passively monitored the decrab manoeuvre, as if they were carrying out an automatic landing. Groen concluded that the perception of heading alignment primarily depended on simulator sway and roll motion as well as visual cues, rather than simulator yaw motion. Furthermore, simulator yaw motion was masked by simulator sway motion, which was consistently perceived as being too strong, even when attenuated by motion filter gains of less than unity. The results of Groen's study, conducted in a different simulator, using different pilots and with a different flight manoeuvre, supported the conclusion of Schroeder[10-11] by suggesting that aircraft yaw motion is not always a relevant cue to reproduce in a flight simulator.

Two further simulator studies[13-14] and a pilot modelling study[15], have attempted to confirm Schroeder's findings[10-11], relating to the relative importance of translational and yaw motion cueing in helicopter flight simulation. The first study[13] was conducted using the University of Toronto Institute of Aerospace Studies (UTIAS) flight research simulator, and the second study[14] was carried out on the SIMONA simulator at the Delft University of Technology; both facilities have very capable hexapod motion platforms. These studies repeated the 15º yaw capture task and confirmed Schroeder's findings in terms of the importance of translational motion on pilot performance. However, the studies also found that yaw motion had a more significant effect on pilot performance, workload and subjective opinion than was previously indicated by Schroeder.

Under existing regulations the qualification of a flight simulators motion cueing system is largely achieved using objective, or 'robotic' 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 Ref. 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[16]. 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'. This statement acknowledges the need for high motion gains in the rotational axes, but translational motion gains are not explicitly mentioned. In contrast, the research reviewed[9-14] suggests that translational motion is at least as important as rotational motion if not more so. The purpose of the study reported in this paper was to investigate the relative importance of yaw rotation and translational motion; and to determine how the cues from a relatively 'small' motion platform might be optimised for low-speed yaw axis manoeuvres.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

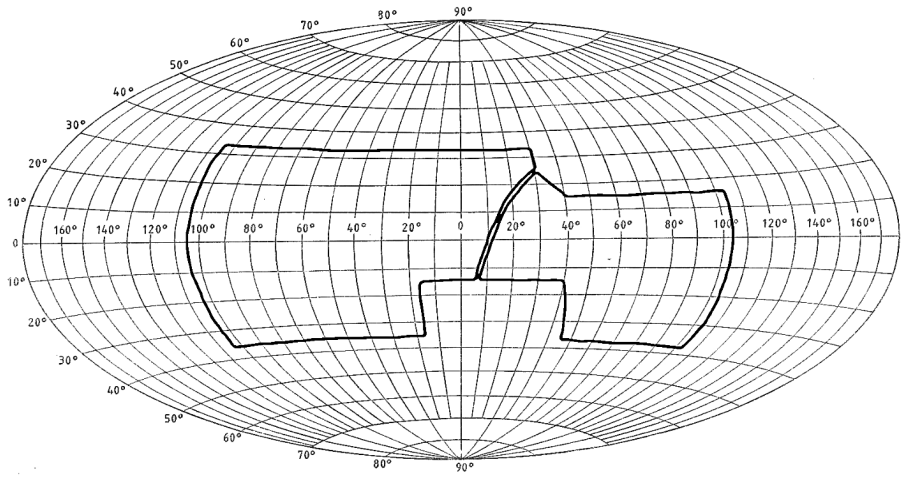


Figure 3. HELIFLIGHT-R outside world image field-of-view (left-hand seat).

3.0 EXPERIMENTAL SETUP

3.1 Simulator facility

The simulator facility used in the study is HELIFLIGHT-R operated by the University of Liverpool (Ref. 6). HELIFLIGHT-R is a fully re-configurable research simulator, consisting of a generic rotorcraft cockpit housed inside a 12ft diameter visual display dome, mounted on a short-stroke electric motion platform (Fig. 1). The simulator cabin houses a twin-seat cockpit, with a third seat at the rear for an instructor or simulator operator. The primary cockpit instruments are presented on two wide-screen flat-panel displays. Three Liquid Crystal on Silicon (LCoS) projectors are used to project an outside-world image onto the inside surface of the dome. The three images are geometry corrected and edge-blended, before being projected, so as to present a single continuous scene to the pilot. The projectors are equipped with wide-angle lenses and provide a horizontal field-of-view of approximately 210º (±105º) and a vertical field-of-view of approximately 70º (+30º/–40º). The resolution of the image generation system was limited to 1,024 by 768 pixels, whilst the projectors themselves were capable of running at a higher 1,400 by 1,050 pixels, with a refresh rate of 60Hz. Figure 3 provides a more detailed description of the simulator field-of-view from the left-hand seat.

The total latency from pilot input to visual system response has been measured at approximately 125 milliseconds. Around 60 milliseconds of this being due to the geometry correction and projection system hardware and just over 16 milliseconds are due to the image rendering process. The aircraft model simulation was updated at a rate of 100Hz. The HELIFLIGHT-R motion platform is of the standard hexapod arrangement, comprising six electric actuators each with a 24 inch stroke. The performance capabilities of the device in each individual degree-of-freedom are given in Table 1.

The motion platform transfer function was measured before the experiment using system identification techniques, by injecting a computer-generated frequency-sweep forcing function into each motion axis independently. Platform response data was collected from the frequency-sweep tests and input into the Comprehensive Identification from Frequency Response (CIFER) tool, which was used to identify a linear model of the motion platform. The results of the CIFER analysis

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

Table 1
HELIFLIGHT-R Motion Envelope

Axis	Displacement	Velocity	Acceleration
Surge	–1·5/+1·87ft	±2·3ft/s	±0·71g
Sway	±1·5ft	±2·3ft/s	±0·71g
Heave	±1·3ft	±1·6ft/s	±1·02g
Roll	±23·3°	±34°/s	>225°/s^2
Pitch	–23/+25·6°	±35°/s	>225°/s^2
Yaw	±24·3°	±36°/s	>225°/s^2

shows the response of the motion platform is well represented by a pure time delay of around 60 milliseconds. A four-axis electronic control-loading system provides the capability to configure the force-feel characteristics of both the pilot and co-pilot's cyclic, collective and pedal controls to represent a wide range of aircraft types. In this experiment the yaw pedals were configured to have a travel of ±2·25in, with a breakout force of 17·7N and a spring force gradient of 63·3N/inch. Audio cues are presented to the pilot using a system of loudspeakers distributed throughout the cockpit. Generic rotor noise was played during the experiment primarily to mask the noise of the motion platform actuators.

3.2 Yaw capture task

The same yaw capture task used in previous motion cueing experiments (Refs 9-11, 13-14) was adopted for this study. The course layout for the task is shown in Fig. 4. From an initial heading offset of 15° to either the left or right, denoted by the two outer poles, the pilot must rotate the

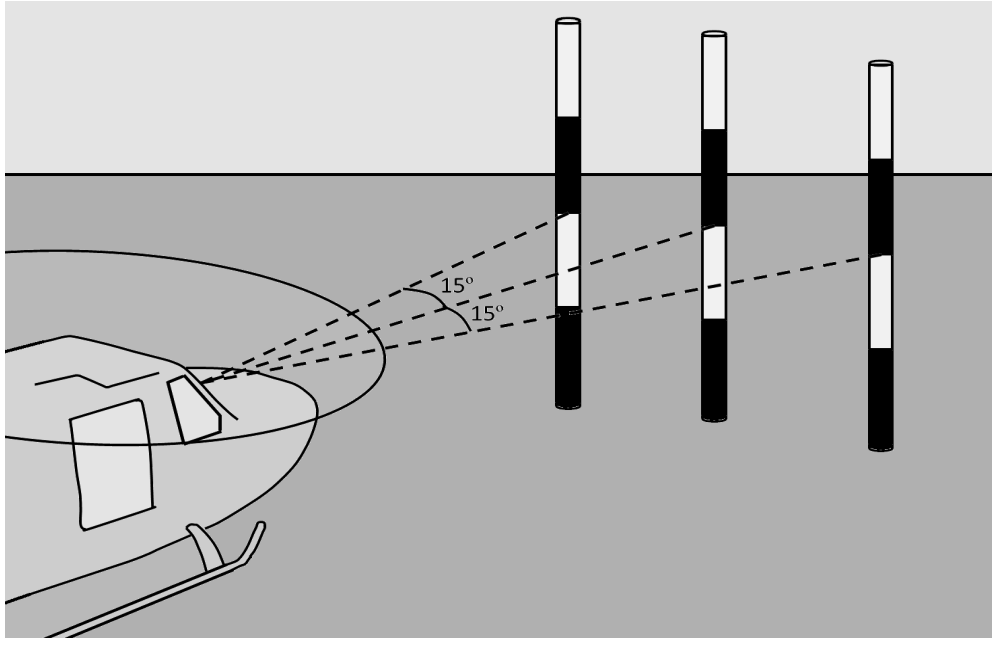


Figure 4. Yaw axis capture task.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

aircraft to point at the centre pole as rapidly as possible. Desired performance was achieved if the pilot captured the centre pole and maintained heading within ±1°, denoted by the edges of the pole, with two or fewer overshoots. Adequate performance was achieved if the pilot captured the centre pole and maintained heading between ±2°, with four or fewer overshoots. A head-up display presenting a cross-hair, drawn along the centreline of the aircraft, at pilot-eye height, was used to give the pilot a point of reference; the width of the cross-hair was ±1°. The task was conducted in a detailed airfield environment, in good visibility, and with no atmospheric turbulence.

3.3 Vehicle dynamics

The pilot controlled the vehicle in the yaw axis only, by making pedal inputs. The vehicle's directional axis dynamics, shown in Equation (1), were selected to be a low-order representation of a UH-60 helicopter in hovering flight. According to Ref. 17 the UH-60 has a normalised yaw damping derivative, N_r, of –0·33sec^{-1} in the hover. A yaw pedal sensitivity, N_δ, of ±0·25rad/s^2 for full pedal deflection was selected, by matching the response of a nonlinear, six degree-of-freedom, model of a UH-60 to a yaw pedal step input. In a real helicopter the tail rotor will also cause a side-force in addition to a yawing moment, but in this experiment only the yawing moment was modelled.

$$\frac{\ddot{\psi}}{\delta_{ped}}(s) = \frac{N_\delta s}{s - N_r} \quad \ldots (1)$$

For all aircraft the pilot's seat is situated some distance ahead of the centre of gravity. This means that, for a pure yaw motion, the pilot will also be subjected to linear accelerations. Figure 5 shows the surge and sway specific forces sensed at the pilot's seat, during a pure yaw manoeuvre, when located a distance, x_p, ahead of the aircraft's centre of gravity, see Equations (2-3); to model the dimensions of the UH-60, x_p, was set to a value of 10ft.

$$f_x = - x_p \dot{\psi}^2 \quad \ldots (2)$$

$$f_y = x_p \ddot{\psi} \quad \ldots (3)$$

3.4 Motion drive algorithm

The motion drive algorithm scheme employed in the current study is shown in Fig. 6 and is based on the classical washout algorithm described in Ref. 18. The motion filter used in the yaw channel was a second-order high-pass filter with break frequency, $\omega_{hp\psi}$, set equal to 0·5rad/sec. The motion filters used in the surge and sway channels were both third-order filters with break frequencies, ω_{hpx} and ω_{hpy}, of 1·0rad/sec. The third-order poles, ω_{bx} and ω_{by}, were taken to be one-tenth of the second-order break frequencies (i.e. 0·1rad/sec) following the guidelines in Ref. 19. The damping ratios of all the motion filters were set to 0·9 and the motion filter gains, K_ψ, K_x and K_y, were varied as part of the experiment (see the Motion configurations section).

The matrix transformation, T, in Fig. 6 is used to transform the motion simulator commands from the simulator reference frame through the simulator yaw angle, ψ_s, into the inertial reference frame. Because the rotational centre of the HELIFLIGHT-R motion platform is located directly beneath the pilot's seat then, when motion is applied in the yaw axis only, the pilot will sense a pure rotation with no spurious longitudinal or lateral motion.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

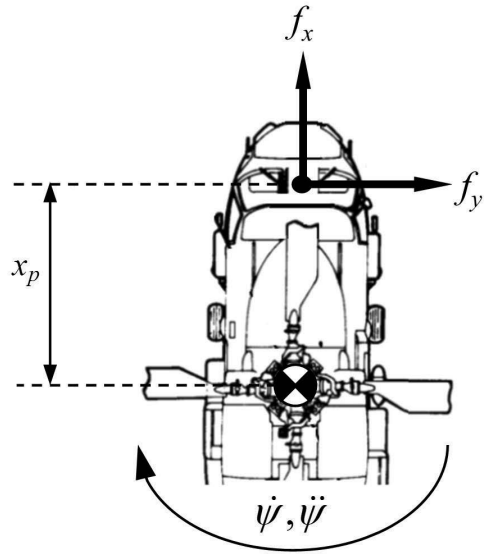


Figure 5. Specific forces due to pure yaw motion.

3.5 Motion configurations

The motion filter configurations examined in this experiment are shown in Table 2. Four baseline configurations were examined – (D1) No Motion, (D2) Rotational-only motion, (D3) Translational-only motion, and (D4) Rotational + Translational motion. Figure 7 shows a schematic of the cockpit motion for each of these four configurations. As well as the baseline configurations (D1 – D4) the motion filter gains, K_ψ, K_x and K_y, were varied to provide different weightings between the rotational and translational motion cues. The rotational gain, K_ψ, was adjusted independently of the translational channel gains, K_x and K_y.

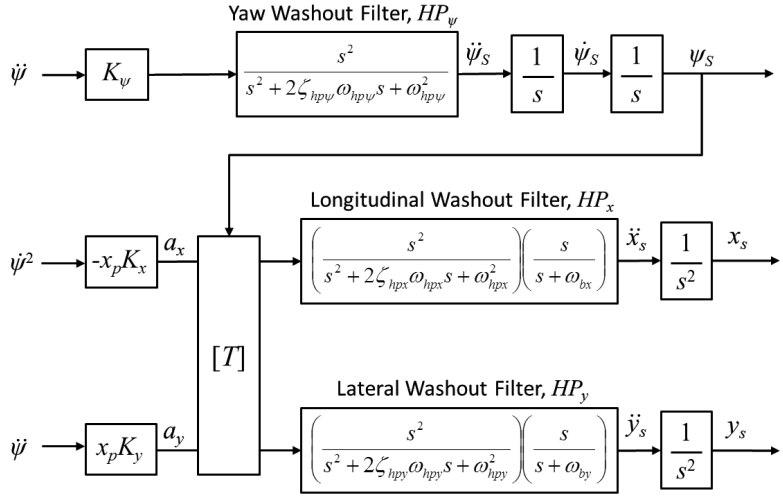


Figure 6. Motion drive algorithm block diagram.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

Table 2
Motion filter configurations

Config	Motion Cues	K_ψ	K_x	K_y
D1	No Motion	0·0	0·0	0·0
D2	Rotational-only	0·5	0·0	0·0
D3	Translational-only	0·0	0·5	0·5
D4	Rotational + Translational	0·5	0·5	0·5
D5	Rotational-only	0·25	0·0	0·0
D6	Rotational + Translational	0·25	0·5	0·5
D7	Rotational + Translational	0·5	0·25	0·25
D8	Rotational + Translational	0·5	0·3	0·3
D9	Rotational + Translational	0·5	0·4	0·4
D10	Rotational + Translational	0·6	0·3	0·3
D11	Rotational + Translational	0·6	0·4	0·4
D12	Rotational + Translational	0·7	0·4	0·4

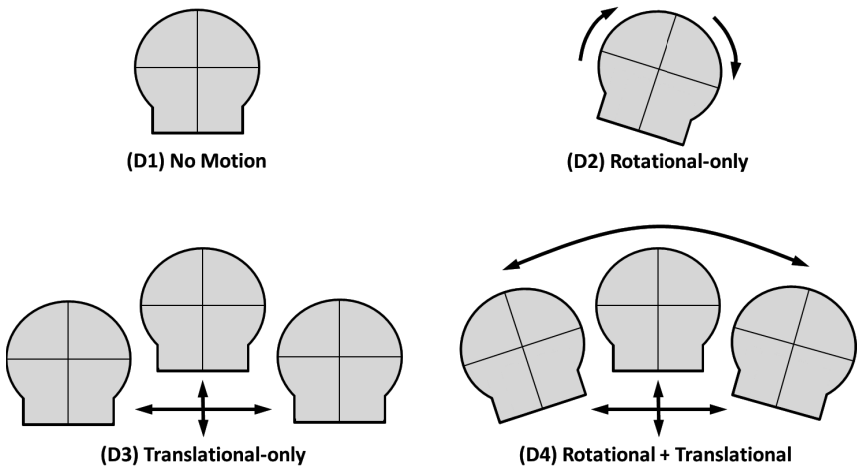


Figure 7. Definition of baseline motion configurations D1 to D4.

3.6 Experimental procedures and measures

The pilot who took part in this experiment is a former military rotary-wing test pilot and a current fixed-wing airline pilot, with a wealth of experience on a variety of different aircraft types and research and training simulators. It is recognised by the authors that further work is needed to confirm that the results of this research are applicable to a wide cross-section of the pilot population. However, it is argued that the involvement of an experienced test pilot should help to prevent some of the inconsistencies between performance and subjective ratings found during previous experiments with non-pilot subjects.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

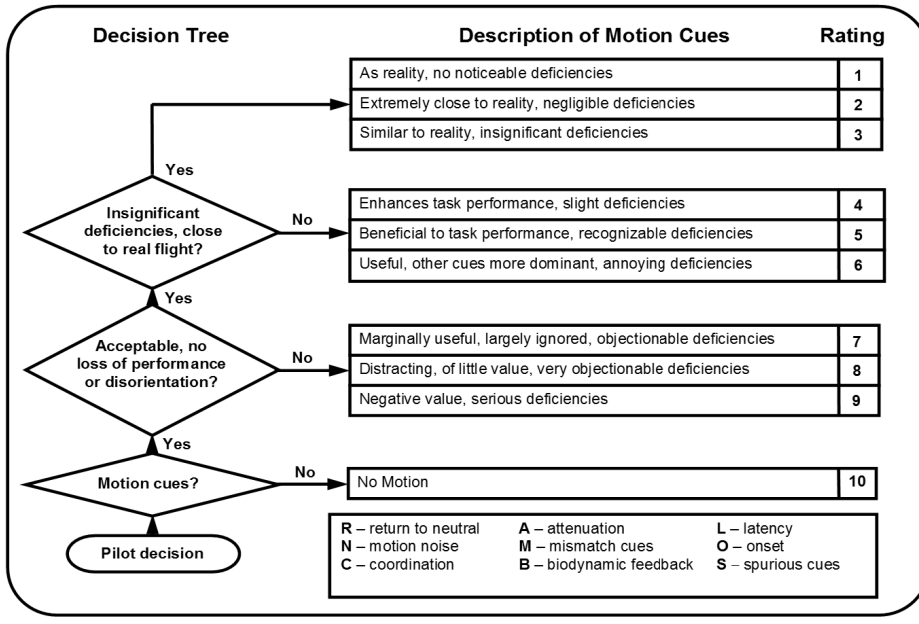


Figure 8. Motion fidelity rating scale.

The subject pilot was briefed that he would experience a range of different motion cues, but was given no specific details regarding the nature of the cues or the motion filter settings. The pilot was presented with each configuration (Table 2) in a random order and was afforded as many opportunities as necessary to repeat the task; subjective ratings were only awarded after repeating the task at least five times, from the Cooper-Harper handling qualities rating (HQR) scale[20] and from a purposely developed motion fidelity rating scale. The existing 3-point motion fidelity rating scale, developed by Sinacori[21] and later refined by Schroeder[9], was considered too coarse to measure what can often be subtle differences in the motion cues experienced by the pilot. Therefore, a new 10-point motion fidelity scale was devised[8]. This new scale is based on the same structure as the established Cooper-Harper HQR scale i.e. a decision tree, with descriptors leading to numerical ratings. To use the motion fidelity scale, pilots must systematically work through the decision tree, starting at the bottom left-hand corner. Because the scale was specifically designed to quantify the value of body-force motion cues, the first decision in the tree is – 'are there any perceivable motion cues?'. If the answer to this question is 'no', then a rating of 10 must be given. It should be understood that a rating of 10 does not mean that this is the poorest possible configuration – no motion cues might, in fact, be better than poor motion cues; it simply means that no cues were perceived, at a conscious level, on which to base a rating. The remaining questions on the tree help guide the pilot to three coarse levels, which, from top to bottom, are – (*i*) motion cues are acceptable, sensations are close to real flight or have insignificant deficiencies; (*ii*) motion cues are acceptable with some noticeable but not objectionable deficiencies; and (*iii*) motion cues are not acceptable, there are obvious and objectionable deficiencies leading to loss of task performance and, in extremes, disorientation; these coarse levels are broadly equivalent to the levels on the existing 3-point scale. However, at these three coarse levels, three more descriptions are provided, each one associated with a numerical rating covering the full-range between 1 and 9. Pilots must select the rating which they feel best describes their perception of the simulator (vestibular) motion cues. A number of letter suffixes are also included in the scale. The intention

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

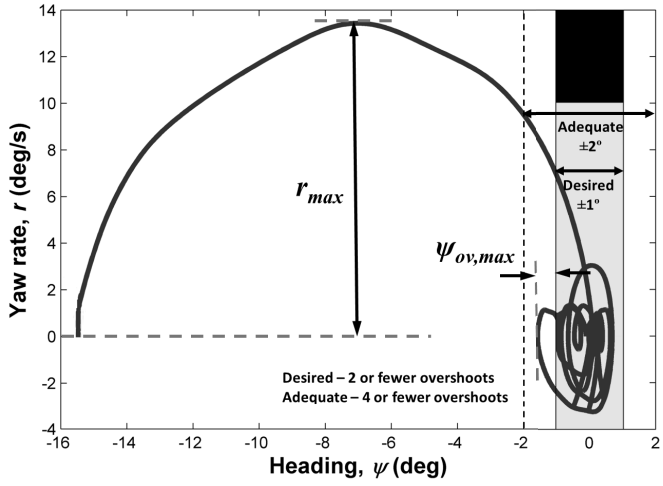


Figure 9. Phase-plane portrait of a single yaw capture.

is that letters could be assigned, where appropriate, to augment the ratings and help identify the cause of any motion cue deficiencies. It is thought that this feature may be particularly useful during motion tuning; an exercise carried-out during simulator qualification where the motion filter coefficients are adjusted by a washout filter expert, guided by pilot feedback, until acceptable motion cues are achieved[19]. Examples of situations where suffixes may be used are – where the platform washout (return to neutral) is too intrusive (R), where spurious or unexpected cues are experienced such as hitting displacement limits (S), or in situations where adverse pilot-simulator (biodynamic) coupling is experienced (B). The development of the motion fidelity rating scale complements other research being conducted at the University of Liverpool under the auspices of the 'Lifting Standards' project, which aims to develop objective measures of predicted fidelity together with subjective measures of perceived fidelity, to underpin the qualification of future rotorcraft flight simulators[22].

4.0 RESULTS

4.1 Objective performance

One method of looking at pilot performance in the yaw capture task is with a phase-plane portrait[9] showing the trajectory taken during a capture, in terms of vehicle yaw rate, r, and yaw angle, ψ. Figure 9 gives an example phase-plane portrait for a single capture manoeuvre, where the bar represents the centre pole, also illustrated are the maximum yaw rate, r_{max}, and the maximum overshoot, $\psi_{ov,max,}$.

Figure 10 shows the trajectory that was used to capture the centre pole, with the four baseline motion configurations, during two consecutive captures. In general, pilot performance always meets the desired criteria, irrespective of motion configuration. Nevertheless, differences in performance can still be observed. The largest overshoot, beyond the edges of the centre pole, occurred with the No motion configuration (D1). The addition of Rotational-only motion (D2) appears to have slightly enhanced performance, since no overshoots beyond the edges of the pole are apparent. A slight degradation in performance can be seen for the Translational-only motion configuration (D3),

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

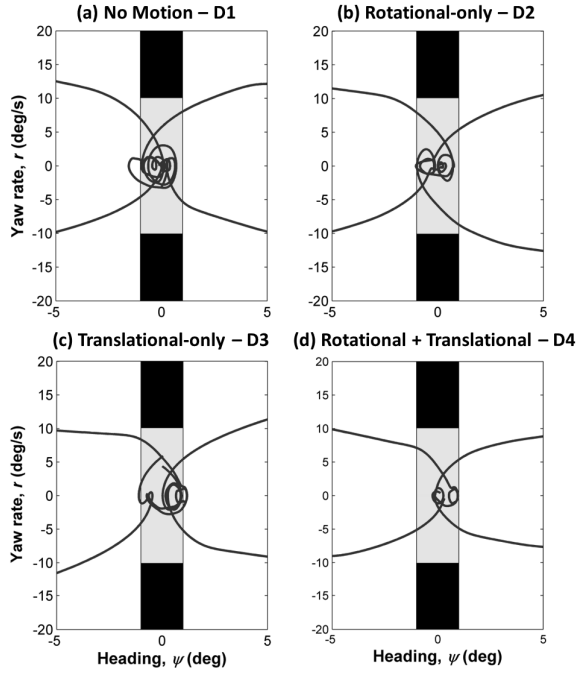


Figure 10. Pilot performance capturing centre pole with baseline configurations (D1-D4).

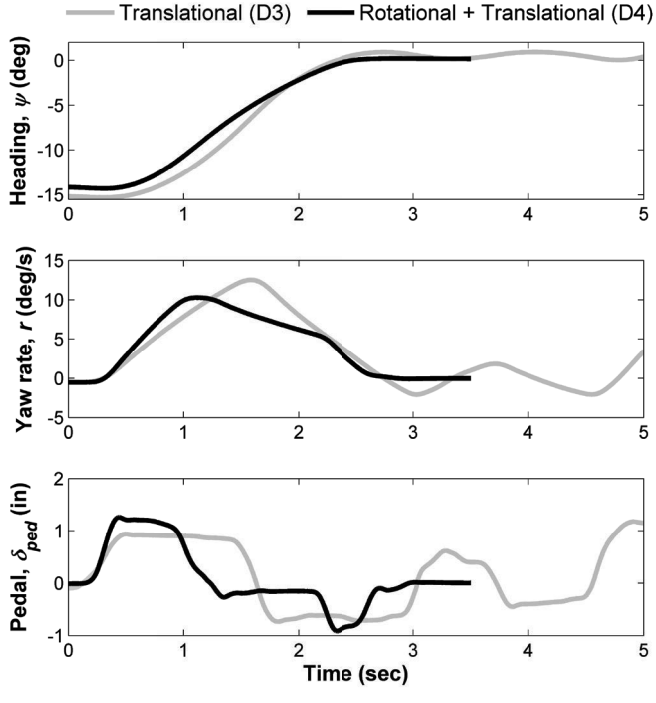


Figure 11. Pilot control activity.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

causing two small overshoots to occur. The best performance is clearly obtained with Rotational + Translational motion (D4); in this case no overshoots occurred and oscillations around the pilot selected capture point are negligible.

An alternative method of looking at pilot performance is to examine the pilot's control strategy. Figure 11 shows the difference between pilot control activity with the Translational-only motion (D3) and the Rotational + Translational motion (D4) configurations. The pilot's first pedal input is used to set-up an initial yaw rate and is likely to be performed in an 'open-loop' manner, the pilot waiting until the yaw angle approaches the target before closing the loop. In both cases the pilot selects an initial yaw rate of between 10 and 15deg/s. When the aircraft heading is close to the capture point (i.e. 0 deg for the centre pole) the pilot will begin to make 'closed-loop' pedal inputs to capture and maintain the target heading, bringing the yaw rate back to zero. For the Rotational + Translational motion configuration (D4) the pilot selects an initial pedal input and makes only minor adjustments as the yaw rate increases, then momentarily centres the pedals, and finally, reverses the pedal input for a short time at the end of the manoeuvre; capturing the desired heading in one smooth movement and bringing the yaw rate to zero, without any overshoots or undershoots. In handling qualities parlance, the pilot-vehicle response for this configuration could be described as well damped, or 'dead-beat'. For the Translational-only motion configuration (D3) the pilot makes two pedal inputs, both of approximately the same duration, but in opposite directions, and then requires several more input reversals as he attempts to null-out the yaw rate. This apparent change in control strategy, between the two configurations, suggests that the pilot uses rotational cues, from the motion platform, to enable him to select an appropriate peak-yaw rate and then cancel-out the yaw rate at the end of the manoeuvre, in order to stop at the capture point. Without the presence of yaw motion the pilot experienced difficulty in judging the amplitude and the moment at which to apply the capture input, which resulted in overshooting and undershooting around the target heading. Figure 12 shows the HQRs awarded for each of the baseline motion configurations (D1-D4). Interestingly, the Rotational + Translational motion configuration (D4), which provided the best yaw capture performance, was not awarded the lowest workload rating.

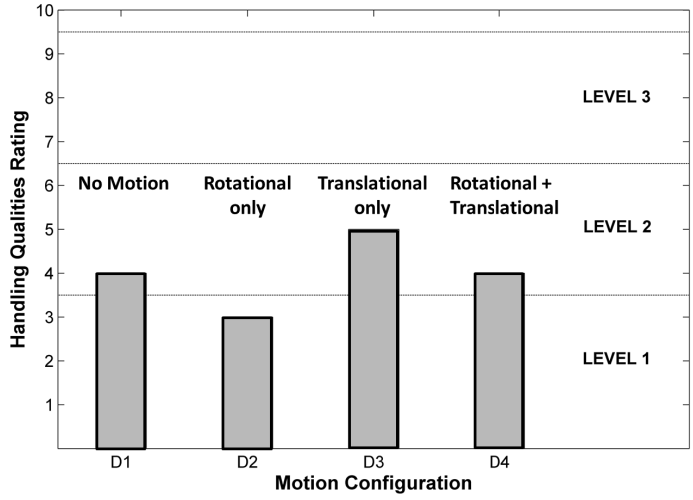


Figure 12. Handling qualities ratings with baseline configurations (D1-D4).

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

4.2 Pilot perception of motion cues

Figure 13 shows the pilot's motion fidelity ratings for the yaw capture task. The pilot correctly described the task without motion cues (D1) as a purely visual one. The pilot commented that his ability to capture the centre pole accurately was purely a function of his ability to anticipate the moment at which to begin the capture. With the Translation-only motion cues (D3) the pilot's comments, only seconds into the task, were 'I don't like it'. The pilot correctly reported that the motion was in the translational axes only, saying – 'Feels like I'm swaying from side-to-side instead of rotating, very odd feeling'. The pilot found lateral motion, without any accompanying yaw motion, to be very disconcerting, hence awarding a rating of 9 corresponding to the description – 'Negative value, serious deficiencies'. In contrast, yaw motion alone (D2) or together with translational motion (D4), was considered 'beneficial' to task performance. The only recognisable deficiency being that for the Rotational-only case (D2), small yaw rates appeared imperceptible and for the baseline Rotational + Translational motion case (D4) the lateral motion cues were considered too dominant compared to the yaw motion cues. This observation is consistent with

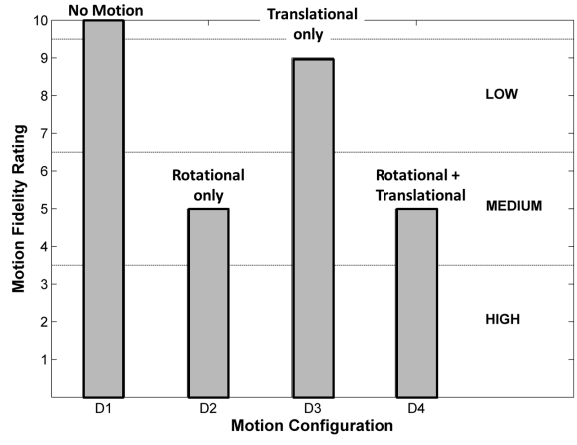


Figure 13. Motion fidelity ratings with baseline configurations (D1-D4).

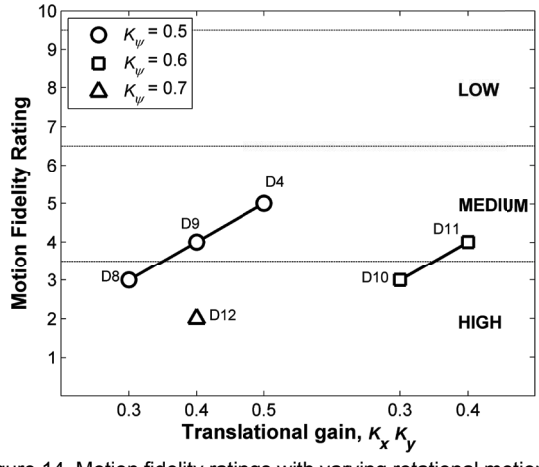


Figure 14. Motion fidelity ratings with varying rotational motion gain.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

the findings of Ref. 12, were passive subjects observed that simulator yaw motion was masked by simulator sway motion, which was consistently perceived as being too strong. Figure 14 shows the pilot's motion fidelity ratings for various weightings of rotational motion gain, K_ψ, and translational motion gains, K_x and K_y (see Table 2). These subjective ratings show that 'high' fidelity motion was achieved with configurations other than the baseline configurations; and shows the pilot's clear preference for a rotational motion gain that is greater than the translational motion gains.

4.3 Motion perception modelling

In the simulator the pilot will obtain yaw error information visually, from the outside-world scene; and will obtain yaw rate cues from the visual scene and, where body motion cues are available, through his vestibular organs. Figure 15 shows a simple model of the human perception system for the yaw capture task.

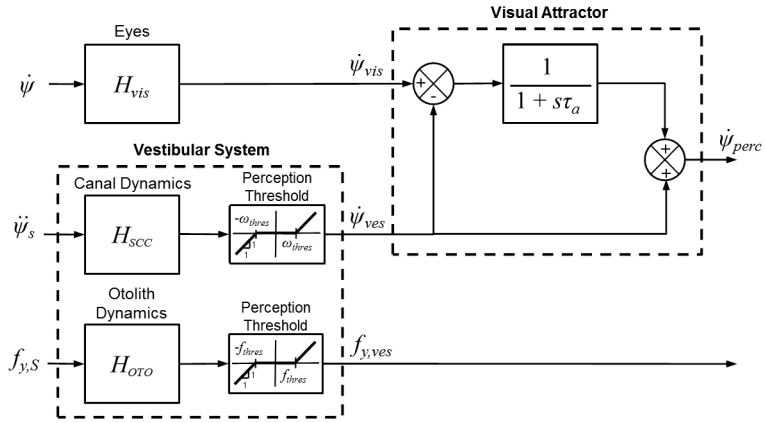


Figure 15. Model of human perception system for yaw capture task.

The human visual system, H_{vis}, is modelled as a pure time delay of 0·15 seconds following Ref. 23. The vestibular system is modelled by the transfer functions H_{scc} and H_{oto} given in Equations (4)-(5) after Ref. 24, where the semicircular canal neural lead term is τ_L = 0·11s, and lag time constants are τ_1 = 5·9s and τ_2 = 0·005s; the otoliths contain a neural lead term of τ_n = 0·3s and lag time constant τ_3 = 0·12s.

$$H_{SCC}(\omega) = \frac{(1+j\omega\tau_L)}{(1+j\omega\tau_1)(1+j\omega\tau_2)} \quad \ldots (4)$$

$$H_{\mathrm{OTO}}(\omega) = \frac{1+j\omega\tau_{\mathrm{n}}}{1+j\omega\tau_3} \quad \ldots (5)$$

The input to the semicircular canal transfer function, H_{scc}, is angular acceleration of the head and the output is equivalent to the sensed angular rate. The input and output of the otolith transfer function, H_{oto}, are the specific force acting on the head and the sensed specific force respectively. The final part of the model is the visual attractor proposed by van der Steen[25]. In van der Steen's model motion perception is 'attracted' towards the visual information from the eyes. Hence, in

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

situations where conflicts exist, between the information from the visual and vestibular systems, then the visual system will eventually dominate the vestibular system.

Included in the model of the vestibular system are the human motion perception thresholds. However, there appears to be little universal agreement in the literature regarding the actual value of these thresholds. In particular, thresholds measured in laboratory experiments with passive subjects, experiencing motion in a single axis, differ significantly from those measured in a flight simulator environment using subjects who are actively engaged in a flying task. In short, motion perception thresholds are strongly influenced by experimental factors such as the environment, the subjects taking part, the task and the subject workload. Table 3 shows the threshold values measured in a recent simulator study[26]. It can be seen that the yaw perception threshold is an order of magnitude greater than those measured in the other two rotational axes. Furthermore, a review of low amplitude yaw motion sensing given in Ref. 27 found that human yaw rate detection thresholds were around 1·1deg/s, which is close to the value given in Table 3.

Table 3
Human motion perception thresholds measured in a flight simulator

Sensor	Axis	Threshold
Otoliths	*x*-surge	0·24ft/s^2 (0·0076g)
	y-sway	0·24ft/s^2 (0·0076g)
	z-heave	0·04ft/s^2 (0·0013g)
Semicircular Canals	*x*-roll	$5{\cdot}21 \times 10^{-3}$ rad/s (0·3deg/s)
	y-pitch	$7{\cdot}34 \times 10^{-3}$ rad/s (0·42deg/s)
	z-yaw	$1{\cdot}66 \times 10^{-3}$ rad/s (0·95deg/s)

Figure 16 shows the response of the human perception model[15] during a yaw capture task. It can be seen that small yaw motions are sub-threshold (below the human perception threshold) at the same time that the accompanying lateral acceleration is super-threshold (above the human perception threshold). This situation is most likely to occur when the distance between the pilot's head and the aircraft's centre of gravity is large; since the lateral acceleration experienced by the pilot is proportional to the yaw acceleration scaled by the pilot offset (see Equation (3)). This goes someway to explaining the pilot's preference for a high motion gain in the yaw axis.

5.0 DISCUSSION

The results of the yaw capture experiment show that yaw motion had a greater influence on pilot performance and subjective opinion than has previously been suggested. In this respect, the conclusions of this research agree more closely with the recent simulator studies reported in Refs 13-14. The pilot who took part in the current experiment expressed an extreme dislike of Translational-only motion cues. This phenomenon has not been reported in any of the previous studies of this type, where pilots appear to have been unconcerned by the presence of side-force cues without congruent yaw motion cues; and in some cases have performed better without yaw motion. However, several differences exist between this experiment and those reported in previous studies[9-14]. Firstly, the simulator equipment was different; in particular there were differences in the simulator field-of-view, the transport delay, and the motion platform performance and dynamics. Secondly, in this study motion filters were employed with gains less than unity. In previous studies either the full math-model motion was reproduced, without

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

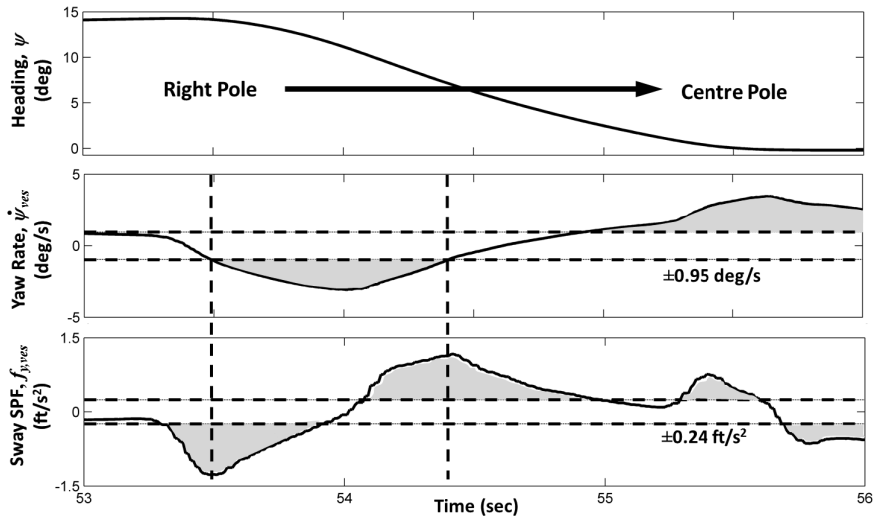


Figure 16. Response of human perception model for yaw capture task.

any scaling or filtering[9-10], or motion filters with very low break frequencies and approximately unity gain were used[13-14]. Such configurations, however, do not represent the normal operation of hexapod-type motion platforms, where some displacement capability must be reserved for motion in other axes. Finally, and perhaps most significantly, there was a difference in the distance between the pilot's seat/head and the simulated aircraft's centre of gravity. Previous studies simulated an un-augmented Apache AH-64 helicopter, with the pilot's seat located 4·5ft ahead of the centre of gravity. In the current experiment a hovering UH-60 helicopter was simulated, with a pilot seat to centre of gravity offset of approximately twice that distance (i.e. 10ft). This will have had a significant influence on the lateral acceleration cues experienced by the pilot. It is difficult to comment further on the exact cause of the differences in results between this and the previously reported experiments without further work. The repetition of simulator experiments on different facilities is an area of great concern for researchers. The yaw axis motion experiments reviewed in this paper[9-14] are probably the most comprehensive example of a standard experiment being repeated on multiple simulators available in the literature. Nevertheless, there have been some significant discrepancies in the reported results, even in cases where great effort has been made to eliminate the differences in simulator set-up. In Ref. 13 Grant points out that if small differences in simulator set-up can lead to different experimental results then producing generic results for flight simulators will prove difficult. The extent by which the results of research conducted on one facility can be generalised across multiple simulators is, therefore, an area which warrants further research.

The results of the current experiment summarised in Fig. 17 with tentative boundaries based on pilot comment, suggest that the best pilot performance, lowest workload and most favourable opinion of motion fidelity, will be obtained when congruent motion cues are provided in both the translational and rotational axes. Furthermore, when simulating an aircraft with a large offset between the pilot's seat and the centre of gravity, a rotational motion gain should be selected that is greater than the translational motion gain. It is postulated that this requirement is driven by the relatively high perception threshold of the semicircular canals to the detection of yaw motion.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

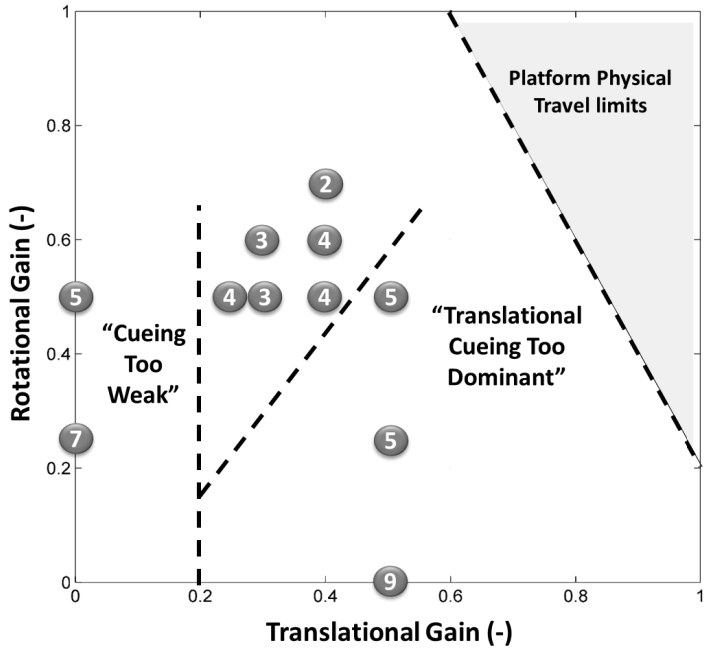


Figure 17. Summary of motion fidelity ratings.

The discussion in Ref. 14 suggests that the offset between pilot seat and aircraft centre of gravity, used in previous studies, was too small to observe significant differences between the perceptions of yaw and sway motion. Reference 14 goes on to call for further studies to obtain human perception thresholds, for yaw a-nd sway motion sensing, and to use these in the analysis of an active control task, where the distance between the pilot and the aircraft rotational centre is varied. By examining an aircraft model with a greater pilot offset than has previously been used, the results of the current experiment confirms that pilot location does influence the relative perception of yaw and sway motion and, therefore, strengthens the case for further study.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This research has provided both subjective and objective information on the value of the yaw-axis motion cues which are available from a typical short-stroke hexapod motion platform. These results fill a gap in the current knowledge, since very few motion cueing studies have concentrated exclusively on short-stroke platforms. The results also lead to the general conclusion that the motion feedback from even a modest motion platform, with a limited workspace, can furnish positive cues that benefit the pilot's performance and enhance simulator fidelity; more specifically the following conclusions are drawn:

- Platform yaw motion was found to have a greater influence in the yaw capture task than has been suggested by previous research.
- The best pilot-vehicle performance, lowest workload and most favourable opinion of motion fidelity was obtained when congruent motion cues were provided in both the translational

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

and rotational axes, whereas previous experiments found rotational motion to be of less importance.

- When simulating aircraft with a significant offset between the pilot seat and centre of gravity, rotational motion will always be accompanied by translational motion. Because the threshold (of the semicircular canals) to the detection of yaw motion is relatively high, then with some combination of pilot offset and motion filter gains, the platform yaw motion will be sub-threshold, at the same time that the corresponding lateral motion is super-threshold leading to the perception of inconsistent motion cues.
- The motion cueing experiment described in this paper should be repeated with a number of subject pilots, to ensure that the results can be generalised across the pilot population. The effect of varying the distance between the pilot's seat and the aircraft centre of gravity should also be investigated.
- The motion fidelity rating scale developed in this work has proved useful for gathering subjective data regarding pilot's perceptions of motion cueing fidelity. The scale should be adopted for use in future experiments and refined where necessary.

ACKNOWLEDGEMENTS

This study was conducted as part of a part-time PhD programme followed by the first author. The first author would like to thank his employers BAE Systems, for supporting this research, particularly Mike Southworth, Engineering Fellow in the Simulation Department at Warton, for his continued encouragement. The authors would like to gratefully acknowledge the significant contribution made by our professional test pilot Andy Berryman.

REFERENCES

1. TAKATS, J. Motion Cueing Requirements – ICAO 9625 Ed 3 and Beyond, RAeS Flight Simulation Group conference on Flight Simulation Technology: Future Potential, London, UK, 9-10 June, 2010.
2. Anon, Manual of Criteria for the Qualification of Flight Simulators, ICAO Doc 9625, International Civil Aviation Organization, Montreal, Canada.
3. PADFIELD, G.D. and WHITE, M.D. Flight simulation in academia – HELIFLIGHT in its first year of operation at the University of Liverpool, *Aeronaut J*, September 2003, **107**, (1075), pp 529-538.
4. BARNES, A.G. Operating Experience of a Small Six Axis Motion System Inside a Dome with a Wide Angle Visual System, Paper AIAA 1987-2437, AIAA Simulation Technologies Conference, Monterey, California, USA, August 1987.
5. ALPONSO, B., BEARD, S.D. and SCHROEDER, J.A. NASA Ames Vertical Motion Simulator – A Facility Engineered for Realism, RAeS Flight Simulation Group conference on Flight Simulation: Towards the Edge of the Envelope, 3-4 June 2009, London, UK.
6. WHITE, M.D., PERFECT, P., PADFIELD, G.D., GUBBELS, A.W. and BERRYMAN, A. Acceptance and Testing of a Rotorcraft Flight Simulator for Research and Teaching: The Importance of Unified Metrics, 35th European Rotorcraft Forum, Hamburg, Germany, 22-25 September 2009.
7. BURKI-COHEN, J. Literature for Flight Simulator (Motion) Requirements Research, US Department of Transportation, September 2006.
8. MEIRY, J.L. The Vestibular System and Human Dynamic Space Orientation, NASA CR 628, 1966.
9. SCHROEDER, J.A. Evaluation of simulation motion fidelity criteria in the vertical and directional axes, *J the American Helicopter Society*, April 1996, **41**, (2), pp 44-57.
10. SCHROEDER, J.A. and JOHNSON, W.W. Yaw Motion Cues in Helicopter Simulation, AGARD FVP Symposium Proceedings on Flight Simulation – Where are the Challenges?, Braunschweig, Germany, 22-25 May 1995.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press

11. SCHROEDER, J.A. Helicopter flight simulation motion platform requirements, NASA TP-1999-208766, 1996.
12. GROEN, E.L., SMAILI, M.H. and HOSMAN, R.J.A.W. Perception model analysis of flight simulator motion for a decrab maneuver, *J Aircr*, March-April 2007, **44**, (2), pp 427-435.
13. GRANT, P.R., YAM, B., HOSMAN, R. and SCHROEDER, J.A. Effect of simulator motion on pilot behavior and perception, *J Aircr*, November-December 2006, **43**, (6), pp 1914-1924.
14. ELLERBROEK, J., STROOSMA, O., MULDER, M. and VAN PAASSEN, M.M. Role identification of yaw and sway motion in helicopter yaw control tasks, *J Aircr*, July-August 2008, **45**, (4), pp 1275-1289.
15. HOSMAN, R. The use of pilot models to support flight simulation: the sky is the envelope, RAeS Simulation Group Conference on Flight Simulation: Towards the Edge of the Envelope, 3-4 June 2009, London, UK.
16. ADVANI, S.K. and HOSMAN, R.J.A.W. Revising Civil Simulator Standards – An opportunity for Technological Pull, Paper AIAA 2006-6248, AIAA Modeling and Simulation Technologies Conference, 21-24 August, Keystone, Colorado, USA.
17. FRANKLIN, J.A. *Dynamics, Control and Flying Qualities of V/STOL Aircraft, AIAA Education Series*, American Institute of Aeronautics and Astronautics, Reston, Virginia, USA, 2002.
18. NAHON, M. and REID, L.D. Flight simulation motion-base drive algorithms – A designers perspective, *J Guidance and Control*, 1989, **13**, (2), pp 356-362.
19. GRANT, P.R. and REID, L.D. Motion washout filter tuning: rules and requirements, *J Aircr*, March-April 1997, **34**, (2), pp 145-151.
20. COOPER, G.E. and HARPER, R.P. The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, April 1969.
21. SINACORI, J.B. The Determination of Some Requirements for a Helicopter Flight Research Simulation Facility, NASA-CR-152066, September 1977.
22. PERFECT, P., WHITE, M.D., PADFIELD, G.D. and GUBBELS, A.W. Rotorcraft simulation fidelity: new methods for quantification and assessment, *Aeronaut J*, March 2013, **117**, (1189), pp 235-282.
23. WENTINK, M., BOS, J., GROEN, E. and HOSMAN, R. Development of the Motion Perception Toolbox, Paper AIAA 2006-6631, AIAA Modeling and Simulation Technologies Conference, 21-24 August 2006, Keystone, Colorado, USA.
24. HOSMAN, R.J.A.W. Pilot's Perception and Control of Aircraft Motions, Ph.D. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands, 1996.
25. VAN DER STEEN, H. Self-Motion Perception, Ph.D. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands, 1998.
26. HEERSPINK, H.M., BERKOUWER, W.R., STROOSMA, O., VAN PAASEN, M.M., MULDER, M. and MULDER, J.A. Evaluation of Vestibular Thresholds for Motion Detection in the Simona Research Simulator, Paper AIAA 2005-6502, AIAA Modeling and Simulation Technologies Conference, 18-21 August 2005, San Francisco, California, USA.
27. SAMJI, A. and RIED, L.D. The Detection of low-amplitude yawing motion transients in a flight simulator, *IEEE Transactions on Systems, Man and Cybernetics*, March-April 1992, **22**, (2), pp 300-306.

https://doi.org/10.1017/S0001924000010228 Published online by Cambridge University Press