Optimising the roll-sway motion cues available from a short stroke hexapod motion platform

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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 simulations were conducted for a typical helicopter low-speed sidestep manoeuvre. To correctly simulate the sidestep manoeuvre the motion platform must translate laterally at the same time as it rolls. If the motion in these two axes is not properly harmonised then the pilot can experience significant false motion cues. This is a particular concern for short-stroke hexapod platforms, where displacement limits can severely constrain the available lateral travel particularly during motion in multiple axes (e.g. roll and sway). During the experiment the motion filter gains in the roll and sway axes and the roll-axis motion filter break-frequency were varied. Objective and subjective measures of pilot performance and motion fidelity were gathered for each motion filter configuration, the latter using a new motion fidelity rating scale. The key findings show that acceptable motion cues could only be achieved by careful harmonisation of the motion filter gains in the roll

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and sway axes. A high gain in the roll axis coupled with a low gain in the sway axis resulted in motion which was abrupt and uncomfortable. On the other hand, too large a gain in the sway axis resulted in extreme lateral displacements of the motion platform leading to undesirable side-effects. The phase distortion between the visual and platform motion cues, introduced by the roll-axis motion filter, also had a significant impact on the pilot's perception of motion fidelity. These results are presented in the form of proposed motion fidelity criteria for short-stroke hexapod platforms and compared with results from previous research conducted on a range of large motion systems.

NOTATION

$\mathbf{a}$	linear acceleration vector $[a_x\ a_y\ a_z]$ft/sec^2
$\mathbf{f}$	specific force vector $[f_x\ f_y\ f_z]$ft/sec^2
$\mathbf{g}$	gravity vector [0 0 g], where g = 32·174ft/sec^2
HP	high-pass filter
K	motion filter gain, non-dimensional
L_p	normalised vehicle roll damping derivative, 1/sec
L_δ	lateral cyclic sensitivity derivative, rad/sec^2/inch
p	vehicle roll rate, rad/sec
r_z	vertical offset of pilot vestibular centre (i.e. the inner ear) from simulator rotational centre, ft
s	Laplace operator
v	vehicle body-axis lateral velocity, ft/sec
Y	vehicle earth-axis lateral position, ft
y_s	simulator platform lateral displacement, ft
δ_{lat}	lateral cyclic position, inches
ϕ	vehicle roll angle, rad
ϕ_s	simulator roll angle, rad
ω_b	first-order high-pass break frequency, rad/sec
ω_{hp}	second-order high-pass break frequency, rad/sec
ζ_{hp}	second-order damping ratio, non-dimensional

1.0 INTRODUCTION

In flight simulators, as in real aircraft, pilots sense body motion largely through their vestibular system, which consists of two important sensors, both located in the inner ear — the semicircular canals and the otoliths. The semicircular canals sense angular accelerations in the roll, pitch and yaw axes; and the otoliths detect translational acceleration or specific force acting on the head in the longitudinal, lateral and vertical directions. Specific force is defined as the external force acting on a body per unit mass of the body, excluding gravitational forces (Equation (1)).

$$\mathbf{f} = \mathbf{a} - \mathbf{g} \qquad \ldots (1)$$

The ultimate role of a flight simulator motion platform is to stimulate the vestibular system to provide the pilot with sensations (rotational accelerations and specific forces) identical to that of real flight. In order to do this, the platform's position and attitude commands must be computed, in real-time, based on the rotational accelerations and specific force computed by the aircraft

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simulation model. One solution would be to drive the motion platform with the full value of the outputs from the aircraft simulation. However, due to the inherent limitations of ground-based motion platforms, it is necessary to reduce the amount of platform travel compared with the full aircraft motion, so that the maximum travel (or stroke) of the actuator legs is not exceeded. This is achieved by processing the aircraft model accelerations using a motion drive algorithm incorporating two features – (*i*) the motion drive signals are scaled (multiplied by a gain of less than unity) so that only a fraction of the full aircraft motion is reproduced; (*ii*) the motion drive signals are filtered, through so-called 'washout' filters, so that high-frequency motions are passed and low-frequency motions, which would otherwise result in large platform displacements, are blocked. Note that in this paper the terms motion filter and washout filter will be used interchangeably. The choice of washout filter transfer function is largely dependent on the simulator application. For example, Reid and Nahon[1] found low-order, such as first and second-order, filters were generally sufficient for the simulation of large transport aircraft. In other applications, where more dynamic manoeuvres are performed on short-stroke motion platforms, third-order filters are preferred as they provide more scope for response shaping. The transfer function of a third-order washout filter can be written by cascading first and second-order washouts; the transfer function for a third-order roll-axis washout filter is given in Equation (2)

$$K_{\phi}\, HP_{\phi}(s) = K_{\phi}\left(\frac{s^2}{s^2 + 2\zeta_{hp\phi}\omega_{hp\phi}\, s + \omega_{hp\phi}^2}\right)\left(\frac{s}{s+\omega_{b\phi}}\right) \qquad \ldots (2)$$

where $\zeta_{hp\phi}$ and $\omega_{hp\phi}$ are, respectively, the damping ratio and break-frequency of the second-order filter, and $\omega_{b\phi}$ is the break-frequency of the first-order filter. An additional high-frequency gain, or scaling factor, K_{ϕ}, is applied at the input of the washout filter, as described above. The filters' coefficients and high-frequency gain must be carefully selected to provide 'good' motion cues, while at the same time containing platform excursions within the device's achievable envelope. The process of systematically adjusting these coefficients to achieve the 'best' platform motion response is known as 'motion tuning'[2]. The initial, onset, acceleration is important because it 'cues' the pilot's vestibular system that motion is commencing. To a large extent it is the value of this initial onset cue, the magnitude and shape of which is determined by the motion filter parameters, which determines the cueing effectiveness of the platform motion. However, the elimination or mitigation of negative motion cues is equally important; particularly for small motion systems, with limited travel, the initial onset cue must be followed by a washout. This washout should stay below the threshold of human motion perception to avoid generating false cues. The shape and duration of the washout is also influenced by the motion filter parameters.

During flight simulator motion tuning the roll and sway (lateral) motion axes must be considered together for two important reasons. First, in a simulator the pilot's vestibular centre (i.e. the inner ear) will usually be located above the simulator's centre of rotation (Fig. 1). Therefore, any roll motion must be accompanied by sway motion to prevent the pilot from feeling a false lateral acceleration induced by the roll motion of the platform different from the real aircraft. Second, for manoeuvres where the aircraft (and simulator) is banked, but where the pilot would not feel any lateral specific force in the real aircraft (e.g. a lateral translation from hover) (Fig. 2), a false cue resulting from tilting the gravity vector, with respect to the pilot's head, will be experienced in the simulator, unless compensated for by 'opposite' sway motion. This false cue causes a sensation known as the 'leans'[3] and is illustrated in Fig. 3, showing a 40ft sidestep manoeuvre performed in an aircraft and in a simulator with only roll motion. From Fig. 3 it can be seen that in the roll axis, compared to the aircraft, the simulator response is scaled and also 'washed-out' back to the

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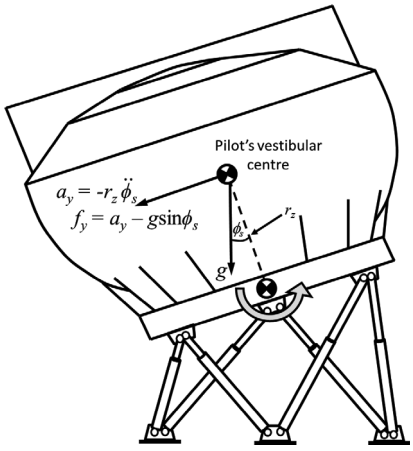


Figure 1. Flight simulator motion platform in a roll-sway manoeuvre (viewed from front).

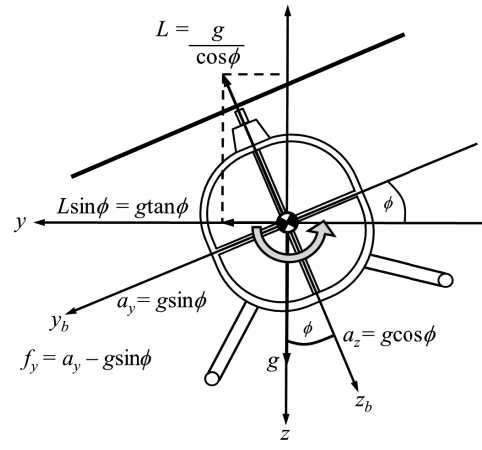


Figure 2. Helicopter in a roll-sway manoeuvre (viewed from front).

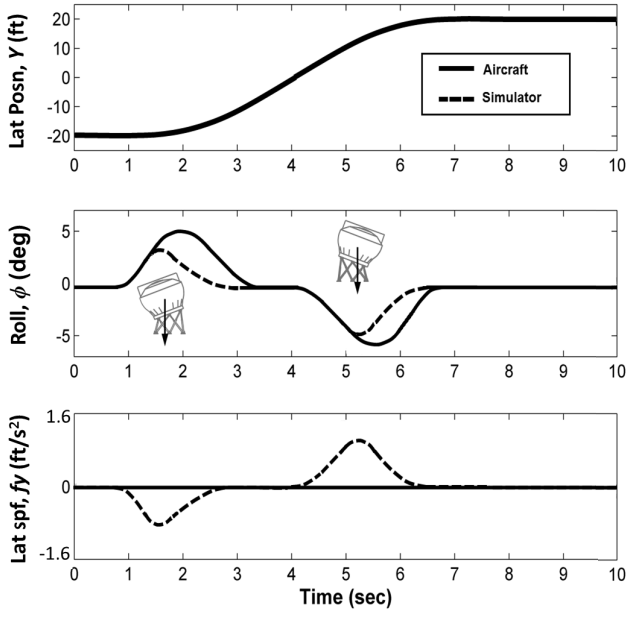


Figure 3. Sidestep manoeuvre showing aircraft and simulator roll angle and lateral specific force.

neutral position, due to the effect of the washout filters. The lateral specific force, sensed at the pilot's vestibular centre, due to simulator roll angle is shown at the bottom of Fig. 3, whereas in the aircraft the pilot would feel no lateral specific force; with the thrust line of the rotor oriented approximately along the aircraft *z*-axis, at low speed there is no mechanism to generate a sideforce, hence lateral acceleration, along the aircraft *y*-axis. Therefore, from a simulator fidelity perspective, both the roll and sway axis motion cues contribute to the pilot's perception of fidelity. An added difficulty for short-stroke motion platforms is the amount of platform displacement required to

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compensate for these false cues, which in the case of the 'leans' will be considerable. This paper examines the requirements for 'good' motion cues in both the roll and sway axes, and explores the interaction between these two important motion cueing axes, using a typical short-stroke hexapod motion platform.

2.0 BACKGROUND

Several researchers have examined the roll and sway motion axes either separately or together. A selection of that work is reviewed below and summarised in Table 1.

Stapleford *et al*[4] examined a roll control experiment for a simulated vertical take-off and landing (VTOL) vehicle hovering in gusty air, using a six degree-of-freedom motion base capable of roll angles of ±35º and lateral displacements of ±9ft. In Stapleford's experiments, pilots were instructed to minimise roll deviations using cues from the motion platform and from a horizon display showing aircraft roll angle, but were given no information regarding their lateral position. A first-order washout filter was used in the roll axis and a second-order filter was used in the sway axis. Stapleford concluded that for manual tracking tasks the translational (sway) motion cues appeared to be less important than rotational motion cues and suggested roll motion cues of 'good' fidelity should be provided over the frequency range 0·5 to 10rad/sec for accurate target tracking. According to Stapleford, pilots were unaware of motion washout in the roll axis when the break frequency, $\omega_{b\phi}$, was 0·5rad/sec and increasing the break frequency to 2·0rad/sec had only a minor effect. Tracking performance was not influenced by changes in the sway motion cues, but there was however, an effect on pilots' subjective impressions of the simulation, with motion configurations that produced higher lateral accelerations resulting in increased complaints of disorientation. The primary focus of Stapleford's experiments was to develop a multi-modal pilot model, including both visual and motion feedback, and Ref. 4 contains much useful information relating to this objective; but unfortunately, gives no further information regarding what constitutes 'good' motion cues.

Table 1
Summary of roll-sway motion research findings

Reference	Roll-motion	Sway-motion	Conclusions
Stapleford, 1969[4]	First-order	Second-order	Roll-axis first-order break frequency between 0·5 and 2·0rad/sec
Jex, 1978[5]	First-order	-	Roll-axis motion gain of between 0·5 and 0·7 and first-order break-frequency of 0·3 to 0·5rad/sec
Bray, 1972[6]	Second-order	Second-order	Roll-axis break-frequency less than 0·5rad/sec
Van Gool, 1978[7]	Second-order	-	Roll-axis break-frequency of 0·1 to 0·5rad/sec
Bergeron, 1971[8]	Scaling	-	Roll-axis motion gain no less than 0·25
Shirachi & Shirley, 1981[9]	Second-order	Second-order	Roll-axis motion gain no less than 0·5
Jex, 1979[10]	Second-order	Second-order	Pilot objections increased when amplitude of false sway cue was greater than 0·1g
Sinacori, 1977[11]	Second-order	Second-order	Sway filter motion gain of 0.6 and roll-axis motion gain of 0·4
Schroeder, 1997[3]	Scaling	Scaling	Roll-axis gain no less than 0·4 and sway-axis gain greater than 0·6

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A study conducted by Jex *et al*[5] again investigated pilot performance for target tracking and disturbance rejection, this time using an air-to-air combat task, were the disturbance input produced roll motions comparable in amplitude and frequency to the target motion. This experiment examined motion cues in the roll axis only, but the motion system could be configured so that pilots rolled the simulator either sitting upright or lying on their backs. The first case represents the normal situation, where false tilt cues due to re-orientation of the gravity vector (i.e. the 'leans') would be present, while the second case provides no such false cues. Jex examined various motion cases including full motion, no motion, scaled motion and various combinations of first- and second-order washout filters, with the aim of selecting the optimum motion drive algorithm that would achieve the best compromise between realistic roll rate cues and suppression of false sway cues. Jex found that using scaled motion or motion filtered through first-order washout filters produced very similar pilot performance, but selected the optimum washout filter as being a first-order high-pass filter with a high-frequency gain of between 0·5 and 0·7 and a break frequency, $\omega_{b\phi}$, of 0·3 to 0·5rad/sec. The conclusions of Ref. 5 suggest that roll motion cues allowed pilots to improve their disturbance rejection performance compared to the no motion case. Furthermore, pilots used the false tilt cues, experienced during upright rolling, to improve their tracking performance, despite the fact that in some cases the lateral specific force was less than 0·1g; the resulting improvement was very small but the use of false motion cues by the pilot has implications for pilot training simulators.

Bray[6] carried out initial experiments on the Flight Simulator for Advanced Aircraft (FSAA) investigating the handling qualities of large transport aircraft. The FSAA's cascaded design meant that it was capable of lateral displacements of up to ±50ft and roll angles of ±45º. As part of these experiments Bray conducted a limited exploration aimed at developing general motion cueing requirements for flight simulators. These tests involved constraining the motion of the FSAA using second-order washout filters and scaling the motion drive signals. Bray found that with a roll-axis motion gain of unity and a break-frequency, $\omega_{hp\phi}$, of 0·5rad/sec, pilots reported a slight contradiction between visual and motion cues. Increasing the roll-axis break-frequency to 1·0rad/sec and 1·4rad/sec significantly reduced the pilots' ability to stabilise the Dutch-roll mode (an oscillating motion in the yaw- and roll-axis). A roll-axis motion gain of 0·5 reduced the phase-related contradictions, described above, and halved the corresponding sway-axis excursions, significantly reducing the distracting mechanical noise generated by the motion system's mechanisms. However, with simulated turbulence, the reduced roll motion was apparent and, incorrectly, interpreted by pilots as a reduction in turbulence intensity. A general conclusion of Ref. 6 is that for large aircraft, the cockpit sway motion cues appeared to be much more important than roll motion cues.

In Europe, van Gool[7] conducted an investigation to establish the influence of motion drive algorithms, in the pitch and roll axes, on pilot performance while stabilising an aircraft in turbulence. The simulator used for van Gool's experiment had a four degree-of-freedom motion system which was not capable of producing motion in the sway-axis. Second-order high-pass washout filters were used with only the break frequency being varied; filter gain and damping ratio remained fixed at unity. The results of the investigation concluded that no significant differences in pilot performance, or subjective feedback, could be observed when the break frequency, $\omega_{hp\phi}$, was varied from 0·1rad/sec to 0·5rad/sec.

In Ref. 8, Bergeron *et al* investigated the effects of angular motion on a compensatory control task, where the pilot attempted to track a randomly moving target, using a very stable aircraft. When the task was conducted in a single-axis (e.g. roll, pitch or yaw) the difference in pilot performance under full-motion and no-motion conditions was negligible. However, differences in pilot performance were observed, when motion was added, during two-axis tests which required pilot compensation in two angular axes simultaneously (e.g. pitch-yaw or pitch-roll). Additional tests

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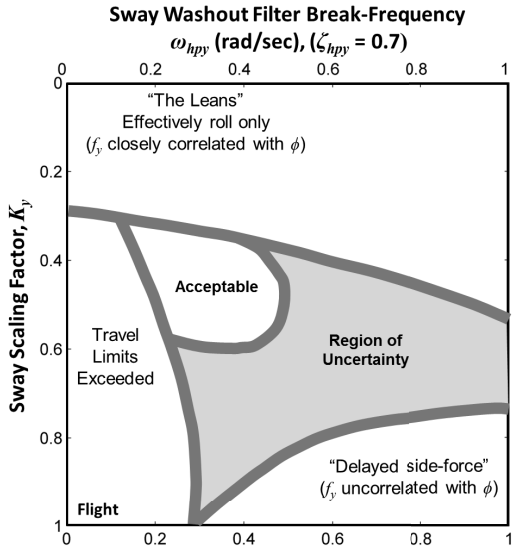


Figure 4. Jex's sway axis motion fidelity criteria[10].

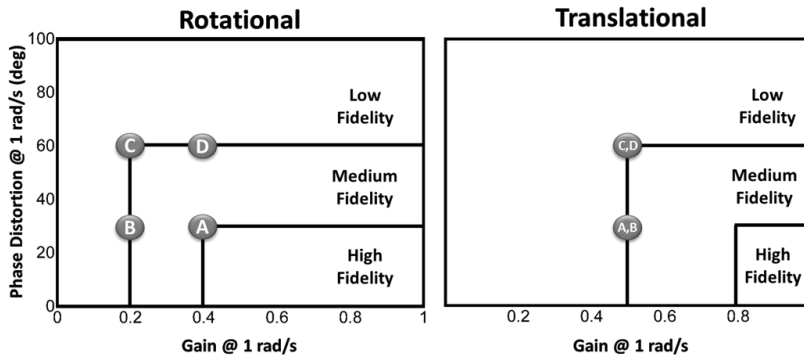
examined the effects of scaling the motion cues with a gain of between zero and unity. In these tests pilot tracking performance remained constant for motion gains of between 1·0 and 0·25 but degraded with further reductions in motion gain.

Shirachi and Shirley[9] also investigated the effects of motion scaling on pilot performance. This time in a roll-axis disturbance rejection task, using a model of a jet transport aircraft. Their research attempted to determine the scaling threshold below which pilot performance was significantly degraded when compared to full (unscaled) motion. Second-order filters were employed in the roll and sway axis with a damping ratio of 0·7 and a break-frequency of 0·7rad/sec; motion gains of 1, 0·75, 0·5 and 0·25 were evaluated. According to Ref. 9 when the roll-axis motion gain was reduced below 0·5, then pilot performance similar to the no-motion case was observed.

In a follow-on to his earlier study, summarised in Ref. 10, Jex investigated the effects of various second-order washout filter configurations using a motion platform with ±10ft of lateral travel. Based on pilots' subjective impressions of the motion cues, a fidelity criteria was proposed defining acceptable combinations of gain and break frequency for the sway axis. The proposed criteria are shown in Fig. 4, where the region of uncertainty is due to the limited number of test points considered. However, pilot opinion was not always consistent and changed depending on the nature of the task (e.g. sidestep or target tracking), besides which, changes in the motion cues caused by varying the washout filter coefficients were deemed very subtle, making it difficult for pilots to provide subjective feedback on an absolute basis. In general, the results showed that pilot objections increased when the amplitude of the false sway cues was greater than 0·1g; pilots also disliked hitting sway-axis displacement limits.

In Ref. 11, Sinacori used the FSAA motion platform to investigate an 'S-turn' manoeuvre along a runway at 60kt with a six degree-of-freedom model of a high-performance helicopter. Sinacori found that an acceptable simulation was maintained with a sway filter gain of 0·6, while values of 0·4 or less elicited pilot objections, because of anomalous side-forces. In addition Sinacori

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High: Motion sensations are close to those of visual flight
Medium: Motion sensation differences are noticeable but not objectionable
Low: Differences are noticeable and objectionable, loss of performance, disorientation

Figure 5. Sinacori's rotational and translational motion fidelity criteria[11].

proposed further motion fidelity criteria based on a limited number of test runs (A-D shown in Fig. 5). Sinacori postulated that motion fidelity could be predicted by examining the gain and phase shift between the aircraft model accelerations and the commanded motion system accelerations at a frequency of 1rad/sec. Any attenuation and phase shift between these two signals is caused by the washout filters in the motion drive algorithm. Figure 5 shows Sinacori's rotational and translational motion fidelity criteria and the three point rating scale used by Sinacori to elicit pilot subjective opinion. In Ref. 11 Sinacori acknowledges that these criteria 'have little or no support other than intuition'. Nevertheless, they remain the most complete and coherent set of motion fidelity criteria available today and many researchers have since made valuable contributions to their development; of these contributions the work of Schroeder in Refs 3 and 12 has been most significant. In Ref. 3 Schroeder investigated a roll-sway sidestep task on the NASA Ames Vertical Motion Simulator (VMS), which has ±20ft of lateral travel. Motion platform commands were scaled from zero (no motion) to unity (full motion) in both the roll and the sway axes, with no washout filters applied. Roll and sway motion gain variations were found to have a significant effect on pilots' perceptions of motion fidelity and handling qualities, but not on their positioning performance; although pilot control activity did decrease as the motion gains increased. A fidelity criteria was proposed by Schroeder for roll-sway motion, which suggested that, for high fidelity motion, the roll-axis gain should not be less than 0·4 and the sway-axis gain should be greater than 0·6. Pilot opinion of the full motion condition was less positive than expected, because of undesirable side-effects, such as mechanical noise caused by extreme motion system displacements. Further studies by Mikula[13] conducted on the NASA VMS, Chung[14] on an 80in stroke hexapod and Beykirch[15] on an anthropomorphic robot-arm simulator, found similar results to those reported by Schroeder.

The results of Stapleford[4], Jex[5], Bray[6], van Gool[7], Bergeron[8] and Shirachi and Shirley[9] are summarised on Sinacori's rotational fidelity criteria in Fig. 6. Also shown in Fig. 6 are the roll-axis motion configurations (A1 – A6) used in the present study, which will be discussed later.

Finally, a recently developed modification to the conventional motion drive algorithms used in the previous research, known as lateral manoeuvring motion or LM^2, is described in Ref. 16. This modification significantly reduces the false sway cues experienced by the pilot during lateral

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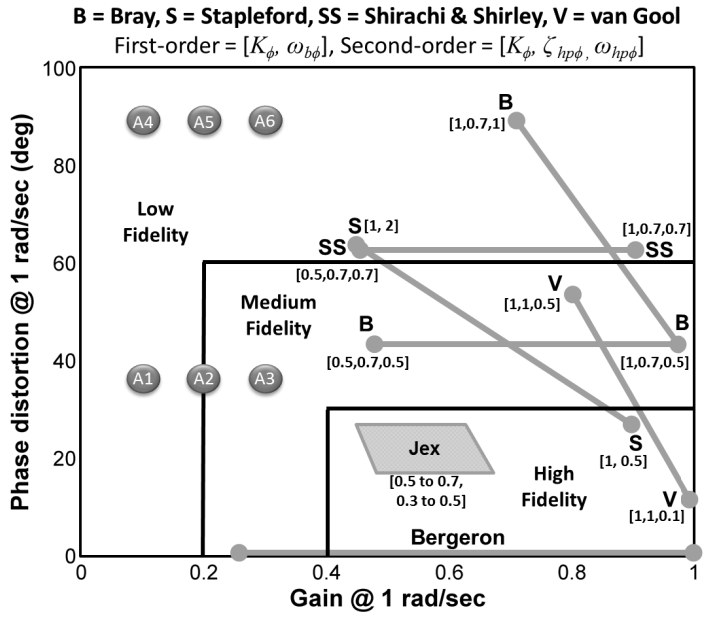


Figure 6. Summary of roll-axis motion fidelity criteria.

manoeuvres, but accomplishes this by sacrificing some fidelity in the roll-axis. Nevertheless, the LM[2] algorithm has been 'retro-fitted' to a number of flight training simulators, which are currently in service, and has received positive feedback from pilots. The importance of motion in training simulators is still a vexing question and our research, like the other works described above is aimed at providing a solid engineering evidence base for decision making on this topic.

3.0 ANALYSIS

In the case of a flight simulator (Fig. 1) the lateral specific force experienced at the pilot's vestibular centre during a pure roll-sway manoeuvre is defined by Equation (1) as

$$f_y = a_y - g\mathrm{Sin}\phi_s \qquad \ldots (3)$$

where the first term on the right-hand side is the lateral acceleration at the pilot's vestibular centre. If the pilot's vestibular centre is displaced vertically from the simulator's rotational centre by a distance, r_z, then the lateral acceleration will be given by

$$a_y = \ddot{y}_s - r_z \ddot{\phi}_s \qquad \ldots (4)$$

Substituting Equation (4) into Equation (3) gives

$$f_y = \ddot{y}_s - r_z \ddot{\phi}_s - g\mathrm{Sin}\phi_s \qquad \ldots (5)$$

The first term on the right-hand side of Equation (5) is the lateral acceleration of the motion

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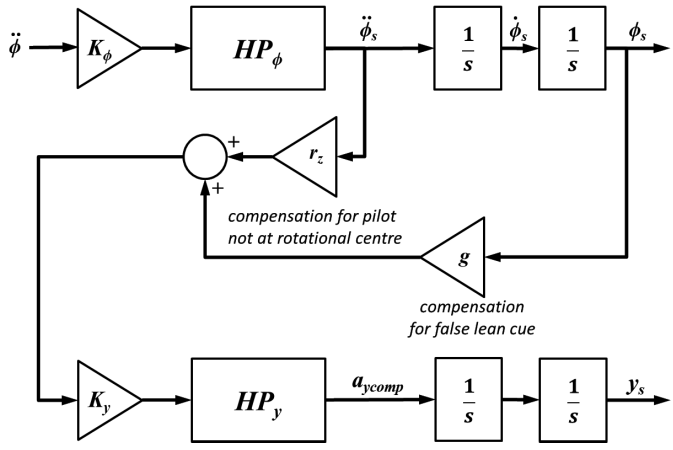


Figure 7. Motion drive algorithm block diagram.

platform's centre of rotation. This is a desired motion cue generated by pure translational motion of the platform. The remaining terms are undesirable side-effects or 'false cues', with the second term being the lateral acceleration induced by platform roll acceleration and the final term being caused by orientation of the gravity vector relative to the pilot's head.

Figure 2 shows a helicopter performing a lateral translation manoeuvre (sidestep). Assuming that the pilot is located at (or close to) the centre of gravity, then the pilot will sense no lateral specific force (as previously explained), and in this case

$$f_y = a_y - g\mathrm{Sin}\phi = 0 \qquad \ldots (6)$$

If this manoeuvre were simulated using a typical hexapod motion platform then by Equation (5) it can be seen that in the simulator

$$f_y = -r_z \ddot{\phi}_s - g\mathrm{Sin}\phi_s \neq 0 \qquad \ldots (7)$$

Hence, the lateral specific force experienced by the pilot in the simulator (Equation (7)), will be significantly different to that which would be experienced in the aircraft (Equation (6)). This constitutes a significant false cue, which must be compensated for in the simulator's motion drive algorithm. Therefore, Equation (7) must be modified by an additional lateral acceleration component, a_{ycomp}, giving

$$f_y = a_{ycomp} - r_z \ddot{\phi}_s - g\mathrm{Sin}\phi_s \qquad \ldots (8)$$

Ideally, the compensation term, a_{ycomp}, would completely cancel out the two remaining terms, which are responsible for the false sway motion cues described above. However, the limited displacement capability of hexapod motion platforms, particularly short-stroke platforms, means that insufficient lateral (sway) travel is available to achieve cancellation. Therefore, three methods are commonly used to reduce the amount of required platform displacement — (*i*) the platform roll angle is reduced relative to the aircraft model (and hence visual cues), thus requiring less lateral displacement to compensate for the false cues; (*ii*) less than the desired amount of lateral

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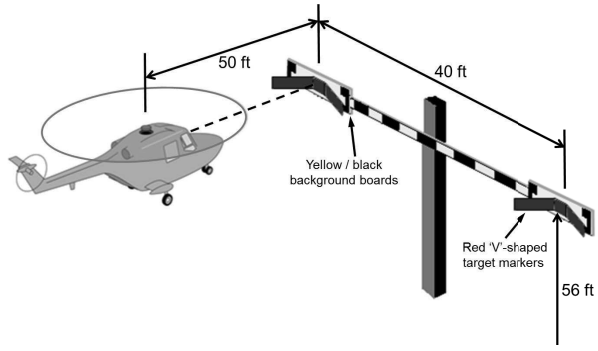


Figure 8. Roll-sway sidestep task using NASA Ames hoverboards.

travel is used, accepting that the false cues will not be entirely eliminated; and (*iii*) high-pass washout filters are used to provide frequency dependent attenuation of both the roll and sway motions, thus reducing the time period during which false cues can occur (i.e. by filtering out low frequency sustained roll motions and passing higher frequency motions of shorter duration). Figure 7 shows a motion drive algorithm incorporating these methods. From Fig. 7 using small angle approximations, it can be shown that Equation (8) becomes

$$f_y = K_y HP_y \left(r_z K_\phi HP_\phi \ddot{\phi} + g K_\phi HP_\phi \phi\right) - r_z K_\phi HP_\phi \ddot{\phi} - g K_\phi HP_\phi \phi \quad \ldots (9)$$

Finally, re-arranging Equation (9) yields

$$f_y = -r_z K_\phi HP_\phi \ddot{\phi} \left(1 - K_y HP_y\right) - g K_\phi HP_\phi \phi \left(1 - K_y HP_y\right) \quad \ldots (10)$$

It can then be seen by comparing Equation (6) and Equation (10) that the false sway motion cues, experienced in the simulator, will be reduced and, therefore, the simulation 'fidelity' increased, when the gain of the sway-axis motion filter, $K_y HP_y$, is close to unity; and when the gain is equal to unity the false cues will be entirely eliminated. Alternatively, a reduction in the roll-axis motion filter gain, $K_\phi HP_\phi$, will also result in a reduction in the false sway motion cues, but at the expense of the roll motion fidelity.

4.0 EXPERIMENTAL SETUP

4.1 Simulator facility

The simulator facility used in the study is HELIFLIGHT-R operated by the University of Liverpool. The 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 (24in) electric motion platform. The motion platform is capable of roll-axis displacements of ±23·3º and sway-axis displacements of ±1·5ft. However, these are maximum displacement capabilities for motion in a single axis; motion in multiple axes will severely restrict the available travel. The outside world image has a field-of-view of 210º (±105º) by 70º (+30º/−40º). Total simulator transport delay from pilot input to visual system response has been measured at approximately 125 milliseconds. The response of the motion platform is well represented by a pure time delay of around 60 milliseconds. Further details of the HELIFLIGHT-R simulator can be found in Ref. 17.

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Table 2
Roll motion filter configurations

Config	K_ϕ	$\omega_{hp\phi}$ (rad/s)	Gain at 1 rad/s	Phase at 1 rad/s (deg)
A1	0·11	0·3	0·1	36
A2	0·21	0·3	0·2	36
A3	0·32	0·3	0·3	36
A4	0·17	0·9	0·1	89
A5	0·33	0·9	0·2	89
A6	0·40	0·9	0·3	89
A7	Fixed Base – No Motion			

Table 3
Sway motion filter configurations

Config	K_y	ω_{hpy} (rad/s)	Gain at 1 rad/s	Phase at 1 rad/s (deg)
T1	0·16	0·9	0·1	89
T2	0·33	0·9	0·2	89
T3	0·5	0·9	0·3	89
T4	0·66	0·9	0·4	89
T5	Fixed Base – No Motion			

4.2 Roll-sway sidestep task

The course layout for the roll-sway sidestep task is shown in Fig. 8. The task was performed in a detailed airfield environment in front of a model of the NASA Ames hover-boards[18]. Starting with the aircraft aligned with the left-hand target-board, the pilot must perform a 40ft lateral sidestep, to reposition the aircraft at the opposite target. Desired performance was achieved when the pilot captured the opposite target within six seconds, in one smooth movement, with one overshoot or undershoot, and stabilised at the target position within ±2ft. Adequate performance was achieved when the pilot captured the opposite target within 10 seconds, with two overshoots or undershoots, and maintained position within ±5ft of the target. The pilot was able to judge positioning accuracy by observing the relative position of the red ('V'-shaped) target markers against the yellow and black background boards. The task was conducted in good visibility with no atmospheric turbulence.

4.3 Vehicle dynamics

The pilot controlled lateral position of the vehicle through roll attitude using lateral cyclic stick inputs. Roll-sway vehicle dynamics were representative of a hovering helicopter with a roll-rate command system and height hold autopilot. The equations of motion of the model are given in Equation (11).

$$\begin{bmatrix} \dot{p} \\ \dot{v} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} L_p & 0 & 0 \\ 0 & 0 & g \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ v \\ \phi \end{bmatrix} + \begin{bmatrix} L_\delta \\ 0 \\ 0 \end{bmatrix} \delta_{lat} \qquad \ldots (11)$$

The normalised roll damping derivative, L_p, was set to $-4{\cdot}5\text{sec}^{-1}$ and the lateral cyclic sensitivity, L_δ, was selected to give a roll acceleration of $\pm 2\text{rad/s}^2$ for full lateral cyclic deflections; according to Ref. 19 these values are typical of a moderately agile helicopter.

4.4 Motion configurations

The motion filter configurations examined in this experiment are shown in Tables 2 and 3. Both the roll and sway-axis motion filters were third-order filters (see Equation (2)) with damping ratios, $\zeta_{hp\phi}$ and ζ_{hpy}, set to 0·9 and first-order break-frequencies, $\omega_{b\phi}$ and ω_{by}, set equal to 0·1rad/sec. Tables 2 and 3 also show the gain and phase shift properties of each filter configuration with an input signal frequency of 1rad/sec, a metric consistent with the existing motion fidelity criteria proposed by Sinacori[11]. The roll-axis motion filter configurations are shown located on the Sinacori criteria

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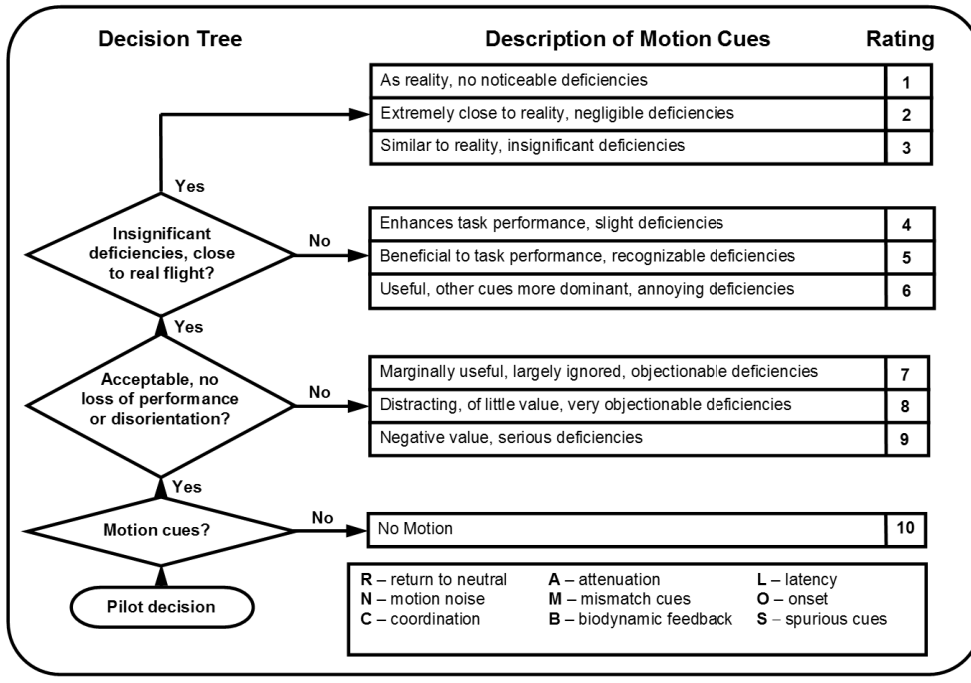


Figure 9. Motion fidelity rating scale.

in Fig. 6, where it will be seen that most configurations would be classified as low fidelity, with some configurations achieving medium fidelity. All of the sway-axis filter configurations would be classified as low fidelity using the Sinacori criteria.

4.5 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 wider cross-section of the pilot population. However, enough existing research is available[3-12] to enable a useful comparison of the key findings for a single subject pilot.

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 motion filter configuration (Tables 2 and 3) 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 newly developed motion fidelity rating scale. The three-point motion fidelity rating scale (Fig. 5) used by Sinacori in Ref. 11, 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 rating scale was devised (Fig. 9). This new scale is based on the same structure as the established Cooper-Harper HQR scale, with a decision tree that leads the pilot, first to descriptors, and then to numerical ratings. The motion fidelity rating scale compliments other research conducted under the auspices of the University of Liverpool's 'Lifting Standards'

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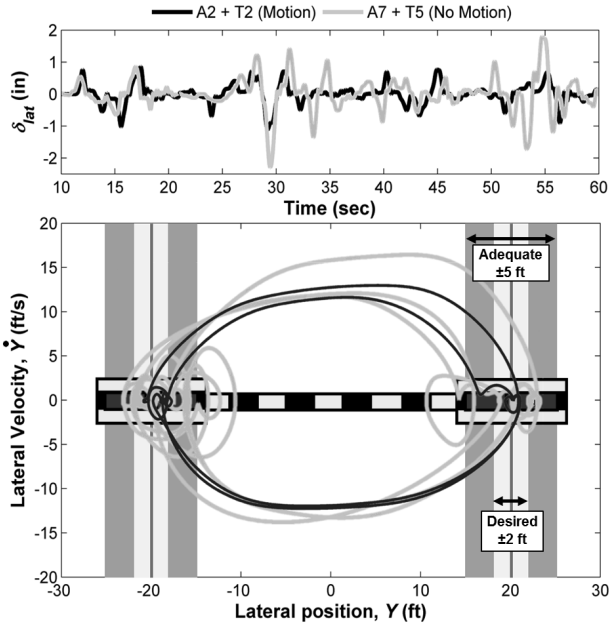


Figure 10. Lateral stick activity (top) and phase plane portrait (bottom) with motion and no motion.

project, including the development of a Simulation Fidelity Rating (SFR) scale[21]. Further details regarding the development and use of the motion fidelity rating scale can be found in Ref. 22.

5.0 RESULTS

The results of the experiment will now be discussed in terms of four key relationships: (*i*) the effects of introducing motion cues compared to the no motion case; (*ii*) the effects of increasing the compensatory sway motion filter gain at fixed roll axis gain; (*iii*) the effects of increasing the roll motion filter gain at fixed sway gain; and (*iv*) the effects of increasing the roll motion filter break-frequency.

5.1 Motion versus no motion

Figure 10 shows the pilot's lateral cyclic control activity and the phase-plane portrait for the sidestep manoeuvre, performed with and without motion cues. It can be seen that without motion cues the pilot could not achieve the desired performance criteria and was over-controlling, i.e. applying large oscillatory inputs. Positioning accuracy was poor without motion cues (A7 + T5), and several large overshoots and undershoots are evident around the target locations (±20ft). On the other hand, with appropriately tuned motion cues (A2 + T2), positioning accuracy was good with only a few small overshoots and undershoots around the targets. This finding is consistent with the results of previous studies[5]. Without platform motion, the vehicle acceleration cues, which normally aid the pilot to anticipate (or lead) during position capture and stabilisation, are absent. The pilot must, therefore, compensate by adjusting his control strategy based on the remaining (mainly visual) cues. In the event, the pilot did not manage to accomplish the task successfully

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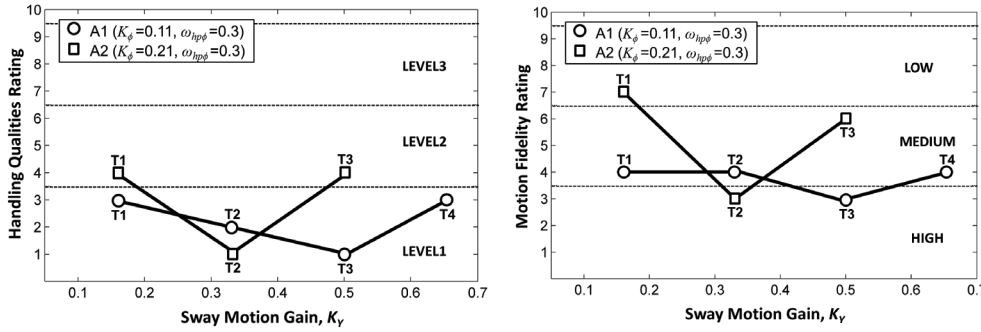


Figure 11. Handling qualities and motion fidelity ratings with increasing sway motion gain.

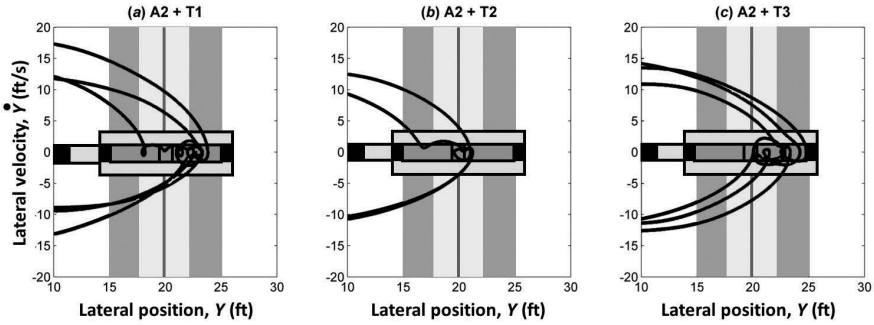


Figure 12. Phase plane portrait with increasing sway motion gain (left to right).

in the time allowed without motion cues, returning a HQR of 5 ('Adequate performance requires considerable pilot compensation'). It is conceivable that, given practice, desired performance and Level 1 HQRs could be achieved, but the training implications of the pilot developing a different piloting strategy compared to real flight are serious.

5.2 Increasing sway motion gain

Figure 11 shows the pilot's HQRs and motion fidelity ratings and Fig. 12 shows the phase-plane portraits, with increasing sway motion gain. Figure 12 shows only the right-hand target-capture portion of the manoeuvre. At low values of sway gain the pilot described the motion cues as 'abrupt' and 'harsh', because of the false sway accelerations induced at the pilot's seat by the roll motion of the platform. This situation was only improved by either reducing the roll motion gain (discussed later) or increasing the sway motion gain. Increasing the sway motion gain resulted in increased lateral platform travel to compensate for the false sway accelerations; this led to improved task performance, reduced pilot workload and an improved impression of motion fidelity, which is reflected in the pilot's subjective ratings (Fig. 11). However, when the amount of lateral travel became large, then the pilot complained that audible noise, generated by the motion system's mechanisms, became intrusive and also that he could feel the platform washout. These are unfortunate side-effects of high motion gains. The increased noise and washout sensations both had a detrimental impact on the pilot's performance, workload and opinion of motion fidelity at the highest sway motion gain (Fig. 11). The negative impact of audible noise on pilots' perceptions

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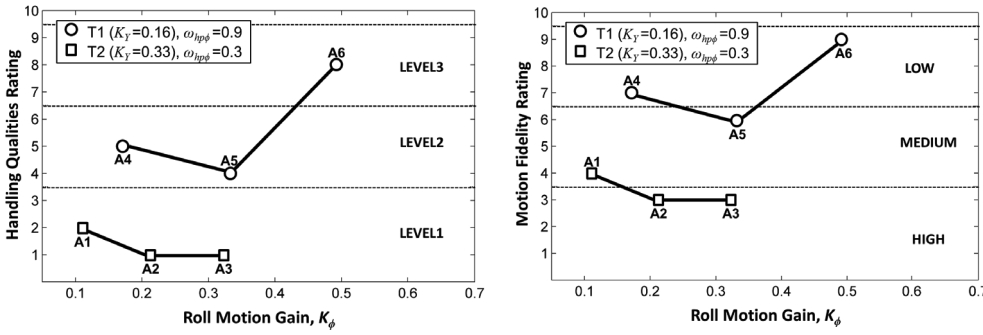


Figure 13. Handling qualities and motion fidelity ratings with increasing roll motion gain.

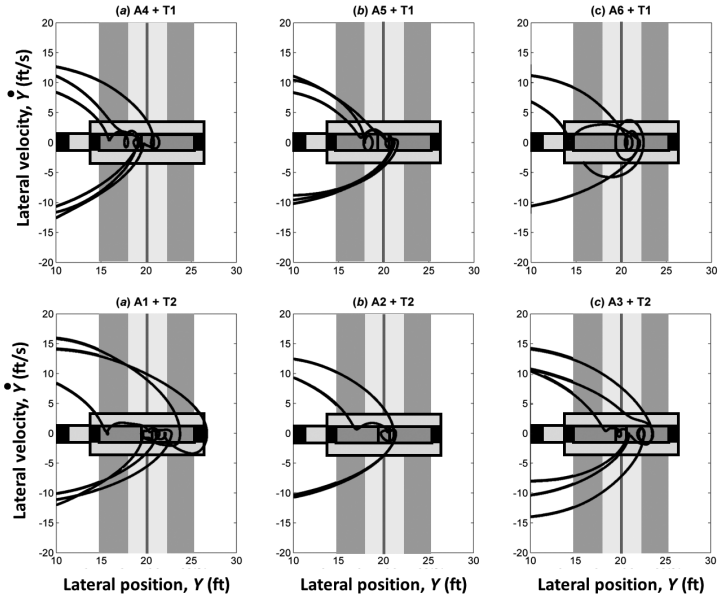


Figure 14. Phase plane portraits with increasing roll motion gain (left to right), at low sway gain (top row) and medium sway gain (bottom row).

of simulator fidelity and task immersion within a synthetic environment has also been reported in Refs 3 and 6.

5.3 Increasing roll motion gain

Figure 13 shows the pilot's HQRs and motion fidelity ratings and Fig. 14 shows the phase-plane portraits, with increasing roll motion gain; again only the right-hand target-capture portion of the manoeuvre is shown. The impact of increasing the roll motion gain depended on two other factors – (*i*) the sway motion gain; and (*ii*) the roll-axis motion filter break-frequency. The effect of the roll-axis break-frequency will be discussed separately. At the low sway motion gain (top row of Fig. 14) the effect of increasing the roll motion gain was to amplify the false sway accelerations caused by roll motion of the platform. High roll motion gains coupled with a low sway motion gain resulted in motion cues which, according to the pilot, were 'uncomfortable' and 'unrealistic'. In

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fact, at the highest roll motion gain (A6) biodynamic feedback was experienced and the pilot had to abandon the task, reporting that 'sharp acceleration-deceleration cues are causing body-sway, resulting in bio-coupling with the stick, got to let go to stop'. Biodynamic feedback occurs when sharp movements of the motion platform cause the pilot to make involuntary movements of the cockpit controls, leading to further sharp platform movements[23]. It was also clear that at high roll motion gains the pilot was acutely aware of the location of the motion platform's rotational centre, since he made the comment 'it's almost as if the aircraft rotation is occurring beneath me'. On the other hand, with the higher sway motion gain (bottom row of Fig. 14), which provided more lateral travel to compensate for the false sway accelerations, then increases in roll motion gain did not degrade the pilot's opinion of motion fidelity or significantly reduce his task performance (Fig. 13).

5.4 Increasing roll motion break-frequency

Figure 15 shows the pilot's subjective ratings with two different roll-axis motion filter break-frequencies. The pilot's comments with the highest break frequency were — 'No impression of continuing bank angle from the motion cues' and 'subtle mismatch between the visual and motion cues'. These comments reflect the greater attenuation of low-frequency, sustained roll motion cues and the increased phase shift between the vestibular and the visual motion cues, resulting from the increased break-frequency. The effect of increasing the motion filter break-frequency on the platform roll response is illustrated in Fig. 16, which shows the motion platform roll rate for a single sidestep manoeuvre. The solid grey line in Fig. 16 is the platform roll rate command from the motion drive algorithm, $\dot{\phi}_s$, the dotted grey outline is the achieved platform roll rate measured by a sensor mounted inside the cockpit, and the solid black line is the roll rate that would be commanded if the roll-axis motion filter, HP_ϕ, was removed from the motion drive algorithm, thus removing the source of the phase shift, i.e. if $HP_\phi = 1$ in Fig. 7 then the commanded platform roll rate would be equal to the outside-world visual roll rate, $\dot{\phi}$, scaled by the motion gain K_ϕ. It can be seen that at the lower break-frequency, the two versions of platform roll rate are in very close agreement. However, at the higher break-frequency, significant distortions are introduced by the washout filter. This distortion will, of course, manifest itself as a mismatch between the vestibular motion cues and the cues from the visual scene as experienced by the pilot. The pilot's subjective ratings show that, at the high break-frequency, the only way to improve pilot opinion is to reduce the roll motion filter gain (Fig. 15). This effectively masks the problem by reducing the amplitude of the roll motion cues, making the vestibular motion to visual motion cue mismatch less obvious; a similar finding was reported by Bray in Ref. 6. On the other hand, at the low break-frequency, pilot opinion either improves or remains unchanged with increasing roll motion gain (Fig. 15).

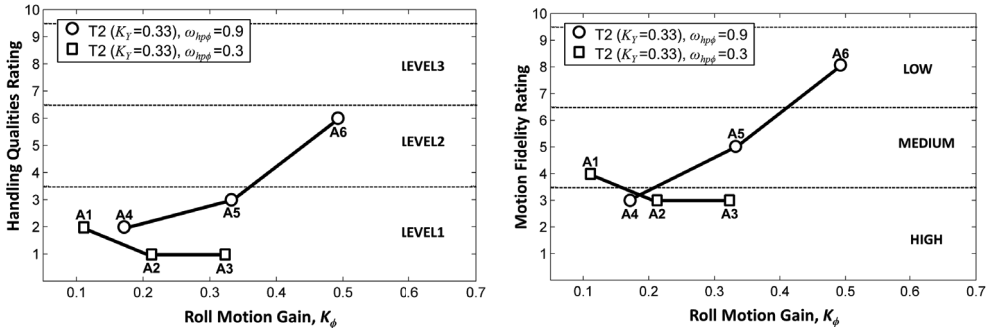


Figure 15. Handling qualities and motion fidelity ratings with increasing roll motion gain and two different values of roll-axis break-frequency.

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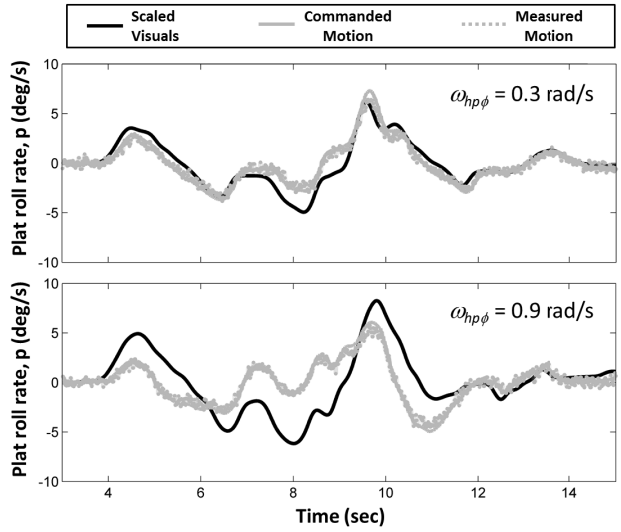


Figure 16. Motion platform roll rate experienced with two different roll-axis motion filter break-frequencies.

6.0 DISCUSSION

Earlier, in the analysis section, it was stated that false sway motion cues are reduced and, therefore, simulation 'fidelity' increased, when the gain of the sway-axis motion filter, $K_y HP_y$, is increased to compensate for false cues and, alternatively, that a reduction in the roll-axis motion filter gain, $K_\phi HP_\phi$, would also lead to reductions in the false sway motion cues (Equation (10)). This statement is largely confirmed by the results of the simulator experiment. Figure 11 shows that as the sway-axis motion gain increased the pilot's subjective ratings improved. The exception, at the highest sway gain, is when mechanical noise from the motion platform, and the more obvious 'washout' sensation, became a distraction. Pilot objections to the mechanical noise associated with large sway-axis displacements have also been noted by Bray in Ref. 6 and Schroeder in Ref. 3. Bray's solution was to halve the roll-axis motion gain, thus reducing the lateral travel required to compensate for false sway motion cues. It can be seen from Fig. 11 that in this experiment halving the roll-axis motion gain had a similar effect, allowing a higher sway-axis gain to be achieved before degradation of the pilot's subjective ratings occurs.

If the best combination of filter gains is a high sway-axis gain and a reduced roll-axis gain, then from Equation (10) it can also be seen that the worst combination is the reverse (i.e. a high roll-axis gain and a low sway-axis gain). This is also confirmed by the experimental results (Fig. 13), where a high gain in the roll-axis, coupled with a low sway-axis gain, led to adverse pilot-simulator biodynamic coupling. This phenomenon has not been reported in any of the previous studies and may be a particular issue with short-stroke electric motion systems, which have the potential to react much faster to motion commands than larger hydraulic or hybrid systems. The higher acceleration onset capability, or 'jerk' rate, of modern electric motion systems can sometimes be perceived as too 'strong' or 'sharp'[24]. One method of reducing this effect is, of course, to increase the corresponding sway motion travel to compensate for false sway cues induced by roll motion, particularly those induced by transient roll accelerations. In our experiments the 'abrupt' and 'uncomfortable' nature of the false sway cues caused by transient roll-axis accelerations was

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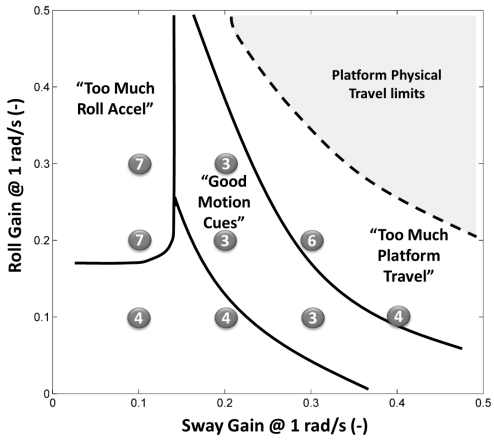


Figure 17. Summary of motion fidelity ratings with $\omega_{hp\phi}$ = 0·3.

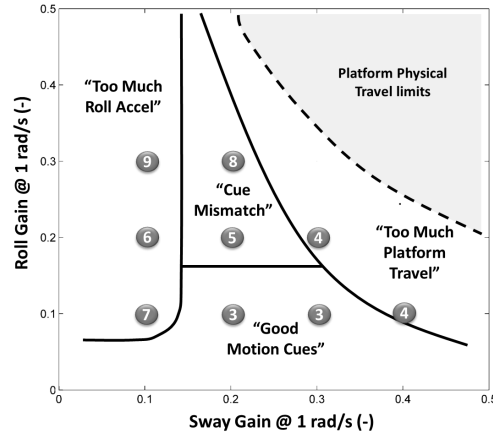


Figure 18. Summary of motion fidelity ratings with $\omega_{hp\phi}$ = 0·9.

a far bigger issue than false tilt cues caused by orientation of the gravity vector (i.e. the 'leans'). The latter being the main focus of much of the previous research carried out on large motion systems. One explanation, for this apparent disagreement, is that producing sustained simulator bank angles, which lead to false tilt cues, is much more challenging with small motion systems employing high-order washout filters.

Another important result is the effect of increasing the roll-axis motion filter break-frequency. The pilot's preference for reduced roll motion amplitude at the highest break-frequency (i.e. the highest phase shift between vestibular and visual motion cues) is striking (Fig. 15). This reflects a strong desire by the pilot to reduce those vestibular cues which are in conflict with the cues from the visual scene. A similar finding was reported by Bray[6], who found that a roll-axis break-frequency of 0·5rad/sec led to pilot complaints of a slight contradiction between visual and motion cues, and only by halving the roll-axis motion gain did pilot opinion improve. Bray expands upon this in Ref. 25 suggesting that a break frequency above 0·7rad/sec can lead to phase distortions in cockpit rotational motion, that produce strong sensations of motion-visual cue disparity. The phase shift introduced by Bray's motion filters was between 43º (0·5rad/sec) and 62·5º (0·7rad/sec) at an input frequency of 1rad/sec. Grant and Lee[26] discovered that the average detectable motion-visual phase error threshold measured in a simulator was around 57º. Furthermore, Sinacori[11] and Schroeder[12] both suggested that motion filter break-frequencies should be selected to give less than 30º of phase error at the predominant task frequency. In this experiment the roll-axis filter with the lowest break-frequency (0·3rad/sec) introduced a phase shift, between the visual and vestibular motion cues, of around 36º at 1rad/sec; this filter meets the Bray and Grant criteria and comes close to meeting the Sinacori/Schroeder criteria. On the other hand, the roll-axis motion filter with the highest break-frequency (0·9rad/sec) introduced a phase shift of nearly 90º at 1rad/sec, which meets none of the above criteria. The results of this experiment would, therefore, tend to reinforce the previous research. However, without further testing, at a range of break-frequencies, it is unclear where the threshold lays, beyond which pilots can sense disparities between the vestibular and visual motion cues.

The motion fidelity ratings are summarised in the form of proposed fidelity criteria for short-stroke hexapod platforms in Figs 17 and 18, showing tentative boundaries based on pilot comment and informed by the above discussion.

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7.0 CONCLUSIONS AND RECOMMENDATIONS

This research has provided both subjective and objective evidence regarding the impact of motion filter settings in the roll-sway axes on pilot perceptions of motion cueing fidelity in a typical helicopter low-speed sidestep manoeuvre. These findings fill a gap in the current knowledge, since very few motion cueing studies have concentrated exclusively on short-stroke platforms. The results have been compared to other research conducted on a range of large motion systems and, although in some cases the capabilities of the short-stroke platform have limited this comparison, many of the results appear to be in agreement. 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. The results confirm that appropriate selection of motion filter coefficients (i.e. motion tuning) is, as ever, critical to achieving high fidelity simulation. More specifically the following conclusions are drawn:

- In a roll-sway sidestep task, good motion cues were obtained by careful selection of the roll- and sway-axis motion gains. Selecting a sway-axis gain which was too low and a roll-axis gain that was too high, resulted in 'harsh' and 'abrupt' motion cues, due to lateral accelerations induced at the pilot's seat by platform roll motion. This led to poor motion fidelity ratings and significantly degraded performance.
- The roll-axis motion filter break-frequency should not be set too high. In this experiment a break-frequency of 0·9rad/sec elicited strong pilot objections, due to mismatch (phase shift) between the vestibular and the visual motion cues. With a break-frequency of 0.9rad/sec the only way to reduce pilot objections was to decrease the roll-axis motion gain, effectively 'masking' the contradictions between the visual and motion cues.
- It was difficult to use the full sway motion performance of the platform, due to audible noise generated by the motion system's mechanisms during large lateral displacements. The washout period of the platform response was also more evident for large simulator displacements.
- The motion cueing experiments 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. Intermediate values of roll-axis motion filter break-frequency (e.g. 0·6 and 0·7rad/sec) should also be investigated to determine the threshold of pilot indifference to phase disparities between the visual and vestibular motion cues.
- The motion fidelity rating scale, extended relative to previously used scales, 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.
- The motion cueing experiments should be repeated on a different simulator, using the same task and rating scales. This would help to determine if the results are repeatable and could, therefore, be generalised across a range of different simulators.
- The results from this experiment are so compelling with regard to the value and utility of vestibular motion cues for low-speed helicopter flying tasks, achievable using small agile motion platforms, that the implications for the importance of motion in training simulators should not be ignored. This research study has not addressed this matter directly but we recommend that the results be used as the basis of further work, to quantify the importance of vestibular motion cues in the acquisition, development and assessment of flying skills using current and future training devices.

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REFERENCES

1. REID, L.D. and NAHON, M.A. Response of airline pilots to variations in flight simulator motion algorithms, *J Aircr*, July 1988, **25**, (7), pp 639-646.
2. GRANT, P.R. and REID, L.D. Motion washout filter tuning: Rules and requirements, *J Aircr*, March-April 1997, **34**, (2), pp 145-151.
3. SCHROEDER, J.A., CHUNG, W.W. and LAFORCE, S. Effects of roll and lateral flight simulation motion gains on a sidestep task, 1997, American Helicopter Society 53rd Annual Forum, 29 April-1 May 1997,Virginia Beach, VA, USA.
4. STAPLEFORD, R.L., PETERS, R.A. and ALEX, F.R. Experiments and a model for pilot dynamics with visual and motion inputs, 1969, NASA CR-1325.
5. JEX, H.R., MAGDALENO, R.E. and JUNKER, A.M. Roll tracking effects of G-vector tilt and various types of motion washout, 1978, NASA CP-2060, pp 463-502.
6. BRAY, R.S. Initial operating experience with an aircraft simulator having extensive lateral motion, 1972, NASA-TM-X-62155.
7. VAN GOOL, M.F.C. Influence of motion wash-out filters on pilot tracking performance, 1978, AGARD-CP-249, AGARD Flight Mechanics Panel Specialists' Meeting on 'Piloted Aircraft Environment Simulation Techniques', 24-27 April 1978, Brussels, Belgium.
8. BERGERON, H.P., ADAMS, J.J. and HURT, G.J. The effects of motion cues and motion scaling on one- and two-axis compensatory control tasks, 1971, NASA TN D-6110.
9. SHIRACHI, D.K. and SHIRLEY, R.S. Visual/motion cue mismatch in a coordinated roll maneuver, 1981, NASA-CR-166259.
10. ASHKENAS, I.L. Collected flight and simulation comparisons and considerations, 1985, AGARD-CP-408, AGARD Flight Mechanics Panel Symposium on 'Flight Simulation', 30 September-3 October 1985, Cambridge, UK.
11. SINACORI, J.B. The determination of some requirements for a helicopter flight research simulation facility, 1977, NASA-CR-152066.
12. SCHROEDER, J.A. Helicopter flight simulation motion platform requirements, 1999, NASA-TP-1999-208766.
13. MIKULA, J., CHUNG, W.W. and TRAN, D. Motion fidelity criteria for roll-lateral translational tasks, 1999, AIAA Paper 99-4329, AIAA Modeling and Simulation Technologies Conference, 9-11 August 1999, Portland, OR, USA.
14. CHUNG, W.W., ROBINSON, D.J., WONG, J. and TRAN, D. Investigation of roll-lateral coordinated motion requirements with a conventional hexapod motion platform, 1998, AIAA Paper 98-4172, AIAA Modeling and Simulation Technologies Conference, 10-12 August 1998, Boston, MA, USA.
15. BEYKIRCH, K., NIEUWENHUIZEM, F.M., TEUFEL, H.J., NUSSECK, H.G., BULTER, J.S. and BULTHOFF, H.H. Control of a lateral helicopter side-step maneuvre on an anthropomorphic robot, 2007, AIAA Paper 2007-6801, AIAA Modeling and Simulation Technologies Conference, 20-23 August 2007, Hilton Head, SC, USA.
16. VAN BIERVLIET, F. LM^2 — Lateral manoeuvring motion, 2008, RAeS Flight Simulation Group 'Expanding Horizons: Technology Advances in Flight Simulation' conference, 4-5 June 2008, London, UK.
17. HODGE, S.J., PERFECT, P., PADFIELD, G.D. and WHITE, M.D. Optimising the yaw motion cues available from a short stroke hexapod motion platform, *Aeronaut J*, January 2014, **118**, (1210).
18. FIELDING, C. and SOUTHWORTH, M.R. Piloted simulation developments of STOVL aircraft handling qualities, 2001, AIAA Paper 2001-4263, AIAA Guidance, Navigation and Control Conference, 6-9 August 2001, Montreal, Canada.

https://doi.org/10.1017/S000192400001023X Published online by Cambridge University Press

19. PADFIELD, G.D. *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling*, Second Edition, 2007, Blackwell Publishing, Oxford, UK.
20. COOPER, G.E. and HARPER, R.P. The use of pilot rating in the evaluation of aircraft handling qualities, 1969, NASA TN D-5153.
21. 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.
22. HODGE, S.J., PERFECT, P., PADFIELD, G.D. and WHITE, M.D. Optimising the cues available from a short-stroke hexapod motion platform, 2011, American Helicopter Society 67th Annual Forum, 3-5 May 2011, Virginia Beach, VA, USA.
23. VENROOIJ, J., YILMAZ, D., PAVEL, M. D., QUARANTA, G., JUMP, M. and MULDER, M. Measuring biodynamic feedthrough in helicopters, 2011, 37th European Rotorcraft Forum, 13-15 September 2011, Gallarate, Italy.
24. GRANT, P.R. and HAYCOCK, B. Effect of jerk and acceleration on perception of motion strength, *J Aircr*, July-August 2008, **45**, (4), pp 1190-1197.
25. BRAY, R.S. Visual and motion cueing in helicopter simulation, 1985, AGARD-CP-408, AGARD Flight Mechanics Panel Symposium on 'Flight Simulation', 30 September-3 October 1985, Cambridge, UK.
26. GRANT, P.R. and LEE, P.T.S. Motion-visual phase-error detection in a flight simulator, *J Aircr*, May-June 2007, **44**, (3), pp 927-935.

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