Analysis of Motion Parameter Variations for Rotorcraft Flight Simulators

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ABSTRACT

No standard guidelines currently exist for tuning rotorcraft flight simulation motion platforms. This often leads to systems that are poorly utilized. This paper presents results from a study to determine effects of parameter variations in two rotorcraft research simulators. Investigations were conducted using three Mission Task Elements (MTEs), and both subjective and objective analysis is used to determine the suitability of motion settings. Motion settings are compared with recommended Objective Motion Cueing Test (OMCT) boundaries for fixed-wing aircraft. Results show differences in the fidelity of motion settings, and recommendations specifically for rotorcraft simulation are presented.

NOTATION

F = Fitness of the motion response, -
G = Maximum gain of the motion filter, -
H = Gain, -
HP = High pass motion filter
K = Maximum gain of the motion filter, -
K_1, K_2, K_3, K_4 = Constant weighting factors, -
L_{IS} = Transformation from simulator to inertial reference frame, -
LP = Low pass motion filter
N = Number of axes used in fitness calculation, -
T_s = Transformation from scaled angular rates to Euler angle rates, -
X = Function used to penalize results where large imbalance between motion parameters is found

f_x, f_y, f_z = Specific force of the aircraft, m/s^2
g_I = Gravitational force, inertial reference frame, m/s^2
p, q, r = Rotational velocities of aircraft, deg/s
u, v, w = Translational accelerations of the aircraft, m/s^2

Δ = Change in parameter, deg, $-$
Φ = Phase of the motion response, deg

ω = Break frequency of motion filter, deg/s
ζ = Damping ratio of motion filter, -
$\angle H$ = Phase distortion, deg

$_{HP}$ = High pass filter
$_{LP}$ = Low pass filter
$_i$ = Response in the i-th axis
$_{|\omega=j}$ = Response at the frequency $j\ rad/s$

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INTRODUCTION

Despite many successful and fruitful research campaigns, there remains no clear method to employ when tuning flight simulator motion platforms. This is primarily due to uncertainty regarding the best settings for motion filter parameters. This is true both for fixed- and rotary-winged simulation.

Motion platforms rely on a compromise between maximum motion cueing and available platform space. The size of the motion platform defines the available design space. To utilize motion space, motion washout algorithms are employed. A version of the Classical Washout Algorithm (CWA), originally developed by Reid and Nahon (Ref. 1) is shown in Fig. 1. The washout algorithm attenuates motion gain, and produces a frequency dependent response. Vehicle rate and specific forces are used as inputs to the algorithm. One-to-one motion would be where these forces are perfectly reproduced by the platform. In currently operational rotorcraft simulators, it is not possible to perfectly reproduce these required forces.

NASA's Vertical Motion Simulator (VMS) has the ability to reproduce very large motion in a number of axes, which can be configured as required for investigations (Ref. 2). Novel simulator platform configurations, departing from the traditional hexapod approach, have yet to become both affordable for the mass market and demonstrated in training scenarios. Examples are both the Desdemona simulator (Ref. 3), and Max Planck's CyberMotion (Ref. 4) and CableRobot simulators (Ref. 5). The German Aerospace Center (DLR) also operates a Robot Arm simulator, which has been used to demonstrate flying tasks (Ref. 6). To the authors' knowledge, all current training, both in fixed- and rotary-wing simulators, where full motion is used, is conducted using a hexapod type platform. This is due to experience and cost. Six actuator legs are connected to a fixed lower platform and a free upper platform to provide six degrees-of-freedom (DoF). The actuators are rigidly fixed to form a constrained system. Unfortunately, for the majority of flight conditions, these motion platforms cannot reproduce forces expected in-flight. This is particularly

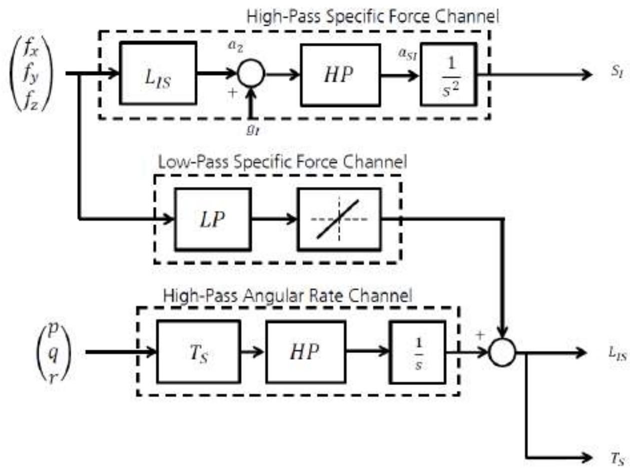


Fig. 1: Classical Washout Algorithm (CWA) motion filtering strategy.

true of sustained translational specific forces.

Hexapod platforms usually feature a filtering strategy that includes both high-pass (HP) and low-pass (LP) filtering elements. Within the filtering strategy, both HP and LP filters can feature different structures in order to improve the motion response. Previous researchers have concluded that 3rd order filtering, with 'return to neutral' capabilities is required for rotorcraft simulators featuring hexapod motion platforms (Ref. 7). Manufacturers often attempt to improve the utility of the motion platform by employing adaptive filtering techniques. One example of this is used DLR's Air Vehicle Simulator (AVES), where an Advanced Platform Kinematics block (APK), which is propriety software of MOOG (Ref. 8), is used within a structure similar to the CWA shown in Fig. 1. The use of adaptive and non-linear filtering techniques can lead to difficulty in analysis of the quality of the filter settings.

Currently, no objective methods (relating specifically to the motion filter settings) must be applied during the commissioning of motion platforms used for training. Other aspects of the simulation, such as the visual and control systems, require stringent assessment using both software and system tests. Motion platforms are usually tuned during delivery of the simulator, by the manufacturer and a chosen pilot. This is subjectively conducted, through communication between the pilot and the engineer. Often the end user of the simulator has either no direct access or experience to re-tune filter parameters if required. Tuned motion is usually the result of the experience and heuristics (Ref. 9)

For rotorcraft, unlike Handling Qualities (HQ) evaluations, there are no specific guidelines for delivering subjective opinion of the quality of motion cues. This leads to low confidence in the perceived fidelity of systems, and large scatter between systems across the world. Unstructured comments by assessing pilots are used to reach a suitable point where motion does not adversely affect performance. Not only are filters the result of the assessing pilots opinion, they are also in little respect optimized and robust to the future use of the simulator. Subjective tuning is usually conducted through both open-loop (i.e. isolated control inputs) and closed-loop (i.e. specific task performance) scenarios.

Although some researchers have suggested improvements to the subjective guidelines for tuning (Refs. 7, 10), most research regarding motion fidelity has been to design and test objective criteria, to be used for both tuning and evaluation (e.g. for rotorcraft (Refs. 11, 12)). These objective techniques have not been readily applied due to a lack of demand from manufacturers and operators. Whilst systems meet current certification requirements (Refs. 13, 14), there is little demand for improvement from operators. Recently, renewed efforts have been made to introduce new criteria to improve the quality of motion configurations (Refs. 15–17). Researchers have also published academic papers outlining best practices to achieving useful motion cueing behavior. These are summarised in Ref. 18.

Although methods to objectively asses the quality of motion cueing are not new, many early experiments failed to consider the impact of the complete simulation on motion fidelity, without specific thought for visual and motion systems, tasks, and vehicle dynamics. This led to significant inconsistencies between results (Ref. 12). Furthermore, a large amount of valuable motion research, for both fixed- and rotary-wing systems, was conducted over 20 years ago. Since this time, there have been many advancements in both simulator motion platform capabilities and the simulators themselves. Particularly important for rotorcraft simulation, significantly wider field-of-view (FoV) is achievable within simulation devices. CS-FSTD(H) standards require Level D simulators to feature a FoV of at least 180°x60° (Ref. 14). This is significantly larger than the FoV available from rotorcraft motion cueing investigations conducted in the VMS (Refs. 11, 12), University of Toronto (UTIAS) Simulator (Ref. 19), and Technical University Delft SIMONA Simulator (Ref. 20). Whilst all experiments offer great insight into the effects of motion cueing, it is hypothesized that modern simulators require an update to proposed motion requirements.

Principles of Motion Cueing

The inputs to the motion algorithm are both the vehicle body rotational rates (p, q, r) and specific forces (f_x, f_y, f_z). Specific force is defined as the gravitational-less force acting on the aircraft. These two primary input channels are fed into the three primary channels of the algorithm; the HP specific force channel, the LP specific force channel, and the HP angular rate channel.

The specific forces are fed into both HP and LP channels. The HP channel is used to remove low-frequency motions, which would result in the motion platform reaching actuator travel limits. The LP filters produce low frequency roll motion, in order to produce additional specific forces, removed through the HP filter. This is achieved through the manipulation of the gravity vector, as is often referred to as 'g-tilt'.

It is only effective if the pilot cannot sense that it is provided through rotation and, therefore, the channel is rate limited to around 2-3 deg/s (Ref. 7).

The vehicle specific force is fed both into the LP filter channel, and into the transformation matrix, to transfer the forces from the simulator coordinate system to the inertial coordinate system (L_{IS}). Once forces are in the inertial coordinate system, gravity (removed in the calculation of specific force) is re-applied. Filtering is then completed, giving motion accelerations, which are integrated twice to obtain platform displacement.

The HP filtering in the rotational channel is conducted using a similar method. First the signals are translated into Euler angular rates (T_s), before filtering is conducted. The output of the 3rd order filter is integrated once to obtain angular displacement. At this stage, the output from the LP channel is added to the result, to give the total angular displacement of the motion platform.

When setting motion filter parameters, the engineer can use a number of techniques to ensure good motion cues. Firstly, the accelerations at low frequency are not as important, and visual is dominant in this range (<0.1 Hz/0.6 rad/s (Ref. 7)). Secondly, in the specific force delivery, the HP and LP filters add phase lead and lag respectively. Therefore, a combination of the two can lead to a reduction in overall phase distortion. Motion filter preferences vary depending on simulator utility and manufacturer, and are very dependent upon the utilization of the simulator. For this reason, the motion parameters used in fixed-wing simulators are not usually appropriate for rotorcraft simulators.

This paper reports results from new investigations, conducted in two motion-based research simulators, to determine the influence of motion parameters on the fidelity. These experiments are necessary to update the literature of cases for rotorcraft simulators regarding motion requirements.

A number of candidate tasks for motion research are investigated, and parameter variations are made in key axes. Attempts are made to ensure that all other motion settings are acceptable. Both subjective and objective measures are used to evaluate the fidelity, specifically for the application of each task, of each motion setting. Conclusions from this work, conducted with a single very experienced test pilot, are drawn from results obtained. Results obtained are compared with those contained within the literature, to further validate the conclusions.

The paper proceeds as follows. Firstly, the role of motion cueing is discussed in more detail, outlining the methods used to provide the pilot with vestibular motion cues, and the methods used for tuning. Secondly, the test platforms and vehicle models used for the investigation are introduced. Next, results from the application of the Objective Motion Cueing Test (OMCT) technique on the two platforms are discussed, along with an overview of assessment methods used in this investigation. Next, results obtained from the investigation are presented. Conclusions are drawn from results obtained, and refined OMCT boundaries are presented. Results from one optimized motion case are presented. Finally, conclusions from the complete test campaign are drawn, and recommendations for future work are outlined.

EXPERIMENTAL SETUP

Motion Platforms

In 2013, DLR opened the AVES simulation center, which consists of two full flight simulators; one featuring an A320 cockpit and one EC135 cockpit (See Fig. 2a, (Ref. 21)). The EC135 cockpit is configured to represent the Active Control Technology/Flying Helicopter Simulator (ACT/FHS), a highly modified version of the aircraft type. The facility features interchangeable cockpits, which can be installed onto a hexapod platform provided by MOOG. The simulator is capable of achieving the highest motion standards recommended by EASA (Ref. 14). In addition, each actuator leg has a maximum displacement (stroke) of approximately 1.5m. AVES houses a purpose built cockpit of the ACT/FHS experimental helicopter.

AVES is used for both research and pre-flight testing of the ACT/FHS. The simulator includes a full non-linear flight simulation model of the ACT/FHS bare airframe in addition to the full hardware and software used in the aircraft's experimental system (Ref. 22). This creates an ideal platform for pre-flight testing, where test pilots and engineers can assess configurations prior to in-flight testing. The use of the simulator for flight test preparation increases safety and reduces the required in-flight testing time.

The University of Liverpool (UoL) maintains and operates the HELIFLIGHT-R simulator (see Fig. 2b, (Ref. 23)). The simulator dome is mounted on a short-stroke 6-DoF motion platform (Ref. 7), also manufactured by MOOG. It features a generic and reconfigurable helicopter cockpit. The simulator is used both for teaching and research projects. It was used extensively within the project Lifting Standards (Project No:EP/G002932/1) where model validation and transfer of training studies were conducted in collaboration with the Canadian National Research Council (NRC) (Ref. 24).

Both simulators benefit from large visual projection, which is of significant benefit for rotorcraft flight investigations. AVES has a maximum FoV 240°x93° and HELIFLIGHT-R has a maximum FoV 210°x70°. A comparison of the limits of both motion platforms for both simulators is shown in Table 1.

Vehicle Models

For this investigation, vehicle models most frequently used within both simulators were used. This was to observe whether general motion requirements and recommendations could be exposed from the study. This is the same practice that was used in investigations to obtain OMCT fidelity boundaries (Ref. 16). Both vehicle models featured Rate Command

Table 1: AVES and HELIFLIGHT-R motion platform limits.

	AVES			HELIFLIGHT-R		
	Max. Exc.	Max Vel.	Max Acc.	Max. Exc.	Max Vel.	Max Acc.
$Surge(Tx)$	+1.44 m/-1.45 m	$\pm 1.0\ m/s$	$\pm 0.66\ g$	+0.57 m/-0.46 m	$\pm 0.5\ m/s$	$\pm 0.71\ g$
$Sway(Ty)$	+1.26 m/-1.26 m	$\pm 1.0\ m/s$	$\pm 0.66\ g$	+0.47 m/-0.47 m	$\pm 0.7\ m/s$	$\pm 0.71\ g$
$Heave(Tz)$	+0.95 m/-0.95 m	$\pm 0.75\ m/s$	$\pm 0.92\ g$	+0.39 m/-0.39 m	$\pm 0.7\ m/s$	$\pm 1.02\ g$
$Roll(Rx)$	+27°/-27°	$\pm 21°/s$	$> \pm\ 140\ °/s^2$	+23.2°/-23.2°	$\pm 35°/s$	$> \pm\ 300\ °/s^2$
$Pitch(Ry)$	+34°/-31°	$\pm 21°/s$	$> \pm\ 140\ °/s^2$	+25.6°/-23.3°	$\pm 34°/s$	$> \pm\ 300\ °/s^2$
$Yaw(Rz)$	+32°/-32°	$\pm 24°/s$	$> \pm\ 240\ °/s^2$	+24.3°/-24.3°	$\pm 36°/s$	$> \pm\ 500\ °/s^2$

systems. The HQs of the ACT/FHS and Bell-412 models used in the investigation are discussed in detail in Ref. 25 and Ref. 24 respectively. For comparison, Table 2 displays some of the HQ levels of some of the HQ parameters of the models.

Table 2: HQs of vehicle models at low speed.

HQ Criteria	DLR (ACT/FHS)	UoL (Bell-412)
Bandwidth Pitch	Level 1/2	??
Bandwidth Roll	Level 1	??
Cross Coupling	Level 1/2	??
Quickness (all axes)	Level 1	??
Low Frequency Phugoid (Full and Divided Attention)	Level 2	??
Control Power (all axes)	Level 1	??

In previous research, it was hypothesized that the results are influenced by the HQs of the vehicle, and that this should be more prominent in future motion research regarding rotorcraft (Ref. 26). Due to the link between motion and HQs, vehicles with very good HQs are likely not to expose as many deficiencies as those with poor HQs. Furthermore, vehicles with poor HQs can impact the pilot assessment of the quality of the motion. During completion of test maneuvers, pilots could be unable to identify whether deficiencies they feel come directly from the vehicle model or from the motion delivered. Finally, it is important to remember that the motion which is suitable for one vehicle is not necessarily applicable to others. For this reason, it is important to have a continuous tuning method for changes to simulation models, and is the reason why research defining objective tuning techniques has been initiated (Refs. 26–28).

Objective Tuning Techniques

The current study uses two objective methods to compare against pilot subjective comments and objective analysis. These two methods are discussed below.

Objective Motion Cueing Test Technique (OMCT) The Objective Motion Cueing Test Technique (OMCT) is an objective procedure, recently included within the 3rd revision of ICAO 9625 (Manual of Criteria for the Qualification of Flight Simulation Training Devices, (Ref. 13)). It is designed to determine the characteristics of the motion filtering between the range of 0.1 rad/s to 15 rad/s. A full description of the test procedure, and results that have been determined to date through its application are included within Ref.16.

The test comprises of 12 constant frequency sinusodial input signals. These are then fed into 10 input/output combinations to determine the response of the motion platform with respect to the input signal in question. The technique comprises of both on-axis and off-axis responses. Boundaries suitable for transport aircraft have been published (Ref. 16). These were ascertained from undertaking the OMCT procedure in 10 simulation devices, ranging from uncertified simulators to full (Level D) training simulators.

To date, research only from the application of the method to fixed-wing simulation has been published. The boundaries recommended for fixed-wing transport aircraft, are shown for the on-axis responses in Fig. 3. Fidelity of the simulation with respect to the off-axis OMCT boundaries is not dealt with explicitly in this paper.

Several open questions remain regarding the application of OMCT, and the proposed boundaries for transport aircraft. These have been considered by Hosman and Advani (Ref. 16). Boundaries have been determined as a compromise between currently tuned systems. Whilst these systems have been tuned subjectively, no clinical investigation into the quality of these cueing systems has been conducted to validate the fidelity of motion filter settings. It has been suggested that further research is conducted to refine boundaries presented (Ref. 16). Zaal et al. (Refs. 29, 30) have made efforts to begin this research, through application of the technique using various fixed-wing tasks in the VMS. These initial results are encouraging.

Another reservation with the application of OMCT is its susceptibility to system non-linearities. Possible results from subsequent non-linearities are shown in Ref.16. This must be considered further in the future application of the tool. Since initial tests including the results from a number of simulation platforms, the method has been investigated on a number of additional platforms (Refs. 31–35).

Sinacori/Schroeder Criteria The Sinacori criteria (Ref. 11), which was later refined by Schroeder (Ref. 12)

(a) AVES - DLR, Braunschweig

(b) HELIFLIGHT-R - UoL, Liverpool

Fig. 2: Research simulators used in investigation.

was developed using the NASA Vertical Motion Simulator (VMS) and has since been applied to a number of simulators within a number of research campaigns (Refs. 29, 36–38). A number of drawbacks with the criteria have led to reluctance in its general application. These include the lack of Low-Pass filter observation and the difficulty in achieving ‘High-fidelity’ requirements.

Sinacori presented boundaries outlining Low, Medium, and High fidelity motion. These were later refined by Schroeder (Ref. 12). Motion requirements are separated by translational and rotational settings. In the same study, Schroeder also proposed criteria for rotational/translational balance in filtering. Grant (Ref. 19) confirmed some results from Schroeder’s yaw capture task. It has been stated in previous studies that these motion boundaries are not achievable with standard hexapod motion platforms (Ref. 7). This is primarily due to the translational requirements.

Evaluation Prior to any specific investigations, standard motion settings used in the two simulators were assessed using both the OMCT test procedure and the Schroeder fidelity boundaries.

Figure 3 shows the standard motion settings used in both AVES and HELIFLIGHT-R. These are shown with respect to current boundaries obtained for transport-airplane type aircraft. It is not expected that the boundaries will be directly applicable to rotorcraft. However, the boundaries are shown for comparison.

The two sets of motion filters shown have been obtained through extensive pilot subjective tuning efforts. Subsequently, they have been used in various large research campaigns at their respective institutions. An initial comparison between results and the fixed-wing OMCT boundaries shows a mismatch in some axes. This supports the hypothesis that the boundaries are not directly applicable, or tailored, to rotorcraft simulators.

A number of differences are found between the results from both simulators and the OMCT boundaries. The first is the lower frequency (less than 1 rad/s) translational forces (surge and sway). These are found to be much lower than the OMCT boundaries. Furthermore, this has an influence on the phase distortion, which is larger than the OMCT boundaries. AVES is closer to the boundaries, and also has a very low phase distortion at 1 rad/s (the frequency at which the vestibular system is most sensitive (Ref. 12)). The second difference is the pitch channel response. In the OMCT guidelines, this is determined from a pitch input and the corresponding signal in the surge translation axis (pitch causes a translation). As the g-tilt cueing is lower in both rotorcraft simulators, the pitch boundaries below 1 rad/s are not reached. Moreover, pitch motion in the entire envelope is not considered large enough to meet boundaries. Roll motion is also found not to meet the requirements of the OMCT boundaries.

The same filter settings are shown against Schroeder fidelity boundaries in Fig. 4. As shown, for both simulators, all filter parameters lie within the low fidelity region. Furthermore, due to the lack of LP filters in the calculation, all translational results appear very low fidelity. Compared to OMCT results, results plotted against Schroeder boundaries suggest lower fidelity for both settings of both simulators.

As both simulator motion settings have been evaluated in previous investigations by a number of pilots, a mismatch is apparent between the objective fidelity requirements and the subjective feeling of motion. Both motion systems have been deemed acceptable by assessing pilots for a number of task manoeuvres. The mismatch between the subjective and objective appraisal acts as motivation for the current study.

TASKS

Task selection is paramount when the motion tuning suitability is to be observed. Motion is task (and operator dependent); Motion in one situation may not be acceptable in another. For this reason, it is unlikely that OMCT boundaries shown in Fig.

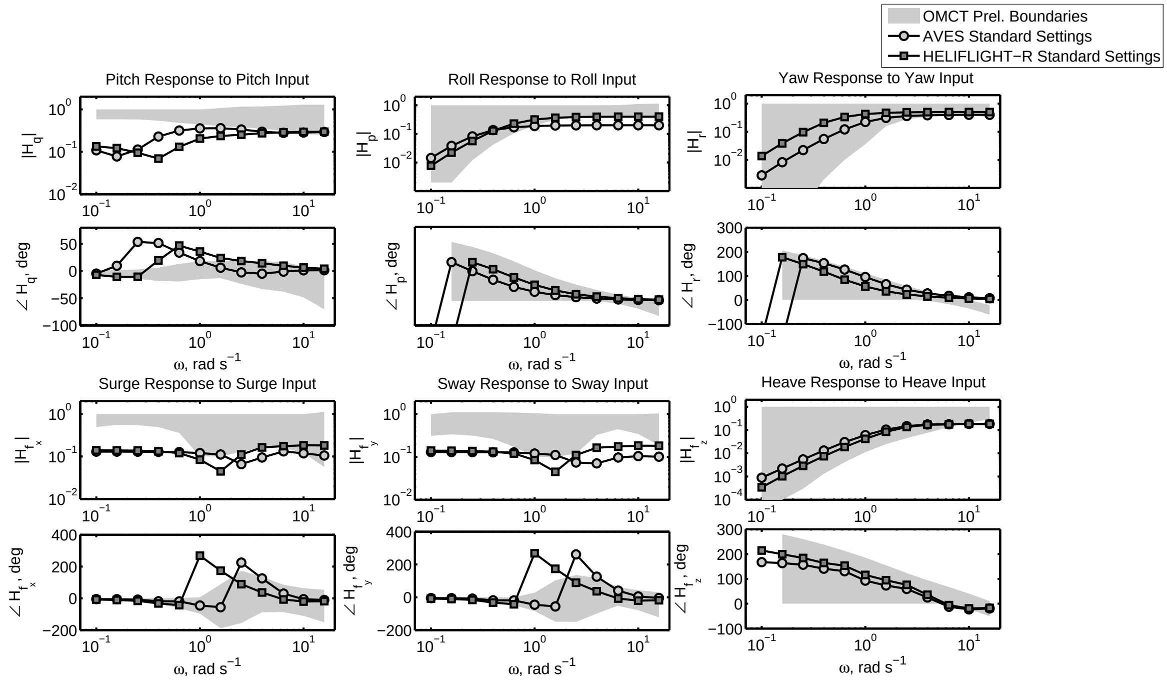


Fig. 3: Comparison of 'standard' motion settings.

3 will be directly transferable to rotorcraft simulation, due to the difference in motion utilization between the two vehicle types.

In this study, candidate tasks are presented, used to evaluate the motion characteristics under parameter variation. Many previous studies have focused on single axis tasks to expose specific motion deficiencies (Refs. 7, 11, 12). Further research has focused on simplified tests in order to expose directly the characteristics of the operator (Ref. 39). Whilst both these approaches are valid and produce valuable information with regards to the motion fidelity, this study wishes to investigate motion in realistic operational scenarios.

These scenarios are derived from HQ tasks, so called Mission Task Elements (MTEs), and in future may be refined specifically for motion testing. The tasks are selected specifically to expose deficiencies within specific axes. The tasks investigated were the Pirouette, Lateral Reposition, and Superslide tasks. These are discussed in detail below.

Pirouette Task

The Pirouette task is contained within ADS-33 (Ref. 40) and is used to determine the HQs of the rotorcraft simultaneously in pitch, roll, yaw, and the heave axes. This makes it a suitable task when observing the cross-couplings and interactions within the vehicle dynamics. The maneuver uses a circular ground track, with markers and cones that indicate the desired and adequate performance requirements. A schematic of the test course layout is shown in Fig. 5. The visual scene used for the completion of the Pirouette task is shown in Fig. 6.

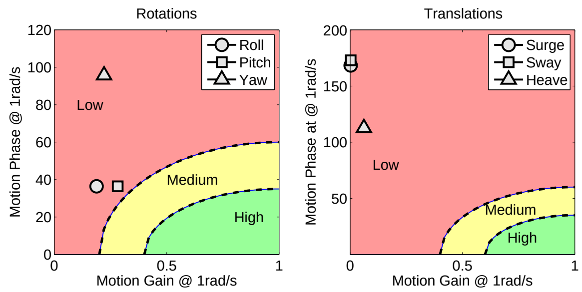
Table 3 displays performance requirements used for the pirouette task. These were taken directly from ADS-33 (Ref. 40) and are contained here for completeness. The aggression of the task can be engineered by modifying the time for one complete revolution around the circular track.

Table 3: Pirouette performance requirements (Ref. 40)).

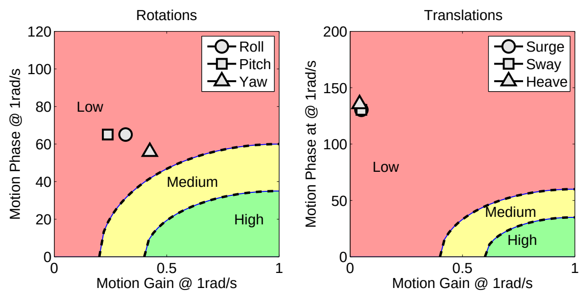
Requirement	Desired	Adequate
Maintain a selected reference point on the rotorcraft within ±X of the circumference of the circle	10 ft	15 ft
Maintain altitude within ±X ft	3 ft	10 ft
Maintain heading so that the nose of the rotorcraft points at the center of the circle within ± deg	10 deg	15 deg
Complete the circle and arrive back over the starting point within	45 sec	60 sec
Achieve a stabilized hover (with desired hover reference point)±	5 sec	10 sec
Maintain the stabilized hover for X sec	5 sec	5 sec

Lateral Reposition

A Lateral Reposition task was undertaken which was based upon ADS-33 task performance guidelines. The task course layout is shown in Fig. 7. Similar lateral reposition tasks were used in investigations to determine the acceptability of roll/lateral motion cueing in previous research investigations



(a) AVES - DLR, Braunschweig



(b) HELIFLIGHT-R - UoL, Liverpool

Fig. 4: Appraisal of Sinacori/Schroeder results for simulators used in this study.

(Refs. 7, 12). In the test campaigns stated, distance X (as shown in Fig. 7) was significantly shorter. In research presented in Ref. 12, a distance of X=20ft was used, with a desired completion time from one reference point to the other of 10 seconds. When the task was repeated by Hodge (Ref. 7), the course size was increased and the aggression was significantly heightened. The advantage of using lower aggression is that there is a wide variety of motion settings that can be used. As the aggression increases, the platform demands also increase.

The performance requirements used for the Lateral Reposition task are shown in Table 4 displays performance requirements used for the lateral reposition task. Performance requirements, with the exception of the time to complete the maneuver are as ADS-33 requirements for cargo/utility type aircraft. In order to slightly reduce aggression of the task, to allow for larger range of motion conditions, the time to complete the maneuver was increased.

Table 4: Lateral Reposition performance requirements.

Requirement	Desired	Adequate
Maintain longitudinal track within ±X ft	10 ft	20 ft
Maintain altitude within ±X ft	10 ft	15 ft
Maintain heading within ±X deg	10 deg	15 deg
Time to complete maneuver	25 sec	30 sec

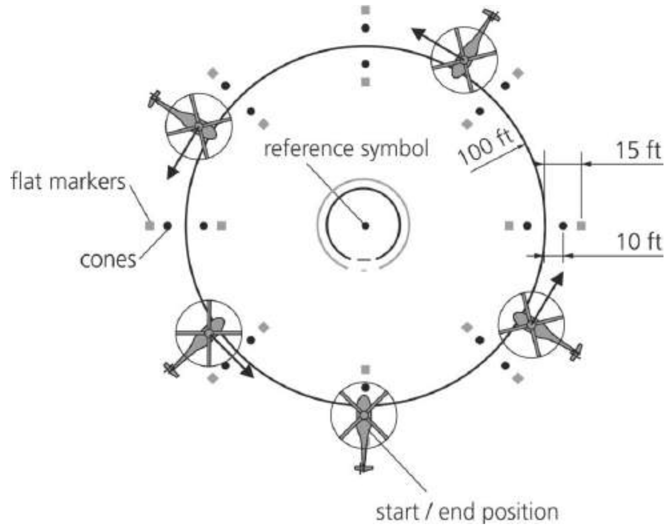


Fig. 5: Test course used for completion of the Pirouette maneuver.

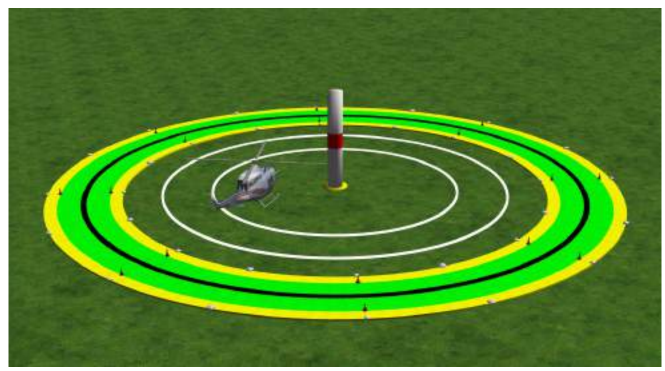


Fig. 6: Pirouette test course used for observation of roll, pitch, and yaw cueing.

Superslide Task

Ref. 41 presents task description and details for a Shipborne Landing Flight Test Maneuver (FTE). This task is used to simulate the helicopter/ship interface on land, specifically first the stabilized hover element and then the landing element. The task essentially combines the Bob-up, Sidestep, and Hover MTEs (Ref. 41). The hover element of the task required tracking of a moving hover board. This hover board is driven both in vertical and lateral position. Tolerances are similar to the ADS-33 Hover maneuver (Ref. 40), with the added exception that the lateral and vertical requirements are changing with respect to time. This is to simulate the motion of the ship, which is generally moving in pitch, roll, and yaw (Ref. 41). In this study, it was decided to take only this hovering portion of the task, in order to observe the motion fidelity during a specific tracking task. The transition between hover points and the transition to the initial point was not included in the study. The generation of a ‘tracking-type’ task means that the pilot is required to remain in closed-loop control of the vehicle. This is not always the case within the standard ADS-33

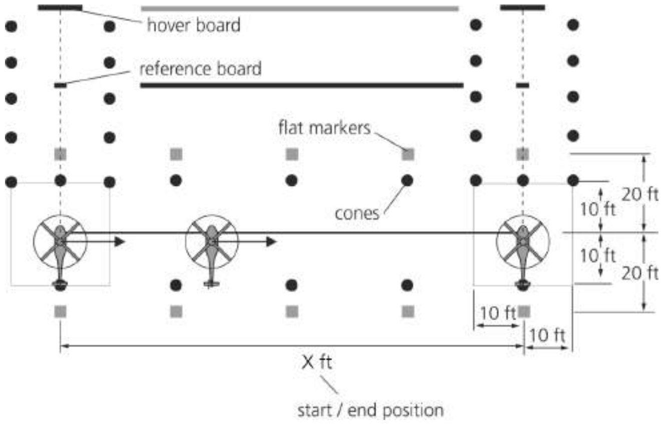


Fig. 7: Lateral Reposition test course schematic.

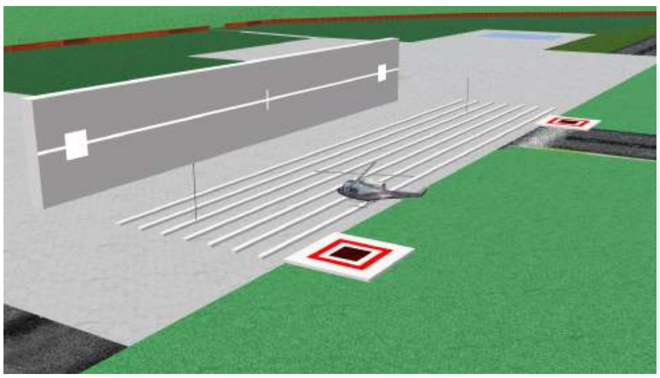


Fig. 8: Lateral Reposition task employed for observation of roll cueing.

Hover task.

For this investigation, the Superslide task was set up to replicate 'Sea State 4' conditions. This represents a flight deck that moves vertically and horizontally 11.77 ft and 7.58 ft respectively (Ref. 41). The input signal for the motion of the hover board and pillar was generated from data collected from a Canadian City Class Frigate measured in both low and very high sea states. The trajectories used for the motion use a continuous four minute loop. The motion has predominant frequencies between 0.1 and 0.2 Hz (Ref. 41).

The objective of the maneuver was to observe the ability to maintain a precise and relative position, altitude and heading. Furthermore, it was used ot check the suitability of motion cueing in the vertical, lateral, and longitudinal axes, whilst also exposing any cross-coupling, off-axis deficiencies. Figure 9 displays the visual scene used for the completion of the task. The higher hover point (red marker) was used throughout the investigation. This offers slightly more relaxed tolerances than the lower hover point (green marker). Performance requirements for the task are shown in Table 5.

Table 6 displays the intended use of the tasks completed in this investigation. From the tasks investigated, not one maneuver is currently considered to evaluate all aspects of the motion cueing. The Superslide task used in this investigation uses only the hover element of the task. Therefore, through-

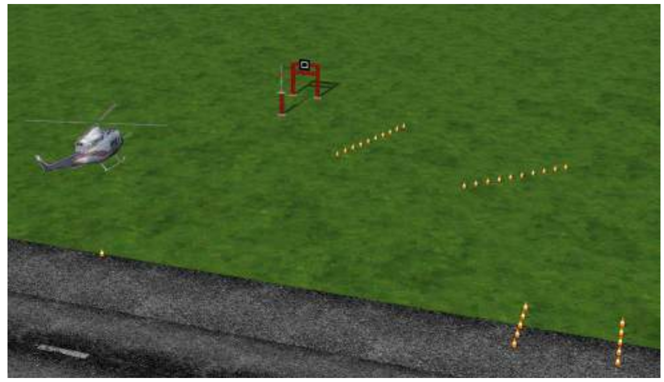


Fig. 9: Superslide task employed for observation of heave and roll cueing.

Table 5: Superslide performance requirements (Ref. 41).

Requirement	Desired	Adequate
Maintain a stabilized hover for at least	30 sec	30 sec
Maintain the longitudinal ±X ft of a point on the ground	10 ft	15 ft
Maintain heading within ± deg	5°	10°
Maintain altitude within ±X ft of center of moving target	?? ft	?? ft
Maintain lateral position within ±X ft of center of moving target	?? ft	?? ft

out the task completion, no sustained translational cueing is felt by the pilot and cannot be accurately evaluated. The disadvantage of the Superslide task during evaluation campaigns is the requirement for a moving visual scene, which can be difficult to implement in simulation (also in-flight test campaigns). The Pirouette task features rotational, translational and yaw cueing, primarily in the roll/lateral axes. For vehicles with poor HQs, the task will likely induce pitch/longitudinal motion. Large heave motions (outside of the required stabilization) are not likely to be encountered. The Lateral Reposition task features both roll and lateral elements, but will not be expected to significantly require motion in both the heave and yaw axes.

Table 6: Expected usefullness of tasks employed.

Task	Rotational	Translational	Heave	Yaw
Superslide*	Good	-	Good	Fair
Pirouette	Good	Good	-	Good
Lat. Rep.	Good	Good	-	-

*Hover element only

Objective Measures and Feedback

A number of methods were used to assess the influence of motion parameters. The majority of the analysis was conducted through the use of subjective assessment. As the study was conducted through the use of MTEs, pilot strategy and approach is different for the same maneuvers. For this reason, it is often not easy to determine objective parameters that can be used to judge the influence of motion. For this reason, analysis here is conducted predominantly using subjective results. This is supported through objective analysis.

During the campaign, two motion scales were used to collect subjective opinion. The first scale was presented by Jones, and used in research investigations detailed in Refs. 26–28. This scale was developed in order to expose deficiencies and motion characteristics in specific axes. When tuning, this can assist with the efforts to remove false or undesirable cueing. In this scale, pilots are asked first to assess Attitude/Attitude Rate, Translational, and Vertical acceleration. This should be evaluated within a specific task. If motion cannot be adequately assessed within the task, it is considered insignificant within the simulation and is not required to be assessed. After completing these evaluations, the pilot is asked to give an assessment of the Overall MTE. This is based upon the importance of each of the cueing elements. The reference to the specific MTE application is prominent in this scale. It is divided into three levels; Unacceptable, Limited Benefit, and Benefit. These are transposed to Low, Medium, and High fidelity. Only motion that adversely affects performance through a mismatch in cues is unacceptable. Ratings determined from the use of this scale are referred to as Overall Motion Ratings (OMRs).

The second scale was presented by Hodge et al. (Ref. 7), and subsequently used in research campaigns conducted at UoL (Refs. 42–44). The scale is developed from the Cooper-Harper Handling Qualities Rating (HQR) Scale, where subjective ratings are awarded through the use of a decision-tree structure. The scale is separated into four levels, in the same way as the Cooper-Harper scale. Ratings obtained using this scale are referred to as Hodge Motion Ratings (HMRs).

Further to these subjective assessment methods, HQRs were collected throughout investigations. This was employed first to find the HQs of the vehicle being tested and then to observe the influence of motion. For many motion configurations, changes were not large enough to cause a subjective change in HQs. However, for a number of cases, the presence of motion decreased task difficulty, and HQRs improved.

Constraints within the HQ tasks are sufficiently relaxed as so the pilot can approach the task with varying strategies and aggressions. Attempt should be made at all times to reach desired performance standards, however these can be achieved in any way the pilot sees fit. For example, the pilot may choose either to fly the task as high aggression and precision as possible, or to fly the task only to reach desired tolerances. This variation in pilot strategy increases realism within the task, and accounts for different piloting styles.

Test Procedure

One experienced test pilot was used in the investigation. This pilot had previous experience flying in both simulators, and has significant teaching experience. He had previously used all rating scales employed during the investigation, and previously completed most of the tasks.

Prior to the tests, the pilot was briefed on the test procedure. He was aware that parameter changes were made for each test point. However, at no time was he aware of the nature of the changes; either with respect to vehicle axes or with respect to the parameters being varied. For most test points, it was desirable to obtain the pilot initial comments with regards to the motion configuration. Therefore, the pilot was asked to give an initial assessment on the first completion of the task. If he was unsure about the motion response, or his task performance, he was permitted to attempt the task a second time before awarding complete ratings. For any HQ assessments, he was required to complete at least 3 repeats, in accordance to HQ guidelines (Ref. 40).

RESULTS

Initial Tuning

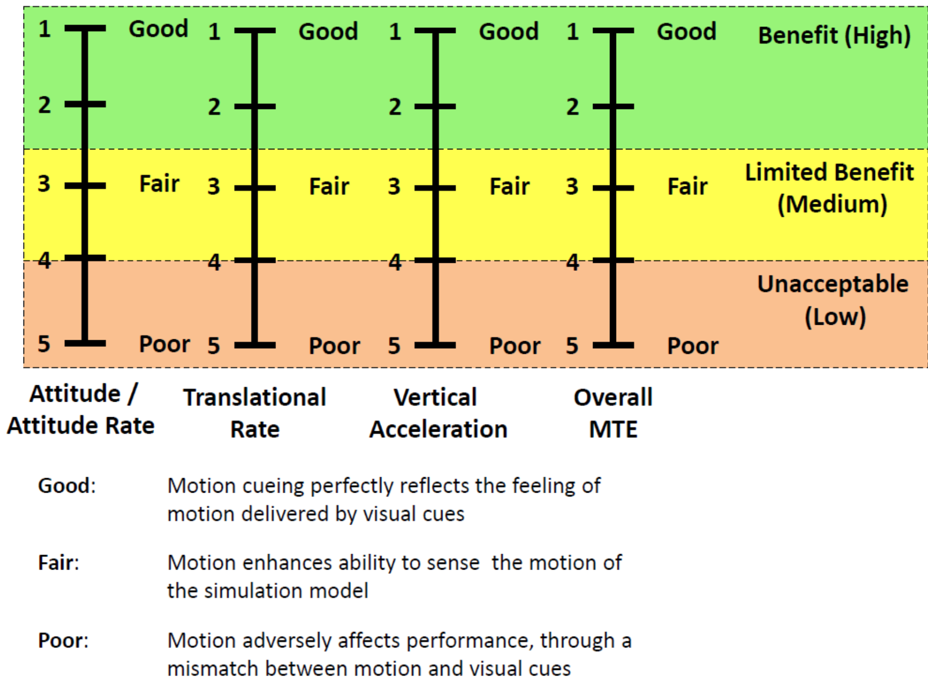
One goal of the study was to compare results with OMCT fixed-wing objective boundaries. Therefore, prior to the parameter variation studies, efforts were made to provide a general filter set which reached as well as possible the boundary requirements. As shown above, with the standard settings used in both simulators, boundaries recommended from fixed-wing analysis were not met.

Due to the size and requirements of the motion platforms, it was not possible to achieve both desired translational motion gain and phase requirements. Individually, they were possible to achieve. The decision was taken to achieve phase distortion requirements (and minimize this as far as possible) and try to achieve a gain that was as high as possible. This set of motion filters was used in both the Pirouette and Superslide tests (HELIFLIGHT II). For the Lateral Reposition task, an attempt was made to match filters used in a previous investigation in AVES. Therefore, settings that were used for AVES were used within HELIFLIGHT (HELIFLIGHT I). As stated previously, AVES uses adaptive filtering and HELIFLIGHT-R was used, in this investigation, with a standard CWA using 3rd order HP channels. Therefore, only an approximate match was found between simulators. OMCT results are shown in Fig. 11.

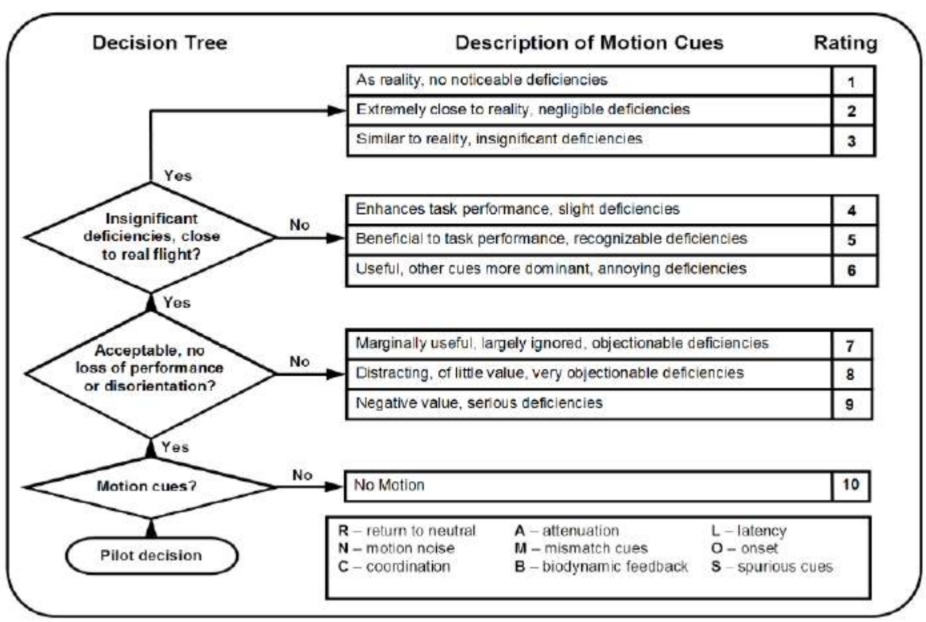
Test I: Pirouette Parameter Variation (Roll/Pitch/Yaw Rotational)

The Pirouette task was undertaken to determine the influence in parameter variation within the rotational axes (pitch, roll, and yaw). The Pirouette task primarily focuses on lateral, yaw, and rotational motion of the vehicle. The pilot must also maintain longitudinal position and height. The workload in these axes will have dependency upon the HQs of the vehicle.

Throughout the investigation, the translational (including heave) dynamics remained constant. Changes to the rotational axes were made together, varying the gain (K_p, K_q, K_r)



(a) Jones Motion Rating Scale, for determining OMRs.



(b) Hodge Motion Rating Scale, for determining HMRs. (Ref. 7)

Fig. 10: Subjective motion rating scales used in this investigation.

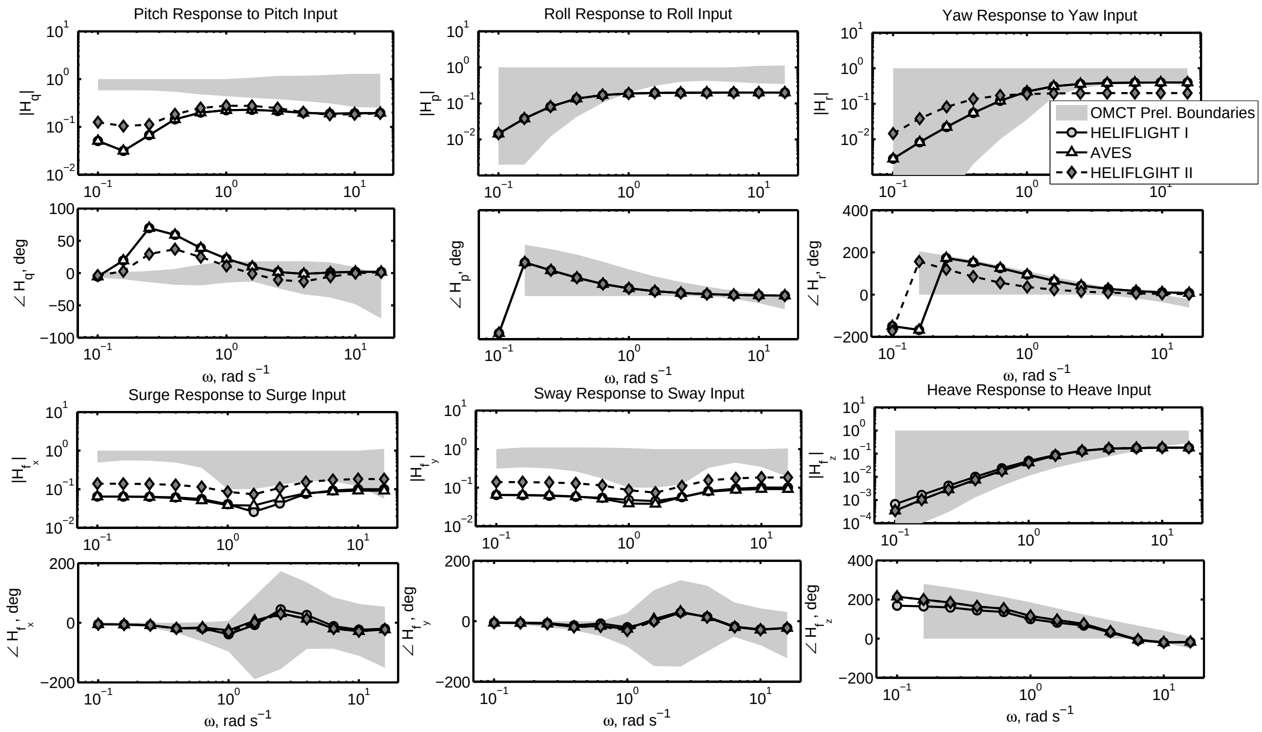


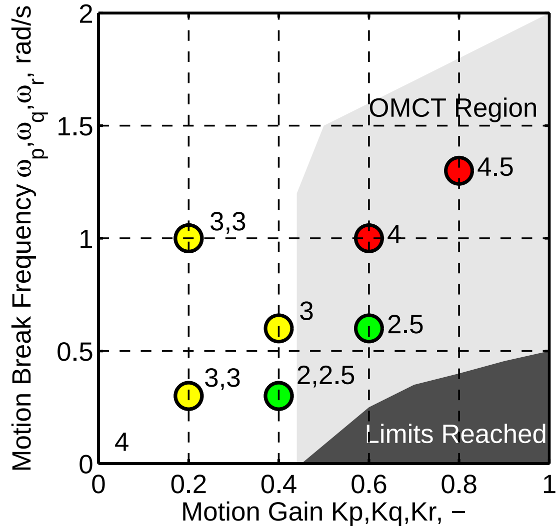
Fig. 11: Comparison of filters used for parameter variation study.

and the break frequency ($\omega_p, \omega_q, \omega_r$) of the filters. Changes were made in all axes, to maintain the balance in the motion sets. Translational settings remained as shown in Fig. 11 (HELIFLIGHT II). Results were recorded with varied motion parameters, and subjective feedback was awarded. Results from the application of both motion rating scales are shown in Fig. 12a and Fig. 12b. Also shown in both figures are two shaded regions. The darker region represents the approximate limits of the motion platform during completion of the given task. These have been calculated through post-processing recorded simulation data, and determining platform limitations using a motion toolbox (Ref. 26). The region is only representative, and is not necessarily the same for all completions of the task (i.e. varying pilot aggression, vehicle performance differences). The second region shows the approximate current OMCT region for the channels modified during the task. It was found when observing OMCT boundaries that almost identical regions were drawn for roll and yaw channels. This was due to the phase requirements which are the same for both axes. The pitch region could not be drawn as no parameter sets led to boundaries being met. This is due to the LP element required to achieve boundaries. For both roll and yaw, OMCT boundaries require a minimum motion gain of between 0.4-0.5 at the highest frequencies. Despite easily achieving phase requirements, approximately half of configurations tested in this investigation fail to meet the gain requirement.

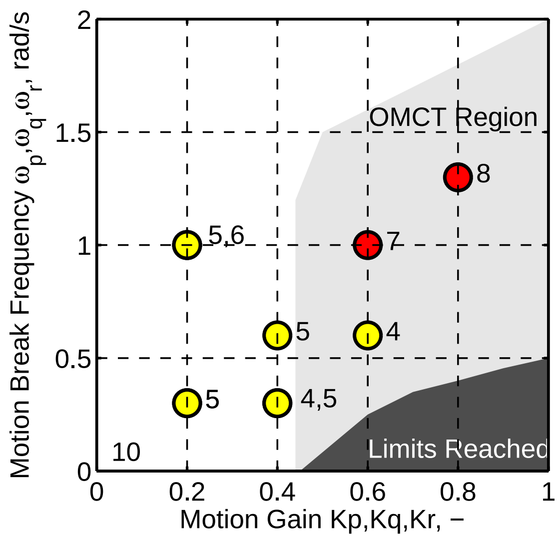
Figures also show two regions. The darker region shows an approximation of where the motion travel limits are reached for the specific task. Setting filters in this region would result in excessive leg extension. The second region displays the OMCT region, directly from the fixed-wing application of the tool. These are shown for the parameters which have been modified during the investigation.

Figure 12a displays results from the application of the Jones Motion Rating Scale. As shown, two of the test cases were awarded ratings suggesting 'benefit' of the motion configuration. Settings with a motion $K < 0.4$ were awarded ratings in the limited benefit region, whist the single motion configuration with high motion break frequency was deemed unacceptable (OMR = 4.5). Figure 12b displays HMRs obtained for the same test points. Results reflect those show with the application of the other motion rating scale. Cases indicating 'loss of performance or disorientation' were found to reflect those where the motion offers no benefit or is unacceptable.

Results show a significant different between subjective opinion and the current OMCT region. This suggests that it is not directly applicable to the Pirouette task. This task is rotorcraft specific and therefore has not been attempted during the construction of these boundaries. In terms of boundaries reflecting 'acceptability' of the motion cueing, limiting the break frequency to below 1 rad/s for cases with motion gain above 0.4 appears to be necessary. This situation causes high phase distortions, detectable by the pilot. The lower motion gain appears to play less of a role than the high phase distortion, and results suggest that lower motion gain is better when the system is not capable of achieving high motion without large washout. A reduction in motion fidelity (given by the subjective ratings) was found when the motion gain was lowered. However, motion was still deemed by the pilot to be beneficial. This is in contrast to the points contained within



(a) Results from the Pirouette task - OMR.



(b) Results from the Pirouette task - HMR.

Fig. 12: Motion ratings awarded - Pirouette task.

the OMCT region, which were deemed to offer no benefit or actually adversely affect performance.

Figure 13 displays frequency response data from three cases of the Pirouette (those used to evaluate the motion subjectively). These are namely the best case (OMR = 2.5), the worst case (OMR = 4.5) and the no motion case (OMR = 4.0). There is significant difference between the lateral control input from each of the completions of the maneuver. For the no motion case, there is significantly lower input content as frequency increases. However this case has the highest content at low frequencies. The good motion case also features high content at low frequencies, with a peak at a slightly higher frequency than the no motion case. Frequency content at higher frequencies is visibly higher. The result from the worst case is contrary. There is no large peak at low frequency, and it appears that the pilot has intentionally decreased his gain during completion of the task. This is believed to be to suppress the motion response. In terms of task performance, both the best and worst motion cases show the same time to complete the maneuver (30-40 seconds).

Figure 14 displays a comparison of the motion attitudes for both the Best and Worst Case motion ratings for the Pirouette maneuver. As shown, motion usage is very similar for both cases, despite the large difference in motion gain. More motion has been induced for the case with low motion gain, and it appears that no advantage has been gained from setting the motion gain high. Observation of the vehicle attitudes indicates that the Worst motion case has led to some harsher, high frequency oscillations during completion of the maneuver. Observation of the motion travel usage in these two runs also shows no benefit from using the high motion gain. Lower overall travel usage is used in this case, in comparison to the Best motion case.

Test II: Lateral Reposition Task (Roll Rotational)

The Lateral Reposition task was undertaken both in HELIFLIGHT-R and AVES, using the same pilot for both investigations. This task was selected to determine only the influence in parameter variation within the roll rotational axis. For all completions of the task, other parameters remained constant. This meant that the ratio of lateral force to rotational motion was different with parameter changes. The Lateral Reposition focuses primarily on roll and sway motion characteristics. The pilot must also maintain the height and longitudinal position throughout completion of the task.

Throughout the investigation, only rotational gain (K_p) and break frequency (ω_p) of the filters were changed. As discussed above, AVES uses an adaptive filtering method which is propriety of the manufacturer (MOOG). The OMCT result of both simulators was matched for this case, with results shown in Fig. 11. HELIFLIGHT-R was configured with ‘HELIFLIGHT I’ settings. As displayed, the match between these settings and those in AVES was good. Results were recorded with various motion settings, and subjective feedback was awarded. Results from tests completed in both simulators are shown in Fig. 15a and Fig. 15b.

Results show good correlation between results obtained in the two simulators. Only attempts to match the motion between the two simulators was made, and no attempt to use the same visual scenes, FoV, cockpit, aircraft model, or other simulator specific nuances were made. As shown, motion ratings were more favorable in AVES for the low gain ($K_p = 0.2$) cases. In HELIFLIGHT-R, the pilot particularly noted that he felt attenuation for these cases. In AVES, this was not the case. This is perhaps a results of the more immersive environment in AVES, whereby the replica cockpit, rather than a generic one, is used.

Despite the smaller motion platform of HELIFLIGHT-R, and the lower motion limits, both platforms show similar performance (with respect to limits) for the lower motion gain

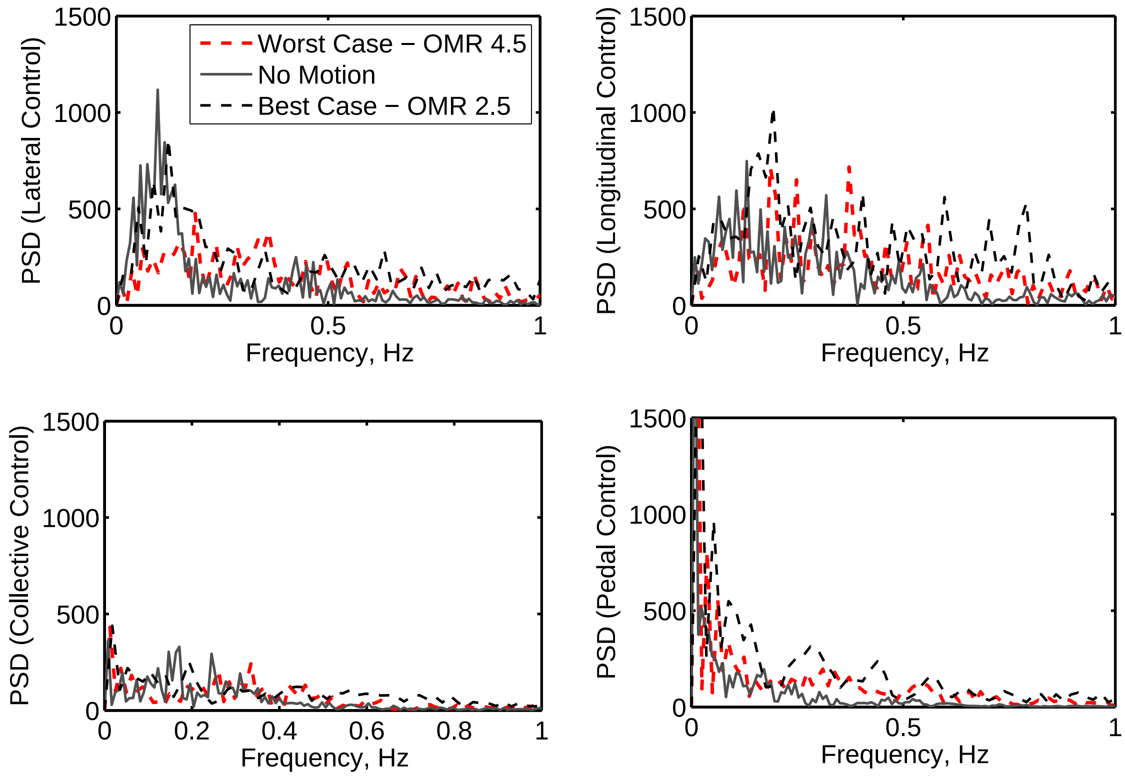


Fig. 13: Comparison of frequency of control inputs during Pirouette task.

cases. For larger motion cases, AVES is capaple of larger motion with lower break frequency. However, results suggest that setting motion in this region ($K_p > 0.5, \omega_p > 0.8 rad/s$) may not lead to higher fidelity motion cueing. Furthermore, the imbalance between the rotational and translational channels will become more dominant, and will likely cause false/unrealistic cues. This should be further investigated in future research.

Figure 15c displays results obtained from the application of the Hodge Motion Scale. As show, results here were also found to correlate well with the other scale used. However, this correlation was not as strong as for the Pirouette task. For one of the cases, the pilot awarded HMR = 6, and OMR = 2.5. The difference was caused by some minor deficiencies where the pilot sensed motion washout as motion limits were close. These deficiencies did not directly impact his task performance, and he still thought that the motion set offered significant benefit.

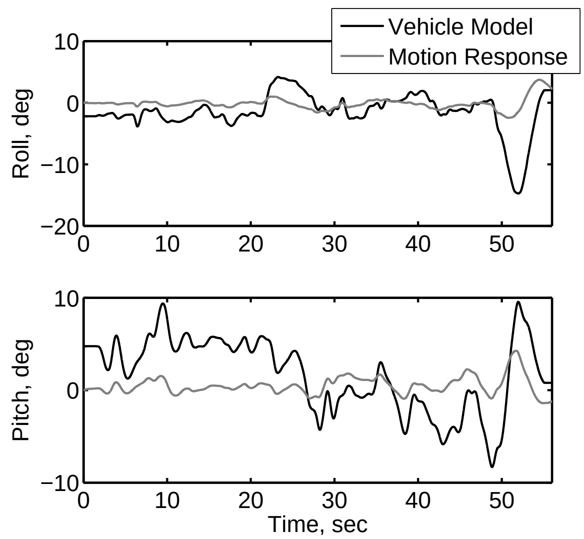
Due to motion limits of both simulators, it was not possible to test cases with high motion gain ($K_p > 0.5$) and low motion washout ($\omega_p < 0.5 rad/s$). To investigate this region, it is necessary to significantly reduce task aggression further. This would help to observe roll to sway requirements for good motion fidelity. For cases investigated here, a roll/sway ratio between $0.2/0.1$ and $0.4/0.1$ appeared acceptable for all cases with a break frequency lower than 0.8 rad/s. In AVES, all of these cases were subjectively assessed as giving (high fidelity) benefit, and for all cases was motion considered beneficial for task completion.

As with the Pirouette task, there are significant between the results obtained and OMCT boundaries, and again suggests that these are not directly applicable to rotorcraft tasks. As shown, for the Lateral Reposition task, points lower than the acceptable minimum gain are found to offer benefit subjectively during the completion of the task.

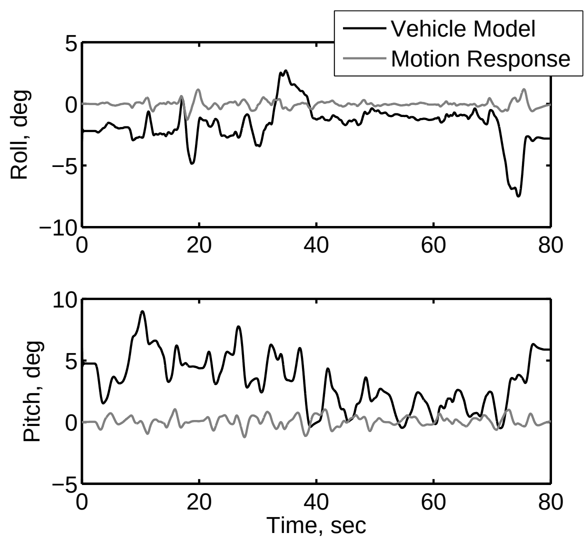
Test III: Superslide Task (Rotational including Heave)

The Superslide task was undertaken in HELIFLIGHT-R. The task was undertaken to observe both changes in the roll and pitch filter parameters. Unlike other tasks, the Superslide requires significant compensation in heave. This is in addition to pitch, roll, and yaw motion, which is required to both capture the target and to maintain the correct vehicle position.

For the purposes of this task, tracking of the moving hover board was achieved through compensation in lateral position and height. Constant heading and longitudinal position was desired throughout the completion of the test. Changes in both longitudinal and lateral parameters was made in order to maintain balance within the cueing. Therefore, for all tests, gain and break frequency was the same for both pitch and roll channels. As in other tests, no modifications were made to the translational motion settings, and these were configured

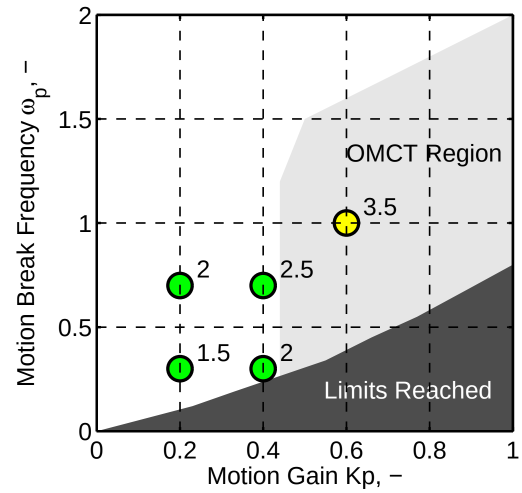


(a) Attitude response for best motion case (OMR = 2, $K_p, K_q, K_r = 0.4, \omega_p \omega_q \omega_r = 0.3 rad/s$).

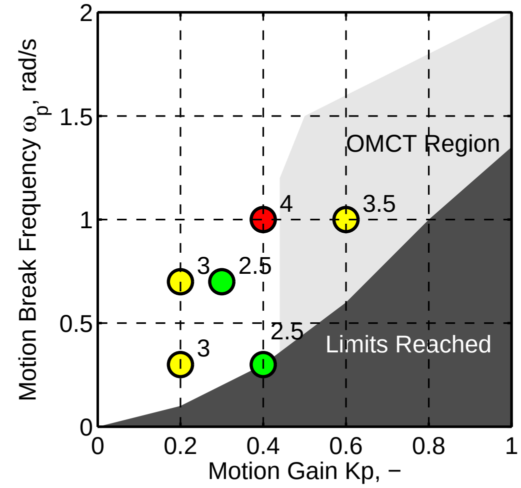


(b) Response for worst motion case, (OMR = 4.5, $K_p, K_q, K_r = 0.8, \omega_p \omega_q \omega_r = 1.4 rad/s$).

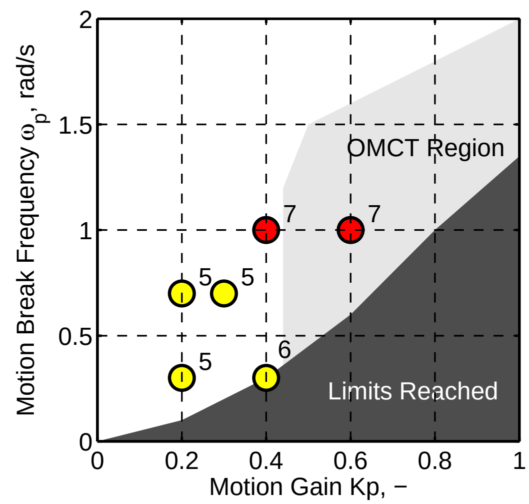
Fig. 14: Motion and vehicle attitude response during completion of Pirouette maneuver.



(a) Results from Lateral Reposition task - AVES.



(b) Results from Lateral Reposition task - HELIFLIGHT-R.

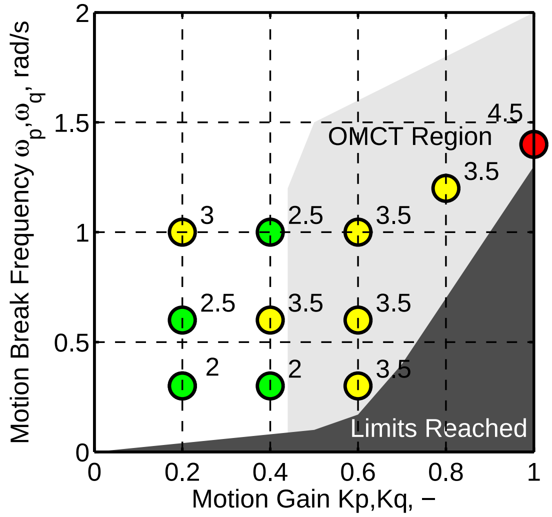


(c) Results from Lateral Reposition task - HELIFLIGHT-R, HMR.

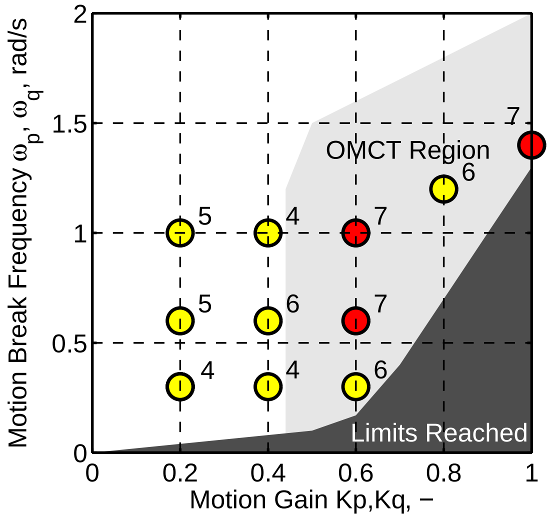
Fig. 15: Motion ratings awarded - Lateral Reposition task.

as HELIFLIGHT II settings. Subjective results obtained are displayed in Fig. 16.

Through the use of the OMRs, one motion case was deemed unacceptable, which was the case where unity gain (1-to-1) motion was used. The unsuitability of this case is confirmed through the HMR = 7. This is interesting as the case is within the OMCT region. For this case, $\omega_p, \omega_q = 1.4$ rad/s. Again, this is well within the OMCT boundaries. In this case, the pilot was unsure whether to award this motion OMR = 3.5 (limited benefit) or OMR = 4.5 (unacceptable). The pilot found that the sharp and large cueing response was helping him to initially determine the motion response. However, the large washout led to a very false impression with respect to the 'real-world' motion. Furthermore, the differences between the perceived motion from the visual projection and the



(a) Results from the Superslide task - OMR.



(b) Results from the Superslide task - HMR.

Fig. 16: Motion ratings awarded - Superslide task.

vestibular system were large, and the pilot felt he could not continue with the case for a significant amount of time. This is apparent from the motion attitudes during the case, shown in Fig. 17. Due to the large washout in this case, the motion has significant phase lead, and if the frequency of pilot input were to increase further, out-of-phase oscillations may occur. As shown however, due to the closed-loop nature of the task, motion attitude response is of similar magnitude to the actual vehicle model. This analysis supports the pilot comments that the initial motion is helping performance, but that the washout produces unrealistic response following.

From completion of the Superslide, the two best cases, shown through application of both rating scales were those where the break frequency was low ($\omega = 0.3 rad/s$). For the case where $K_p, K_q = 0.6$, the motion was found to be approaching the motion limits. This led to a reduction in the fidelity. This could have also been due to the difference between the longitudinal and lateral motion and the translational (particularly heave), which remained constant and considerably lower gain throughout (i.e. $K_w = 0.1$).

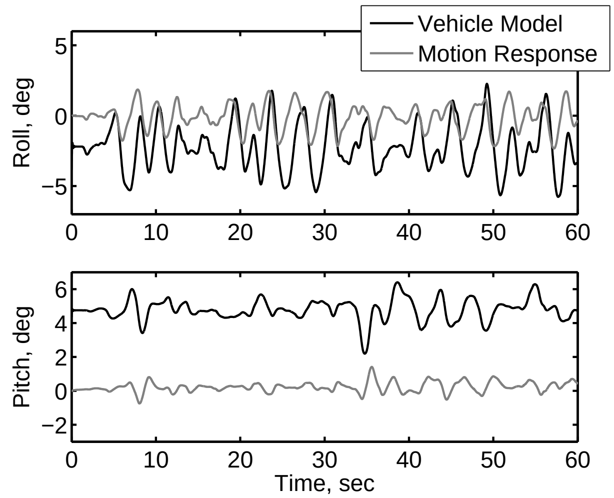


Fig. 17: Attitude of the vehicle and motion during completion of Superslide task, OMR = 4.5.

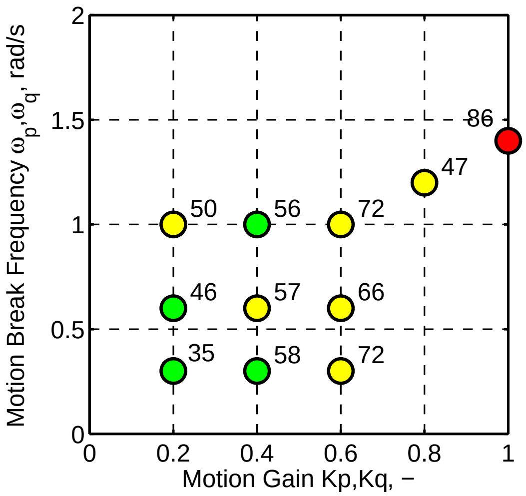
The Superslide task employed featured no sustained translational element. This had the advantage that a larger motion envelope could be utilized for the investigations. This is in contrast to the other tasks investigated in this research. Despite the difference in the task, the results suggest correlation to the other tasks (Pirouette and Lateral Reposition). One difference was more favorable ratings (marginally) obtained for the cases with $\omega = 1.0$ rad/s. This could be a result of the nature of the task. As the pilot is constantly closed-loop in the task, it appears that the result is less susceptible to larger break frequencies. This is only however for cases where $K > 0.5$.

Further analysis of the Superslide manouver is shown in Fig. 18a and Fig. 18b. Here, motion perception thresholds are used to observe the amount of time in which the motion is detected by the pilot. These are compared against subjective rating and motion configuration. The roll and pitch perception thresholds are taken as 0.3 deg/s and 0.42 deg/s respectively (as stated in Ref. 7).

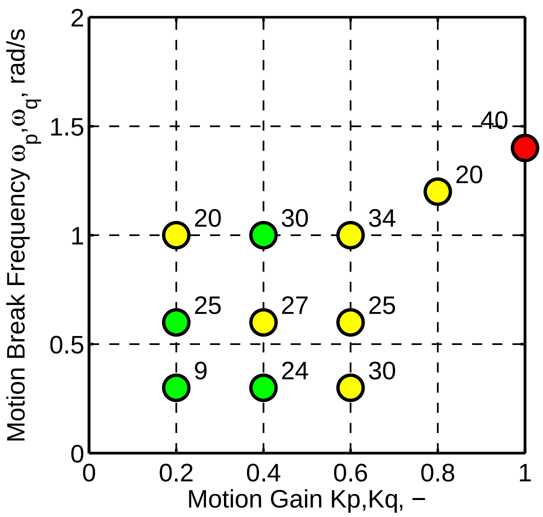
As shown, throughout the maneuver, as an element of the task is lateral tracking, lateral motion is more detectable. As motion gain increases, this is logically also found to increase. There appears to be no clear increase or decrease in motion detection with changes in break frequency.

Overall Appraisal of results

To gain an understanding of the influence of motion parameters, all results discussed were plotted together. There are a number of caveats that must be taken into account when comparing directly the results obtained from the different task. The first is that the ratings were influenced by the motion usage and limits. This could lead to mismatches between the

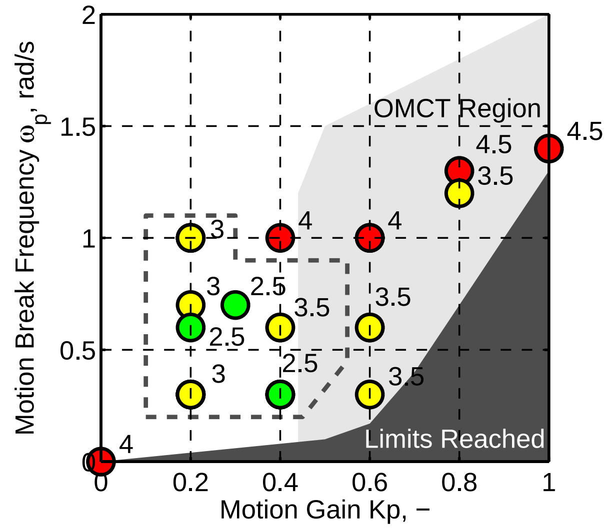


(a) Percentage time motion above perception threshold, lateral.

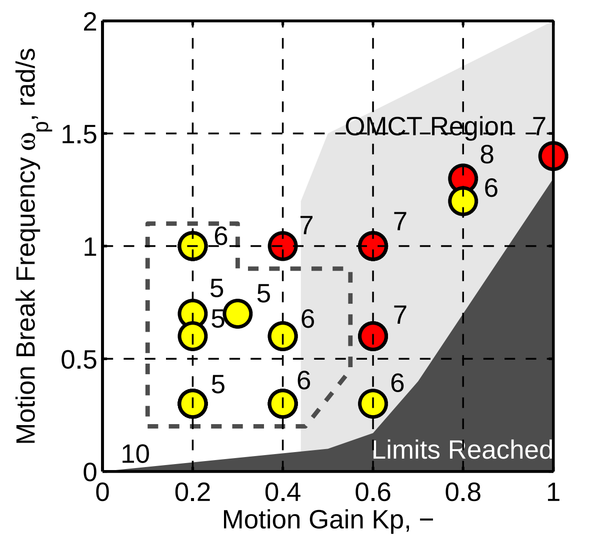


(b) Percentage time motion above perception threshold, longitudinal.

Fig. 18: Motion ratings awarded - Superslide task.



(a) Comparison of all OMRs awarded.



(b) Comparison of all HMRs awarded.

Fig. 19: Combination of all ratings obtained in HELIFLIGHT-R.

awarded ratings in different tasks. The second is that for different tasks, modifications were made in other motion channels. Therefore, a direct comparison between individual axes from the tasks cannot be completed. Care must be taken when observing the average ratings, as this does not determine if the motion case is acceptable for all conditions.

However, all tasks featured changes in the roll axes, in terms of both motion gain (scaling) and motion break frequency. The worst ratings obtained for each parameter configuration set are shown in Fig. 19a and Fig. 19b. The worst rating rather than the average rating is preferred. If two ratings of OMR = 1 and OMR = 5 are averaged, the result will be OMR = 3. This would be misleading, as the motion platform is clearly unacceptable for one point and acceptable for another.

Overall, results from the application of parameter variations in the two simulators suggest that the OMCT boundaries are not, as expected, suitable directly for implementation in rotorcraft simulation. The investigation has not extensively investigated all axes, but the roll axis has been observed in a number of different tasks and parameter settings.

As displayed, a region exists from the tests where both OMR and HMR ratings showed that the motion was beneficial. This region is not in agreement with the OMCT region and is dependent on the maximum motion travel. Results demonstrate that lower roll motion gain (K_p) can result beneficial motion cueing, which was considered by the assessing pilot to reflect cueing experienced in-flight. For simulators that do not feature large motion travel range, this is very beneficial. During the investigation, no large change in motion benefit was determined through increasing motion gain to levels achievable in HELIFLIGHT-R. Further investigations in AVES could help to determine whether increasing motion gain can improve the fidelity of the simulation.

Acceptable motion washout (ω_p) was not found to correlate with OMCT boundaries. Setting roll motion filters with $\omega > 1.0$ was always found to result in motion that was either of very limited benefit or detrimental to task performance. This included the Superslide task, where motion break frequency was found to have a lower influence on motion ratings due to a lack of sustained translational elements within the task. Pilot subjective opinion is supported by observation of the motion attitude responses during task completion.

The large FoV's of both simulators are likely to have played a significant role in the results obtained in this investigation and is of particular interest to rotorcraft simulation and motion requirements. Due to the mission requirements of rotorcraft, it is necessary to have large FoV to replicate cueing expected in flight. The large projection provides a completely immersive environment. In some tests within these investigations, the pilot was not aware if the motion was off or on, due to the immersion provided by the visuals. Often the noise from the platform was a primary indication that the motion was active.

As the visuals are compelling within both simulators used in this investigation, the primary requirement for the vestibular motion is that it reflects this motion. Within simulators that have a lower FoV, it is likely that the pilot has higher reliance upon the motion cueing to replace the missing visual cues. As the FoV of the simulators used in this investigation reflect those used within training simulators, it is believed that the results found here should be directly applicable to these simulators. Rather than emphasizing motion gain, as shown through OMCT transport aircraft boundaries, the focus for rotorcraft simulation should be on minimizing the washout, to ensure that the phase of the motion response is as close to the visual channels as possible.

Investigations should be undertaken using simulation scenarios with degraded visual environments (DVE). The problem in these DVE tests is that subjective opinion can be difficult to ascertain, as pilots may find it challenging to judge their performance. For these tests, objective measures of performance and benefit of the motion must be employed more prominently.

Figure 20 shows the boundaries of the OMCT test if the motion deemed acceptable in this investigation was used. Throughout the completion of the three MTEs, roll parameters were always varied. Therefore, the OMCT regions shown are for all tasks, specifically for the roll region. Results are obtained from tests where the translational cueing is set to settings in Fig. 11. Therefore, the gain of these channels is between $K = 0.1 - 0.2$, and lower than required for current OMCT boundaries. Results display three four regions. The region of darkest shading is the region identified as 'Acceptable' in this study. The lightest shaded region displays OMCT boundaries as presented for fixed-wing aircraft in Ref. 16. The other shaded region represents settings that were found to lead to objectionable motion during completion of MTEs.

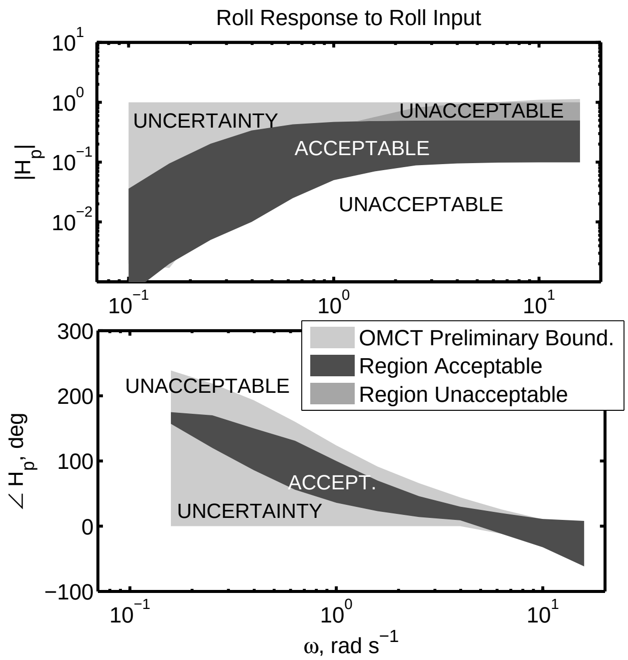


Fig. 20: OMCT boundaries suggested from results obtained in this investigation.

A number of regions are marked with 'uncertainty'. These regions were not investigated as part of this study, but theoretically should offer good motion cueing. In OMCT boundaries, these regions were included as 'high fidelity', despite the lack of supporting test data. Theoretically this is correct, however further results should be obtained to conclude upon definitive boundaries. These regions are both in the gain and phase response.

Correlation to Optimization Fitness

In Refs. 26, 27, a technique for the continuous objective tuning of motion platforms was introduced. This method uses an optimization technique to tune motion for specific tasks and scenarios. The primary consideration is that the motion is suitable for the utilization of the simulation platform. Results from the generic application of the function used for the optimization process were discussed in Ref. 28. Further work has been conducted to improve the function, both in terms of the end motion fidelity and in terms of convergence of solutions obtained using the optimization method. This has led to further refinement of the function, using DLR's AVES simulator. The results presented in this investigation have been used to further refine the function parameters. This is presented here.

Using recent results the fitness function previously presented in Ref. 28 was refined. The general structure of the optimization function or principles behind have not been changed. However, equations used and scaling factors were modified. The main changes from the function previously presented were;

- **Separation of Gain and Phase Terms**; previously these terms were grouped into a single equation. However, it was found to be more practical when these two terms are separated. This allows the scaling of phase and gain influence to be completed independently.
- **Increase in Observation Range**; In all previous investigations, the range of $\omega = 1 : 10$ (rad/s) was used for the function. However, by considering previous research, some results obtained, and the OMCT boundaries, this was changed to $\omega = 0.5 : 10$ (rad/s).
- **Use of Maximum Gain and Phase**; previously, the gain and phase was evaluated at different points. This was found to be cumbersome. As a result, the maximum gain and phase, observed over the observation range, is now used for calculation.
- **Variance Term**; the term originally used was also found to be cumbersome during analysis. This has been replaced by a new term, which effectively serves the same purpose. The term acts only upon the gain terms of the function and, not as previously, on the phase terms.

The limiting factors remain unchanged. The fitness of the system will be zero if any of the motion limits (position, velocity, and accelerations) are reached. Furthermore, all filter elements (Gain, washout, and damping) must be non-zero and positive. Finally, no non-linear elements on the system should be encountered. This is as equations used to determine fitness are done so using linear theory. Whilst the analysis can eventually be extended to include non-linear terms, this is not included in the current study. Furthermore, during previous investigations as part of this research, it has been observed that the non-linearities in the system appear to contribute to a reduction in motion fidelity. The fitness function is shown in Eqn.1.

$$F = X \sum_{i=1}^{N} K_1 G_i e^{-K_2 G_i \Delta G_i} + \sum_{i=1}^{N} K_3 \Phi_i e^{-K_4 \Delta \Phi_i} \tag{1}$$

The fitness function evaluates both the Gain and the Phase distortion of the motion settings. The first half of the equation evaluates the gain characteristics of the system. The exponential function is used in conjunction with a term to evaluate the change in motion gain. It is desirable for the system to have high gain, and low change in gain. As gain of the system increases, pilot sensitivity to changes will increase. ΔG_i is given by,

$$\Delta G_i = max(G_{i|\omega=0.5:10}) - min(G_{\omega=i|0.5:10}) \tag{2}$$

The maximum gain of the motion over the range of observation is used within the calculation, given by,

$$G_i = max(G_{i|\omega=0.5:10}) \tag{3}$$

The function is maximum when the gain is equal to unity and the change in motion is zero ($e^0 = 1$). A term is added to evaluate the difference in gain between the axes. This is given by X, and multiplies only the gain term. This term is used to calculate the difference between the gain of each axis.

The second half of the function evaluates the phase distortion of the system. Previously this was grouped with the gain equation (Ref. 28). However, it was found to be more suitable when it is separated from the gain evaluation. The phase term also applies the exponential function to evaluate the change in phase over the frequency range of observation, namely;

$$\Delta\Phi_i = max(\Phi_{i|\omega=0.5:10}) - min(\Phi_{i|\omega=0.5:10}) \tag{4}$$

The result of this is multiplied by a term to account for the maximum phase distortion in the axis, given by;

$$\Phi_i = 2\pi - [min(|\Phi_{i|\omega=0.5:10}|), max(|\Phi_{i|\omega=0.5:10}|)] \tag{5}$$

K1,K2,K3 and K4 are used to scale the results. This is also important to ensure that the scaling of the gain and phase terms are relative, and one of these does not have an overpowering influence on results obtained.

Figure 21 displays the OMRs awarded with respect to the fitness. Currently, there is no objective measure on the numerical value of fitness. However, higher fitness denotes higher quality/fidelity motion. Results are separated for each of the tasks attempted. Fitness is calculated for the complete motion settings. Therefore, despite changes only being made in specific axes, the fitness is the result of the complete system.

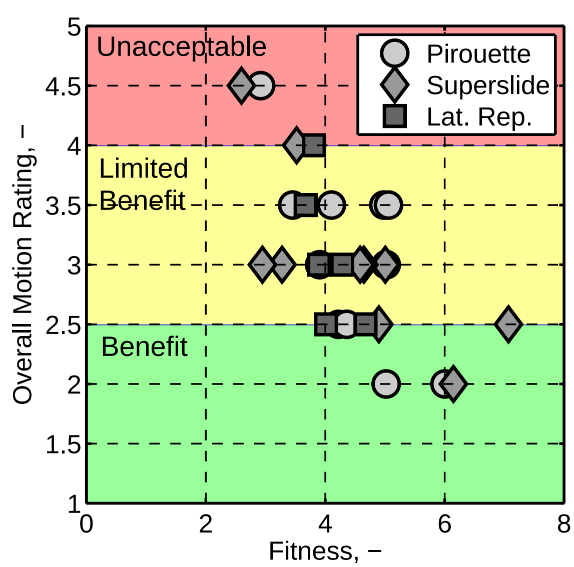


Fig. 21: Fitness with respect to OMR.

As shown, results are very encouraging. There is good correlation between the OMRs and the fitness calculations. The fitness appears more sensitive than the motion ratings, and there is a spread in the results across the different regions. For example, some cases within the 'Medium' fidelity region have lower fitness than those in the 'High' fidelity region. However, a strong indication of a link between the subjective and objective results is shown. One case from the Pirouette case has been excluded from the analysis, as motion limits were reached. This would ultimately lead to a fitness of zero.

OPTIMIZED CASES

In addition to cases shown in the above analysis, the Pirouette and Superslide tasks were used with optimized motion cases. These cases were determined by using the optimization technique proposed by Jones (Refs. 26–28). This is a scenario-based procedure, whereby the motion settings are determined through optimization of a specific test case recorded in the simulation. The test data is used to determine the expected motion in the simulator and, therefore, the parameters which will likely cause motion limits to be reached. The fitness function shown in Eqn. 1 was used to optimize the motion, using one case obtained from completion of the Pirouette task. This was used as it was found that the Pirouette task required more motion than the Superslide task.

During investigations in HELIFLIGHT-R, drift of the motion platform was found to be a problem when the translational break frequencies were set low. In order to ensure that the platform did not drift, the break frequencies of the lateral and longitudinal translational channel were kept constant and not optimized. Motion Gain of these channels however was optimized. The Heave axis was also not optimized. During the optimization, the platform travel range was decreased to 50% maximum travel. This was to account for different piloting styles and possible differences in task performance. This was also cautious, as it was the first time it had been tested in HELIFLIGHT-R. Figure 22 shows the resultant optimized filter parameters.

The optimized motion was found to have a fitness F=6.014. Referring to Fig. 21, for the specific tasks completed, this is expected to result in motion that offers High fidelity, and benefit. Both manoevers were flown in HELIFLIGHT-R by the assessing test pilot. Ratings obtained are shown in Table 7.

Table 7: Results from motion optimization cases.

Task	HQR	Rot.	Trans.	Vert.	OMR
Superslide	4	2.0	-	2.0	2.0
Pirouette	3	1.5	2.0	3.0	2.0

For both tasks, the pilot awarded OMR = 2. This indicates high fidelity motion that offers significant benefit. Furthermore, it is equal to the highest rating awarded in the complete investigation (within HELIFLIGHT-R the pilot did not award a rating less than OMR = 2). The result is also in agreement with results shown in Fig. 21.

The pilot stated that in the Pirouette task, the motion had actually significantly improved task performance, and awarded HQR = 3 (Level 1). For the no motion case, the pilot awarded HQR = 4 (Level 2). Figure 23 displays the pilot control inputs, with respect to frequency, for both a no motion case and optimized motion case. These cases are representative of others flown.

As shown, during completion of the task, the pilot applies control at significantly higher frequency with the motion feedback. Furthermore, a peak in longitudinal control input frequency is apparent with motion. Results show that the motion has influenced the pilot control strategy, and subjective ratings suggest that this is an improvement given by the motion.

CONCLUSIONS AND FUTURE WORK

The following are the key conclusions that have been made from the work reported.

A number of candidate tasks were found to be successful at exposing the benefits and weaknesses of motion configurations in helicopter flight tasks. These tasks were developed using the Mission Task Element approach, as used in ADS-33 standards, and offer a realistic scenario in which to explore motion utilization. From tasks investigated, key axes of observation were defined. The hovering element of the Superslide task emerged as a very good task for appraisal of both the rotational and heave cueing. This study was the first to use the task for evaluation of motion fidelity.

Two sets of standard motion settings, used within both University of Liverpool's HELIFLIGHT-R simulator and the German Aerospace Center's AVES simulator have been presented and compared with current Objective Motion Cueing Test (OMCT) advisory boundaries. These boundaries have been generated for transport type aircraft, and therefore were not expected to correlate with rotorcraft flight tasks. Results from the application show that this is the case, with both simulators displaying a difference between settings and the boundaries.

Two subjective rating scales have been used to assess the fidelity of motion cueing provided, using scenario-based evaluation. Both scales, which have been used in previous investigations, were found to show good correlation for the majority of tests. Some inconsistencies between scales were found.

Results from the application of all tasks showed suitability for their use in motion fidelity/tuning campaigns. Ratings obtained with respect to parameter variations in all tasks were found to be well correlated throughout the investigation. For all tasks, the subjective ratings were not found to be in agreement with the OMCT boundaries. This was true for both acceptable break frequency and for minimum motion gain allowable. Tasks were found to be better at exposing lateral motion than longitudinal motion.

Results from the overall application of subjective opinion suggests a suitable region for tuning of the roll motion parameters is a simulator of similar size to HELIFLIGHT-R (short-stroke hexapod platform). This region requires break frequency to be below 1 rad/s for all motion gains greater than

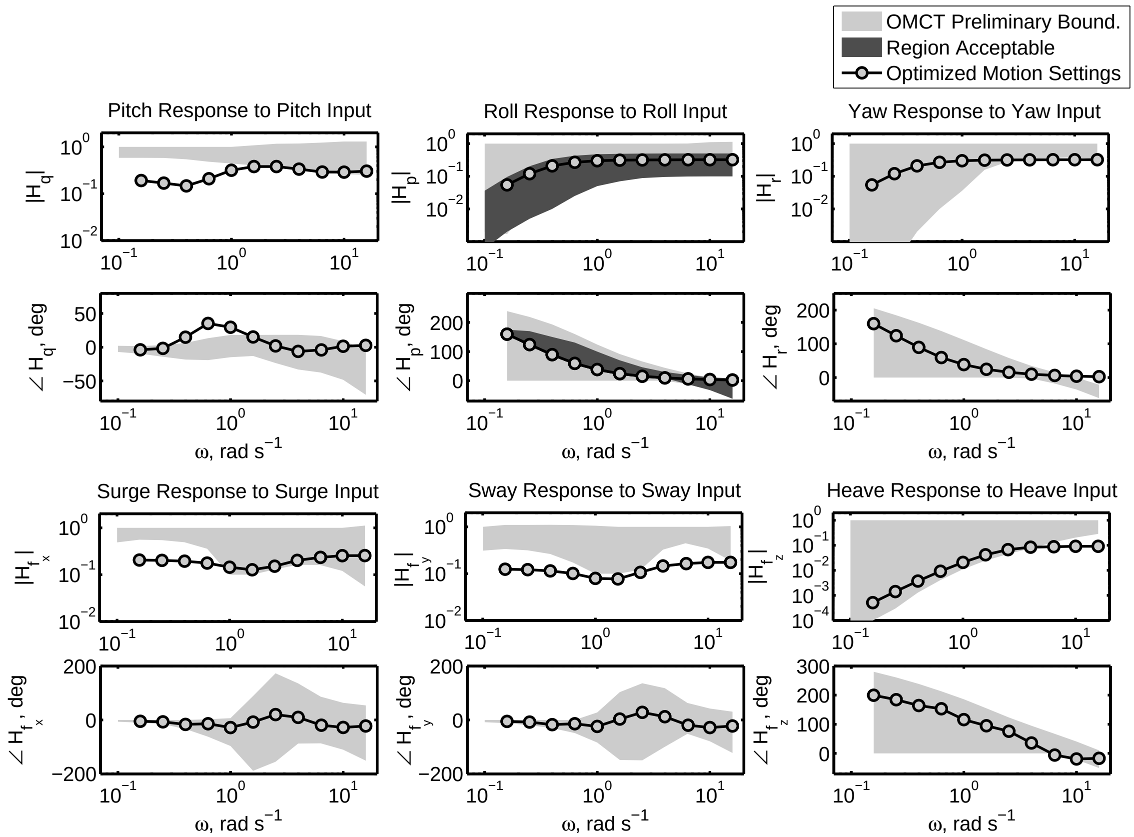


Fig. 22: Optimized filter parameters against OMCT boundaries.

0.3. Motion gain cannot be set too high, as this would cause imbalance between the rotational and translational cueing.

An updated optimization function has been presented and used to analyse data determined in the investigations. The calculation of fitness of motion settings was found to be well correlated with pilot subjective opinion and shows promise for its future use within an optimization routine.

One optimized motion case was flown within HELIFLIGHT-R and the assessing pilot completed both the Pirouette and Superslide maneuvers. For both maneuvers, the optimized motion was found to offer high fidelity motion cues, and offer significant benefit for completion of tasks. Furthermore, for the Pirouette task, the HQR awarded was found to changed from Level 2 (without motion) to Level 1 (with motion). This improvement demonstrates the benefit of the motion suggested by the subjective assessment.

Future work will focus on improving both the motion tuning method and the subjective evaluation procedure. Firstly, all tests completed in HELIFLIGHT-R will be repeated within AVES at DLR. This will give further insight into the difference between both simulators, and show if the motion parameters are independent of the simulation environment. This includes dependency with regards to vehicle model, simulator cockpit environment, and motion platform capabilities. Using the updated fitness function presented here, further optimization will be conducted, with motion settings used in both simulation platforms. This will demonstrate the generic application of the motion tuning method. It is recommended that following these tests, the motion optimization test technique is used within a training simulation environment, and its benefit in terms of simulation fidelity is outlined.

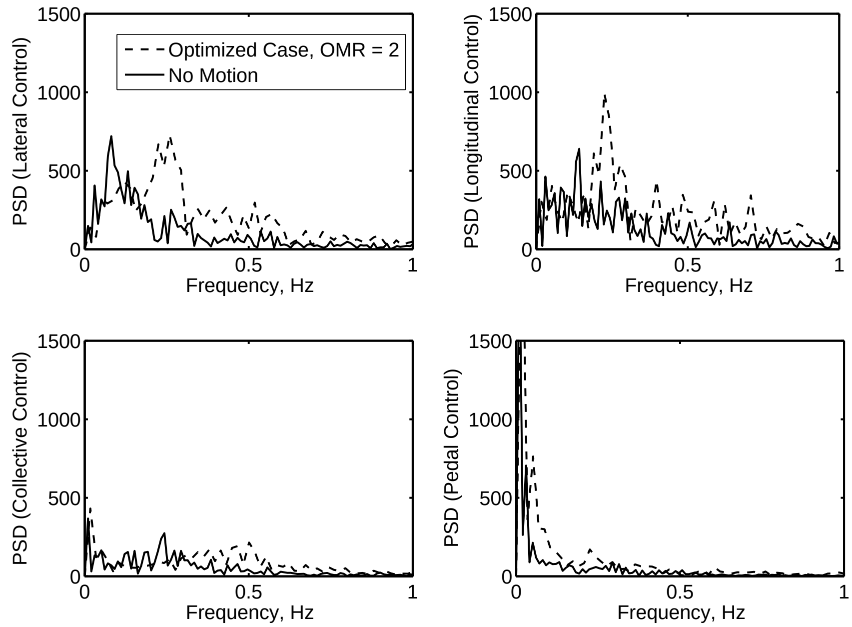


Fig. 23: Comparison of frequency of control inputs during Pirouette task.

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