Preliminary Progress in Establishing Motion Fidelity Requirements for Maritime Rotorcraft Flight Simulators[1]

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The UK's Royal Navy and Royal Fleet Auxiliary regularly perform launch and recovery operations of helicopters to and from their ships. These operations are carried out in challenging conditions such as confined ship deck space, irregular ship motion, sea spray and unsteady airflows, posing a high risk to the helicopter, ship and the crew. Together these elements form the Helicopter Ship Dynamic Interface (HSDI) environment (Ref. 1). To determine the limitations of the safe operability of helicopters to ships, a safety envelope is constructed through First-of Class Flight Trials (FOCFT) for every combination of helicopter/ship, to determine Ship Helicopter Operating Limits (SHOL) (Ref. 2), which detail the safe environmental conditions for launch and recovery operations. FOCFTs are performed at sea and are inevitably very expensive, which can typically take weeks to construct a SHOL envelope and very often the required wind and sea conditions may not be available, resulting in the development of a conservative SHOL (Ref. 3). Therefore, Modelling and Simulation (M&S) of the HSDI environment is being used to mitigate these risks, making SHOL testing safer, quicker and cost-effective and aims to inform the key test points of high uncertainty to test at sea (Ref. 4-6). The reliability of this support depends upon the identification of the fidelity requirements of the M&S elements, such as the motion and visual cueing, the flight dynamics model and the integration of unsteady airflow to represent the ship's airwake (Ref. 5). Attempts have been made to assess the fidelity of the rotorcraft simulators (JSHIP (Ref. 5)), however, a standardized guideline to quantify the overall simulation fidelity is a challenge which is yet to be fully addressed (Ref. 7). The research presented in this paper is part of a project being carried out at the University of Liverpool, funded by QinetiQ and Dstl, which aims to achieve the following objective (Figure 1):

"To undertake a structured examination of the M&S elements of the HSDI simulation environment to develop a new robust simulation fidelity matrix to support at sea flight trials."

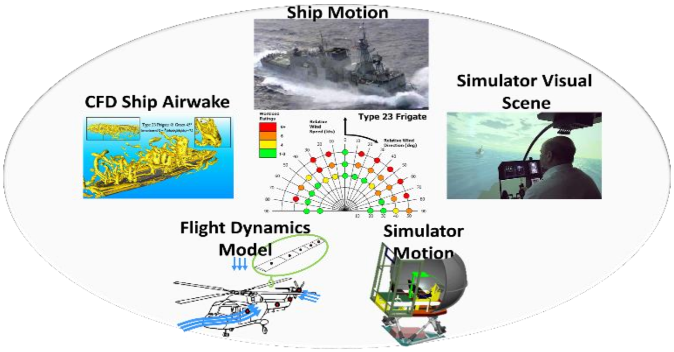

Figure 1: HSDI Modelling and Simulation Elements

Among the core elements of HSDI modelling and simulation, motion cueing is the initial focus of the project. This has remained an important topic of concern due to a gap in existing knowledge regarding simulator motion fidelity requirements specifically for HSDI operations. Existing literature on motion cueing is primarily focused upon single/multi-axis (not full-axis) based motion assessment and optimisation potentially using frequency domain techniques, pilot subjective opinions or genetic algorithms (GA) (Ref. 8, 9), which is typically undertaken in the absence of factors such as an unsteady airwake and landing spot movement, which are significant fidelity elements in the HSDI environment. An objective motion fidelity assessment technique OMCT ICAO-9625 is also available to assess the simulator motion fidelity in absence of the pilot and real-world tasks (Ref. 10). However, in

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HSDI operations, unsteady aerodynamic forces act upon the helicopter due to the airwake produced by the wind over the ship. The inclusion of such effects has not been fully examined in the literature. Therefore, further research is required to assess the motion fidelity characteristics and to determine the fidelity requirements of the simulator motion drive laws to identify acceptable motion cueing for HSDI operations in different airwake conditions. This paper reports the initial results of motion cueing research that has been conducted to optimise motion drive laws for helicopter operations in the turbulent environment of the HSDI.

Motion cues in the simulators are perceived from visual information projected onto the human eye (i.e. visual motion cues) and from a simulator's motion platform movement detected by the vestibular system in the human ear (i.e. vestibular motion cues) (Ref. 11). Poor synchronisation of the stimulation and response of optical flow and inertial motion can result in inaccurate vestibular or visual motion cues, leading to vague overall self-motion perception and compromised subjective ratings from the pilots during piloted flight trials (Ref. 12). To objectively assess and optimise the motion cues and determine high fidelity motion cueing for HSDI operations, an offline motion fidelity optimisation technique known as Vestibular Motion Perception Error (VMPE) is proposed in this research (Figure 2), based on motion perception error minimization strategy. The VMPE is the measure of the deviation between estimated perceived inertial motion by the pilot in the aircraft and simulator, which is minimized for motion cueing optimisation.

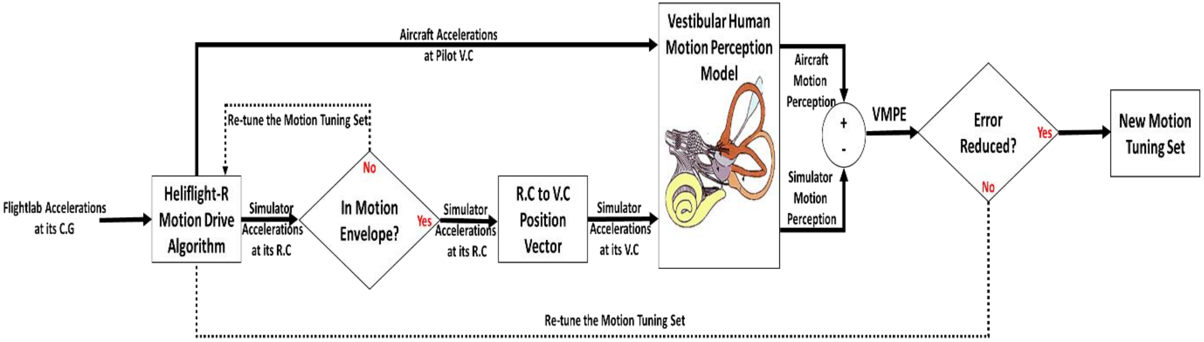


Figure 2: Vestibular Motion Perception Error (VMPE) Technique Architecture (Combined with Motion Drive Algorithm)

The motion demands of the flight simulator are produced by a motion drive algorithm also known as washout algorithm, as detailed by Reid and Nahon (Ref. 13). A generic simulator motion drive algorithm consists of high-pass and low-pass washout filters which attenuate the simulated aircraft accelerations and produce simulator motion demands. The quantity and the quality of the attenuation depend upon the tuning of the filter coefficients: gains, k, and washout frequencies, ω_n, which alter the motion base's response. The collection of these coefficients in all six axes forms a motion tuning set. The proposed VMPE model is incorporated within a Simulink-based motion drive algorithm, Figure 2. The combined system undergoes a five-step process, which begins with capturing the helicopter accelerations obtained from the FLIGHTLAB model and calculates the simulator motion demands at its rotational centre (RC). The simulator and helicopter accelerations are then transformed to the pilot's vestibular centre (VC) using the position vector. The VC helicopter and simulator accelerations are utilised to estimate the perceived motion by the pilot's vestibular system in helicopter and simulator, using vestibular system transfer functions (acquired from (Ref. 14)), which are then compared against each other to calculate the VMPE (RMS error) between them. The primary fidelity objective of the simulator is to provide initial accelerations to the pilot which are representative of the real helicopter. Therefore, the VMPE between the two is minimised by tuning the filter coefficients, constraining the simulator excursion in its motion envelope (i.e. 0.6m stroke). The technique is utilised to optimise the motion cueing in the University of Liverpool's Heliflight-R simulator (Ref. 7) for an SH60 FLIGHTLAB model landing on the Queen Elizabeth Class aircraft carrier (QEC) at three different airwake conditions (25, 35 and 45kts headwind 'H00'). A subsequent pilot simulated flight trial was conducted to assess the motion perceptions and validate the predictions.

The technique was applied in three phases: Pre-validation, Offline optimisation and Simulated flight trial.

- Pre-validation phase consisted of calculating VMPEs for six motion tuning sets obtained from an ADS-33E-PRF (Ref. 15) pirouette task motion trial conducted in Liverpool's simulator (Ref. 8); which provided multi-axis cueing demands. The VMPEs were compared against the subjective motion fidelity ratings (HMFR) obtained from Jones motion experiment (Ref. 8), to assess the viability of VMPE technique for offline pre-trial motion assessment and optimisation, see Figure. 3. The process was repeated for ADS-33E-PRF Lateral Reposition (Ref. 15) and ADS-33 (Maritime) Superslide (Ref. 16) tasks which will be discussed in the paper.

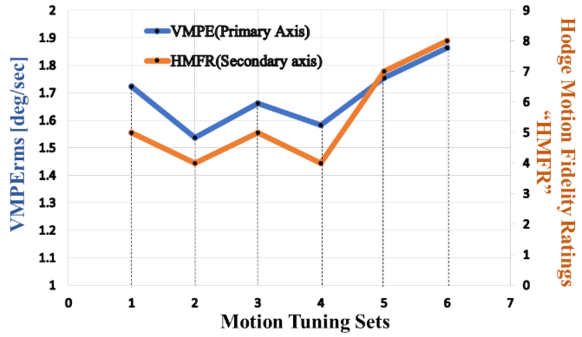


Figure 3: Pre-validation of VMPE Technique for Motion Cueing Assessment & Optimisation

- In the optimisation phase, four new motion tuning sets (Benign, Intermediate, Responsive and Optimised) were derived offline for the QEC deck landing task at three different wind conditions using the VMPE model shown in Figure 2. The helicopter accelerations needed for the optimisation were obtained from non-motion dedicated QEC deck landing flight trial (Ref. 17). RMSs of motion perception errors were calculated individually for each axis and averaged to determine the VMPE for a motion tuning set. The 'Benign' motion tuning set was predicted to provide the worst motion cueing and 'Optimised' as the best, based on average angular velocity motion perception error (VMPE_{rms}) minimized from 0.855deg/s to 0.53deg/s, see Figure 4.

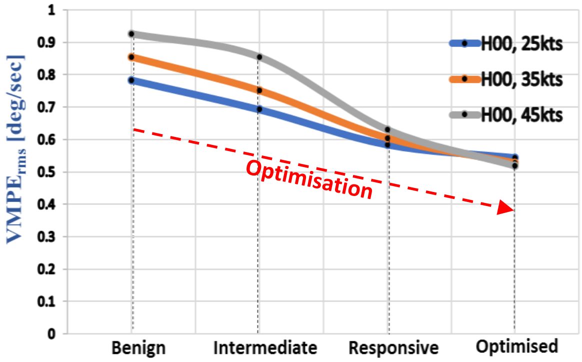


Figure 4: Motion Cueing Offline Optimisation Phase for Deck Landing Task

- A piloted flight trial was conducted by an experienced ex-Royal Navy pilot in the Liverpool's simulator consisting of twelve QEC deck landings at three Wind over the Deck (WOD) conditions and four motion tuning sets, obtained within the optimisation phase. Figure 5 shows the comparison between the motion fidelity ratings (HMFR) and the VMPEs averaged at three wind conditions for each motion tuning set. An overall agreement was obtained between offline motion optimisation predictions and online simulator flight trial results, as shown in Figure 5. The 'Benign' motion set was subjectively rated worst and 'Optimised' as best by the pilot, as predicted during the offline optimisation using VMPE technique (Figure. 4). Also, the time histories of the simulator pitch-rate response against helicopter pitch-rate in Figure 6 shows progressive improvement in the amplitude ratio and phase distortion from 'Benign' to 'Optimised' motion tuning set.

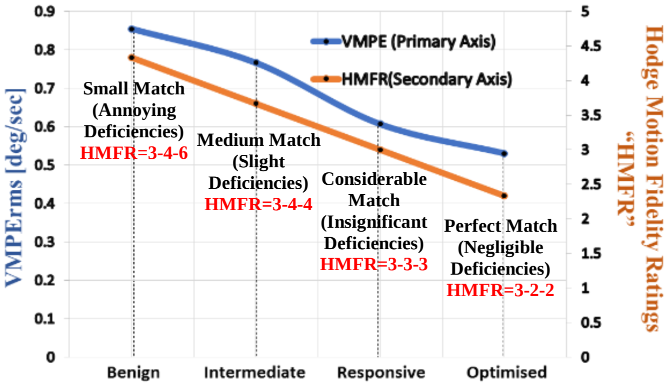
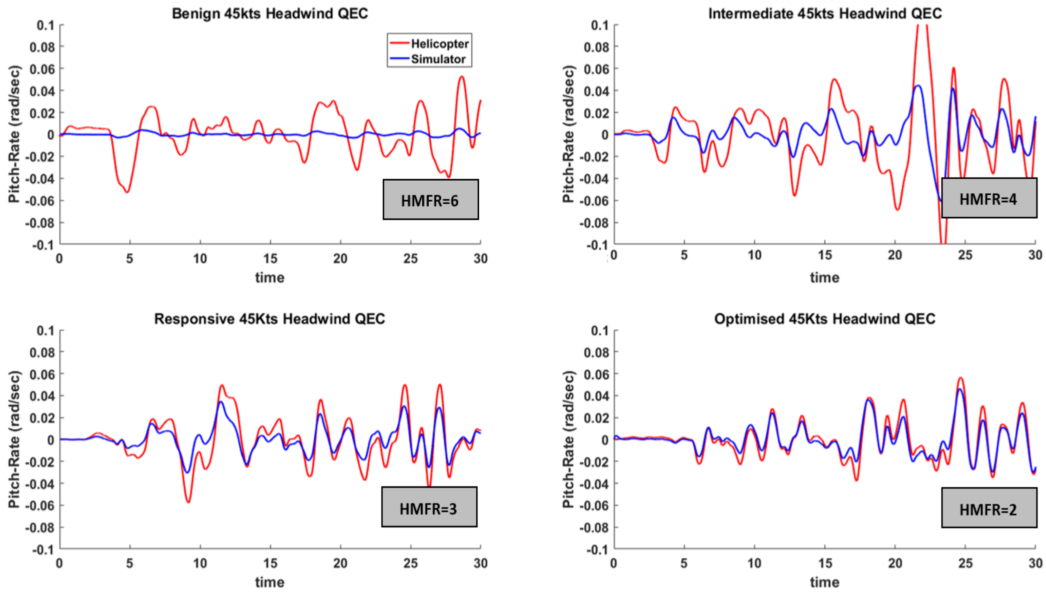


Figure 5: Piloted Flight Trial Result "Comparison of VMPE Prediction and Pilot HMFR Ratings"
(Pilot comments and HMFR ratings **[$\text{HMFR}_{25\text{kts}}$- $\text{HMFR}_{35\text{kts}}$- $\text{HMFR}_{45\text{kts}}$]** ***are summarised in text***


Benign 45kts Headwind QEC

Intermediate 45kts Headwind QEC

Responsive 45Kts Headwind QEC

Optimised 45Kts Headwind QEC

Figure 6: Comparison of Time Histories of Helicopter and Simulator Pitch-Rate for Four Motion Tuning Sets

Table 1: Hodge Motion Fidelity Ratings (HMFR) Scale Descriptions (Ref. 9)

Hodge Motion Fidelity Ratings (HMFR) Scale Descriptions		
HMFR	**Description**	**Decision**
2	Extremely Close to reality, negligible deficiencies	Close to real flight
3	Similar to reality, insignificant deficiencies.	
4	Enhances task performance, slight deficiencies	Not close to real flight
6	Other cues more dominant, annoying deficiencies.	

Table 1 illustrates the descriptions of a subjective motion fidelity rating scale (HMFR) proposed by Hodge et al. (Ref. 9), that has been used to rate the motion cueing by the pilot in the flight trial. From this preliminary motion fidelity study, it was found that the “high-fidelity” motion cueing becomes more desirable at higher airwake wind conditions than at lower winds, due to higher perturbations in the airflow over and around the ship deck and the subsequent disturbance of the helicopter which the pilot needs to compensate for. The pilot HMFR ratings at 25kts WOD condition remained the same (i.e. HMFR 3-3-3-3) when flying the simulator with any of the four motion tuning sets. However, when the WOD airwake condition was increased to 35kts and 45kts, the motion cueing for the pilot flying the simulator with ‘Benign’ motion set degrades (i.e. HMFR 4-6), while it gets more representative (better) with ‘Optimised’ motion set (i.e. HMFR 2-2), see Figure 5.

The paper will extend the initial motion fidelity assessment and optimisation results obtained during this research. Also, VMPE predictions from offline assessment, pilot HMFR ratings and pilot subjective comments from the simulated flight trial will be discussed and summarised in detail.

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