Effects of visual and motion cues in flight simulation of ship borne helicopter operations

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Abstract

Good visual cues are necessary in flight simulation of ship borne helicopter operations. Operating in a degraded visual environment has a negative impact on pilot workload and task performance. However, the need for motion cues in piloted flight simulation is still a widely debated issue. This paper describes a preliminary piloted flight simulation study into the effects of visual and motion cues on the operation of ship-borne helicopters and pilot workload. Unsteady CFD airwakes have been computed and integrated into the FLIGHTLAB modelling and simulation environment with a simulated rotorcraft model, configured to be representative of an SH-60B helicopter. A series of ship-deck landing and hover manoeuvres have been conducted using the University of Liverpool's HELIFLIGHT-R motion-base flight simulator representing different visual and motion cues, for a range of ship airwakes and sea states (ship deck motions). The usable cue environment (UCE), handling quality and pilot workload ratings were assessed using visual cue ratings (VCR), handling quality rating (HQR) the Bedford workload rating scale and the Deck Interface Pilot Effort Scale (DIPES). This paper presents the results from simulation trials with two test pilots examining the effect of the simulation cueing on task performance and workload. Visual cues were found to have a significant impact both on the usable cue environment ratings and pilot workload ratings. In degraded visual environments, the pilot's ability to make corrections in attitude and translational rates was reduced. Pilot experienced higher workload in terms of compensatory control inputs to complete the same mission task compared to operations in a good visual environment. Analysis of the pilots' workload ratings and control activity shows that motion cueing can cause differences in the perceived pilot workload. For the simulation of ship borne operations, the motion cueing effects are dependent on other simulation conditions, which include visual environments, airwake, sea states and ship deck motion. The effect of motion cueing on pilot workload and control activity was found to be more significant when the visual cueing was degraded. The variation in pilot workload ratings and control activities under different motion and visual cues indicate that the Ship Helicopter Operating Limits (SHOL) can be affected by the simulation cueing fidelity.

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Introduction

Landing a helicopter on a ship at sea is one of the most demanding and hazardous tasks for helicopter pilots. As well as operating to a restricted landing area over a pitching, rolling and heaving ship, the pilot must also contend with the presence of a highly unsteady airflow over the flight deck. This phenomenon, known as the ship's 'airwake', is caused by the air flowing over and around the ship's superstructure as a result of the combined effects of the prevailing wind and the forward motion of the ship. The nature and severity of the airwake also varies significantly with wind-over-deck (WOD) speed and direction.

As the pilot manoeuvres the helicopter through the airwake during an approach to landing, the highly unsteady airflow causes large fluctuations in the aerodynamic loads and the rotor response of the helicopter. The pilot is then required to take corrective actions via the control inputs in response to displacements in altitude, attitude and heading of the helicopter. Consequently, for certain WOD conditions, the pilot workload required to maintain aircraft stability is so high and the pilot's spare capacity to perform mission tasks is so reduced, that landing is deemed unsafe.

The safe operating envelopes for helicopter-ship operations are known as the Ship Helicopter Operating Limits (SHOL), which are derived from at-sea flight trials. However, high-fidelity piloted simulation is increasing being proposed [1, 2, 3] as a complimentary method for the informing the initial boundaries of a SHOL, as illustrated in Figure 1. In the piloted flight simulation, the SHOL is determined by the pilot carrying out the landing task under different wind conditions, and evaluating the task based on workload, accuracy and consistency using the Deck Interface Pilot Effort Scale (DIPES) and Bedford workload rating scale [2, 4].

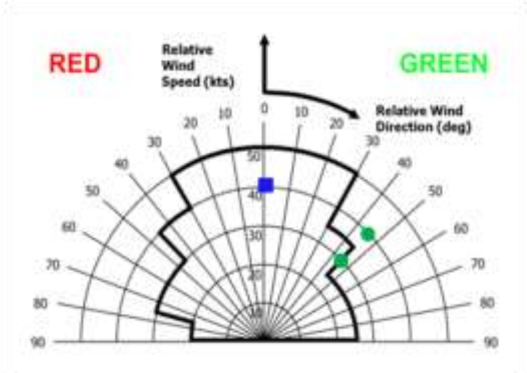


Figure 1: Ship-Helicopter Operating Limits (SHOL) diagram obtained in the Liverpool flight simulator [4]. The square and circular marks indicate the test points in this study.

Rotorcraft and fixed-wing flight simulation facilities have been developed for teaching and research over the past ten years at the University of Liverpool. The University's two seat HELIFLIGHT-R motion-base flight simulator is pictured in Figure 2. Central to this research has been a focus on improving the fidelity of flight simulation and one particularly successful aspect has been the simulation of operations at the ship-helicopter dynamic interface [2, 5, 6]. Computational Fluid Dynamics (CFD) has been used to generate time-accurate unsteady ship airwakes at different wind speeds and directions [7, 8]. Ship deck motion has also been calculated at different sea states using recorded deck motion time history data and scaling and analysis methods [4].

(a) (b)

Figure 2: The University of Liverpool's HELIFLIGHT-R motion base flight simulator outside (a) and inside (b) view.

In addition to the ship airwake and ship motion, different visual environments or cues also play an important role in defining of the fidelity of flight simulations of rotorcraft ship borne operations. When flying close to ship or other obstacles, the pilot needs good visual cues for flight path guidance and for attitude stabilisation. These visual cues are severely restricted when the light levels and visibility are poor. When the pilot can no longer make aggressive and precise control inputs during manoeuvres due to the inadequacies of the visual cueing environment, the pilot is considered to be operating in a degraded visual environment (DVE). In order to quantify the effect of any degradation of the visual environment, pilots can assess their ability to judge translational rates and attitudes during a manoeuvre using ADS-33E-PRF criteria to award a Visual Cue Rating (assuming a Level 1 rated handling qualities vehicle) to determine the usable cue environment (UCE) [9]. The VCR scale is a subjective pilot rating scale intended to quantify the usability of all available visual cues. The VCR ratings are applied to the

UCE chart to determine the overall UCE [9, 10]. A UCE of 1 indicates that all of the visual information required by a pilot is present within a scene, while at the opposite end of the scale a UCE of 3 indicates that a majority of the visual cues are lacking in a scene, limiting the aggression that can be applied a task. In the ship landing task, the UCE is also dependent on ship motion (sea state) and the handling qualities vary with UCE and ship motion [10, 11]. Degraded visual cues certainly affect pilot workload in a piloted simulation. Therefore, they have impacts on the SHOL, as the SHOL boundary is defined by the pilots' workload ratings. This study attempts to quantify the visual cueing effects on pilot workload by carrying out piloted simulation trials in the good and degraded visual environments that reflect the weather conditions in which helicopter ship borne landing could be operated.

The requirement of motion cueing in flight simulation is still a widely debated issue and there are different opinions as to whether motion is necessary for pilot training and evaluation flight simulation [12, 13, 14, 15, 16], but when a pilot is operating at his high workload capacity, and at the same time the aircraft may be close to the limits of its control margins, motion provides invaluable cues to the pilot [15]. This is especially true when the pilot is exposed to degraded visual cueing environments. In the helicopter ship landing operations, the unsteady airwake and the ship deck motion play dominant roles in determining the SHOLs. In the previous SHOL simulations carried out at University of Liverpool, high DIPES workload ratings awarded to the approach and landing tasks were often found to be caused by simulations carried out at University of Liverpool, the high DIPES ratings awarded to the approach and landing tasks were often found to be caused by P (Pitch Control) and R (Roll Control) attitudes of the deck and T (Turbulence) of the airwake. This suggests that airwake turbulence was causing severe disturbances notably in the roll and pitch degrees-of-freedom. The main cues that will make the pilot aware of these disturbances in the simulator are the acceleration cues from the motion platform and the visual cues provided by the outside world scene. Therefore, it is plausible to suggest that motion cueing is important for the fidelity of the SHOL simulations due to the unsteady nature of the airwake disturbances that the helicopter is subjected to. In reference [4], a motion cueing simulation study of lateral sidestep manoeuvre indicated the importance of motion cueing. It was reported that without motion cues the pilot could not achieve the desired accuracy without heavily over-controlling. The pilot cyclic input and aircraft roll angle had larger peak values and were more oscillatory in nature without motion cues when compared to data taken from a similar run where motion cues were present. Without motion cues, positioning accuracy was also reported to be poor, with several very large overshoots and undershoots occurring around the target locations. On the other hand, with motion cues present, the positioning was accurate with few small overshoots and undershoots. It was demonstrated that when motion cues are absent, then the lead information, which is normally supplied by vehicle acceleration cues, is missing and the pilot must compensate by adjusting his control strategy based on the remaining (mainly visual) cues.

In this paper, the effects of visual cues as well as the motion cues presented to a pilot are examined in a flight simulator when executing a task within a high workload environment. This has been demonstrated by conducting simulation trials to determine pilot workload, control activities, and handling qualities. for a helicopter landing to the deck of a ship. The simulation trials were carried out, using the HELIFLIGHT-R simulator. Two former Royal Navy pilots took part in these trials and both had significant experience of ship operations. During the trials the pilots were asked to fly the deck landing mission using the Royal Navy port side landing approach (Figure 3). This involves an approach to a hover over the sea alongside the port-side of the ship, followed by a lateral translation to a hover over the flight deck and then a descent to the landing spot. The simulator motion modes were set to full motion or no motion to compare the motion effects on pilot workload. Visual cueing impacts on pilot's workload and handling quality ratings were also studied by simulating a helicopter landing to a ship deck in day time, night, twilight, and fog visual environments.

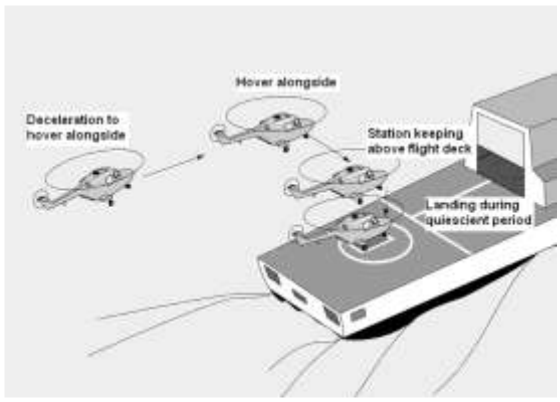


Figure 3: Standard UK Royal Navy (RN) Approach Technique

Simulation set-ups and procedures

The helicopter used in the simulation trials is a FLIGHTLAB Generic Rotorcraft model, which was configured to be similar to a SH-60B helicopter in terms of its landing configuration. The ship used in the study is a photo-textured Type 23 frigate model. It has a 'standard' pattern of deck markings, deck-lock (harpoon) grid and hangar door markings. Only one visual aid enhancement was simulated, which is a gyro-stabilised horizon bar on the top of the hangar and lit by a string of individual point-light sources. In degraded visual environments, a spot light was projected onto the land deck to illuminate the painted markings on the flight deck around the landing spot (Figure 4). These visual aids afford the pilot some basic references at night and in low visibility conditions. They are similar to those found on Royal Navy single-spot ships.

The flight simulation tests were conducted using two wind directions (Headwind and Green 45) at various wind speeds. CFD-generated time accurate Type 23 airwake were integrated into the FLIGHTLAB helicopter flight mechanics model. Sea states of 0, 3, 4 and 5 were selected in trials. The Type 23 ship deck motion data at sea state 5 was scaled from a recorded deck motion data on a larger ship. The ship motions at other sea states were synthetically generated using analytical methods and the standard sea spectra.

The good visual environment (GVE) and the degraded visual environments (DVEs) were designed to represent different visual conditions in which the helicopter ship landings could be operated. The external views of these visual environments are shown in Figure 4. The GVE is set at day time (1200). The sky, ocean, waves and the land deck markings and ship texture are clearly presented. The DVEs are generated by altering the light level and far field visibility. Light levels were chosen as twilight (0700) and night (2200). Visibility was changed from 90000ft (normal) to 500ft to simulate fog.

The HELIFLIGHT-R flight simulator uses three high resolution projectors, with wide-angle lenses, to provide a horizontal field-of-view of 210° (±105°) and a vertical field-of-view of -40° to +30°. Two flat-screen chin-window displays in the cockpit foot-well are used to extend the vertical field-of-view. In the simulation of helicopter ship landing operation, the chin-window displays are very useful to provide pilots a clear view of the ship landing deck.

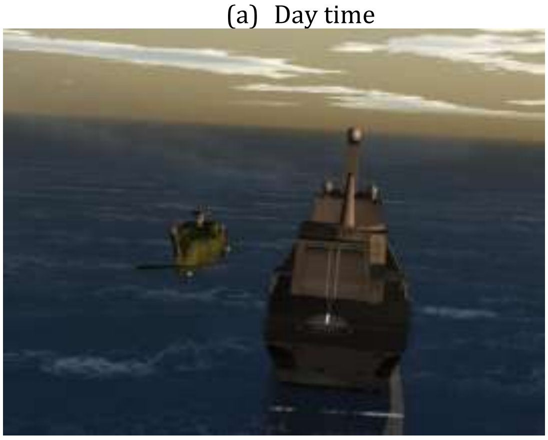
The motion cueing of the HELIFLIGHT-R is provided by six Moog electric actuators arranged in a hexapod structure to deliver full six-degree-of-freedom motion. Each actuator has a stroke of 24 inches, giving peak accelerations of 300°/s2 in each rotational axis, 0.7g in surge and sway, and 1.02g in heave. The platform has an 1800 kg payload capacity [4].

The following pilot subjective rating scales were used in the trials.

- Cooper-Harper rating scale (CH) for handling qualities ratings [9, 17].
- Deck interface pilot effect scale (DIPES) for pilot workload ratings [3].
- Bedford workload rating scale (Bedford) for workload ratings [18].
- Visual cue rating scale (VCR) for assessment of attitude (pitch, roll and yaw), and horizontal (fore and aft, lateral) and vertical rate cueing to determine UCE [9].

In addition to the subjective workload ratings and pilot's comments, quantitative data were obtained in simulations. The data included simulation time steps, traces of pilot control inputs of longitudinal/lateral cyclic, collective and pedals, helicopter position and orientation, ship motion data, engine data, etc.

(a) Day time



(b) Twilight

(c) Fog

(d) Night

Figure 4: Different visual environments used in the simulation trials.

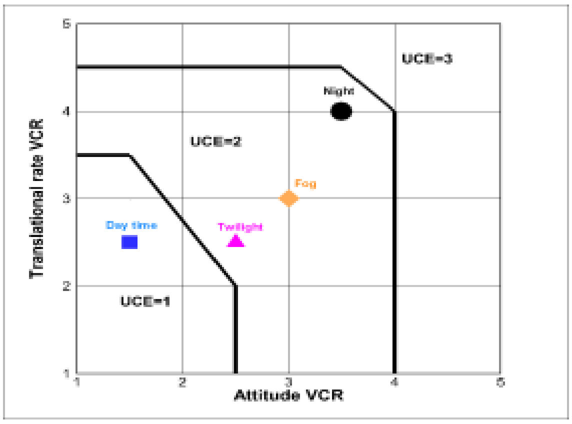


Figure 5: The UCE and VCRs in GVE and DVEs, green 45 airwake at wind speed of 30 kts, sea state 5 and full motion and no motion.

Results and Discussion

Visual cueing effects

The effect of visual cueing was assessed in two separate simulation trials. The standard Royal Navy portside landing task was performed by both test pilots A and B in the GVE and DVEs (Figure 4). The landing task profile was separated into two additional mission task elements of a lateral reposition across deck and hover above deck (station keeping) that were also performed by pilot A.

The ADS-33E-PRF visual cue ratings (VCR) were awarded by the pilots to determine the usable cue environment (UCE) in GVE and DVEs. To determine the UCE, attitude VCRs were recorded for the pitch and roll degrees-of-freedom, and translational rate VCRs were recorded for the horizontal and vertical degrees-of-freedom. The poorest attitude rating was then plotted on the horizontal axis of the UCE chart, and the poorest translational rating was plotted on the vertical axis.

A typical comparison of the UCE scores for each of the visual environments is shown in Figure 5. The day time environment provided the best visual cues (UCE = 1). The Twilight environment had no impact on the pilots' ability to make translational (guidance) corrections, but had an impact on attitude (stabilisation) control. The fog and night environments had an impact both on translational corrections and attitude control. The night scenario had the biggest impact on VCRs and degraded the UCE to the far boundary of UCE=2.

The pilots commented that, in the DVEs, the lack of reference horizon bar during translation across deck and the loss of visual reference to the deck bum-line made it difficult to judge the position and orientation relative to the ship. The correction for drift when positioning over the deck was more difficult, and it was also harder to discern the ship's motion.

The fact that the UCE scores are collapsed on the same points when the motion cueing is on and off indicates that the motion cueing has indiscernible influences on the overall UCE in these visual environments.

The corresponding workload and handling quality ratings obtained in these visual environments are shown in Figure 6. It is evident that the degraded visual environments have a significant impact on the pilots' workload and handling quality ratings. The figure shows that the workload as well as handling quality ratings tend to increase with increasing the degraded level of the visual cues, as would be expected. It is clear that the pilot experiences an increase in workload as the visual environment is degraded. Accordingly, the SHOLs in the degraded visual environment are expected to be reduced. In the day time visual environment, the test point (green 45 airwake at speed of 30 kts) is located inside the SHOL. While in the night environment, the pilot's Bedford workload rating exceeds 6, which pushes the test point outside the SHOL boundary (the SHOL boundary is defined as Bedford workload rating of 6).

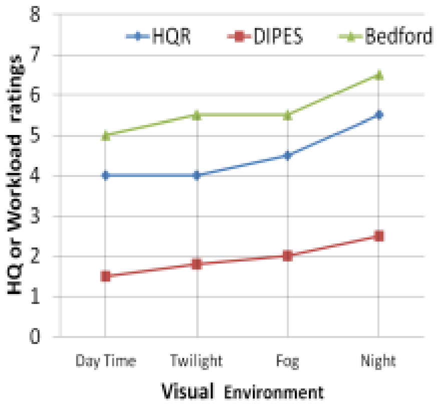


Figure 6: Pilot workload and handling quality ratings in GVE and DVEs, green 45 airwake at wind speed of 30 kts, sea state 5.

In general the results of the trials carried out by two test pilots are consistent in the effects of visual cues. The averaged DIPES and Bedford workload ratings of two pilots in the day time and the night visual environments, regardless of the motion modes, are shown in figure 7. The night visual environment caused an increase in the pilot's workload ratings. The increments were dependent on the test conditions. Quantitatively, an increment of up to 2 points in the DIPES scale and an increment of up to 3 points in the Bedford scale are found in the figure. It is also revealed that the least increments of workload ratings occurred at the condition of green 45 airwake at wind speed of 40 kts and sea state 5. This test point is already beyond the SHOL boundary (see figure 1) in GVE, where the combination of airwake and ship deck motion makes the pilot workload so high that the landing task is unsafe. In such a situation, the degraded visual environment has least significant impact on the pilot's workload.

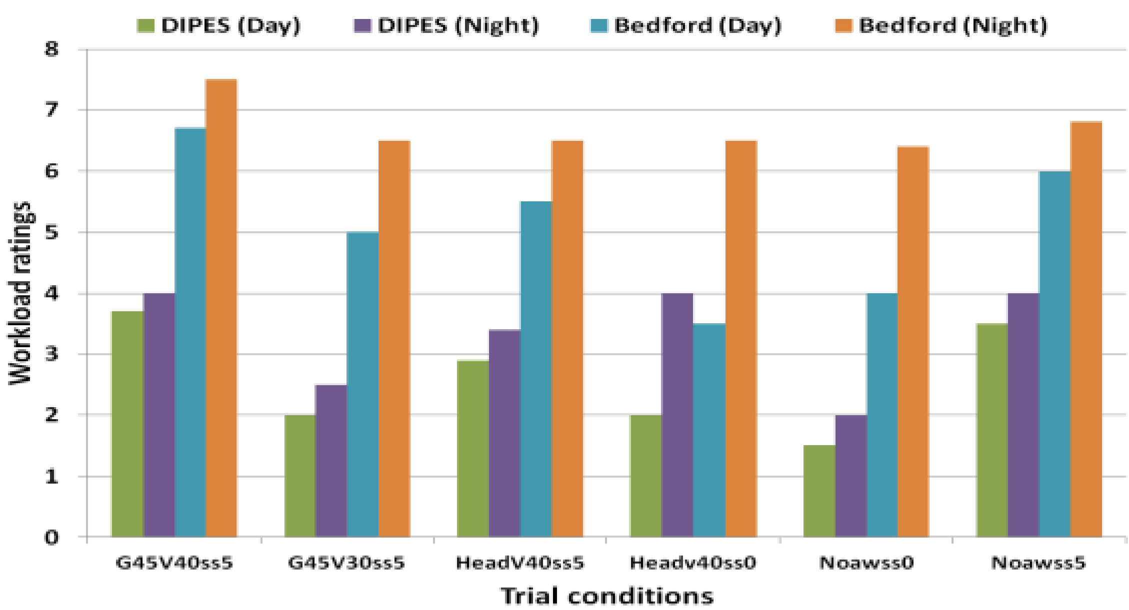


Figure 7: Averaged pilots' workload ratings at all trial conditions in day and night visual environments (Trial conditions: G45: green 45 airwake; Head: headwind airwake; Noaw: no airwake. V40/30: wind speed 40/30 kts. Ss5/ss0: sea state 5/0).

Two essential task elements of the landing manoeuvre, hovering above the landing deck (station keeping) for about 30 second in the headwind airwake, and lateral reposition across the landing deck in the green 45 airwake, were performed in the day time and night environments. The control stick displacements and the helicopter movement can be directly compared to reveal the pilot's control activities and helicopter's response.

The time history of the displacements of the control sticks and pedal, helicopter position and attitude relative to the ship deck during the task elements are shown in figures 8 and 9. The trend of increasing the control activity in the degraded visual environment is evident in the stick and pedal traces. When comparing with these in day time, the pilot needs more control inputs, which are reflected in the larger amplitudes of movements of control sticks and pedal, to complete the same mission element in the night environment. The drifts of helicopter positions and the variations of helicopter orientation are significantly wider than these in day time. All these observations are in agreement with that was found in the pilot workload ratings.

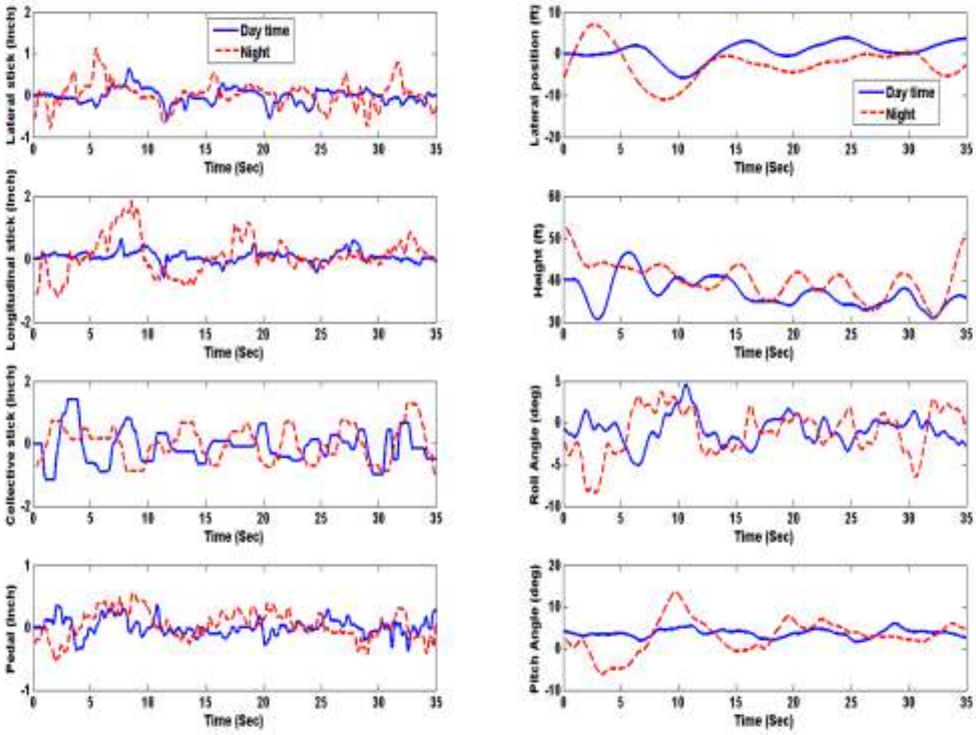


Figure 8: Hover above deck landing spot at sea state 5, headwind airwake at wind speed 30 kts.

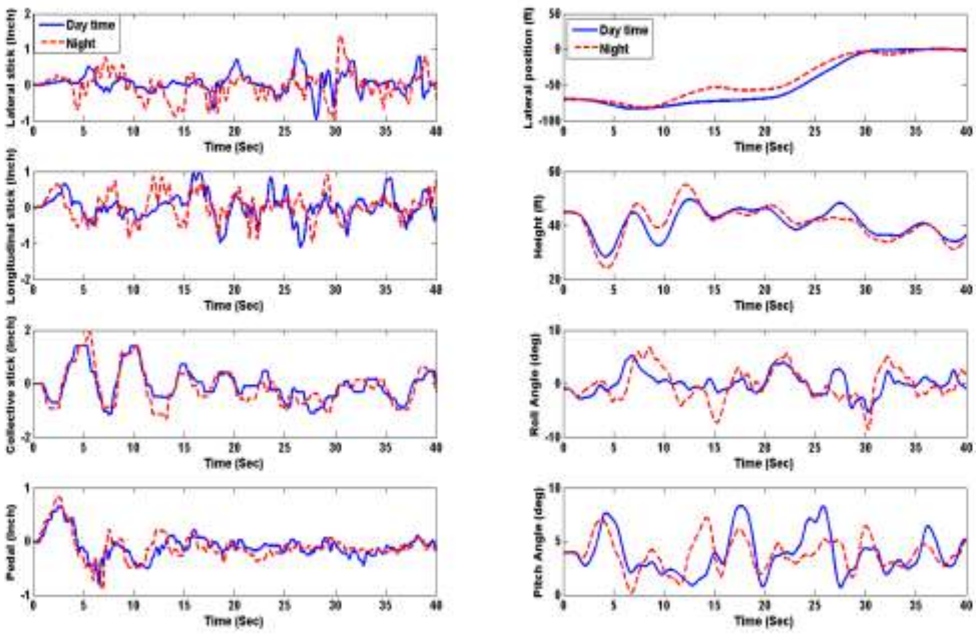


Figure 9: Lateral translation across landing deck at sea state 5, green 45 airwake at wind speed 30 kts.

In helicopter ship borne operation simulations, sea state is an important parameter. Sea state has an impact not only on pilot workload but also on visual cues ratings [10]. The lateral reposition mission task element across the landing deck in the green 45 airwake has been conducted at sea state 3, 4 and 5 in the day time and night visual environments. The pilot determined UCEs at different sea states and day and night environments are shown in Figure 10. In day time environment, whatever the sea states (ship deck motion), the UCE is 1. Higher sea states push the UCE further close to the boundary between UCE=1 and UCE=2. In night environment, the UCE is near to the far boundary of UCE=2. The workload and handling quality ratings at these three sea states are shown in figure 11. The figure clearly indicates that there is a direct correlation between the workload and handling quality ratings assigned by the pilots and the sea state level and the UCE for the lateral reposition task. The higher the sea state is the higher the workload and the handling quality ratings assigned by the pilots. At the same sea state, the degraded visual cueing (night) caused a higher ratings of workload and handling quality.

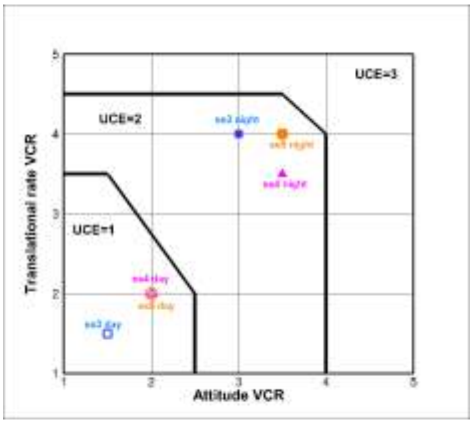


Figure 10: The UCE and VCRs in day and night environments of the lateral reposition task, green 45 airwake at wind speed of 30 kts, sea state 3, 4 and 5.

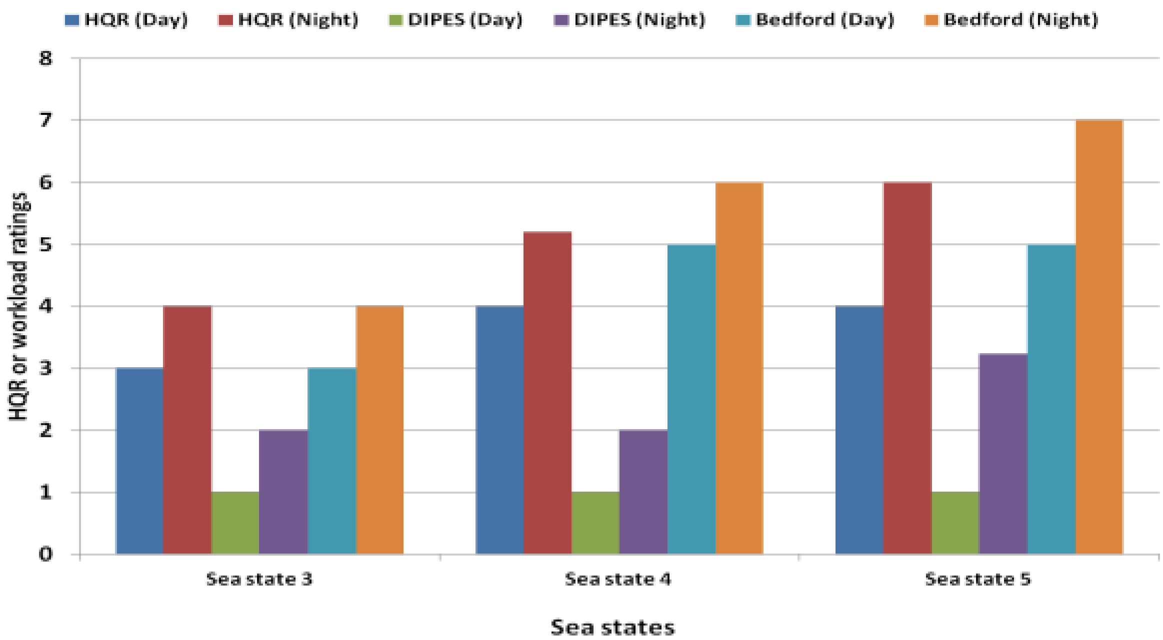


Figure 11: Bar plots of the workload and handling quality ratings in day and night visual environments of the lateral reposition task, green 45 airwake at wind speed of 30 kts, sea state 3, 4 and 5.

Motion cueing effects

Whether the simulator platform motion cueing is necessary or not in simulation is still being debated. Among of the cases for the motion cues, Hall [15] states that non-visual cues are of little importance for primarily open loop, low pilot-vehicle gain, low workload manoeuvres with strong visual cues. Motion cues are, however, more important when the pilot workload increases; when the pilot-vehicle gain rises, or when the vehicle stability degrades. These certainly occur in the helicopter ship landing simulations. A series of investigations of the effect of simulation motion on pilot-vehicle performance were performed by Schroeder [16] using the NASA vertical Motion Simulator and an APACHE helicopter model. His results indicated that both lateral and vertical translational motion cues significantly improved pilot-vehicle performance and reduced pilot workload. The yaw and roll rotational motion cues were, however, not important. This research is an important contribution to understanding the motion cueing in helicopter flight simulation. In the context of pilots' acceptance, pilots prefer simulator motion. During our simulation trials, Pilot A strongly preferred the full motion cueing. The landing simulations conducted at the no motion mode were described as "uncomfortable", "disorientated" and "unpleasant".

For the helicopter ship borne operation simulations, in addition to the visual cues, the ship unsteady airwake and ship deck motion (sea states) are also relative to the effect of motion cueing.

The motion cueing effects on the averaged workload ratings of two pilots in the day time and the night visual environments are compared in figure 12. The test conditions include the headwind and green 45 airwakes and the ship deck motion corresponds to sea state 5. These different test points are marked on the SHOL in figure 1. The results of the day time visual cue do not reveal any clear trends of the motion cueing effect at this stage. However, comparisons of the pilots' workload ratings in the night visual environment indicate that the presence of motion cueing generally reduces pilot workload. The effect is more obvious for the test condition of green 45 airwake at wind speed 30 kts. For this trial condition, simulations were also conducted in the fog and twilight degraded visual environments. The motion cueing effects on the pilots' workload ratings in the four visual environments are compared together in figure 13. While the motion cueing effect was not obvious for the day time (GVE) environment as shown in the figure, noticeable influences on the workload and handling quality ratings were shown when the visual environment was degraded. The motion cueing effect is more obvious for the fog and the night degraded visual environments. In the night environment, when the light level is the lowest and the UCE is the worst, the motion cueing makes a bigger difference on the pilot's workloads.

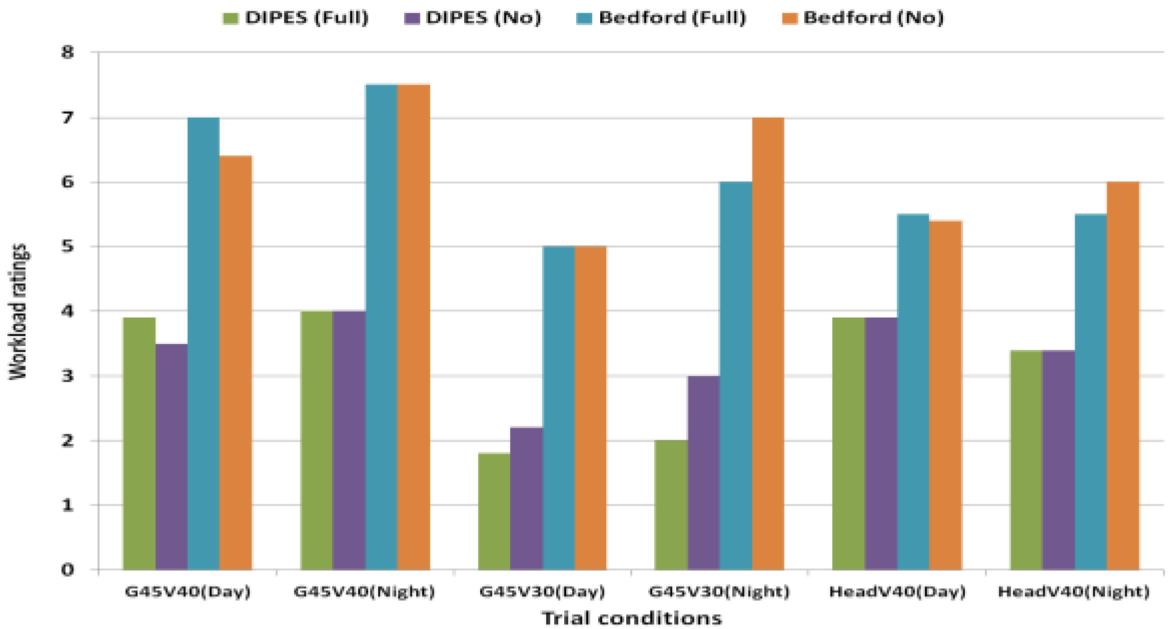


Figure 12: Motion cueing effects on the averaged pilots' workload ratings in day and night visual environments, sea state 5 (Trial conditions: G45: green 45 airwake; Head: headwind airwake; V40/30: wind speed 40/30 kts).

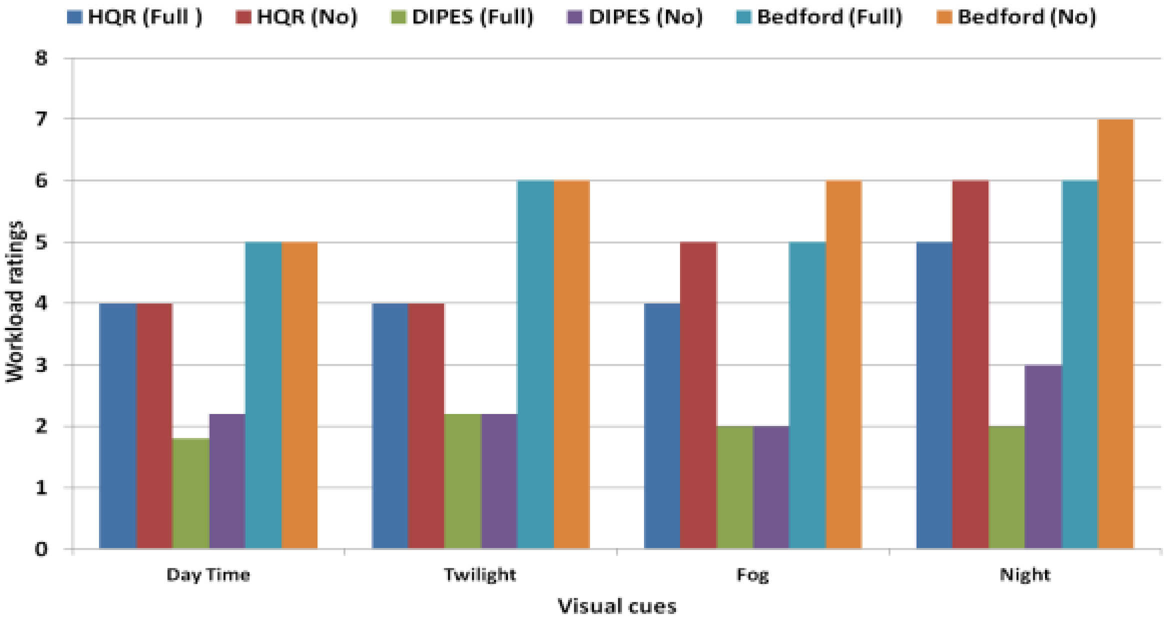


Figure 13: Motion cueing effects on pilots' workload and handling quality ratings in day, twilight, fog and night visual environments, green 45 airwake at wind speed of 30 kts, sea state 5.

The workload and handling quality ratings are subjective and a higher rating might be caused by a variety of reasons. An objective measure is the traces of the pilot's control sticks and pedal, which reflect the extensions of pilot's control activities during the manoeuvre tasks. The traces of the pilot's control sticks and pedal in the day and fog visual environments for the full motion and the no motion cases are shown in figure 14. In the degraded visual environments, without the motion cueing, the trajectories of the pilot's control stick generally display larger excursions, which indicate that the pilot experienced higher control activities in almost all control axes.

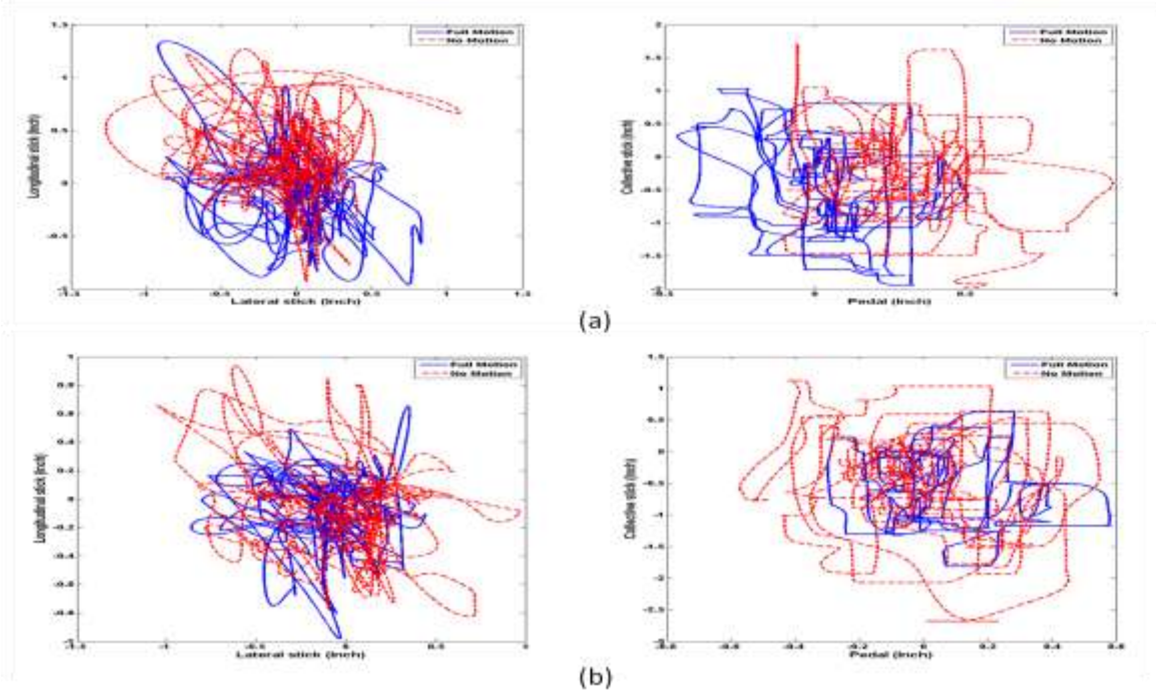


Figure 14: The traces of pilot's control sticks and pedal in the day (a) and the fog (b) visual environments for the full motion and the no motion cases.

Conclusions

Piloted flight simulation trials have been carried out to investigate the visual and motion cues on the fidelity of helicopter ship borne landing operations. Unsteady CFD airwakes were computed for the Type 23 frigate geometry and ship deck motions at different sea states were generated. The airwake and ship motion were integrated into the FlightLab simulation environment and piloted flight simulation trials were conducted in a motion based simulator. Visual cueing had significant effects both on the usable cue environment ratings and the pilots' workload ratings. In the degraded visual environments, and especially in the night environment, the usable cue environment was degraded from UCE=1 to the far end of UCE=2. The pilots' ability to make corrections in attitude, horizontal and vertical translational rates was reduced. Pilot experienced higher workloads and more control inputs were needed to complete the same mission task than that in the good visual environment. For helicopter maritime operations, it can be anticipated that the Ship Helicopter Operating Limits (SHOL) will be reduced in the degraded visual environments.

The results of the piloted simulation trials of motion cues indicate that for the helicopter/ship dynamic interface, the motion cueing effect have to be considered with other simulation parameters, which include visual environments, airwake, sea states and ship deck motion. It was found that under the test points, although motion cueing could cause differences in the pilot's workload ratings, it had no discernible regular trend in the relative good visual environment. However, in the severely degraded visual environments, the motion cueing effect was more significant. The pilot's workload ratings and control activities on control sticks and pedal were normally higher without motion cues.

It is clear that in current study, neither the number of test pilots nor the test points are sufficient. In order to draw concrete conclusions of motion cueing effects, more pilots will be invited to repeat the simulation trials. Additional test points with different airwake, sea states should be tested. Enhanced visual cues including the airwake real time rendering are planned to be implemented in the future simulation trials.

Acknowledgements

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