Assessing the suitability of ship designs for helicopter operations using piloted flight simulation

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Abstract

Ship airwakes have a significant effect on the operation of ship-borne helicopters. This paper describes a piloted flight simulation study into the effect of three different aerodynamic modifications to a generic ship geometry on pilot workload. Unsteady CFD airwakes have been computed using Detached-Eddy Simulation and integrated into the FlightLab 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 for the different ship geometries and the pilot workload was assessed using the Bedford Rating Scale. Analysis of the computed CFD airwake data has shown that the ship modifications have created reductions in turbulence intensity levels in the airflow through the flight path. Significant reductions in pilot workload ratings from flight tests indicate improved workload characteristics for the modified ship geometries compared with the baseline case.

Introduction

Landing a maritime helicopter to the flight deck of a ship is a difficult and demanding task for even the most experienced pilots. As well as operating to a restricted landing area and 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 effect of the prevailing wind and the forward motion of the ship. Over recent years, collaborative international research into the ship-helicopter dynamic interface has investigated flight deck aerodynamics using techniques such as wind tunnel anemometry and flow visualisation [1-5], Computational Fluid Dynamics (CFD) [6-8] and model-scale helicopter aerodynamic loading experiments [9-13]. These studies have done much to increase the understanding of ship airwake flow phenomena and a review of such studies has been published by Zan [14].

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Ships are not generally designed with aerodynamics in mind, so the sharp edges of the superstructure lead to unstable flow separation and the formation of vortices, causing large spatial and temporal gradients in the airflow over the flight deck. The nature and severity of the airwake also varies significantly with wind-over-deck (WOD) speed and direction.

As the pilot moves the helicopter through the airwake during an approach to landing, the highly unsteady airflow causes large fluctuations in the aerodynamic loading and the rotor response of the helicopter in the closed-loop pilot response frequency range of 0.2-2 Hz [9, 10]. The pilot is then required to take corrective action via the control inputs in response to displacements in altitude, attitude and heading. Consequently, for certain WOD conditions, the pilot workload required to maintain aircraft stability is so high and the pilot's spare capacity to perform ancillary tasks is so reduced, that landing is deemed unsafe. Such conditions are then considered to be outside the safe operational limits of the ship-helicopter combination in question. The spare control margins available to the pilot throughout an operation are also an important factor to consider in the establishment of safe operational envelopes. If the pilot is required to move a control to within 10% of its maximum travel during a landing task then the capability to respond to large disturbances in that axis is severely compromised. This typically leads to an operational limit being imposed as the pilot's ability to maintain control of the aircraft and to deal with strong gusts encountered in the unsteady airwake is reduced.

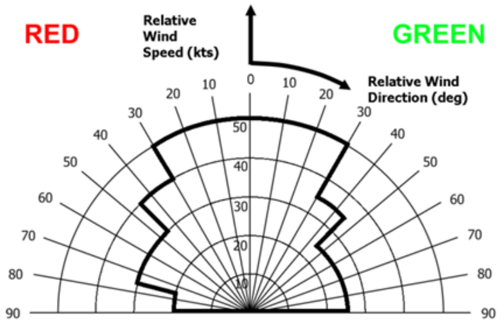


Figure 1: Ship-Helicopter Operating Limits (SHOL) diagram obtained in the Liverpool flight simulator

The demanding nature of ship-borne helicopter operations means that every ship/helicopter combination has its own specific Ship-Helicopter Operating Limits (SHOL) which, as illustrated in Fig. 1, designates the safe operating conditions, based on WOD speed and direction. The terminology Red and Green used in Fig.1 refers to winds coming from the port and starboard side of the ship respectively and will be used throughout.

SHOLs are derived from First of Class Flight Trials (FOCFTs) which are costly and time-consuming as they require ships, helicopters and crews to be taken out of service for weeks or even months at a time. These FOCFTs are also inherently dangerous as test pilots will fly WOD conditions at the very limit of what would be considered safe for fleet pilots to repeatedly attempt. The imposition of the SHOL envelope will also inhibit the responsiveness and therefore the effectiveness of a vitally important naval tactical system during operations in difficult weather conditions [15].

Due to the expenses and inherent dangers associated with FOCFTs and the need to maximise the operational envelope, much of the research concerning the ship-helicopter dynamic interface, at the University of Liverpool and elsewhere, has focused on the development of high-fidelity flight simulation [16-20] as a tool to augment at-sea SHOL trials. Mitigating the costs and risks of FOCFTs with high-fidelity simulation could also improve the efficiency of the trials and thus reduce the conservative nature of the eventual SHOL by allowing critical WOD conditions to be identified more quickly and tested more thoroughly. There have also been international research efforts to reduce the impact of the unsteady airwake on SHOL envelopes through aerodynamic modification of ship superstructures [21]. Recent work at Liverpool has created an experimental facility that places a model-scale AW-101 helicopter in the airwake of a ship to improve the understanding of the complex interactions between the aircraft and the large spatial and temporal velocity gradients encountered in the airwake [12, 22]. This experiment was also used to test the effects of various geometry modifications to the superstructure of a generic frigate-sized model ship that were developed to reduce the unsteady aerodynamic loading of the helicopter model [23]. That study produced a number of successful aerodynamic ship geometry features that could potentially be fitted to existing ships or incorporated into future ship designs. This paper will take those concepts that produced significant improvements in aerodynamic loading characteristics and use piloted flight simulation to investigate impact of those ship modifications on pilot workload.

Dynamic Interface Flight Simulation at the University of Liverpool

Over the past ten years the University of Liverpool's Flight Science and Technology Research Group has developed world-class rotorcraft and fixed-wing flight simulation facilities for teaching and research. The department's two-seater HELIFLIGHT-R motion-base flight simulator is pictured in Fig. 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.

(a) (b)

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

The development of dynamic interface flight simulation at Liverpool can be comprehensively traced through the PhD theses of Roper, Forrest and Hodge [24 - 26]. Central to the work of Roper and Forrest in particular was the accurate modelling of the ship airwake and integration into the FlightLab simulation environment with an appropriate helicopter model so that the unsteady disturbances and pilot workload requirements in a simulated landing were representative of the actual at-sea environment. CFD techniques of increasing complexity have been employed as the state of the art has developed over time, culminating in the use of an unsteady CFD airwake generation method developed by Forrest [6, 25] using Detached Eddy Simulation (DES) turbulence modelling. Some previous methods that had been employed involved using steady airwakes with stochastic turbulence reconstructed from measured data that was often adjusted based on pilot feedback from test simulation trials. This was time-consuming and required comprehensive pilot experience of the ship-helicopter combinations in question and as such is not reliable for use on new or 'prototype' ship geometries. The benefit of using unsteady CFD airwakes, provided the method is well validated, is that the data is 'ship-specific' and captures the medium to large scale flow structures that most-significantly impact on pilot workload. This is especially important if, as in this study and the study by Forrest *et al.* [27], the effect of aerodynamic ship modifications on these unsteady flow structures and the resulting impact on handling qualities and pilot workload is under investigation.

The data from CFD simulations by Forrest *et al.* [6] matched wind-tunnel and full-scale at-sea data very well and ultimately led to piloted simulations with realistic handling qualities [19, 20, 25]. The same CFD airwake generation method has been used in this study to investigate the impact of aerodynamic ship geometry modifications and design features developed by Kääriä *et al.* [23] on pilot workload levels in a motion-base flight simulator.

Shortened Research Frigate

The ship geometry used in this study is a shortened simple frigate shape, which has been named the Shortened Research Frigate (SRF), and consists of a simplified hull and hangar model (Fig. 3). The SRF has been developed as a generic ship that has airwake characteristics representative of more realistic ship geometries. It has an overall length of 1.23m, a beam (b) = 0.26m and a Hangar Height (HH) = 0.11m.

In the study by Kääriä *et al.* [23], a variety of geometric modifications were made to the baseline SRF geometry in an attempt to reduce the unsteady aerodynamic loading caused by its airwake. There are two major goals of this work. The first is to initiate the development of aerodynamic modifications that can be retro-fitted to existing ship geometries to alleviate the effect of their airwakes on helicopter operations. The second, and probably more practical, objective is to serve as a source for future ship designers to enable them to make more informed decisions about how particular geometric features, such as the placement of a walkway or the shape of a hangar, can be designed so as to minimise adverse airwake effects. The study reported herein aims to build on the success of that work by investigating the effect of the ship modifications on pilot workload levels using the flight simulation tools developed at Liverpool.

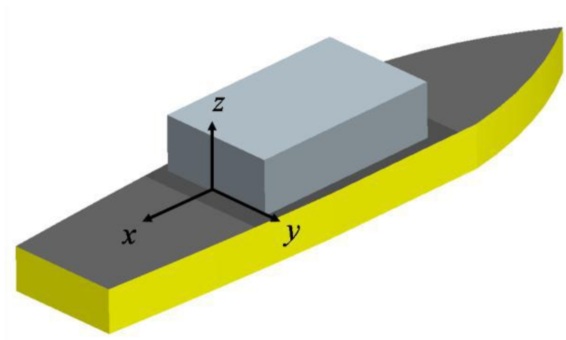
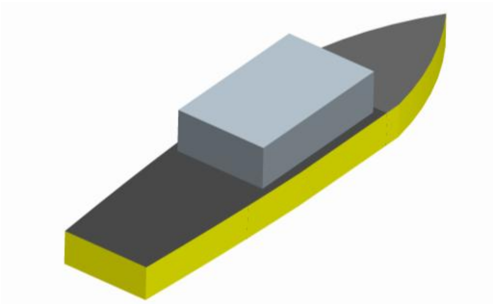


Figure 3: SRF ship geometry

Ship Geometry Modifications

Three modifications to the SRF ship geometry have been investigated for a G45 WOD condition and are pictured in Fig. 4. The Side-Flap and Notch modifications were previously investigated by Kääriä *et al.* [23] and were found to produce significant improvements in terms of unsteady aerodynamic loading of a model-scale helicopter compared with the base SRF geometry. In addition, a larger Side-Flap-2 modification has also been developed and investigated here, using dimensions based on the Notch modification but with a 45° chamfer at the aft corner to eliminate the possibility of creating a vortex that may propagate towards the flight deck and adversely impact on the landing manoeuvre. These modifications were chosen for this investigation not just because they performed well in previous studies, but also because their simple design means there is a greater probability that, given the promising results in experiments and simulations, they could be applied to existing ships or incorporated into future designs.



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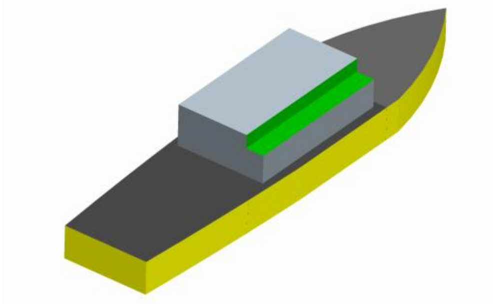

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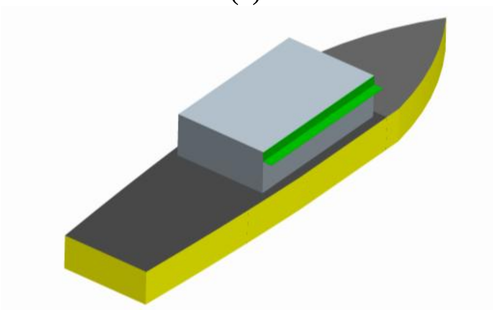

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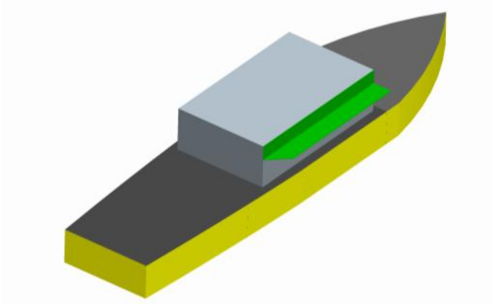

(d)

Figure 4: Baseline SRF (a) and Notch (b), Side-Flap-1 (c), and Side-Flap-2 (d) modifications

Computational Fluid Dynamics

The unsteady airwake data was generated using the commercial CFD code FLUENT, using Detached-Eddy Simulation (DES) to capture the large-scale turbulent structures. Using an unstructured mesh containing approximately 6 million cells, the computations were partitioned across 32 processors of a computing cluster, taking about 60 hours to generate 30 seconds of full-scale airwake data. This airwake generation method has been extensively validated against model-scale and full-scale data, provided by National Research Council (NRC) Canada and Dstl respectively, for a range of generic and realistic ship geometries [3, 25]. The comparisons between the computed and measured airwakes showed good agreement in both the spatial and temporal characteristics.

Airwake Integration and Rotorcraft Model

After computing the ship airwakes, the CFD data was interpolated onto a uniform structured grid with 1m spacing and integrated into the FlightLab flight simulation environment. Due to memory constraints the temporal resolution of the data was reduced from the 100Hz used in the computations to 25Hz and velocity time histories were limited to 30 second loops (with smoothing). This follows the method used in flight simulation studies by Forrest *et al.* [19, 20, 25] which was found to provide highly realistic airwake disturbances and representative pilot workload levels.

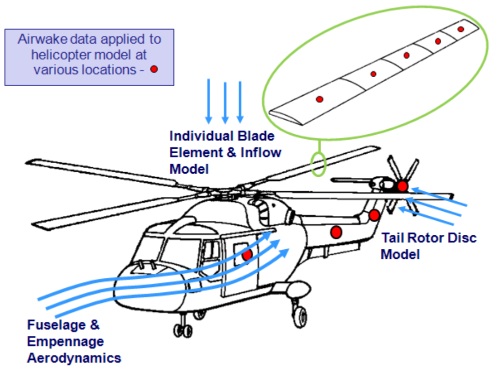

Figure 5: Location of 24 Aerodynamic Computation Points (ACPs)

A UH-60A rotorcraft simulation model has been re-configured to be representative of a Sea-Hawk (SH-60B) helicopter. The model was developed using FlightLab, an advanced multi-body dynamics modelling and simulation environment, which allows complete rotorcraft simulations to be constructed from a set of modular components (e.g. main/tail rotors, fuselage and empennage). In order for the ship airwake to affect the aerodynamic loading of the simulated rotorcraft model the airwake velocity components must be converted into forces and moments at the helicopter's centre of gravity. To do this the airwake velocity components are interpolated from a look-up table at a total of 24 Aerodynamic Computation Points (ACPs) distributed around the model at the fuselage, empennage, tail hub and five elements along each of the four main rotor blades, as shown in Fig. 5 (the pictured helicopter is not an SH-60B and is for illustration purposes only).

The aircraft setup in FlightLab includes a dynamic inflow model and also accounts for the effect of rotor downwash. However, the coupling between the ship airwake and the aircraft model is 'one-way' in that the airwake affects the helicopter response but is not, in turn, influenced by the rotor downwash. The importance of coupled airwake/rotor-downwash simulations is not yet fully understood, and is the subject of further research at the University of Liverpool.

Results and Discussion

CFD Airwake Analysis

Figure 6 shows the CFD-generated vertical turbulence intensity contours at z = 8.91m for the baseline and modified SRF ship geometries when the wind relative to the deck is 45 knots from a direction Green 45°, i.e. in a G45 WOD condition. The plane z = 8.91m is 1½ times the height of the hangar above the deck and roughly 1m above the approximate height of the SH-60B rotor during the lateral translation and hover over the spot phases of the a deck landing. In the baseline case, there are large vertical turbulence intensity levels, particularly over the port edge of the deck as large flow structures are directed towards this region as they separate from the windward (starboard) side-face of the hangar. Indeed, it has been observed in simulation studies and reported from at-sea flying experience, for a variety of ship-helicopter combinations, that for a G45 WOD angle, the largest amplitude airwake disturbances and greatest levels of pilot workload occur through the lateral translation and particularly over the port-edge of the deck [12].

As can be seen in Fig. 6, all the modifications have led to reductions in turbulence intensity levels at the port-side approach position and over the flight deck. This corroborates the reductions in unsteady aerodynamic loading caused by the Notch and Side-Flap-1 modifications in the experimental study by Kääriä *et al.* [23]. The Notch modification (Fig. 6b), has not only reduced the peak turbulence but also shifted the wake slightly towards the port-side, meaning that turbulence intensities levels over the deck at this height are hardly significant at all and should lead to a noticeable reduction in pilot workload when hovering over the flight deck. The Side-Flap modifications have also significantly reduced the peak turbulence levels and should also lead to reductions in the workload in the piloted simulations both for the landing manoeuvre and hover over the flight deck task.

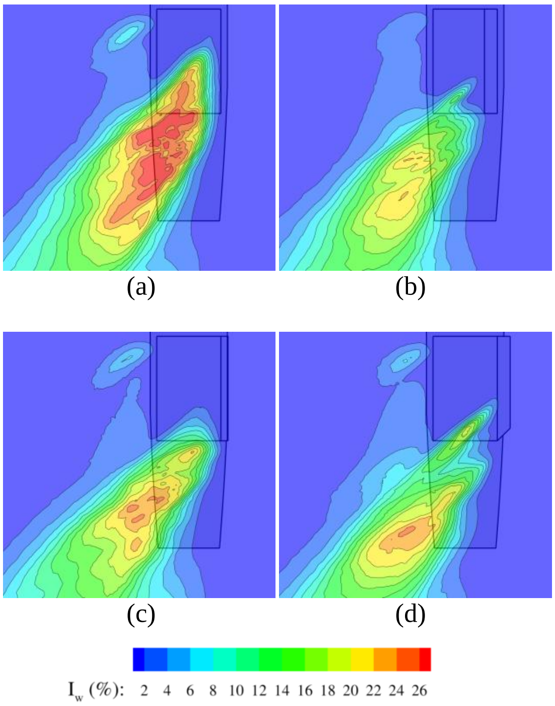

Figure 6: Vertical turbulence intensity contours at z = 8.91m for baseline SRF (a) and Notch (b), Side-Flap-1 (c), and Side-Flap-2 (d) modifications in a G45 wind

Piloted Simulation Flight Test Procedure

After the unsteady ship airwakes of the baseline SRF and modifications had been computed and integrated into the FlightLab simulation environment as described in previous sections, an experienced former Royal Navy test pilot was asked to conduct a series of two different manoeuvres using the HELIFLIGHT-R motion base flight simulator for the baseline and modified SRF ship geometries. Both manoeuvres were carried out for a number of wind speeds for each of the SRF geometry configurations and the pilot was asked to assess the difficulty of the task using the 10-point Bedford Workload Rating Scale shown in Fig. 7.

The first task was a standard Royal Navy approach technique manoeuvre, illustrated in Fig. 8. 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. Royal Navy protocol for the pilot to sit in the right hand seat for a port-side approach was not observed due to technical issues with the controls in the right-hand seat of the HELIFLIGHT-R simulator. Sitting in the left-hand seat for a port-side approach can sometimes lead to increased workload due to loss of visual cues at high bank angles.

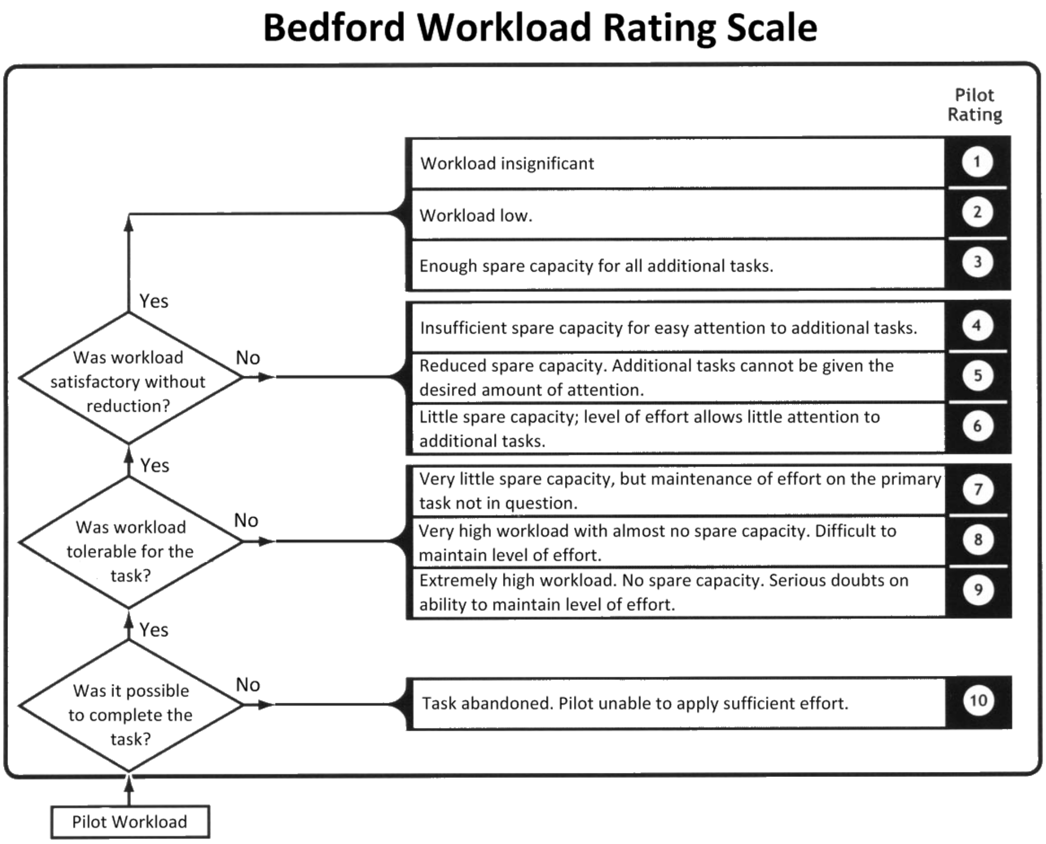

Figure 7: Bedford Workload Rating Scale

However, there was no indication in the pilot's comments that it significantly impacted on his ability to conduct the manoeuvre in the simulation trials.

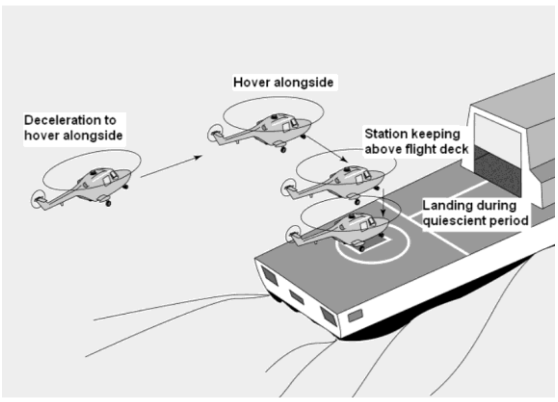

Figure 8: Standard UK Royal Navy Approach Technique

For the second manoeuvre, the pilot was asked to conduct a series of 30 second hover tasks over the flight deck in the location of the spot hover section of a full deck landing.

Piloted Flight Trials

Figure 9 shows Bedford workload ratings given by the pilot for the full landing manoeuvres for the baseline and modified SRF geometries for a range of wind speeds between 20-40kts. Linear best-fit lines have also been added to the figure to indicate the expected general trend of increasing workload levels as the amplitude of the peak airwake disturbances increases with increasing wind speed. Whilst some scatter is to be expected due to the subjective nature of the rating system, generally all the modifications have reduced the workload levels for the full landing manoeuvre, particularly for the Side-Flap modifications. Through the mid-range wind speeds, 25-35kts, in particular there are reductions of one or even two levels compared with the baseline SRF results. This represents a significant reduction in workload that was indicated by the reductions in turbulence intensity observed in the CFD airwake analysis in the previous section. Indeed, ratings of six and below at speeds up to 40kts for the modified ship geometries indicate a potential 5kts increase in the limiting wind speed for a deck landing at G45 compared with the baseline SRF.

Figure 10 shows the results from the 30 second hover manoeuvre flight tests for the baseline and modified SRF ship geometries. Ratings for the corresponding SRF geometry configurations and wind speeds are generally lower than for the full deck landings. This is because in the full landing manoeuvre in a G45 wind the peak workload levels are encountered in the lateral translation phase, particularly over the port edge of the deck, whereas the workload over the flight deck is reduced.

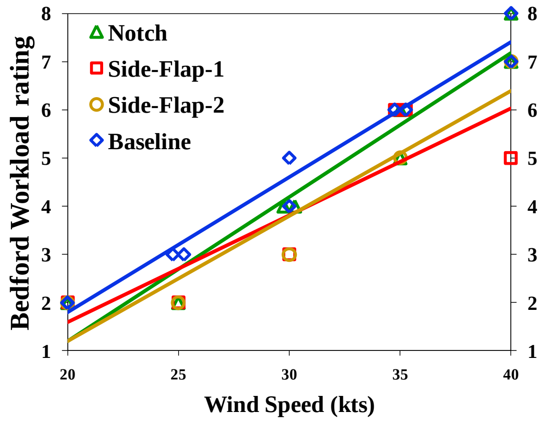

Figure 9: Bedford pilot workload ratings for deck landings using standard Royal Navy port-side approach technique

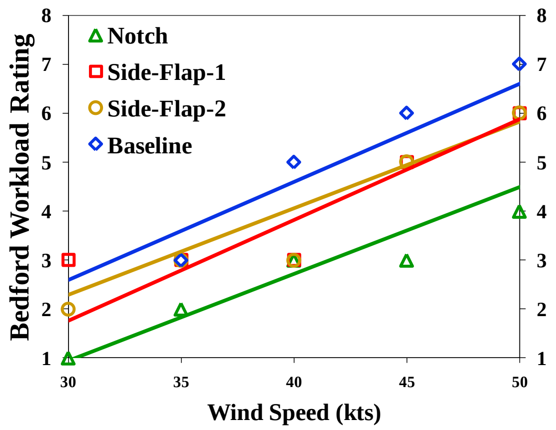

Figure 10: Bedford pilot workload ratings for 30 second hover over the flight deck task

Pilot workload over the flight deck is still significant however, especially if there are large ship motions and the pilot needs to have adequate control of the aircraft to respond quickly during a quiescent period in the ship's deck motion. It is also interesting to perform an isolated investigation into how the ship modifications influence workload over the deck because although a port-side approach in a G45 wind has been investigated as the worst case scenario, during operations, if circumstances allow, a starboard approach will be used. At the starboard side of the ship in a G45 wind angle the aircraft would be in the undisturbed, natural 'free-stream' wind over the sea and therefore airwake-induced pilot workload will only be significant over the flight deck. Thus, significant reductions in workload over the deck would increase the limiting wind speed for a G45 starboard approach. Reducing workload levels over the flight deck is also useful for other hover tasks such as slung-load deployment or in-flight re-fuelling.

Figure 10 shows that the modified SRF geometries produce even more significant reductions in workload ratings than those observed for the full deck landings. In particular, the Notch modification now outperforms the Side-Flaps reducing workload by 2-3 levels for the range of wind speeds investigated. This is caused by the reduction in peak turbulence intensity levels in the airwake but also the displacement of the wake region away from the flight deck towards the port-side, discussed in the previous CFD airwake analysis section. The Side-Flap modifications have again performed well for this manoeuvre with 1-2 level reductions which, when combined with the positive results for the full deck landings, is very encouraging progress for this ship design concept in terms of ultimately reducing the impact of the airwake on helicopter operations.

Conclusions

A Notch and two different Side-Flap modifications have been made to the SRF ship geometry in an attempt to reduce the impact of the unsteady airwake on pilot workload in a G45 wind angle. Unsteady CFD airwakes were computed for the baseline and modified SRF ship geometries and turbulence intensity levels were reduced for the modified SRF ships geometries compared with the baseline case. The Notch modification also shifted the wake region towards the port-side away from the flight deck.

The unsteady CFD airwake data was integrated into the FlightLab simulation environment and piloted flight simulation trials were conducted in a motion-base flight simulator. SRF modifications were found to reduce the pilot workload levels in G45 wind angle for full deck landing tasks, and for a 30 second hover over the deck task. In particular the Side-Flap-2 performed best for the full landing manoeuvres and the Notch modification performed best for the hover task due to the shifting of the wake region away from the flight deck area.

The encouraging improvements in pilot workload caused by the ship modifications highlight the potential for them to be developed further, with the aim of incorporating them into existing or future ship designs to reduce the impact of the airwake and broaden the helicopter operational envelope.

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