AirDyn: An Airwake Dynamometer for measuring the impact of ship geometry on helicopter operations

Christopher H Kääriä[1] c.h.kaaria@liv.ac.uk

Yaxing Wang[2] yxwang@liv.ac.uk

John Curran[3] curran@liv.ac.uk

James Forrest[2] jforrest@liv.ac.uk

Ieuan Owen[4] i.owen@liv.ac.uk

Department of Engineering
The University of Liverpool
Liverpool, UK
L69 3GH

This paper describes an experimental study using an Airwake Dynamometer (AirDyn) to evaluate the effect of geometric modifications to a generic frigate shape (SRF), designed to reduce the adverse effects of the airwake on helicopter operations. The AirDyn is a 1:54 scale model helicopter, based on a Merlin EH-101, capable of measuring unsteady forces and moments resulting from the turbulent airwake of a ship. The AirDyn and the SRF have been submerged in a water tunnel, in preference over a wind tunnel. The AirDyn was fixed in space at various locations relative to the flight deck of the SRF and immersed in its unsteady airwake. The forces and moments at the helicopter CoG have been recorded from which Root-Mean-Square (RMS) loadings have been derived and used to analyse the effect of ship modifications in terms of helicopter handling qualities and potential pilot workload characteristics. The implementation of the modifications proved very effective in reducing the severity of unsteady loading caused by the airwake and there is certainly potential that the concepts under development here could lead to tangible reductions in pilot workload at the dynamic interface. A 'Side-Flap' fitted to the windward side face of the hangar and the incorporation of a 'hangar notch' were particularly effective, reducing RMS forces and moments experienced by the AirDyn by an impressive 40-50% at important locations around the flight deck.

Introduction

The role of naval based air support has become integral to modern armed forces, and the Vertical Take-Off and Landing (VTOL) capabilities of helicopters make them well suited for use on the restricted flight decks of single spot frigates and destroyers (*Fig. 1*). However, although these operations are now routine, the recovery of a helicopter to the flight deck of a ship is fraught with difficulties for even the most experienced fleet pilots. In addition to the operational challenges of restrictive landing areas and movement of the deck caused by the pitch, roll and heave motion of the ship, the pilot must also contend with the presence of a highly unsteady flow field over the flight deck known as the ship's 'airwake'. This phenomenon is caused by the airflow 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.

[1]Postgraduate Research Student, [2]Research Associate, [3]Technician, [4]Professor of Mechanical Engineering. Presented at the 36th European Rotorcraft Forum 2010, Paris, France, 7 – 9 September 2010.

Over recent years, collaborative international research into the ship-helicopter dynamic interface has investigated flight deck aerodynamics using techniques such as flow visualisation [1-5], wind tunnel anemometry [3-5], and Computational Fluid Dynamics (CFD) [6-8]. As a result, the key features of the airwake are now relatively well understood [9]. The superstructure is essentially an assembly of bluff bodies. The flow separates from the sharp edges of the hangar forming shear layers and low-speed recirculation zones leading to large spatial and temporal velocity gradients in the airflow over the flight deck. Vortical flow structures are shed from the hangar and typically have a length scale similar to the helicopter fuselage and main rotor. Smaller-scale geometric features on the ship, such as funnels, radar domes and weapon systems, will also affect the flow to varying degrees depending on their size, orientation and proximity to the flight deck.

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 [10, 11]. The pilot is then required to take corrective action via the control inputs in order to stabilise the attitude, altitude and heading of the aircraft relative to the ship. Consequently, for certain Wind-Over-Deck (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 for fleet pilots to repeatedly attempt. Such conditions are then considered outside the safe operational limits of the ship-helicopter combination in question.

(a)

(b)

Figure 1: UK Royal Navy Type 23 Frigate (a) and Type 45 Destroyer (b)

The demanding nature of ship-borne helicopter operations means that every ship/helicopter combination has its own specific Ship-Helicopter Operating Limits (SHOLs) which are derived from First of Class Flight Trials (FOCFTs). An example of a typical SHOL envelope, derived from piloted simulation tests at the University of Liverpool (UoL), is shown in Fig. 2. The SHOL diagram makes use of 'Red' and 'Green' naval terminology to refer to the port and starboard side of the ship respectively. Therefore, Green 30 (G30) refers to a WOD angle 30° from the bow of the ship on the starboard side. This terminology will be used throughout this paper.

Due to the expense and inherent dangers associated with FOCFTs, much of the research concerning the ship-helicopter dynamic interface, at the UoL and elsewhere, has focused on the development of high-fidelity flight simulation [12-16] to augment at-sea SHOL trials and mitigate their costs and risks.

The aim of the study reported in this paper, however, is to look beyond SHOL classification, and to investigate the impact that the ship's geometry has on the severity of the airwake and the associated pilot workload levels and helicopter handling characteristics. Can current ship geometries be modified to alleviate the adverse effects of the airwake? What design features could be included in future ship designs to minimise the impact of the airwake on helicopter operations?

Recent work at UoL has involved the development of an experimental method, similar to that used by Lee & Zan [10, 11], where a model-scale helicopter is placed within the airwake of a ship and the resulting unsteady forces and moments on the helicopter are measured. As this unsteady loading is a key driver of high pilot workload levels, it can be used to compare the severity of the airwakes of different ship geometries.

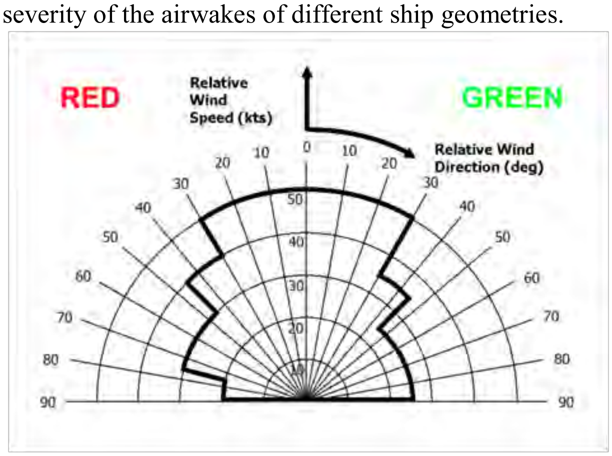
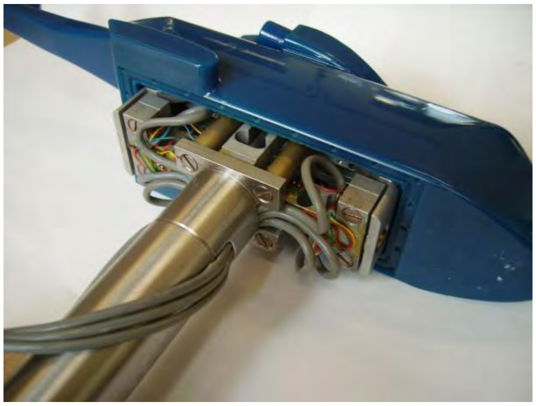


Figure 2: Ship-Helicopter Operating Limits (SHOL) diagram for Sea-Hawk (SH-60B) helicopter operating to a Simple Frigate Shape (SFS2) derived from flight simulation at the UoL

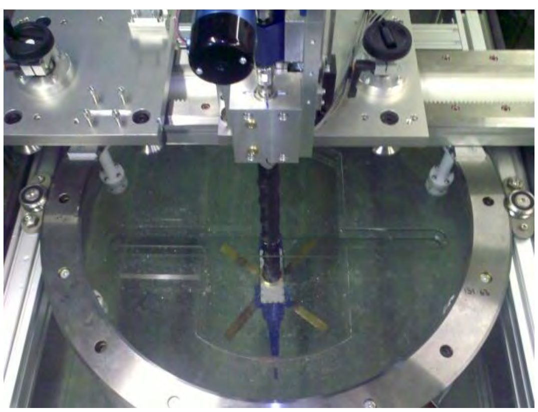
The AirDyn

A 1:54 scale physical model of a Merlin EH-101 helicopter has been manufactured with an externally driven main rotor and a six component force block mounted inside the fuselage (Fig. 3a). The model helicopter is essentially an Airwake Dynamometer (AirDyn), measuring the unsteady forces and moments that it experiences in an airwake. A full description of the design and development of the AirDyn instrument can be found in the work by Wang *et al*. [17].



(a)

(b)



(c)

Figure 3: The AirDyn fuselage and strain-gauge balance (a), AirDyn orientation (b) and linear and rotational traverse system mounted in to UoLI water tunnel facility (c)

Experiments have been carried out in which a model ship with the AirDyn in its 'air'-wake have been completely submerged in a water tunnel, which gives a number of advantages over a wind tunnel. Using a water tunnel means that the Reynolds number matching can be achieved with more modest flow velocities; it also produces larger, and therefore easier to measure, forces; and laser-based flow velocity measurements are easier to obtain. Using an electrically driven rotor, as well as a strain-gauged force block, submerged underwater provided its own challenges but, with intelligent design, these difficulties were overcome [17]. Both the AirDyn and the ship model were placed upside down in the water tunnel, as seen in Fig. 3(b) & (c).

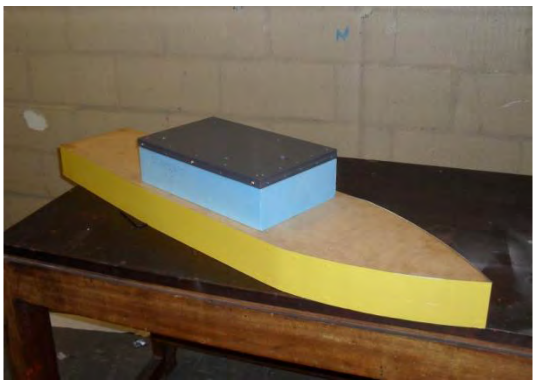
The frequency scaling of the AirDyn rotor compared to the full-scale was chosen to be 1:1 (220 rpm). Therefore a free-stream velocity scale of 1:54 was imposed to match the full-scale Strouhal number. This gives Reynolds numbers (based on the beam of the ship) in excess of 1.2×10^5, which satisfies the minimum requirement for Reynolds number independence for sharp-edged, bluff-body flows.

With the notable exceptions of the work by Lee & Zan, previous research into ship airwake modification has mainly involved analysis of just the aerodynamic data derived from wind tunnel testing and Computational Fluid Dynamics (CFD). Whilst these techniques can give detailed insight into how the airflow has been affected, leading to assumptions of helicopter response, the AirDyn experiment has some significant advantages. For example, when the ship's geometry is modified the nature of the flow structures emanating from its superstructure will be changed. The AirDyn allows greater insight into how a helicopter will react to the difference in the nature of the two flows. The AirDyn technique also inherently incorporates the rotor downwash, which is omitted in the aerodynamic studies. The effect of airwake/downwash coupling is still poorly understood and is impossible to evaluate from looking at airwake aerodynamics in isolation.

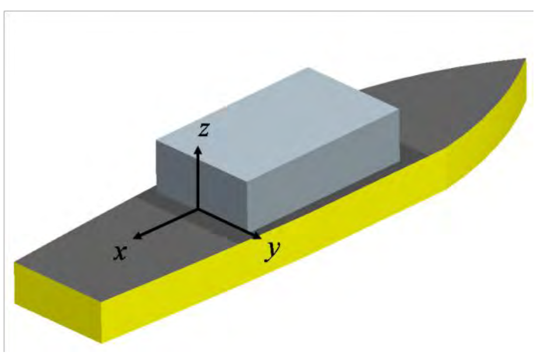
The simulation study by Kääriä *et al.* [18] employed a technique similar to the AirDyn, using airwakes generated through Computational Fluid Dynamics (CFD) and a FlightLab helicopter model. Whilst the technique revealed good insight into helicopter response in an airwake, it did not simulate the effect of the rotor downwash that is inherently incorporated into the AirDyn experiments.

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. 4). 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. The AirDyn has a rotor diameter of 0.344m which equates to the 18.6m of a full scale Merlin main rotor.



(a)



(b)

Figure 4: Unmodified Shortened Research Frigate (SRF) model (a) and CAD geometry with coordinate system (b)

A variety of geometric modifications have been 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.

Experimental Details

During testing, the AirDyn was fixed in space at different positions relative to the flight deck of the SRF. Whilst the AirDyn was held at each location for a period of 210 seconds, the unsteady forces and moments, at the AirDyn Centre of Gravity (CoG), were recorded. A linear and rotational traverse system enables the investigation of different AirDyn locations and a full range of WOD angles (Fig. 3c).

The standard UK Royal Navy (RN) approach technique (Fig. 5) involves a lateral translation from a port side approach position to a hover over the deck. The AirDyn was therefore placed at seven points along this lateral translation for each of the ship geometries tested, to obtain information about handling qualities throughout the manoeuvre. This lateral traverse was also performed for various heights of the main rotor relative to the deck as seen in Figs. 6 & 7.

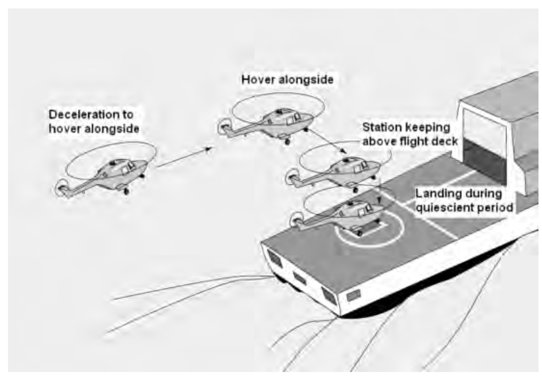


Figure 5: Standard UK Royal Navy Approach Technique

The heights investigated are normalised by the height of the hangar. For example 150% Hangar Height (150% HH), refers to the main rotor at a height above the flight deck one and a half times that of the height of the hangar. For the SRF, 150% HH is roughly 9m above the flight deck in full-scale and is the approximate height of the main rotor of a Merlin EH-101 helicopter throughout the lateral translation and hover over the deck phases. However, other rotor heights (110% HH, 125% HH and 175% HH) have also been investigated (Fig. 7). This accounts for the fact that there will be variation in the height of the rotor when the landings are performed at sea in Merlin helicopters, but also because different helicopters, e.g. Lynx, will approach at different heights relative to the deck. Also, performing tests at different heights may give some insight into the performance of a modification to a ship with a larger hangar, where the clearance of the rotor above the top of the hangar is less than for the SRF geometry.

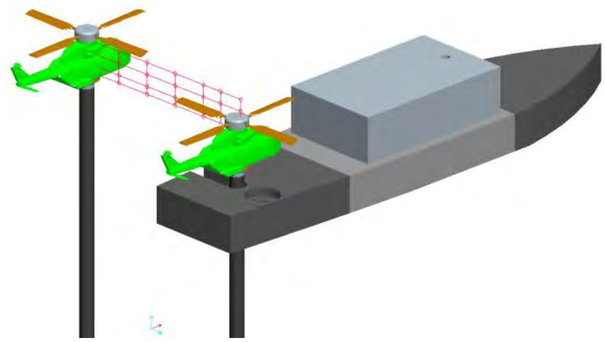


Figure 6: AirDyn test-point location grid with AirDyn pictured at port side approach position and spot hover location

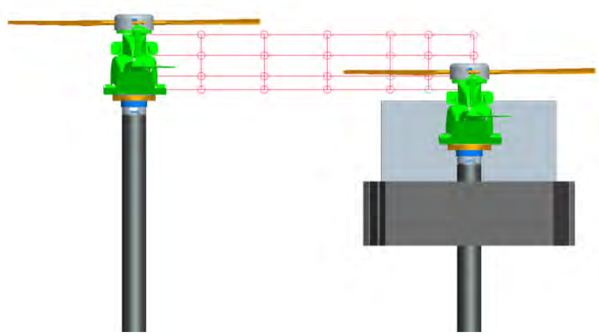


Figure 7: Lateral traverse rotor heights (110%, 125%, 150% & 175% HH)

Unsteady Aerodynamic Loading

After the time-histories of the unsteady forces and moments have been recorded for the specified locations of the AirDyn relative to the ship's flight deck, a method is needed to quantify the impact of the unsteady loading on handling qualities. It is known that disturbances in the closed loop pilot response frequency bandwidth of 0.2 - 2Hz most significantly impact on pilot workload [19]. Therefore, what is required is a measure of the magnitude of the disturbances from within that frequency range.

To do this the method used by Lee and Zan [11, 12] has been employed whereby the Power Spectral Density (PSD) is calculated from the time-histories and the square-root of the integral between 0.2 – 2 Hz is taken as the measure of unsteady loading (Fig. 8). This quantity is then normalised by $\rho(\Omega R)^2 A$ and $\rho(\Omega R)^2 AR$ for the forces and moments respectively, and will be referred to as the RMS (e.g. RMS Pitch). However, it is specifically a measure of the unsteady loading disturbances from within the closed-loop pilot response frequency range. Therefore, reducing the RMS forces and moments experienced by the AirDyn through use of ship modifications will indicate a potential reduction in the associated pilot workload during a deck landing.

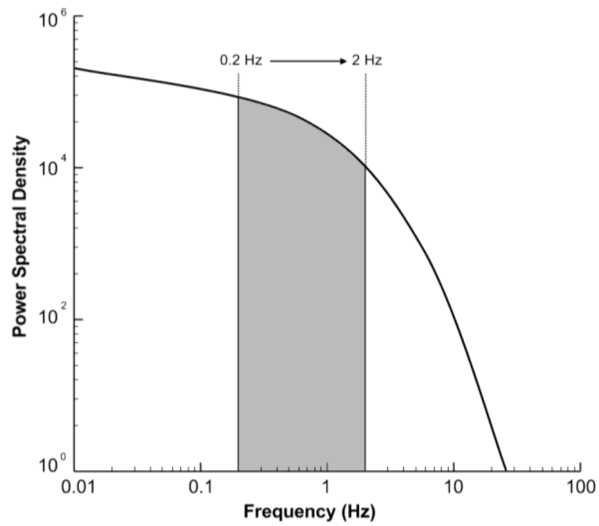


Figure 8: Closed loop pilot response frequency bandwidth

Wind-Over-Deck Conditions

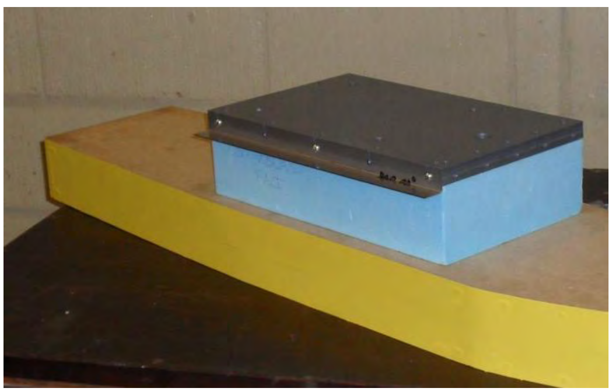
Previous investigations into the effects of ship geometry on the airwake have mainly focused on winds coming from the bow of the ship, between G15 and R15 and especially the headwind condition. Although limited success has been achieved, little practical progress has been made [20-22]. The headwind condition is generally where the SHOL is at its least restrictive and therefore significant flow improvements are more difficult to achieve and, arguably, less important.

It is oblique wind angles, especially G30-G45, that typically produce much more severe flow features over and around the deck, leading to high levels of pilot workload. At these WOD angles, operational envelopes tend to be much more restrictive. It is a little surprising therefore that these wind angles have not been given much consideration when it comes to the impact of ship geometry on the airwake. Not least because it is at these WOD conditions that ship modifications can have the greatest impact in reducing excessive airwake-induced workload levels. This study has therefore focused initially on developing ship modifications and design features that will potentially reduce unsteady loading and workload levels for WOD angles between G30-G45.

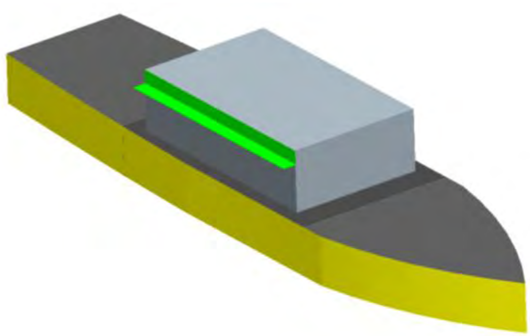
RESULTS AND DISCUSSION

The different modifications to the baseline SRF geometry that have been investigated using the AirDyn can be divided into three categories and will be discussed in turn. First, a range of modifications have been made to the windward side face of the hangar, only a small sample of which will be discussed in detail in this paper. Modifications to the windward vertical edge of the hangar have also been investigated and, finally, the effect of a hangar 'notch', a typical frigate design feature, has been investigated along with the effect of a Phalanx Close-In-Weapons-System (CIWS).

Windward hangar-face modifications



(a)



(b)

Figure 9: SRF with Side-flap modification model (a) and CAD geometry (b)

The first set of modification to be discussed will be a 'Side-Flap' fitted at the windward hangar-face, as shown in Fig. 9. The aim of this modification was to suppress the large-scale vortical structures that cause severe unsteady loading particularly through the lateral translation phase of the landing and over the deck. These vortical structures are caused by the vertical acceleration of the 'free-stream' as it flows towards the windward side face of the hangar. The flow rises up and forms large vortical structures that are directed towards the flight deck and port side approach positions, causing severe unsteady loading of the helicopter throughout the landing manoeuvre, particularly at rotor heights above that of the hangar (125% - 175% HH) [6]. The Side-Flap has been designed to suppress the upward acceleration of the flow at this face, 'breaking-up' the larger scale flow features and reducing the height above the hangar at which they are significant.

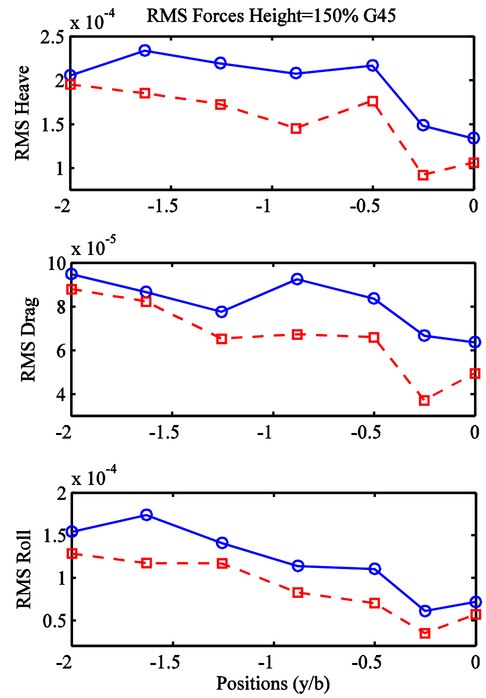


Figure 10: RMS Forces and Moments for G45 Baseline SRF (—o—) and SRF with Side Flap modification (- ▫ -)

The Side-Flap was tested for G30, G40, and G45 WOD angles and was found to be very successful in all cases, reducing unsteady loading of the AirDyn compared with the baseline SRF geometry. For brevity, only results from the G45 case are presented and will be discussed in this paper. Figure 10 shows RMS Heave and Drag Forces and RMS Roll moment for seven points along the lateral translation (Fig. 5), at a rotor height of 150% HH. The implementation of the Side-Flap has significantly reduced unsteady disturbances caused by the airwake. Through the lateral translation, where the peak loading occurs, RMS levels have fallen by 25-32%; and over the deck, $-0.5 < y/b < 0$, RMS levels fall by up to 44%. As 150% HH (approximately 9m in full-scale) corresponds to the height of a Merlin main rotor throughout the port side approach, lateral translation and hover over the deck tasks, in a real landing the severity of the unsteady disturbances would be reduced and the pilot workload required to maintain aircraft stability would also be reduced. Further investigation is required to evaluate how much impact this modification would have on workload levels, but the results are certainly encouraging.

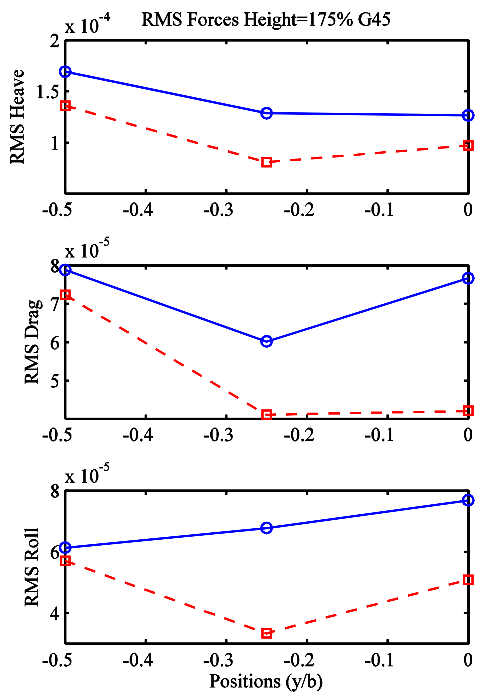


Figure 11: RMS Forces and Moments for G45 Baseline SRF (—O—) and SRF with Side Flap modification (– ⊟ –)

Figure 11 shows three test points from the deck edge to the spot, at 175% HH (roughly 10.5m above the deck). At this height, unsteady disturbances are again greatly reduced over the deck; by as much as 45% over the spot for RMS Drag and 50% for RMS Roll at y/b = -0.25. The second objective of the Side-Flap has, it would seem, been achieved in that it has reduced the height at which wake turbulence is significant over the deck. This would lead to a reduction in required workload levels for tasks performed at higher hover levels, such as slung load deployment.

The Side-Flap was also investigated for lower rotor heights, and similar reductions in the severity of unsteady loading were observed. RMS values in other degrees of freedom, such as RMS Pitch and Yaw, showed similar behaviour to those presented in this paper. After these very encouraging initial results, further work will involve investigating the effect of the Side-Flap to obtain a better understanding of exactly how it has impacted on the aerodynamics of the baseline SRF. This understanding could aid the design of future ship geometries. Investigation is also required to evaluate how the reductions in unsteady loading observed with the AirDyn impact on the subjective pilot workload ratings given to deck landings. This could be done by taking the investigation through to flight simulation, as has been done in the work by Forrest *et al*. [23], or by developing correlations between RMS loading and flight test results similar to those made by Lee & Zan [10, 11].

Windward vertical hangar-edge modifications

Modifications at the windward vertical edge included an angled 30° flap and a saw-tooth flap, pictured in Fig. 12, which have been investigated for a G30 WOD condition. At oblique wind angles, the flow separates from this edge of the hangar to create a well defined boundary between regions of high-speed and low-speed flow that moves or 'flaps' in time.

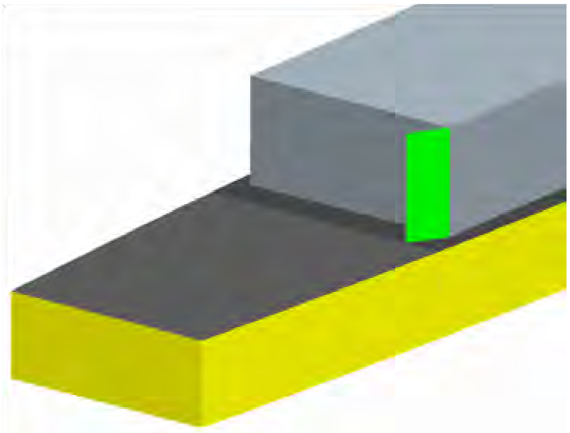
The intention of the angled flap is act as a splitter plate, inhibiting the low-frequency flapping of the shear layer thereby reducing the unsteady loading on the aircraft, particularly over the flight deck. The intention of the saw-tooth is to break-up the flow at the separation point, introducing smaller-scale, longitudinally orientated vortices to increase the mixing between the regions of high speed flow and low-speed flow. These modifications were designed especially to improve loading characteristics at lower rotor heights, 110% & 125% HH, in which case they would be more effective for a smaller aircraft (e.g. Lynx, Sea-Hawk) or for a ship with a larger hangar where shear-layer turbulence is significant at 8-9m above the deck.

The relative performances of the two modifications compared with the baseline SRF geometry is presented in Fig. 13 for RMS Heave, Pitch and Roll at 125% HH. On the whole, the effect of the saw-tooth flap is minimal except at the port deck edged (y/b = 0.5) where there is improvement of 14% in RMS Pitch. This relatively small improvement is unlikely to translate into noticeable reductions in pilot workload, especially as peak roll disturbances increase slightly through the lateral translation.

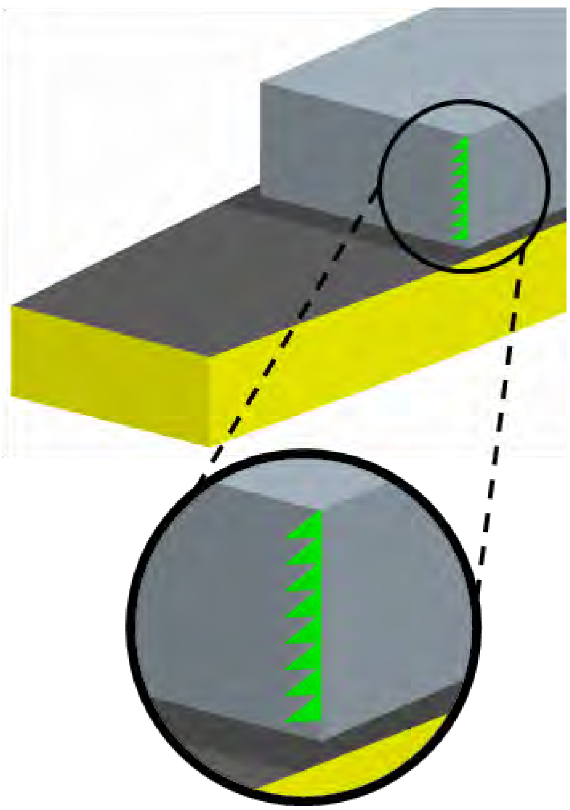
The 30° angled flap on the other hand, has led to significant improvements over the flight deck and in the final stages of the lateral translation where the peak unsteady loading occurs for the G30 WOD condition. This is especially seen at y/b = 0.5 where RMS Heave, Pitch and Roll disturbances have fallen by 40-45%. There is also good improvement over the spot for the angled flap, where RMS Pitch and Roll have decreased by 33% and 34% respectively.

Although, the main benefits of modifications to this hangar edge were targeted to improve loading characteristics at lower rotor heights, some slight improvements are also seen in Fig. 14 at 150% HH, although this time the more significant reductions were observed for RMS Side Force and RMS Yaw moment. Unsteady Side Force and Yaw characteristics are mainly influenced by loading of the fuselage. As the height of the AirDyn rotor increases to 150% HH, the region where the flow has been improved by the modification is now occupied by the fuselage and has led to reduction in RMS Yaw moment of 30% over the spot. Therefore, inhibiting the flapping shear layer has also had a benefit at 150% HH, although to a lesser extent in the heave, roll and pitch axes that are mainly influenced by loading on the main rotor. This is due to the greater significance of the flow features discussed in the previous section as the rotor height above the deck increases.

Figure 14 also shows that the saw tooth flap has again had little effect on the loading characteristics except to increase the peak RMS levels through the translation, particularly for RMS Heave force.



(a)



(b)

Figure 12: SRF with vertical hangar edge modifications 30° angled flap (a) and saw-tooth flap (b)

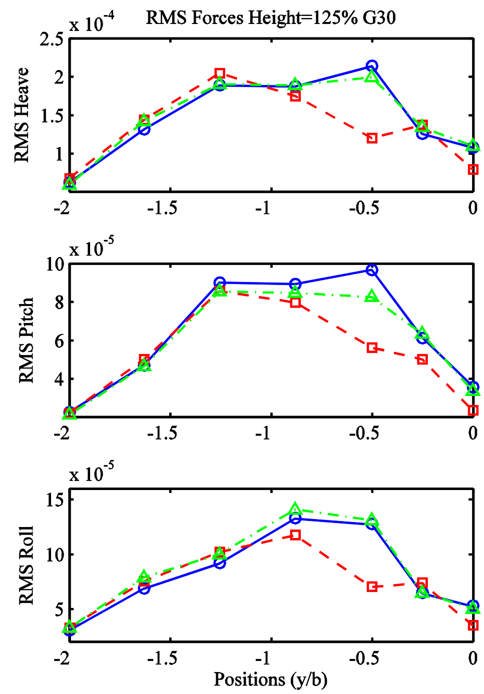


Figure 13: RMS Forces and Moments for G30 Baseline SRF (—o—), SRF with 30° angled flap (– ▫ –) and saw-tooth flap (·-△-·)

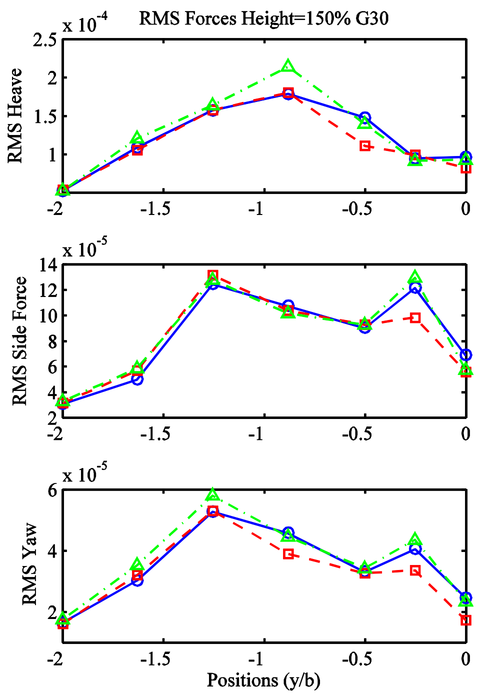


Figure 14: RMS Forces and Moments for G30 Baseline SRF (—o—), SRF with 30° angled flap (– □ –) and saw-tooth flap (·–△– ·)

Hangar Shape Modifications

In this section, the effect of a 'notch' built into the starboard edge of the hangar will be discussed. A similar feature is present on some existing ships including the T23 Frigate (Fig. 1a) and has been incorporated into the initial designs of the RN Type 26 Combat Ship (T26).

A hangar notch was investigated using the AirDyn for a G30 WOD condition and compared with the baseline SRF geometry. The effect of a Phalanx CIWS placed in the notch, in close proximity to the deck (Fig. 15), has also been investigated and the RMS forces and moments for the heights 110% & 150% HH are presented.

Figures 16 & 17 both show very good improvement for the hangar notch compared with the baseline SRF geometry, both over the spot and through the lateral translation. This is especially so at 110% HH (Fig. 16) where RMS Heave, Pitch and Roll have been reduced by as much as 40-45% through the lateral translation and 30-40% over the landing spot. The overall impact of the hangar notch would most likely be to reduce required workload levels for real deck landings

It is suggested that the reasons behind the improvements in RMS loading are similar to those discussed for the Side-Flap earlier where the notch breaks-up the larger scale vortical structures emanating from the windward side face of the hangar. Future work will investigate further the effect of a hangar notch, using time-accurate CFD to obtain a better understanding of how the notch impacts on the development of the main airwake flow features.

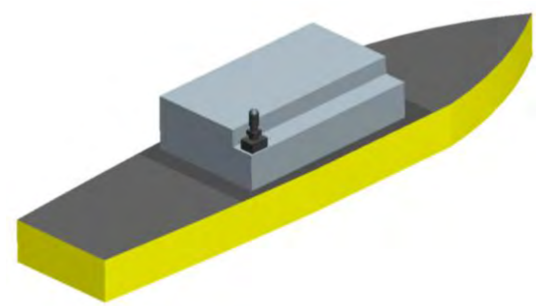


Figure 15: SRF with hangar notch and Phalanx Close-In-Weapons-System (CIWS)

When compared with the hangar notch case, the addition of the Phalanx CIWS increases RMS loading in all six components at 110% HH, especially through the latter stages of the lateral translation between $-0.8 < y/b < -0.25$. The increase in unsteady disturbances will lead to greater levels of pilot workload during deck landings, although Fig. 17 shows this effect is reduced at 150% HH as the turbulent wake of the CIWS impacts more on RMS Side Force and Yaw moment, through unsteady loading of the fuselage, than RMS Heave, Pitch and Roll which are mainly influenced by main rotor disturbances.

Although the addition of the CIWS reduces the benefits of the hangar notch, there is still a general improvement on the baseline SRF geometry. At 110% and 150% HH, reductions seen for RMS heave, pitch and roll disturbances through the lateral translation are maintained, although to a lesser extent than for the hangar notch alone. It is at $y/b = -0.25$ where the CIWS has the greatest impact, increasing RMS loading levels, back to, or even greater than, the original baseline SRF geometry.

It has been shown that the implementation of the hangar notch could be potentially very effective in reducing the impact of the airwake on helicopter operations. Therefore future work will develop this concept further by investigating the effects at different WOD conditions and varying the size, shape and aspect ratio of the notch, as well as the placement of the CIWS. It is hoped that investigation into favourable or adverse design features such as those discussed in this section, will lead to the development of guidelines for ship superstructure design, specifically with helicopter operations in mind.

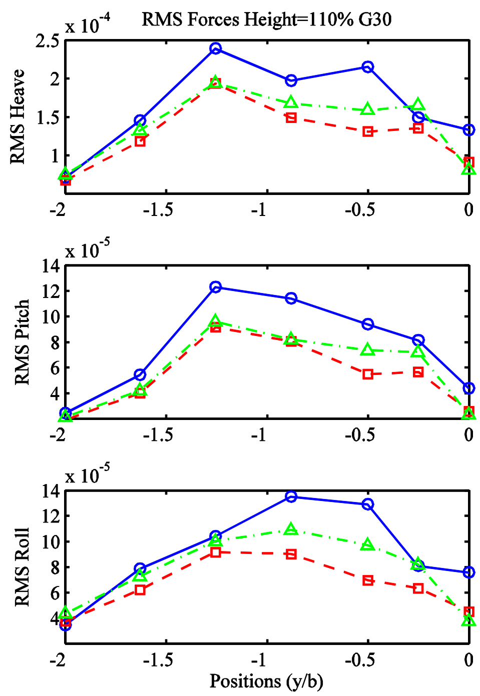


Figure 16: RMS Forces and Moments for G45 Baseline SRF (—o—), SRF with Hangar Notch without (– ▫ –) and with Phalanx CIWS (·–Δ–·)

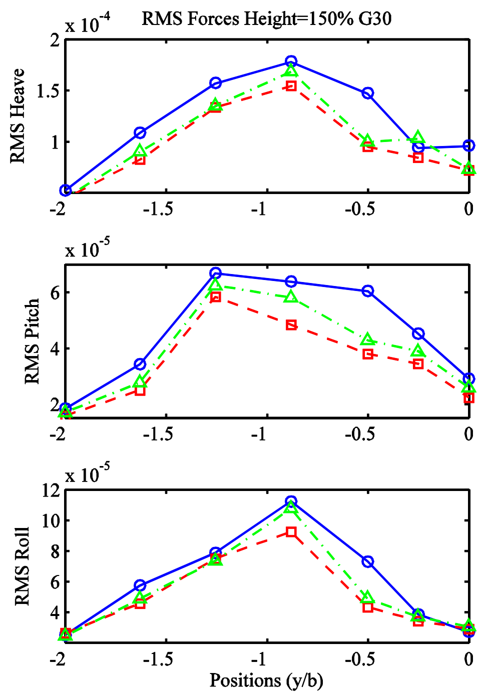


Figure 17: RMS Forces and Moments for G45 Baseline SRF (—o—), SRF with Hangar Notch without (– ▫ –) and with Phalanx CIWS (·–Δ–·)

Conclusions

The effects of modifications to a generic ship geometry, SRF, have been presented in terms of the unsteady loading characteristics of the AirDyn; a model-scale helicopter, fixed in space and immersed in the airwake of the SRF.

A Side-Flap fitted to the windward side face of the hangar significantly improved unsteady loading characteristics by suppressing the large vortical structures emanating from the windward side-face of the hangar. RMS loading reduced by up to 40-50% over the spot and through the lateral translation.

A 30° angled flap, fitted to the windward vertical edge of the hangar reduced the severity of unsteady disturbances by inhibiting the flapping motion of the shear layer close to the hangar face. This modification was only effective over the deck, reducing RMS loading by up to 40-45% and 20-30% over the port edge of the deck and the spot respectively.

A notch cut in to the side of the hangar also reduced unsteady loading in much the same way, and to a similar extent, as the Side-Flap, indicating this is a favourable airwake design feature. The addition of a CIWS placed in the hangar notch was found to increase the RMS forces and moments although, due to the presence of the notch, there was still improvement compared with the baseline SRF geometry.

Acknowledgements

The authors are grateful to EPRSC for its ongoing financial support. The advice of Professor Gareth Padfield and colleagues in the Flight Science and Technology Group at Liverpool is also appreciated. Dr James Forrest is part-supported by the North West Development Agency and the European Regional Development Fund through the UoL Virtual Engineering Centre.

References

[1]Johns, K.M., Healey, J.Val., The Airwake of a DD-963 Class Destroyer, *Naval Engineer's Journal,* Vol. 101, No.3, 1989, pp 36-42.

[2]Healey, J.Val., Establishing a Database for Flight in the Wakes of Structures, *Journal of Aircraft*, Vol. 29, No. 4, 1992, pp. 559-564.

[3]Rhoades, M.M., Healey, J.Val., Flight deck Aerodynamics of a Nonaviation ship, *Journal of Aircraft*, Vol. 29, No. 4, 1992, pp. 619-626.

[4]Cheney, B.T., Zan, S.J., CFD Code Validation Data and Flow Topology for The Technical Co-operation Program AER-TP2 Simple Frigate Shape, National Research Council of Canada, Report LTR-LA-294, 1999.

[5]Zan, S.J., Surface Flow Topology for a Simple Frigate Shape, *Canadian Aeronautics and Space Journal,* Vol. 47 (1), 2001, pp. 33-43.

[6]Forrest, J.S., Owen, I., Investigation of Ship Airwakes using Detached-Eddy Simulation, *Computers and Fluids*, 39, 2010, pp. 656-673.

[7]Polsky, S.A. and Bruner, C.W., Time-accurate computational simulations of an LHA ship airwake, AIAA Paper 2000-4126, *18th Applied Aerodynamics Conference and Exhibit*, Denver, CO, 14-17 August, 2000.

[8]Polsky, S.A. A Computational Study of Unsteady Ship Airwake, AIAA Paper 2000-4126, *40th Applied Aerospace Sciences Meeting and Exhibit*, Reno, NV, 14-17 Jan, 2002.

[9]Zan, S.J., On aerodynamic modelling and simulation of the dynamic interface, *Proceedings of the Institution of Mechanical Engineers, Part G: Aerospace Engineering*, 2005, **219**, pp 393-410.

[10]Lee, R.G., Zan, S.J., Unsteady aerodynamic loading on a helicopter fuselage in a ship airwake, *Journal of the American Helicopter Society*, Vol. 47, No.2, April 2004.

[11]Lee, R.G., Zan, S.J., Wind tunnel testing of a helicopter fuselage and rotor in a ship airwake, 29th *European Rotorcraft Forum*, Freidrichstrafen, Germany, Sept, 2003.

[12]Roscoe, M. F., Thompson, J. H., JSHIP's Dynamic Interface Modeling and Simulation System: A Simulation of the UH-60A Helicopter/LHA Shipboard Environment Task, *59th Annual Forum*, Phoenix, AZ, 6-8 May, 2003.

[13]Hodge, S.J., Padfield, G.D., and Southworth, M.R., Helicopter-ship dynamic interface simulation: Fidelity at low-cost, *Cutting Costs in Flight Simulation - Balancing Quality and Capability*, RAeS Conference, London, UK, 2006.

[14]Hodge, S.J., Zan, S.J., Roper, D. M., Padfield, G.D., Owen, I., Time-Accurate Ship Airwake and Unsteady Aerodynamic Loads Modeling for Maritime Helicopter Simulation, *Journal of the American Helicopter Society*, Vol. 54, No.2, April 2009.

[15]Forrest, J.S., Hodge, S.J., Owen, I., and Padfield, G.D., Towards fully simulated ship-helicopter operating limits: The importance of ship airwake fidelity, *American Helicopter Society 64th Annual Forum*, Montréal, Canada, 29 April – 1 May, 2008.

[16]Forrest, J.S., Hodge, S.J., Owen, I., and Padfield, G.D., An investigation of ship airwake phenomena using time-accurate CFD and piloted helicopter flight simulation, *34th European Rotorcraft Forum*, Liverpool, UK, Sept 16-19, 2008.

[17]Wang, Y., Curran, J., Padfield, G. D., Owen, I., AirDyn: An instrumented model-scale helicopter for measuring unsteady aerodynamic loading in airwakes, *to be published,* 2011.

[18]Kääriä, C.H., Forrest, J.S., Owen, I., Padfield, G.D., Simulated Aerodynamic Loading of an SH-60B helicopter in a ship's helicopter, *35th European Rotorcraft Forum*, Hamburg, Germany, Sept 21-25, 2009.

[19]McRuer, D.T., Interdisciplinary Interactions and Dynamic Systems Integration, *International Journal of Control,* Vol.59 (1), 1994, pp. 3-12.

[20]Findlay, D.B., Ghee, T., Experimental Investigation of Ship Airwake Flow Control for a US Navy Flight II-A Class Destroyer (DDG), *3rd AIAA Flow Control Conference,* San Francisco, CA, June 5-6, 2006.

[21]Greenwell, D.I., Barrett, D.V., Control of ship air wakes using inclined screens, *32nd European Rotorcraft Forum*, September 12-14, Maastricht, Netherlands, 2006

[22]Investigation of Airwake Control for Safer Shipboard Aircraft Operations, *NATO Report* RTO-TR-AVT-102, June 2007.

[23]Forrest, J.S., Kääriä, C.H., Owen, I., Determining the Impact of Hangar-Edge Modifications on Ship-Helicopter Operations using Offline and Piloted Helicopter Flight Simulation, *American Helicopter Society 66th Annual Forum*, Phoenix, AZ, 11-13 May, 2010.