EXTRACTION AND TRACKING OF FLOW FEATURES IN THE TURBULENT AIRWAKE OVER MARITIME PLATFORM FLIGHT DECKS AND THEIR RELATION TO AIR VEHICLE AND PILOT RESPONSE[i]

R Bradley,
School of Computing and Mathematical Sciences,
Glasgow Caledonian University

R B Lumsden,
Air Systems,
Defence Science & Technology Laboratory,
Bedford,

Abstract

This paper describe progress in relating pilot and vehicle response metrics to transient features in the airflow over maritime platform flight decks. The data employed in this study comes from two sources: wind tunnel measurements using PIV and, more comprehensively, CFD data for time dependent flows over a large ship. The vehicle simulated is a generic helicopter similar to a UH60 and a pilot model is employed to generate control activity.

Abbreviations

AER-TP-2	Aerospace Systems Group Technical Panel 2.
ART	Advanced Rotorcraft Technology Inc.
CFD	Computational Fluid Dynamics
DERA	Defence Evaluation and Research Agency
DRA	Defence Research Agency
DSTL	Defence Science & Technology Laboratory
JSHIP	Joint Ship Helicopter Integration Programme
LHA	Amphibious Assault Ship
PIV	Particle Image Velocimetry
RAE	Royal Aerospace Establishment
SOANN	Self Organising Artificial Neural Networks
SHEAR	Ship/Helicopter Model of the Effects of Airflow from Rotors
SDG	Statistical Discrete Gust
STOVL	Short Take Off Vertical Landing
SYCOS	Synthesis Through Constrained Simulation.
TTCP	The Technical Co-operation Programme
WOD	Wind Over Deck

Introduction

The aerodynamic environment in the vicinity of a ship is highly complex and influenced by a large number of factors. It varies significantly and relatively rapidly with time. Consequently it has a significant impact on aircraft performance, from helicopter operating to small ships and offshore platforms, to STOVL and conventional fixed wing aircraft operating to large aircraft carriers. It is known that the air wake represents the most significant element in terms of performance, and hence safety, when considering helicopter/ship operations. Determining the envelope of performance of such operations, through flight trials at sea, is very expensive and relies on achieving a wide range of conditions in order to maximise this envelope, which is seldom achieved in the limited windows of opportunity.

Piloted flight simulation has the potential to overcome the problem of limited opportunities of achieving the required wind and sea conditions but the lack of modelling fidelity has prevented its use for envelope expansion. In particular, until recently, flight simulation has suffered from inadequate representation of the airflow disturbed by the presence of the ship and its superstructure.

The approach described in the paper aims to investigate the feasibility of enhancing the efficiency of the design cycle by using desk top simulation and analysis. A specific and original aim is to be able to compare, for competing ship

[i] Prepared for the 30th European Rotorcraft Forum, Marseilles, September 2004.

superstructure configurations, the responses of existing aircraft and projected aircraft designs. There are two principal strands to the investigation. The first is to identify, and track, flow features with the aim of correlating their presence with vehicle and/or pilot response. The second is to investigate the scope for classifying flows using self-organising neural networks which, when coupled with a ‘knowledge layer’ characterising different helicopter types has the potential for rapid evaluation of the severity of air wake flows as they are experienced for a particular helicopter type.

Progress with these aspects is discussed in relation to wind tunnel measurements carried out by the Department of Aeronautics and Astronautics at the University of Southampton as part of the Dstl Shear II Programme [1], and then with respect to CFD data for an air wake of an USA LHA ship which were produced as part of the J-SHIP programme and provided through the TTCP AER-TP-2 partnership. As part of the latter investigation, the air wake is attached, in an open loop manner, to a simulation of a generic helicopter type similar to a UH60 and responses are obtained using a pilot model which is a development of the QinetiQ SYCOS structure. The aim is to generate metrics generated from the control activity which give an indication of workload. The results may then be compared with the workload levels resulting from only the most significant discrete flow features which have been identified and tracked using wavelet-based analysis.

Wind tunnel data

The wind tunnel data was used as a precursor investigation [2] to validate a number of approaches to feature tracking and flow classification. PIV measurements are essentially two dimensional, being taken instantaneously in a plane (or sheet), and the maximum sampling rate is of the order of 1 second per plane. These practical factors limited the scope of the investigation and the ability to read across some of the results to three dimensional data emanating from CFD.

The work at Southampton employed a TTCP generic ship model SFS2 and a powered model rotor. Measurements were taken with the ship alone, rotor alone and with the rotor/ship combination. Various tunnel speeds and rotor rotation rates were employed to measure, using PIV techniques, two components of velocity in longitudinal planes behind the hangar location, at the mid section, and at the transom, as illustrated in Fig. 1.

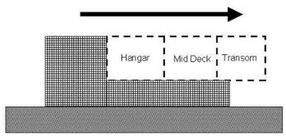


Figure 1. Wind tunnel PVI camera positions

The data consisted of both instantaneous and time averaged measurements giving nearly 20000 files in all. The wind tunnel speed was in the range 0-3 m/s except for one case which ran at 7 m/s. Since the shortest time interval between the sampling of the instantaneous data was 0.5 sec and the length of the section being sampled was about 0.5 m, it is clear that any wake features being advected with the ambient flow would not be observable in successive samples and limited the opportunity for tracking flow features as they were transported downstream.

Flow variables. The wind tunnel data provides measurements of two components of velocity in a longitudinal plane obtained from a PIV sheet sample. A quiver plot (arrows in the direction of flow, with length proportional to flow speed) of a typical flow from this set of data is illustrated in Fig. 2 which depicts both an instantaneous flow pattern and a time averaged flow for the same case. In the present investigation, model scale, that is the data actually supplied, has been used without any subsequent re-scaling.

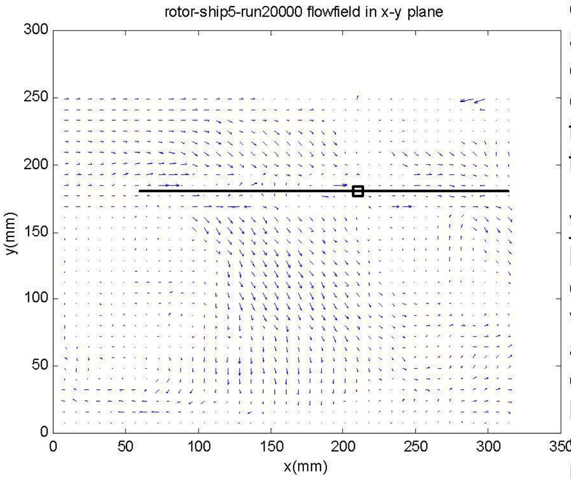


Figure 2(a) Flow-field for sample instantaneous data.

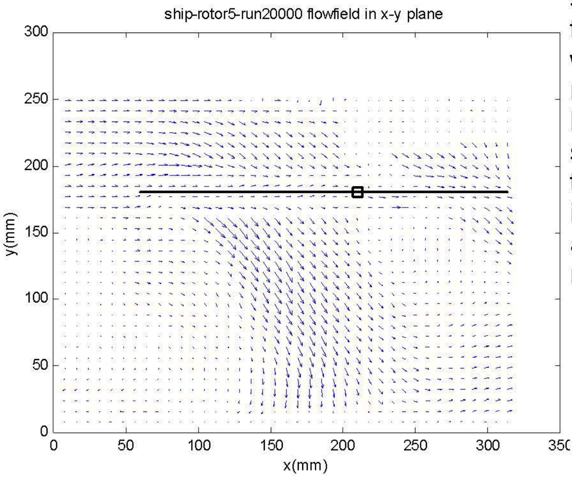


Figure 2(b) Flow-field for sample time-averaged data.

The figures refer to the case where the wind speed is 2 m/s, the rotor speed is 2016 rpm and the rotor location is half the rotor radius to port of the deck. The instantaneous flow shows the evidence of both measurement noise, identified by isolated rogue values, and of transient flows, particularly on the upstream side of the rotor wake. Significant transients are expected, of course, due to the time varying position of the rotor blades and the vortices they generate. As discussed above, the sampling rate was not adequate to allow a study of the development and evolution of such transient flows. In the general case there would be three components of velocity at each point of a three dimensional grid and while these could be viewed electronically by rotating the view point for example, on the printed page sections of the flow would have to be projected into two dimensions.

Vorticity. The primitive variables may not be the ones of primary interest or convenient for subsequent analysis. The vorticity vector indicates the distribution and intensity of shear flows, which can be of major importance in pilot workload and handling qualities. With the two components of velocity available to the present study, only one component of vorticity may be calculated: that in the direction of the z axis, or transverse across the deck. Fig. 3 shows contours of the vorticity component for the flow-fields depicted in Fig 2. The time-averaged flow shows regions of high vorticity surrounding the rotor and along the edge of the rotor wake. That of the instantaneous flow is more fragmented with smaller regions of high vorticity probably arising from vortices shed by individual rotating blades. Clearly the smaller regions of vorticity from the instantaneous flows coalesce, through the averaging process, to give the larger regions observed.

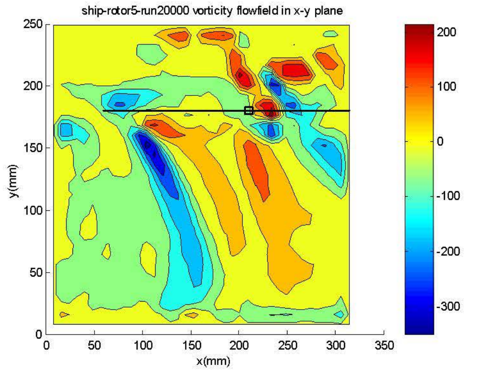
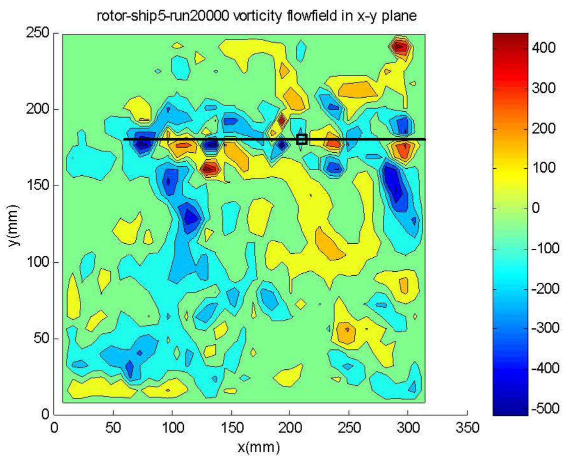


Figure 3a. Vorticity for sample time-averaged data.



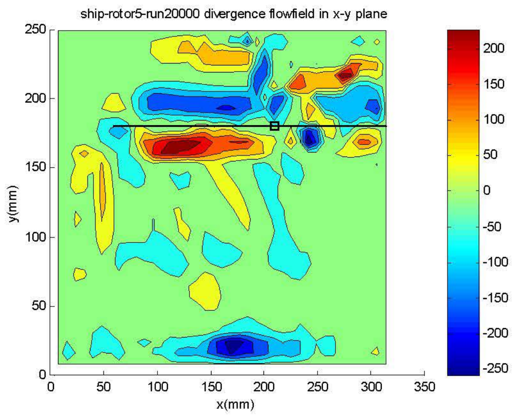


Figure 4a. Divergence for sample time-averaged data.

Figure 3b Vorticity for sample instantaneous data.

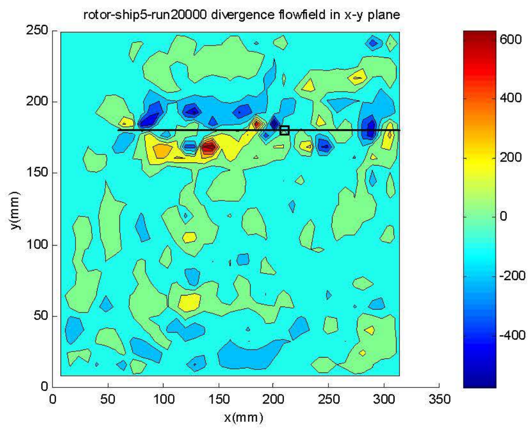


Figure 4b Divergence for sample instantaneous data.

Divergence The divergence of the velocity vector is a zero valued scalar for incompressible three dimensional flow because it measures the conservation of mass in the flow. As a result, the divergence of only two components of velocity field represents the increasing, or decreasing flow in the third - here the z - direction. Figs. 4a and 4b show contours of the two dimensional divergence for the two cases discussed earlier in this chapter. The time-averaged and the instantaneous differ in detail in a similar manner to the vorticity but it is interesting to observe, in the time averaged flow, the overall lateral increasing and decreasing flows immediately above and below the rotor and a more modest changes in the lateral flow at the bottom of the measured region - possibly related to a feature of the tunnel section. These regions, of relatively high absolute values of two-dimensional divergence, do not directly indicate shear flows - they indicate a flow changing magnitude along the direction of the flow. Nevertheless, velocity gradients usually require some intervention by the pilot and therefore the divergence may be a useful quantity to calculate and track.

Wake Classification. In this study we investigated the possibility of classifying wake flows through self organising artificial neural networks (SOANN). The aim is to allow the data itself to form groups, or classes. Variously termed: data mining, cluster analysis, etc., the value of the approach is that no *a priori* view is placed on the data and any required outputs are constructed at a later stage. Thus in the present context, if the airwake flows can be trained to organise themselves into to groups then subsequent knowledge can, for example, rate the groups according to the piloting hazard that they represent.

The technique is simple in essence: the samples of data are represented as vectors and a second set of randomly selected vectors (or weights) is iteratively adjusted until they are directed along the means of the groupings of the original vectors. In the iterative procedure, the weight vectors each gradually capture a group of the sampled data.

As an example of its effectiveness in the current investigation, we consider the v component of the instantaneously sampled flows listed in Table 1. The table also provides a description of the flows taken from Ref. 1. The flows are in six groups with each group containing four instantaneous samples of the experimental configuration. We would hope that SOANN would recognise the similarity of the similarity of the samples for each configuration but would discriminate between the configurations. In other words, we would expect samples 1:4 to be classified together, 5:8 similarly, and so on.

Run number: Instant-aneous data files	**Description**
1-4	Rotor positioned behind hangar on centre-line. Windspeed 3 m/s and rotor speed 2016 rpm
5-8	Rotor positioned behind hangar port of centre-line. Windspeed 3 m/s and rotor speed 2003 rpm
9-12	Rotor positioned behind hangar well port of centre-line. Windspeed 3 m/s and rotor speed 2016 rpm
13-16	Isolated rotor. Windspeed 0 m/s rotation rate 3150 rpm.
17-20	Isolated rotor. Windspeed 3 m/s rotation rate 3015 rpm.
21-24	Isolated rotor. Windspeed 2m/s rotation rate 3015 rpm.

Table 1. Instantaneous PIV data sets for classification

Methodology and results. The v-component matrices, here the vertical component, are simply cast into vectors by concatenating the columns and the standard training carried out. In each of three runs, after training for only 5000 epochs and using 6 neurons, all cases were correctly grouped as shown in Table 1.

Once the network is trained for its classification it is possible to validate it by submitting sets of unseen data. For this exercise 18 different samples of the same experimental configuration were employed. From the 18 cases, only two were wrongly classified; the remainder are correctly assigned to the respective classes. It is interesting to note that the two wrongly classified cases refer to classes that differ only by a small change in rotor rotation rate and an offset to port of the centre line. This is believed to have been the first application of SOANN to the classification of airwake flows and the results therefore represent encouraging progress. The method easily distinguishes between flows that are visibly distinct and has difficulty only with flows that are visually similar. Since only the v component is being incorporated into the training of the network the network is considered to have performed well and potentially, with development, the method will be a reliable technique for classifying flows.

Tracking of features. It was intended to use the instantaneous data from the wind tunnel measurements to investigate the tracking of features through the flow. As has been indicated above, the sampling frequency of the PIV data turned out to be lower than that required to capture advected features. The situation was of sufficient interest to stimulate the construction of an emulation of a fluid feature migrating through a typical flow sequence.

The feature used for this experiment was a vortex with a central core of radius 32mm. The rate of rotation of the core is specified by its rimspeed to allow a simpler comparison with the ambient wind speed. Several values of rimspeed were investigated as discussed below. The vortex was superimposed in different locations in a sequence of flows for the case of Rotor positioned behind the hangar wall to the port of centre-line. The windspeed in this case was 2 m/s and the rotor speed 2016 rpm.

The position of the vortex is tracked by simply detecting the maximum correlation with the original vortex feature - that is when the isolated vortex lines up with the embedded feature. The velocity vector is used in the correlation through the use of the scalar product operation on the vector fields. This operation is readily carried out using two dimensional convolutions. Table 2 shows the sequence of locations of the vortex together with its location as detected by correlation. The locations are expressed in grid coordinates. Because of the difficulties caused by the high velocities present in the underlying mean flow it is desirable to consider whether this underlying flow can be subtracted prior to the correlation process. It is, of course, possible to do this in the emulated situation but not in the real situation because the feature is always present - even if at different locations. Therefore a more generally valid approach has been implemented here. The mean of the flows with the vortex embedded in them has been calculated and subtracted from the instantaneous flow prior to correlation.

Instantaneous PIV data file number used for super-imposition	Actual vortex grid coordinates	Detected vortex grid coordinates 3 m/s	Detected vortex grid coordinates 2 m/s	Detected vortex grid coordinates 1 m/s
1	(8,12)	(7,13)	(7,13)	(6,13)
2	(12,12)	(13,12)	(14,15)	(23,3)
3	(16,12)	(15,12)	(15,12)	(14,12)
4	(20,12)	(21,12)	(21,11)	(22,10)
5	(24,12)	(24,12)	(24,12)	(24,12)
6	(28,12)	(29,13)	(29,13)	(30,14)
7	(32,12)	(33,12)	(33,12)	(34,12)

Table 2: Actual and detected vortex position for rimspeeds 3m/s and 6m/s (Mean removed)

The results in Table 2 are a significant improvement on those where the mean flow is not subtracted and rim speeds down to 1m/s give acceptable results. (A variation of +/-1 grid position in the location can be expected in the discrete correlation without interpolation.) The ability to track distinct features in a flow using straightforward correlation has been demonstrated even at this stage of development and, as will be shown later in this paper when CFD data are considered, it is potentially extendable to higher dimensions and the full 3 components of velocity.

Smooth edge detection. Other work has investigated the multi-dimensional generalisation of the ramp gust of SDG analysis. Ramp gusts are important because velocity increments are known to be important in aircraft response and they have been a focus of study for DERA (previously DRA and RAE) for many years [3,4] and are embedded in UK design and evaluation methodology. In the present study, the previous techniques have to be extended to allow for a ramp gust following a general path in space, for example, one associated with a vortex filament. A full description of the two dimensional work in this area may be found in the references [2]. The extension to three dimensional is more complex and consequently a simpler approach based directly on concentrations of vorticity was followed for such work.

CFD Data

The CFD data available to this study was generated using the COBALT package. Flows round a LHA ship for 30 sec segments of airflow, in time steps of 0.2 sec. have been generated for a 30 knot wind, at azimuth angles of 0° to 355° in 5° increments. The discussion in this paper refers to the single case of a 30 knot wind from ahead, this preliminary set of data having been supplied in advance. For this study the *Fieldview* ® package was employed for visualisation. It was also used for converting the data for processing and analysing in the *MATLAB*® environment and for the simulation using the *ART Flightlab*® environment.

Flow variable visualisation. The flow patterns over the LHA had aroused interest because of the vortices that were shed on the bow section and advected down to the landing spot area at the rear of the vessel between the hangar and the stern. This aspects of the flow are conveniently visualised by plotting iso-surfaces of the magnitude of the vorticity. The shedding of these vortices, dubbed ‘doughnuts’, can be clearly seen in Figs 5a and 5b which show iso-surfaces of $1.25\ sec^{-1}$. They are transported by the ambient flow towards the stern of the ship across the landing spots and hangar area. This aft area is a complex zone of vorticity with the superstructure generating and shedding further vortex elements. The ‘walls’ in Fig. 5 depict the ends of the two computational boxes, one at the bow and one close to the stern used for simulation and analysis

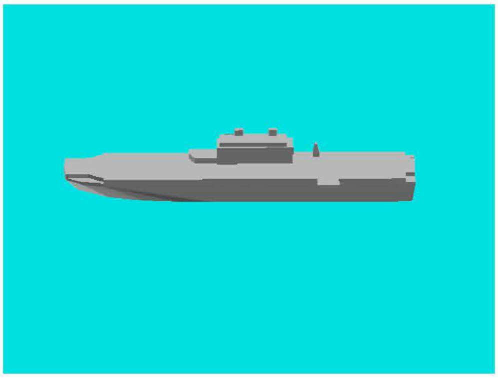


Figure 5a LHA surface

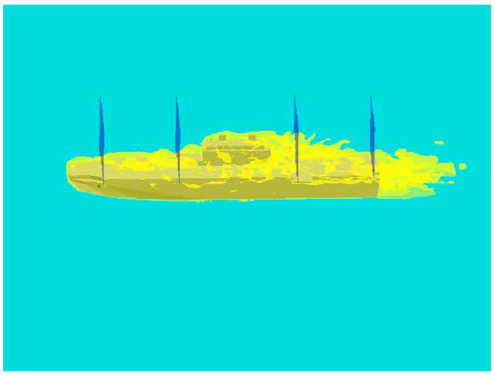


Figure 5b time 0sec, vortex iso-surface

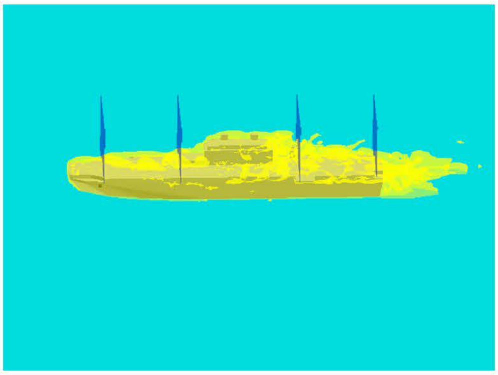


Figure 5c time 1sec, vortex iso-surface

Some concentration of vorticity around the cranes on the deck may also be seen. The vortices corresponding to the highest values of vorticity are, of course, situated on the ship’s surface. The observation of this flow pattern is an important motivation for the current study. We pose three questions about the flow: (i) can these doughnuts be detected in the flow field? (ii) are they preserved as they are advected with the flow? (iii) are they an important source of vehicle response and pilot control activity?

Discrete Features

The doughnuts can be examined more closely by taking a vertical section down the centreline of the ship. The generation of the vortex feature and is transportation down the ship can be seen in a sequence of such sections. Backing off the mean flow reveals the vortex flow and its sign as shown in Figure 6.

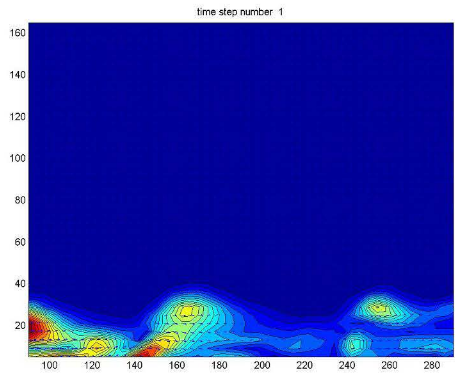


Figure 6a. Contours of vorticity magnitude: bow centreline (time 0 sec.).

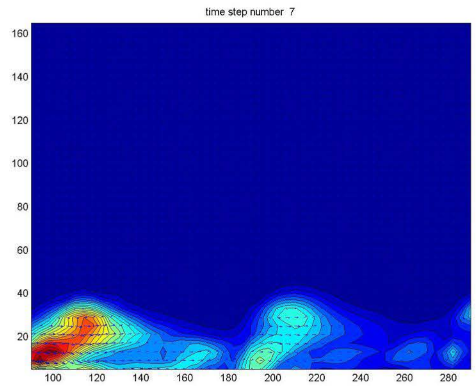


Figure 6b. Contours of vorticity magnitude: bow centreline (time 1 sec.).

The top is towards the incoming flow and opposite, therefore tending to slow the ambient flow down. From the snap-shots of the flow, it is relatively straight forward to estimate the velocity of advection of the vortex tube as around 40 ft/sec., as compared with the ambient velocity of 50 ft/sec. Sampling the velocity in the centre of the section provides verification of the feature velocity. It is possible to take a section through the vortex and establish the change in velocity that occurs over the width of the vortex. This ramp shaped increment - a component of the Discrete Gust approach to aircraft response - can be measured and modelling to provided an idealised vortex flow in order to investigate the vehicle response to such vortex features, Fig 7a,7b.

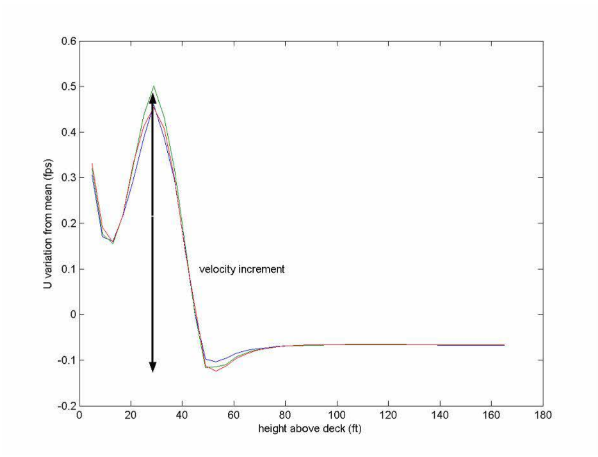


Figure 7a, Velocity, U, profile across typical bow vortex.

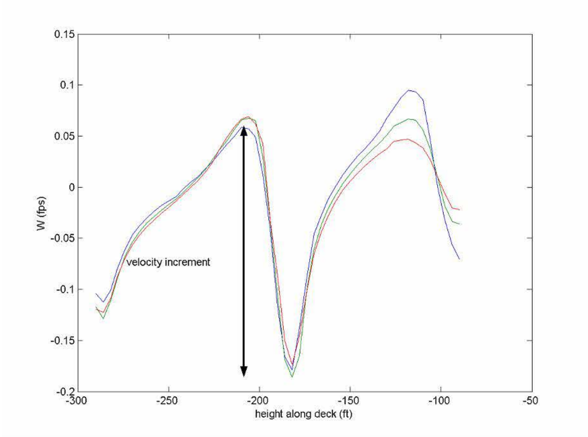


Figure 7b, Velocity, W, profile across typical bow vortex.

Identification and Tracking. A discrete vortex model has been implemented in three space dimensions and can be used through simple correlation methods to locate and track significant vortex concentrations in the rear landing spots. This is a three dimensional extension of the wavelet methods of Jones et al [4] where appropriate adjustment of the amplitude with scale enables both the location and scale of features in the flow to be determined. In its original application, the SDG method contained an implicit scaling of amplitude to mirror the distribution of gusts in the atmosphere. The resonance of a particular scale with the dynamics of the aircraft could be used to produce statistical predictions of the response. In this application, the situation is different. The distribution of scales of the flow is ship specific and concentrated round a particular scale - so the response of a vehicle can be analysed by investigating a discrete set of features sized to accord with those observed in the ship-wake. Identifying the features at each point of a sequence enables their progress and evolution to be followed and potentially linked to vehicle response.

Pilot modelling The SYCOS pilot model [5] was developed for QinetiQ to provide metrics of control activity when performing helicopter manoeuvres. Its formulation is based on the generation of control actions to correct departures from a desired flight-path and is therefore suitable for investigating controlled vehicle response in turbulence. For this work we compare vehicle responses with and without control by the SYCOS pilot in two cases (i) isolated vortex (ii) aft landing spot box .

Isolated vortex. An airwake consisting of an isolated vortex feature of approximately the same scale and intensity as that observed at the bow of the LHA has been generated and moved past a UH60 type of helicopter in stationary trim. The simulation is carried out for the wind over deck (WOD), a combination of the magnitude and direction of the natural wind and the ship, in the range 10-50 knots each for a 10 second run. The airwake is scaled by WOD so there is a correct match with the LHA situation when the WOD is 30 knots. The simulation is carried out with the controls fixed at the trim position and under SYCOS control. (The SYCOS structure was used in its velocity correction mode.) The peak values of pitch rate and roll rate are shown in Fig. 8. As expected, these values increase with WOD, but the figure shows that the SYCOS responses consistently exceed those with the controls fixed.

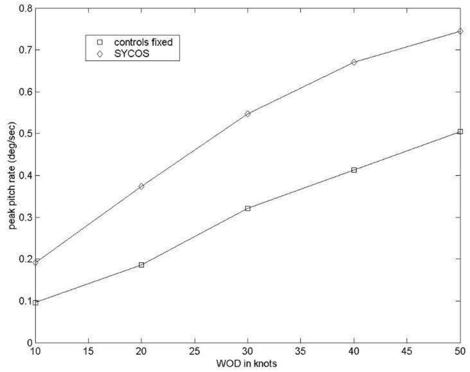


Figure 8 Comparison of pitch rates for isolated vortex.

The SYCOS control stick activity, illustrated in Fig. 9, increases almost linearly as the WOD increases from 10 – 50 knots.

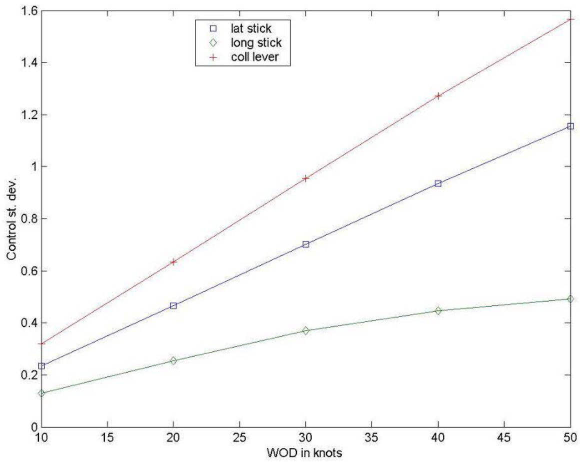


Figure 9, Pilot model stick activity for isolated vortex

To illustrate the effective of the pilot model, Fig. 10, plots the change in position of the helicopter during the transition of the vortex. Each plotted segment is a line between the helicopter's starting and end points in the 10 second simulation. It is clear that the SYCOS control significantly reduces departure from the initial position although it should be borne in mind that the SYCOS structure is not intended to be any kind of optimal controller but is intended to emulate the corrective control activity human pilot.

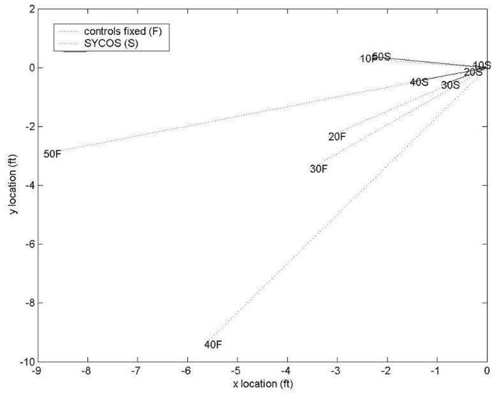


Figure 10. Comparison of change in position.

Time varying airwake. The programme of simulation using the CFD generated airwake is in its early stages. The same helicopter and pilot models as for the isolated vortex case have been used to investigate responses in airwake at the aft location. It should be emphasised that the simulations are open loop as regards aerodynamics. That is, the helicopter is immersed in the airwake but the induced flow through the rotor does not feed back to influence the development of the airwake. It is recognised that the proximity of the deck and the hangar is likely to be a significant factor. Three values of WOD were simulated: 20, 40,and 60 knots, and again, the wake is scaled by these values. Fig. 11 shows the vehicle responses (peak body rates) and standard deviation of stick activity. The roll response, as for the isolated vortex case, is more responsive than that for the pitch axis. All responses, except the collective, increase with WOD, possibly reflecting the increased effectiveness of the collective with airspeed.

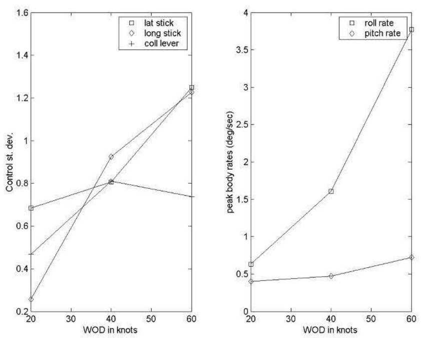


Figure 11. Vehicle responses and pilot model control activity in airwake.

The change in position of the helicopter due to the buffeting received in the air wake is shown in Fig. 12. Surprisingly, the lateral displacement is quite large increasing to 45 ft during the 30 seconds of the simulation. The reason for this excursion has not yet been fully explored but may be a consequence of using SYCOS in the mode where it corrects inertial velocities and not positions directly.

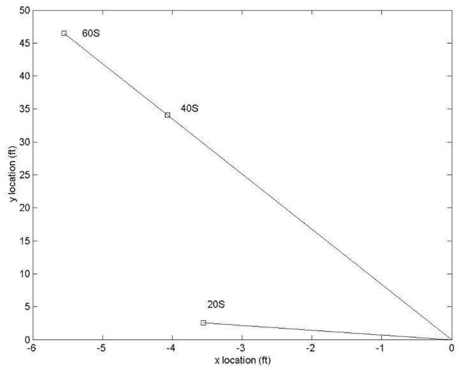


Figure 12. Change in vehicle location in airwake.

Conclusions

The two strands of investigation have both made significant progress.

- The successful application of SOANN in the classification of two dimensional flows is encouraging for its use with three dimensional data.
- The nature of the discrete vortices - 'doughnuts' - at the bow of the LHA has been investigated and modelled for tracking their migration to the aft, hangar region.
- The SYCOS pilot model has successfully flown a helicopter simulation in the stern airwake and has provided stick activity metrics.

Future Work

The study is now poised to address identification and tracking of discrete vortex elements in the flow aft of the hangar. The appropriate analysis techniques have been developed and tested. The subsequent task of relating the advected vortex features to concentrations of stick activity will require some investigation of the most suitable SYCOS structure. Further investigation of the classification flows, and its extension to three dimensional wakes will proceed when suitable data is available. The next step will be to address the design of a 'knowledge layer' which can interpret the wake classes as indicative of the severity of pilot and vehicle responses.

Acknowledgements

The authors would like to acknowledge the contribution of the US Navy in the provision of airwake data, and of the School of Engineering Sciences, University of Southampton for supplying the Wind Tunnel PIV data. The study is being carried out at Glasgow Caledonian University as part of contract RD018-05951 sponsored by the UK Defence Science and Technology Laboratory.

References

1 NEWMAN S., MODHA A.N., Ship/Helicopter Model of the Effects of Airflow from Rotors. Final technical report, Contract AFM 02/01 for Director Air Systems, Dstl Farnborough. February 2002.

2 BRADLEY R., BRINDLEY G., A Feasibility Study of the Extraction of Significant Features of Ship Airwakes and their Modelling and Simulation. Final technical report,

Contract RD018-05951 for Director Air Systems, Dstl Farnborough. May 2002.
3 JONES J. G. The Statistical Discrete Gust Method for Predicting Aircraft Loads and Dynamic Response. J of Aircraft, Vol. 26, No. 4, 1989.
4 JONES J. G., FOSTER G. W., EARWICKER P. G., Wavelet Analysis of Gust Structures in Measured Turbulence Data. J of Aircraft, Vol. 30, No. 1, 1993.
5 BRADLEY R., BRINDLEY G., Progress in the Development of a versatile Pilot Model for the Evaluation of Rotor Performance, Control Strategy and Pilot Workload. The Aeronautical Journal, Vol. 107, No. 1078, December 2003.