CONTROL OF SHIP AIR WAKES USING INCLINED SCREENS

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Abstract: The highly turbulent superstructure air wake on non-aviation vessels can impose significant limitations on helicopter operations from an aft flight-deck. As part of a NATO research program looking at assessing means of expanding ship-helicopter operating limits, a wind tunnel investigation was undertaken at Bristol University of a number of novel flow control devices applied to a generic frigate flight-deck. The most successful of these were a range of inclined porous screens mounted around the hangar door area, with the intention of reducing both turbulence levels and downwash velocities in the ship airwake, which should in turn improve pilot workload and helicopter performance. Such a screen or gauze would also be straightforward to implement in a naval environment, replacing and extending existing deck-edge safety netting.

Overall, a dense screen, mounted on the sides and roof of the hangar and inclined rearwards was found to give the best performance. Addition of a horizontal screen along the flight-deck edges gave a further improvement in turbulence. Device effectiveness was strongly dependent on the region of interest for flight operations, with the greatest improvements obtained lower down in the lee of the hangar. The effect of crosswind was to radically change the flowfield over the flight-deck, giving rise to a highly turbulent vortex flow apparently separating from the deck surface.

1 INTRODUCTION

Naval vessels can be broadly split into two categories – aviation (i.e. aircraft carriers) and non-aviation. Initially, helicopters were only operated from the former class of ship but now most non-aviation ships have some provision for a helicopter, usually in the form of a flight deck at the rear of the ship. Helicopter operations have now become an integral part of shipboard operations, to the extent that constraints on launch and recovery translate directly into limits on operational capabilities.

However, flight of helicopters onto smaller naval ships is a challenging task. The obvious difficulties involved in tracking and landing on a small deck which is moving randomly in six degrees-of-freedom are compounded by the impact of the superstructure air wake. Most non-aviation ships, even those designed from the outset for helicopter operations, solve the problem of aircraft storage with a boxy sharp-edged hangar positioned directly forward of the flight deck. As a consequence, the ship air wake in the vicinity of the flight deck is essentially that of a bluff body, with a very high level of turbulence coupled with large gradients in mean flow speed and direction. The effects of such a flow on helicopter operations are uniformly adverse. Turbulence levels correlate with pilot workload, via the unsteady loads induced on rotor and fuselage [1,2]. Increased downwash and reduced longitudinal velocities aft of the hangar combine to reduce rotor thrust and hence collective margin [4]. High velocity gradients induce significant pitch, roll and yaw moments and hence lead to rapid trim changes during recovery [5]. As a final touch, the flow topology in the wake of a hangar is strongly affected by crosswind angle [6].

The overall effect is that the ship-helicopter operating limit (SHOL) for launch and recovery is almost always reduced when compared with the normal operating envelope for the helicopter. Further, SHOL determination is a difficult and complex task - since recovery performance depends on wind speed, wind direction and sea state, a large number of test cases need to be evaluated, leading to protracted and costly flight test programs. In order to reduce costs and timescales, a wide range of analysis techniques have been/are being developed, with varying degrees of success. These range from semi-empirical correlations based on wind tunnel measurements of ship air wakes to CFD modelling of the combined ship and helicopter flowfield. For the simpler semi-empirical techniques validation remains an issue, while the combination of large-scale separated flows plus moving rotor puts CFD modelling right at the limits of current capabilities.

An alternative approach is to alleviate the adverse elements of the ship air wake by modifying the design of the superstructure, or by the application of flow control devices. There has been surprisingly little work done in this area, perhaps due to a combination of a fundamentally difficult flow control problem and a shape tightly constrained by naval operational requirements. Recently, however, a NATO RTO Task Group AVT-102 was set up to "Assess the Ability of Novel Vortex Flow Devices to Improve the Safety of Air Operations Conducted at Sea". While the activities of the group have focussed primarily on vortex generators of one form or another, some work was also undertaken on the application of porous devices. This paper presents the results of some of that work - a preliminary study (funded by the UK MoD via DSTL) of a novel application of inclined porous screens or meshes [3,7].

2 FLOW CONTROL FOR SHIP AIR WAKES

2.1 Flight Deck Flowfield

With no crosswind, the flight deck flowfield approximates to that of a backwards facing step, with a closed recirculation zone bounded by an unsteady shear layer emanating from the top of the hangar and reattaching on the flight deck (Fig. 1). Also present are vortices shed from the superstructure edges, and an upwash at the flight deck side edges. With a crosswind the flow topology becomes much more complex [6,9], with the recirculation zone intermittently 'spilling' and refilling in a highly unsteady manner. The combination of low velocities and recirculating flow makes visualisation of these flows rather difficult.

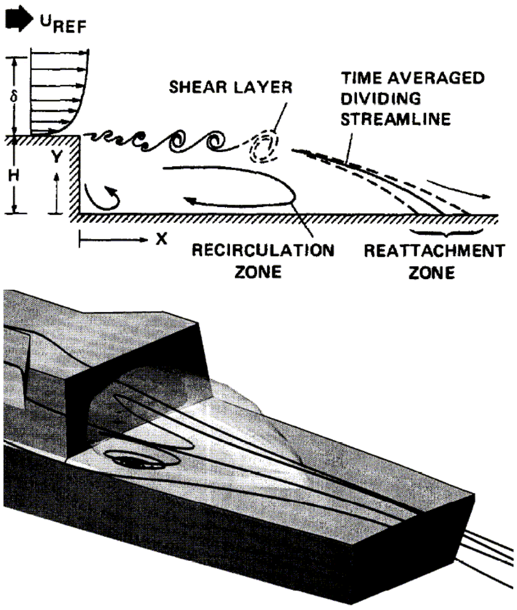


Figure 1. Flight deck recirculation zone [4,8]

2.2 Assessment of Effectiveness

A problem facing any application of flow control is how to assess its effectiveness. A rigorous analysis would require the modelling of the effects of the unsteady 3-D flowfield on helicopter performance, control and pilot workload – clearly impractical for any kind of comparative study. As a first step it was decided to pick out two flow parameters that seemed likely to have the greatest impact on helicopter operations:

1) turbulence intensity → pilot workload
2) downwash velocity component → rotor performance

Zan's work in Refs 1 and 2 indicates that unsteady loads measured on a model helicopter fuselage correlate well with pilot workload. Turbulence intensity should therefore also be a good indicator of pilot workload. The question of a suitable performance parameter was less straightforward, since changes in both vertical (downwash) and horizontal velocity components can affect rotor thrust.

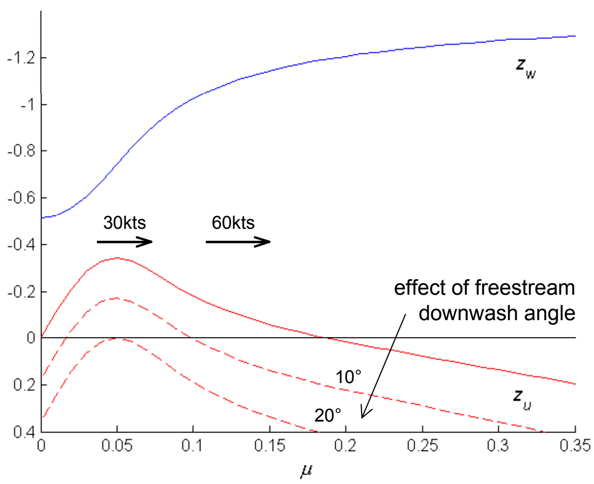


Figure 2. Effect of advance ratio on longitudinal rotor thrust derivatives [10]

Taking as a baseline the 'example helicopter' used in *Bramwell's Helicopter Dynamics* [10], Fig. 2 shows a typical variation of non-dimensional rotor thrust derivatives z_w and z_u with advance ratio μ (a recalculation of Fig. 5.8 in Ref. 10). The sign convention is such that a negative value of z_w indicates that increasing downwash through the rotor disk will reduce thrust, while a negative value of z_u indicates that reducing horizontal velocity component will reduce thrust. Note that the downwash derivative z_w is always negative, while the forward velocity derivative z_u changes sign from negative to positive as advance ratio increases. Further, z_u is also affected by any initial downwash velocity through the rotor disk. It will be seen later that downwash angles at typical hover heights are of the order of 10-15°, so that for advance ratios corresponding to hover at higher windspeeds Fig. 2 shows that $z_w >> z_u$. In terms of assessing device effectiveness, downwash is therefore the more relevant parameter. (Indeed, it is possible for z_u to be positive at high windspeed/downwash conditions, in which case any reduction in overall velocity magnitudes due to application of flow control would increase rather than decrease thrust!)

A further question relates to the area of the flow where the assessment is to be carried out. For a smaller warship, hover positions during recovery tend to place the rotor at or just above the top of the hangar. This suggests that downwash velocities above the hangar roof level and turbulence intensities below the roof level are of most importance; however, many non-aviation ships (fleet supply vessels for example) have much taller superstructures, so that flow conditions within the recirculation region now become critical.

2.3 Use of Inclined Screens

Reference 11 presents a useful review of flow control concepts as applied to ship air wakes, summarised in Fig. 3. In general, flow control devices aim either to reduce/eliminate undesirable flow features, or to shift them away from the area of concern. Porous fences belong to a class of devices with the potential to do both, and are widely used in industrial aerodynamics applications as windbreaks [eg 20,22].

Category	Desired effect	Control device / technique
Condition / filter airwake	Reduce unsteadiness in the flow and/or eliminate undesirable features	1. Blowing
		2. Porous ship surfaces
		3. Vortex generators
		4. Multiple lateral wedges
Both		5. Porous fence
		6. Serrated fence
		7. Flexible skirt
		8. Notched fence
		9. Reticulated foam fence
Move / deflect airwake	Transport undesirable fluid structures to region of lesser importance	10. Columnar vortex generators
		11. Turning vanes
		12. Ramp
		13. Solid fence
		14. Splitter plates

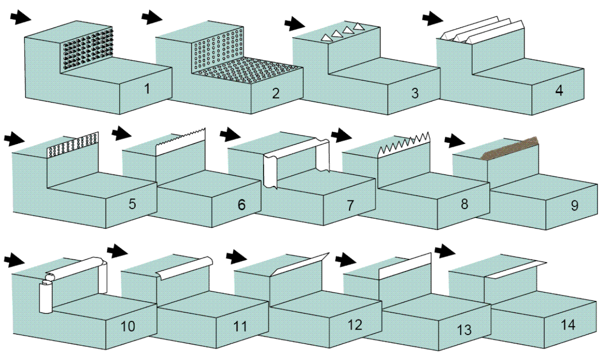
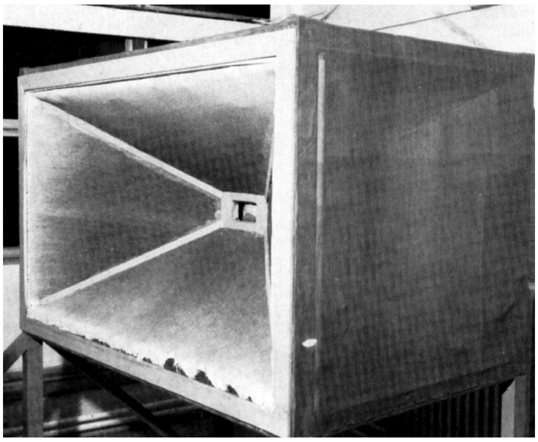


Figure 3. AVT-102 Ship air wake flow control classification [11]

Tests of some solid and porous vertical fence configurations (types 6, 8 & 9 in Fig. 3) were reported in Refs 11, 12 and 19 with inconclusive results; all devices were found to give similar reductions in turbulence and mean velocity over the flight deck. However, assessments were made solely on the basis of single hotwire measurements, which are unreliable in highly turbulent reversing flows. Further, the porous fences were fabricated from perforated plates with a relatively low porosity of 23%, giving a very high pressure loss coefficient of the order of 6 [20,21], which would tend to increase rather than decrease turbulence. In an attempt to break up the shear layer emanating from the hangar roof, the majority of fence-like devices studied in Refs. 11 were serrated rather than rectangular in plan. Best results (in terms of turbulence reduction) were obtained with a serrated reticulated foam fence.

An alternative approach was originally suggested by the wind tunnel 'jet catcher' developed by the RAE [13], in which an arrangement of *inclined* screens was used to catch and dissipate the exhaust jet from a boundary layer tunnel (Fig. 4). The unusual (almost unique) feature of this device was that the screens not only reduced the jet velocity but also deflected it via a process of refraction [23]. This device was remarkably effective, reducing a 50ms^{-1} jet to a barely detectable breeze. The use of inclined screens for external flow control is rather rare; the only recent work identified is Reference 25, which suggests that for a given frontal height an inclined windbreak is marginally more effective than a vertical windbreak in reducing downstream turbulence levels.



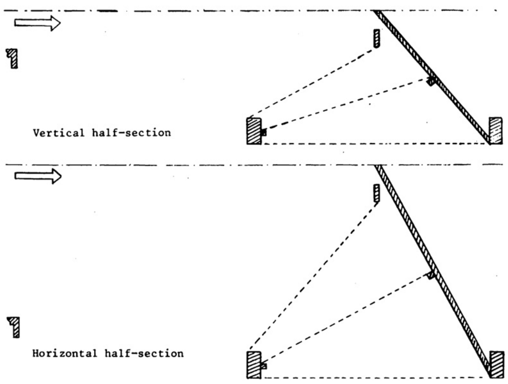


Figure 4. Winter & East's 'Jet Catcher' [13]

Four aspects of screen aerodynamic behaviour were considered to be of particular relevance to ship air wake flow control:

1) the use of high-porosity screens rather than perforated plates will reduce local turbulence levels in the flow separating from the hangar sides.
2) the pressure drop through the screens will tend to reduce velocity gradients in the shear layer.
3) the high tangential drag forces will tend to damp out the swirl velocity component in an impinging vortex [24].
4) inclining screens relative to the freestream will deflect the flow [13,23] and therefore provide a means of controlling downwash as well as turbulence

Finally, a screen or gauze is a much more practical proposition for implementation in a naval environment than a solid fence or flow deflector. In the form of a flexible gauze it can be rigged and adjusted in much the same way as the flight deck safety netting, with little or no adverse impact on superstructure mass or radar cross-section.

3 EXPERIMENTAL PROCEDURE

3.1 Wind Tunnel and Ship Model

Tests were conducted in the Bristol University 0.8m×0.6m Low Turbulence Wind Tunnel [14]. This is of conventional closed circuit design with a large contraction ratio and flow control screens to give turbulence levels well below 0.1%, up to speeds approaching 100ms^{-1}. No atmospheric boundary layer modelling was applied.

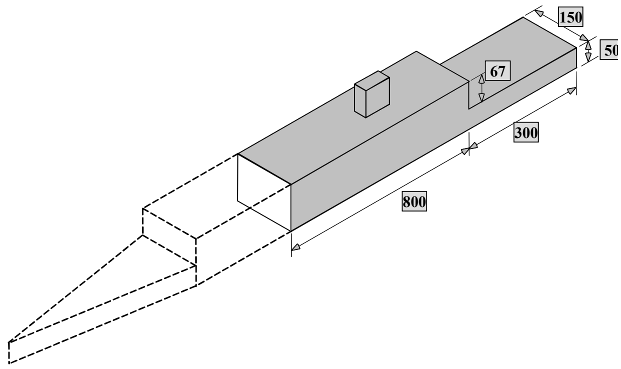


Figure 5. TTCP 'Simplified Frigate Shape'

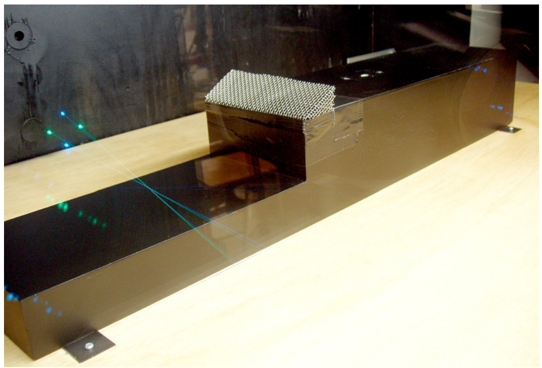


Figure 6. Frigate model with forward-facing 'coarse' hangar roof screen

Flow control devices were applied to the TTCP Simplified Frigate Shape (Fig. 5) – a generic shape originally defined for CFD studies of ship air wakes. The configuration tested was SFS1, representing only the main and flight decks with the bow section removed. In view of the bluff nature of the forebody region and the length of the superstructure it was felt that the omission of the bow region would not have a significant impact on the overall flow structure over the hangar deck. Although a very simplified geometry, tests on the clean configuration showed a similar flow topology to that found on more representative frigate configurations (eg in Refs 6,9,11 & 17),

Some preliminary tests were undertaken with and without the superstructure (funnel/mast) – this was found to have relatively little effect on the aft flowfield, and subsequent tests were all carried out with the superstructure fitted. The frigate model was 800mm long (approximately 1/90 scale), chosen to give maximum size consistent with the avoidance of significant wall interference when at 30° yaw. The model was mounted on a 1.6m long ground board set above the corner fillets on the floor of the working section (Fig. 6).

Most tests were conducted at a freestream speed of 32ms^{-1}, giving a Reynolds Number based on deck width of 330000, well above the minimum of 11000 recommended for wind tunnel testing of ships [15]. A few tests were repeated at 55ms^{-1} (Re = 565000), but comparisons showed no significant Reynolds Number effects.

3.2 LDA

A Dantec three-component fibre-optic coupled laser Doppler anemometer (LDA) was used, with two projection optics of 600mm focal length mounted outside the tunnel on a high precision 3-axis 0.6m×0.6m×0.6m traverse. The system (described in more detail in Ref. 16) was configured to run in off-axis backscatter mode, achieving a near-spherical measurement volume of the order of 0.05mm in diameter. Seeding was provided by a Safex 2001 fogger using a glycol-based fluid, producing a uniform distribution of particles with an average diameter of 1μm.

Longitudinal and lateral flow surveys were made over the flight deck region, consisting of between 100 and 400 data points at each of which 2000 individual data samples were taken. Velocity measurements presented here are the mean downwash velocity component w_{mean}, the total turbulence intensity V_{Trms}, and the mean total velocity V_T. All velocity data are normalised by the freestream velocity U_{fs} (not the local velocity magnitude). As recommended by AVT-102, measurement locations were normalized by the hangar height H

(= 66.7mm), half the deck width *B* (= 75mm) and the position of the landing spot L (in this case assumed to be half-way down the deck at 150mm). For most configurations two surveys were made, one along the flight deck centreline (at $y/B = 0$), and one across the flight deck at $x/L = 1$. For the 30º crosswind cases, three additional lateral traverses were made, at x/L = 0.33, 0.67 and 1.33.

3.3 Flow Control Devices

The flow control devices tested consisted of wire mesh screens fitted to the hangar roof (Fig. 6), hangar door vertical sides, and flight deck horizontal edges (Fig. 7). Device heights were kept constant at 20mm (or in non-dimensional terms $z/H = 0.3$ and $y/B = 0.27$). Inclined devices were set at an angle of ±30° to the horizontal, with the aft edge of the screen aligned with the hangar door so as not to overhang the flight deck region.

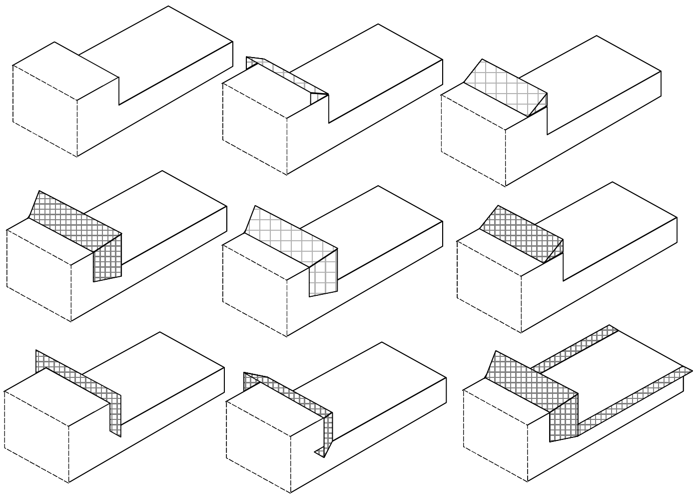


Figure 7. Inclined screen flow control configurations

Wire meshes of two different blockages were used: a 'coarse' low resistance screen with wire diameter 0.58mm and mesh size 3.125mm giving an open area ratio of 66%, and a 'dense' high resistance screen with wire diameter 0.39mm and mesh size 1.11mm giving an open area ratio of 42%. Corresponding resistance coefficients were $C \approx 0.8$ and $C \approx 2.9$, with Reynolds Numbers based on mesh pitch of 6800 and 2400 respectively (note that above Re ≈ 2000, resistance coefficient *C* is almost independent of Reynolds Number [20,21]).

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Effect of Screens at Zero Crosswind Angle

Preliminary feasibility studies looked briefly at a range of flow control devices (from vortex generators to deflector ramps) before settling on inclined screens as the most effective and practical approach. Initial tests placed screens on the hangar roof only, on the assumption that it was the shear layer emanating from this edge (Fig. 1) that is responsible for the majority of the adverse flight deck flow. Figure 8 illustrates the effect of screen inclination (30° fore or aft) and screen porosity (coarse or dense) on downwash and turbulence along the flight deck centreline at zero yaw.

For the baseline 'clear' deck, downwash velocities at the hangar roof level are of the order of 10-20% of freestream (corresponding to downwash angles of ~10°), and much greater in the recirculating flow region in the lee of the hangar. Baseline turbulence levels are 40-50% (!) at roof level, peaking at above 60% in the lee of the hangar. Application of an inclined screen reduces both downwash and turbulence significantly, particularly at heights below the hangar roof. Inclining the screen forward is more effective in reducing downwash, while an aft inclination gives a greater reduction in turbulence. Increasing mesh resistance increases effectiveness, although at a cost of an increased velocity deficit aft of the screen; however, as shown in Fig. 2, for the levels of downwash seen here, variations in total velocity are likely to have relatively little effect either way on rotor thrust. Unless other wise stated, all subsequent testing was carried out with high resistance ‘dense’ meshes.

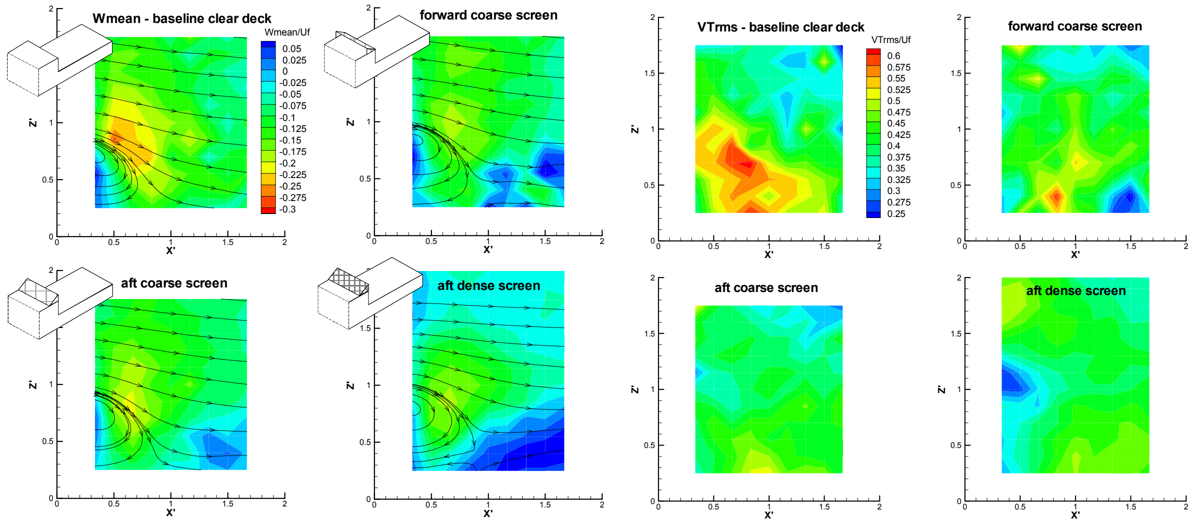


Figure 8. Effect of hangar roof screens on longitudinal distribution of downwash and turbulence intensity (y/B = 0)

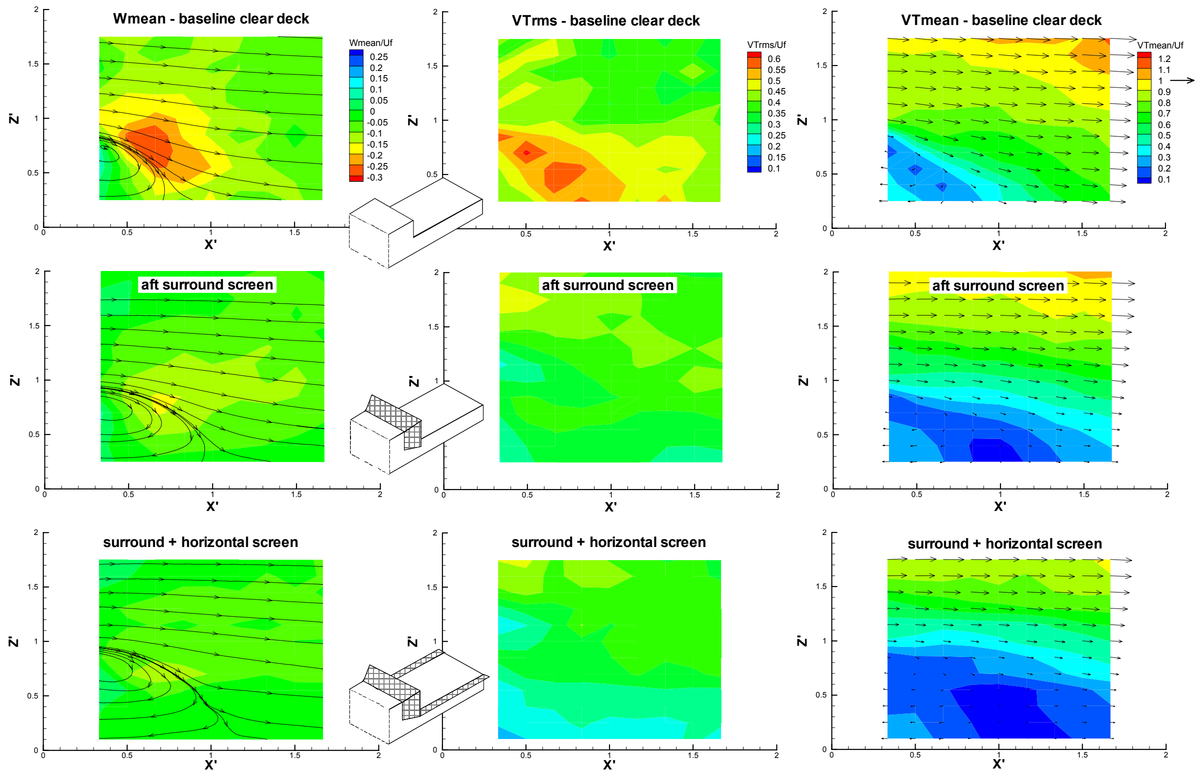


Figure 9. Effect of hangar and flight deck edge screens on longitudinal downwash, turbulence intensity and velocity deficit distributions (y/B = 0)

In terms of centreline flows the aft-facing screen appeared to have a marginal advantage. However, when the lateral distributions (at x/L = 1) were examined it became clear that although turbulence levels had been reduced on the centreline they had increased in the region of the flight deck edge (Fig. 9). This was alleviated in turn by extending the screens down the side of the hangar doors to produce a 'surround' screen configuration. Figure 8 also shows that for a 'surround' screen the performance is much more sensitive to inclination, with the aft screen giving a reduction in turbulence but forward and vertical screens giving an increase. The addition of the hangar side edge screens also improves performance in the longitudinal centreline plane (Fig. 10).

Finally, in an attempt to improve performance in a crosswind (discussed in the next section) horizontal screens were added to the sides of the flight deck. These were also found to give a further reduction in both downwash and turbulence intensity for zero yaw (Fig. 10).

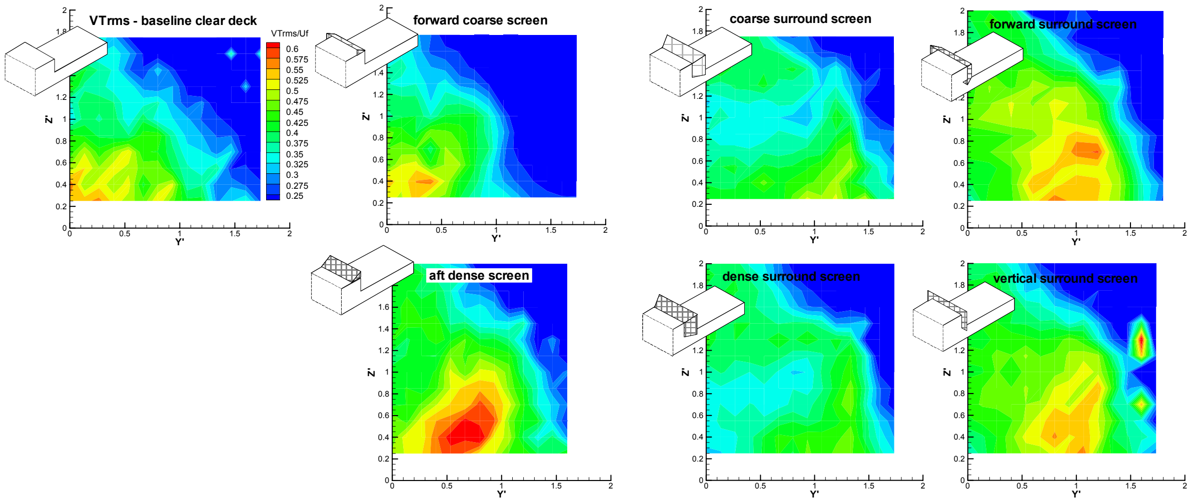


Figure 10. Addition of hangar door side screens to improve lateral turbulence distribution (x/L = 1)

4.2 Effect of 30° Crosswind

A more challenging task for an air wake control device is the yawed case, where the flow becomes much more complex and unsteady. Rather surprisingly, very little work has been done on the flow structure behind a non-aviation ship superstructure with a crosswind (with the exception of Refs 6 and 9), so that there is little data other than qualitative visualisations on which to base the optimisation of a flow control concept.

Figures 11 and 12 show the effect of the surround screen configuration on downwash velocity component and turbulence intensity for a +30° crosswind (from the starboard beam). The crossflow streamlines in Fig. 11 illustrate how much more complex the flow has become, with a number of vortical flow structures apparent in the lateral surveys. The crossflow topology changes rapidly as we move downstream, while the longitudinal survey plane (in the lower left corner of the figure) has missed almost every feature of interest. In an effort to identify the sources of these flow features some smoke and oil flow visualisations were undertaken, but because of the very low local velocities and very high levels of unsteadiness the results were inconclusive. Tentatively, five separate vortex structure can be distinguished:

1) a large anti-clockwise vortex downwind of the flight deck, driven by the upwash flow from the hull side,
2) a small vortex sitting above the hangar roof level on the centreline which dissipates rapidly, possibly shed from the upwind edge of the hangar roof,
3) a small anti-clockwise vortex shed from the upwind edge of the flight deck, and
4) and 5) a counter-rotating pair of 'tornado' vortices shed from the flight deck surface.

Figure 12 suggests that there is not a strong correlation between the vortex structures and the regions of high turbulence, particularly the most intense region downwind of the flight deck edge. Given that turbulence intensities here approach 100% (as also reported in Ref. 9) it seems probable that this unsteadiness is linked with the intermittent filling and bursting of the hangar door recirculation region.

In comparison with the zero yaw case, baseline turbulence levels and peak downwash/upwash velocities are much higher. Figure 11 shows that the screens have little effect on vertical velocity components at the hangar roof level; however, since these velocities are mostly upwards rather than downwards the impact on rotor performance would in fact be beneficial. The two 'tornado' vortices shed from the flight deck surface have become more clearly defined, with flow visualization indicating a small aft shift of their separation focuses. In contrast, the surround screens have had a sizeable impact on turbulence levels, with peak values reduced from 85-95% to 70-75%.

Having observed the impact of the crosswind separation over the flight deck, horizontal screens were added to the deck edges in an attempt to suppress or weaken this flow feature. In fact, as shown in Fig. 13, the deck-edge vortex appears to have become stronger, although this may be due to a change in its interaction with adjacent 'tornado' surface vortex. Nevertheless, the addition of the horizontal screens resulted in a significant improvement in all-round performance, reducing both downwash and turbulence at zero yaw (Fig. 10) and reducing peak turbulence at 30° yaw down to 40-45% (Fig. 13).

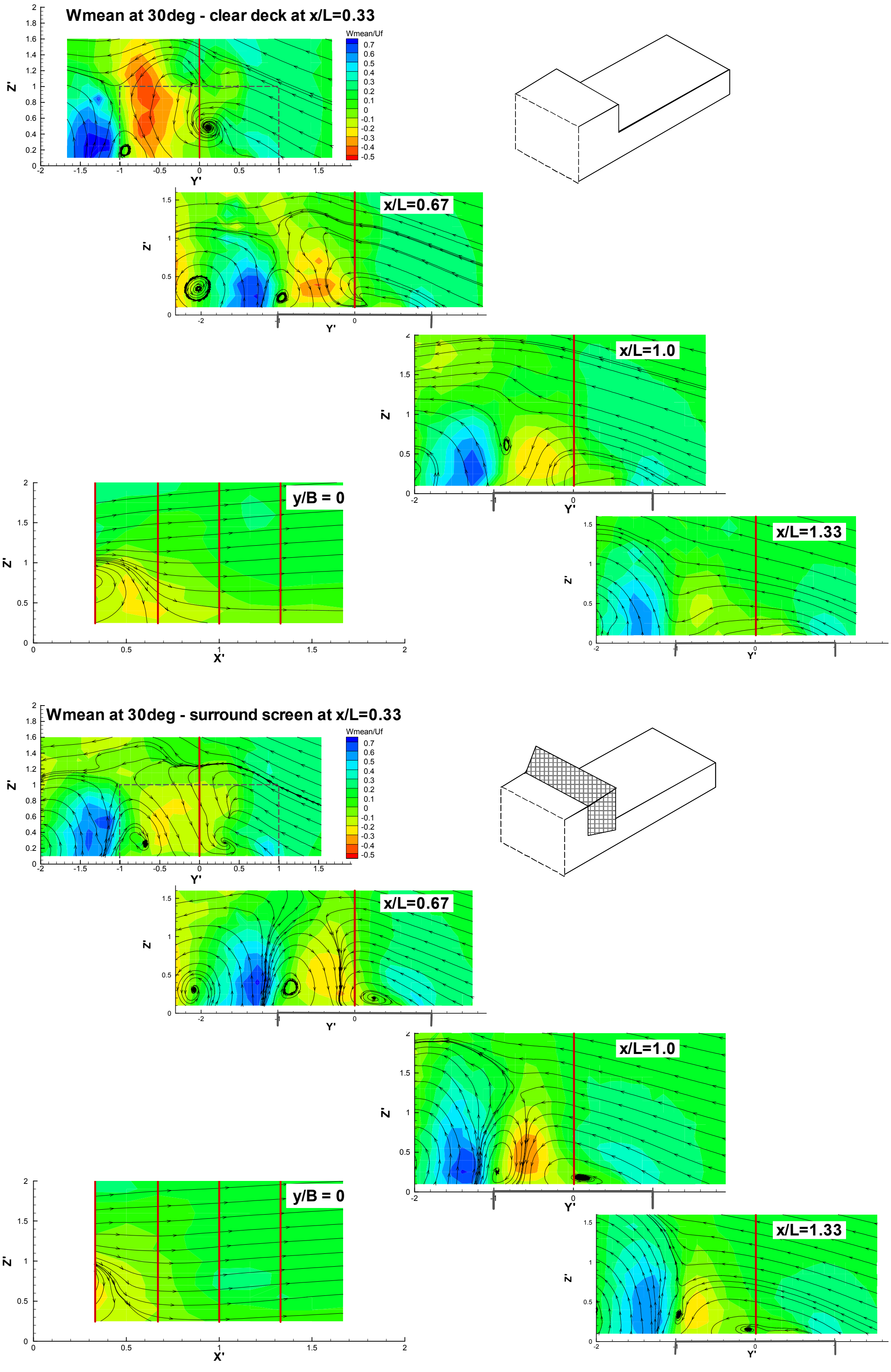


Figure 11. Effect of flow control on downwash distribution with 30° crosswind

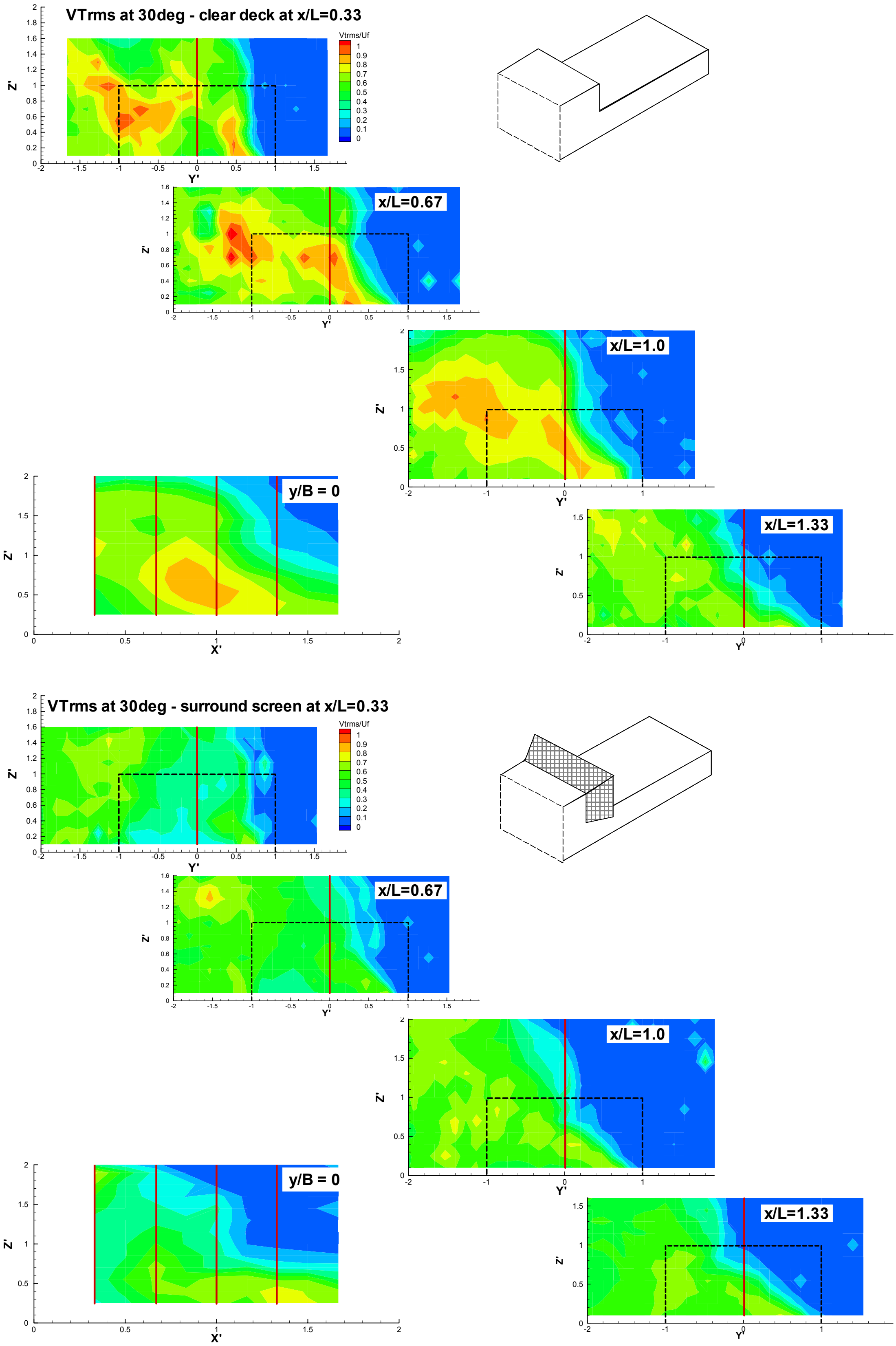


Figure 12. Effect of flow control on turbulence distribution with 30° crosswind

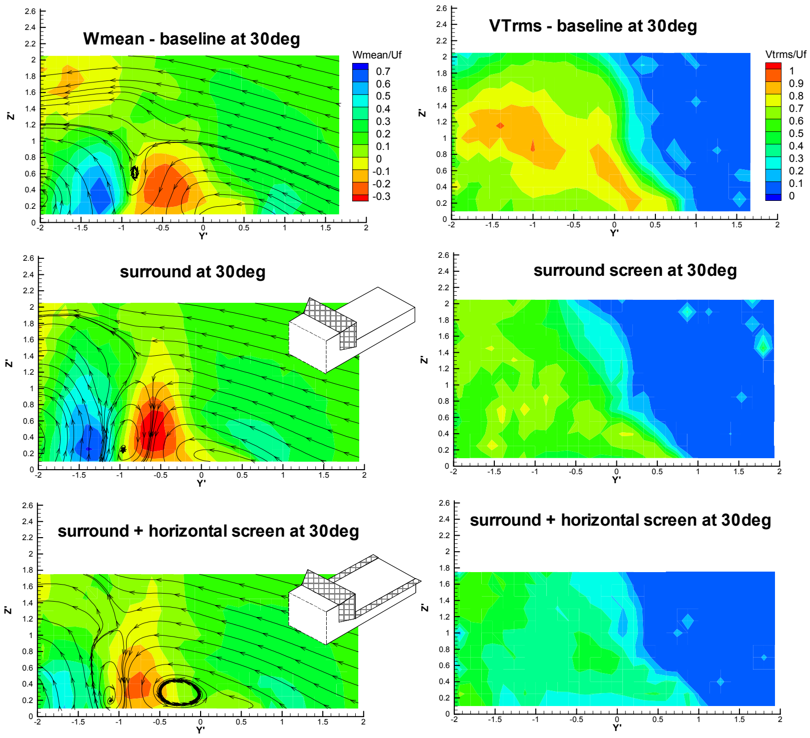


Figure 13. Effect of flight deck edge screens on lateral downwash and turbulence intensity distributions (x/L = 1)

5 CONCLUSIONS

Starting with the zero yaw case, porous screens mounted only on the upper surface had relatively little effect on high level turbulence, but all gave a reduction in downwash (which translates into an increase in rotor thrust). Extending the screens around the hangar sides improved their performance significantly, particularly for turbulence levels at the deck edge. With these 'surround' screens, the effect of device inclination became clearer, with forward facing screens having a greater effect on downwash and aft facing screens a greater effect on turbulence levels. In general, the forward and vertical orientations gave poorer performance, particularly in terms of turbulence levels. A further extension of the screens along the horizontal flight deck edges gives an additional small reduction in both downwash and turbulence levels at zero yaw.

Conversely, with a 30° crosswind the devices tested have a small effect on downwash but greatly reduce turbulence levels. Adding horizontal screens along the flight deck edges gives a further large reduction in turbulence with no additional downwash penalty. In general, the best performance was given by a dense (high-*C*) screen inclined rearwards, and mounted on the upper surface and sides of the hangar coupled with a dense (high-*C*) screen mounted horizontally along the fore-and-aft flight deck edges.

For frigate-like ship configurations with a relatively low hangar, it seems likely that the effectiveness of any flow control device will be limited by the highly turbulent nature of the approaching flow, at least with zero crosswind. However, with increasing crosswind angle the local (flight deck) flow separations will become more important and therefore flow control devices should become more effective. All the devices tested had much more impact on the flow in the immediate lee of the hangar, suggesting that they would be particularly effective on ships with large/high superstructures, where typical hover heights would be below the level of the hangar roof. The devices tested were selected on the basis of ease of implementation, with none of them extending over the edge of the hangar roof (and therefore not likely to foul a rotor). An inclined high-density screen should offer no more difficulty in rigging and de-rigging than the conventional safety netting already used around the flight deck perimeter. Similarly the horizontal screen would simply entail replacing the safety netting with a denser mesh to give the required pressure drop.

The combination of porosity and inclination appears to lead to flow control configurations that tend to improve both turbulence levels and downwash. There is clearly much room for detail geometry optimisation which has been beyond the scope of this project, but one area that stands out as needing further work is the yawed case. Some progress has been made towards understanding the relationship between flowfield structure and turbulence, but this still remains unresolved. It appears likely that the extremely high levels of turbulence encountered are related to large-scale unsteadiness in the flow (eg filling and bursting of the recirculating flow region in the hangar lee), but further investigation is required. Ideally, high speed Particle Image Velocimetry (PIV) should be applied to track the time-dependent behaviour of the flow structures.

6 ACKNOWLEDGMENTS

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7 NOMENCLATURE

B	=	hangar width
H	=	hangar height
L	=	distance from hangar door to landing spot
u,v,w	=	velocity components
U_{fs}	=	freestream velocity
W_{mean}	=	downwash velocity component, $= w_{mean}/U_{fs}$
V_{Tmean}	=	local velocity magnitude, $= \sqrt{(u_{mean}^2 + v_{mean}^2 + w_{mean}^2)}/U_{fs}$
V_{TRMS}	=	turbulence intensity, $= \sqrt{(u_{RMS}^2 + v_{RMS}^2 + w_{RMS}^2)}/U_{fs}$
x,y,z	=	cartesian coordinates, origin at base of hangar door
X'	=	non-dimensional longitudinal distance, $= x/L$
Y'	=	non-dimensional lateral distance, $= 2y/B$
Z'	=	non-dimensional vertical distance, $= z/H$
z_u	=	rotor horizontal velocity thrust derivative, $= -\partial\tau_c/m$
z_w	=	rotor downwash thrust derivative, $= -\partial\tau_c/w$
μ	=	advance ratio, $= V\cos\alpha_{nf}/R\Omega$

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