Vortex Ring and Rotor Wake Interaction with Solid Surfaces

Kate Bourne
Department of Mechanical Engineering
The University of Melbourne

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Abstract

The interaction between vortex structures and solid surfaces represents an inherently complex flow environment. When considering the rotor wake downwash generated by rotary-wing aircraft operating in close proximity to the ground, a phenomenon known as brownout can occur. Brownout is characterised by the entrainment of small ground particles by the rotor wake and when conditions are fully developed, cockpit visibility can be wholly obscured by the dust particles entrained by the rotor wake. In such instances aircrew can rapidly lose situational awareness, significantly increasing the probability of a mishap. Brownout dust cloud characteristics are highly variable, however the development of a very large cloud does not automatically equate to an unacceptable degradation in aircrew situational awareness. In some instances the region of clear air close to the fuselage is maintained throughout landing, despite development of a large cloud beyond the periphery of the rotor disk. Such flow structures are colloquially referred to as "dust donuts", as when viewed from above they have the appearance of a toroid.

Although the wake generated by rotary wing vehicles has been extensively studied, the mechanisms that underlie the development of "dust donuts" are not well understood. The focus of this dissertation is an investigation of the fundamental flow behaviour that potentially yields large-scale toroid flow structures, to enable a more thorough understanding of the phenomenon. The first part of the study implemented a numerical model to assess the interaction between vortex rings and solid surfaces. The vortex-wall interaction was used to investigate the tendency of the flow towards recirculatory behaviour, and to look at the flow pattern generated near the wall for both wall-normal and oblique impacts. It was found that the global flow field recirculation pattern consistent with a large-scale toroid structure was only evident for a wall-normal impact, but that in all test cases the near-wall flow structures generated by vortex ring / wall interactions were congruous with flow patterns required for particle uplift.

This dissertation then experimentally examines the hypothesis that a large-scale "global recirculation" flow structure exists and perpetuates a toroidal flow structure. Compared to the numerical study, the experiments more closely replicated conditions associated with full-scale operations; most notably the generation of a helical rotor downwash, which enabled direct
investigation of the rotor wake interaction with the ground plane. The experiment aims were to assess the flow field generated by the rotor across a range of test conditions in order to identify large-scale structures which could be considered consistent with the global recirculation hypothesis, investigate the conditions under which large-scale structures could be formed, identify the flow features underlying large-scale structures and investigate the effect of flow deflectors. Results showed that a structure consistent with the global recirculation hypothesis could be repeatedly generated and that the strength and core of the global recirculation region was dependent on the rotor thrust. The global recirculation structure reduced in stability with increasing thrust and was only observed at rotational frequencies that yielded blade loading coefficients an order of magnitude smaller than that expected for full-scale operations. Therefore, it cannot be inferred that the global recirculation hypothesis applies to flow fields generated at full scale. The investigation of flow deflectors showed that it was possible to modify the flow structure of the region of flow near to the rotor centre line in a manner that increased the tendency of the flow to move outward along the ground plane. Such an alteration to the flow field has the potential to reduce the tendency of ground-based particles to move back toward the rotor centre line, which could result in improved visibility for aircrew.
Declaration

This is to certify that:

1. this thesis comprises only my original work towards the PhD,

2. due acknowledgement has been made in the text to all other material used,

3. this thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Kate Bourne, September 2017
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## Nomenclature

### Abbreviations

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<td>AFCS</td>
<td>Automatic Flight Control System</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DEHS</td>
<td>Di-2-EthylHexyl-Sebacate</td>
</tr>
<tr>
<td>DST Group</td>
<td>Defence Science and Technology Group</td>
</tr>
<tr>
<td>FVM</td>
<td>Finite Volume Method</td>
</tr>
<tr>
<td>GTOW</td>
<td>Gross Take Off Weight</td>
</tr>
<tr>
<td>IGE</td>
<td>In Ground Effect</td>
</tr>
<tr>
<td>IW</td>
<td>Interrogation Window</td>
</tr>
<tr>
<td>LSWT</td>
<td>Low Speed Wind Tunnel</td>
</tr>
<tr>
<td>MP</td>
<td>Mega Pixel</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OGE</td>
<td>Out of Ground Effect</td>
</tr>
<tr>
<td>OpenFOAM</td>
<td>Open source Field Operation And Manipulation</td>
</tr>
<tr>
<td>PBiCG</td>
<td>Preconditioned Bi-Conjugate Gradient Method</td>
</tr>
<tr>
<td>PDE</td>
<td>Partial Differential Equations</td>
</tr>
<tr>
<td>PISO</td>
<td>Pressure Implicit with Splitting of Operator</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>POD</td>
<td>Proper Orthogonal Decomposition</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations Per Minute</td>
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<tr>
<td>SPIV</td>
<td>Stereo Particle Image Velocimetry</td>
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<td>TPP</td>
<td>Tip Path Plane</td>
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<td>TS1</td>
<td>Trip Strip 1 (rounded profile)</td>
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<td>TS2</td>
<td>Trip Strip 2 (square profile)</td>
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<tr>
<td>UCE</td>
<td>Useable Cue Environment</td>
</tr>
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<td>YPG</td>
<td>Yuma Proving Ground</td>
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**Roman Symbols**

- \((u,v,w)\)  \(\text{Wall-normal, streamwise and spanwise velocities, respectively (m/s)}\)
- \((x,y,z)\)  \(\text{Wall-normal, streamwise and spanwise coordinates, respectively}\)
- \(2D-2C\)  \(\text{Two-Dimensional Two-Component}\)
- \(2D-3C\)  \(\text{Two-Dimensional Three-Component}\)
- \(d\)  \(\text{Diameter (m)}\)
- \(f_{\text{vortex}}\)  \(\text{Vortex ring generation frequency (Hz)}\)
- \(h\)  \(\text{Height (m)}\)
- \(I\)  \(\text{Piston ejection impulse (N.s)}\)
- \(l_{\text{piston}}\)  \(\text{Piston stroke length (m)}\)
- \(M\)  \(\text{Magnification}\)
- \(p\)  \(\text{Pressure (Pa)}\)
- \(r\)  \(\text{Radius (m)}\)
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<th>Symbol</th>
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<tr>
<td>$r_{nozzle}$</td>
<td>Radius of nozzle (m)</td>
</tr>
<tr>
<td>$r_{vortex}$</td>
<td>Radius of vortex (m)</td>
</tr>
<tr>
<td>S1</td>
<td>Lead vortex</td>
</tr>
<tr>
<td>S2</td>
<td>Trailing vortex</td>
</tr>
<tr>
<td>t</td>
<td>Time (s)</td>
</tr>
<tr>
<td>$t_{piston}$</td>
<td>Piston stroke time (s)</td>
</tr>
<tr>
<td>$u_{piston}$</td>
<td>Piston velocity (m/s)</td>
</tr>
<tr>
<td>$u_{tip}$</td>
<td>Blade tip speed (m/s)</td>
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**Greek Symbols**

<table>
<thead>
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<tr>
<td>$\Delta t$</td>
<td>Time increment (s)</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Circulation (s(^{-1}))</td>
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<tr>
<td>$\gamma$</td>
<td>Vortex bubble eccentricity</td>
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<tr>
<td>$\mu$</td>
<td>Kinematic viscosity (m(^2)/s)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Vorticity (s(^{-1}))</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg/m(^3))</td>
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<tr>
<td>$\tau$</td>
<td>Wall shear stress (Pa)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Wall angle (°)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Error</td>
</tr>
<tr>
<td>$\varphi_f$</td>
<td>Convective flux (kg/m(^2))</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>Vortex detection algorithm</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>The del operator (used for taking the gradient, divergence or curl)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity (m(^2)/s)</td>
</tr>
<tr>
<td>$(\Delta X,\Delta Y,\Delta Z)$</td>
<td>In-plane particle displacement in the x-, y- and z-directions, respectively (m)</td>
</tr>
<tr>
<td>$(\Delta x,\Delta y,\Delta z)$</td>
<td>Increment in the x-, y- and z-directions, respectively</td>
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Nomenclature

Subscripts

0          Initial value
ND        Non-dimensional value

Mathematical Symbols

$\varphi_m$  Spatial basis function, also referred to as POD modes
$c_m$       POD coefficient
$D_{RS}$    Rate of strain tensor
$F_{MS}$    Momentum source term
C           Convective divergence term
F           Body force term
S           Face area normal vector
Chapter 1

Introduction

1.1 Background

The fundamental capability of rotary-wing vehicles to hover and manoeuvre at low ground speeds sets them apart from fixed-wing aircraft. Helicopters provide specialised operational capability to both civilian and military organisations, fulfilling roles that range from search and rescue, to troop lift and medical evacuation. However, such specialised operational capability can lead to unique operational issues. The helicopter rotor wake is a highly unsteady, complex flow field characterised by the motion of the blade tip vortices as they are shed from the rotor and convect downward. The flow beneath the rotor, commonly referred to as the rotor downwash, includes a large rotational component resulting in a "corkscrew" flow field, as illustrated in figure 1.1. When operating in free air, referred to as operations Out of Ground Effect (OGE) the wake contracts beneath the rotor disk as the flow is accelerated by the action of the rotor. The resulting flow field is dominated by the vortices shed by the rotor blades and convects downwards before eventually expanding under viscous dissipation. When a helicopter hovers close to the ground, a state referred to as In Ground Effect (IGE) \(^1\), the wake generated by the rotor first contracts beneath the rotor disk, then rapidly expands radially as it impinges upon the ground plane. It is the interaction between the helicopter downwash and the ground, resulting in the so-called rotor "outwash" that expands radially across the ground plane, which in dusty environments can lead to a phenomenon referred to as brownout.

\(^1\)A helicopter is generally considered to be operating in ground effect when is is within two rotor diameters of the ground, although the effect is most pronounced when operating within a distance of one rotor diameter.
Brownout is a complex aerodynamic environment characterised by the entrainment of small ground particles by the rotor wake\textsuperscript{2}. When brownout conditions are fully developed, cockpit visibility can be wholly obscured by the dust particles entrained by the helicopter rotor wake. In such instances aircrew can rapidly lose situational awareness, significantly increasing the probability of a mishap during non-automated landing manoeuvres. The advancement of Automatic Flight Control System (AFCS) upper modes\textsuperscript{3}, which in some cases enable full automation of vertical landing manoeuvres, has proven beneficial to operations in brownout-prone areas. Such modes are generally features of current-generation aircraft and represent technology that is not easily retrofitted to older platforms. In addition, changes to landing procedures through either augmented control systems or flight path optimisation Tritschler et al. (2012) are not always feasible within every operational context, and so do not yet represent a full solution to safe operations in brownout conditions. The 2010 study by Couch and Lindell (2010) assessed rotorcraft safety and survivability within the US Department of Defense, focusing on mishaps that occurred during Operation Enduring Freedom and Operation Iraqi Freedom. Brownout was a primary causal factor and accounted for 24\% of rotary wing non-hostile combat losses. Although no monetary value was quoted, loss of airframes represents significant expense, as do incidents of lesser severity where the airframe was repairable, but significant damage was sustained. Not explicitly mentioned in much of the

\textsuperscript{2}In the case of snow-borne operations, the phenomenon is referred to as "snowball" or "whiteout".

\textsuperscript{3}Upper modes refer to features of flight control augmentation systems which enable certain parameters to be controlled by the AFCS. Examples of such modes typically include heading hold,airspeed hold and hover hold. For current-generation helicopter AFCS, which typically provide pilots fine control over hover-hold settings, the upper modes can be used to automate vertical descent manoeuvres.
publicly available literature is the associated cost of accidents and incidents in human terms, arguably the most important consideration when assessing hazards to the safe operations of aircraft. In addition to the increased risk of mishap during operations, brownout also causes increased wear and tear on engine and exposed dynamic components, which results in increased maintenance costs. The requirement to operate aircraft with specialised engine filters also has implications for aircraft performance, which can reduce the aircraft’s flight envelope.

Brownout presents the greatest hazard to operations during landing manoeuvres, when the pilot’s awareness of aircraft attitude and motion are most critical. From a pilot perspective, the severity of brownout conditions is dictated by the extent to which visual cues are lost, particularly the loss of ground and horizon references. If sight of the ground can be maintained during the final phases of the descent, anecdotal evidence indicates the risk of mishap is reduced Bourne et al. (2014a). Of particular importance is the region of air close to the fuselage, which ultimately dictates the quality of the Useable Cue Environment (UCE)\(^4\) ADS-33E-PRF (2000). Brownout dust cloud characteristics are highly variable, however the development of a very large cloud does not automatically equate to an unacceptable degradation in UCE. In some instances the region of clear air close to the fuselage is maintained throughout landing, despite development of a large cloud beyond the periphery of the rotor disk. Such flow structures are colloquially referred to as "dust donuts", an example of which is shown in Figure 1.2.

\(^4\)The useable cue environment is defined under Aircraft Design Standard 33 ADS-33E-PRF (2000) and relates to the pilot’s ability to maintain aircraft position based on the available visual cues.
Fundamentally, brownout is a phenomenon comprising the flow structure of a helicopter rotor wake as well as the motion of particles. The rotor wake flow structure is dictated by the helicopter flight characteristics and its proximity to the ground, whereas particle motion depends on the size, shape and mass of the particles at the ground surface. As such, the range of factors capable of influencing the development of brownout conditions is extensive, ranging from aircraft-specific details such as the rotor characteristics, to the environmental conditions on the day. Put simply, it is not yet possible to generalise the characteristics of the brownout clouds using simulation or modelling techniques for full operational assessments, owing to the complexity of the problem and current lack of empirical data. Improved understanding of the fundamental flow mechanics that contribute to brownout flow conditions is important both to the development of systems that look to improve the safety of operations, and to overall understanding of the phenomenon.

Sections 1.2.1 and 1.2.2 provide background and context to the brownout flow mechanics that are subsequently discussed in Section 1.3. Sections 1.3.1 and 1.3.2 discuss the current understanding of the fluid mechanics underlying the sediment uplift processes, which leads to the objectives of this study as presented in Section 1.4.
1.2 Rotor Wake Aerodynamics

Following is an overview of the flight regimes that commonly result in brownout when the environmental conditions of the operational area are amenable to sediment uplift.

1.2.1 Hover in Ground Effect

Helicopter design is generally optimised for hover, which demands higher power than cruise flight. The fundamental capability offered by a helicopter is the ability to hover and manoeuvre at low speed, and although required power is reduced when operating IGE, it is not reduced so far as to become more efficient than when flying at typical cruise speeds. The phenomenon of brownout occurs most commonly when the helicopter is IGE, a flight regime generally defined as operations within two rotor diameters of the ground\(^5\). A simple representation is shown in figure 1.3. As described by Prouty (2004) "the source of ground effect is the generation of pressure waves that are reflected back up from the impingement of the wake on the ground to slow the flow at the rotor itself." In other words, ground effect restricts the airflow through the rotor. Thus, helicopters operating IGE require less induced power\(^6\) than when hovering at altitude. The flow conditions associated with this state have been a source of significant research and analysis, both experimentally and computationally. Further detail can be found in the textbooks of Prouty (2004), Johnson (1994) and Leishman (2000).

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\(^5\)Ground effect is most significant when the aircraft is within one rotor diameter of the ground.

\(^6\)Induced power refers to the energy transfer between the rotor and the air during the production of lift.
(1937), and also that of Knight and Hefner (1941) who showed that at rotor heights above one rotor diameter the effect of the ground reduces significantly. Cheeseman and Bennett (1957) extended the analysis to the effect of the ground in forward flight, showing that with increasing forward speed there is increased power required to maintain constant thrust. Empirical models were also derived for power and thrust requirements IGE, such as the work by Hayden (1976), which also provides confirmation to the findings of Knight and Hefner that ground effect is maximal below rotor heights of one diameter.

Studies were limited to qualitative experiments, with most quantitative results related to performance characteristics. The research undertaken by Light (1989) included both experimental and theoretical investigations into the wake geometry and performance of a helicopter rotor. The tip vortex geometry was captured using wide-field shadowgraphs and the changes in trajectory of the tip vortex filaments were consistent with the change in the wake flow structure as illustrated in figure 1.3. The work of Griffiths et al. (2005) assessed rotor performance IGE using a free-vortex wake model. The analysis shows the relationship between wake distortion at the ground interface and the subsequent effect on rotor loads, performance and power requirements.

Experiments conducted by Lee et al. (2008) investigated the fluid dynamics associated with an isolated rotor operating IGE. Flow visualisation and phase-resolved Particle Image Velocimetry (PIV) were used to examine the interaction between the rotor wake and ground plane in order to examine the dynamic features of the wake/surface interaction process. An example of the flow visualisation results are presented in figure 1.4, where a laser sheet was used to illuminate smoke entrained by the rotor blade. Of particular interest are the observations relating to vortex pairing and shearing as the rotor outwash moves across the ground plane. It is these features which are most likely to contribute to the development of brownout flow conditions and Lee et al. conclude that despite the fact some vortex structures were observed to pair together they were also subject to shear forces. This highlighted the unsteady effect of the rotor outwash on the ground plane. Extension of the work undertaken by Lee et al. (2008) to investigate sediment uplift mechanics is presented in Section 1.3.1 and includes the work of Johnson et al. (2009) and Sydney et al. (2011).
1.2 Rotor Wake Aerodynamics

1.2.2 Low Speed Forward Flight in Ground Effect

It is important to understand the fundamental differences in the fluid mechanics that drive brownout conditions during low speed, low altitude manoeuvres. In low speed forward flight IGE, a ground vortex is formed ahead of the rotor as shown in figure 1.5. The strength of the ground vortex is maximal around 15-20 kt forward speed, before becoming weak and disintegrating at approximately 30 kt. The ground vortex plays a critical role in the entrainment of particles ahead of the rotor during non-vertical landing and low altitude manoeuvres, and is accepted as the dominant flow structure in development of brownout dust clouds in such flight regimes.
As the helicopter airspeed increases above 40 kt the rotor wake skews aft and the blade tip vortices begin to move closer to the edge of the wake, rolling-up in the process. This flow structure can be considered similar to the trailing edge vortices generated by fixed-wing aircraft. Such "rotor disk trailing vortices", as distinct from the blade tip vortices, may also interact with the ground plane and initiate dust clouds. As the helicopter speed increases these vortices will quickly sweep back to trail the aircraft and are unlikely to interact with the ground except during very low-level manoeuvres. Both the ground vortex and rotor trailing vortices can be identified in the 3D vortex visualisation presented in figure 1.6.
Curtiss Jr. et al. (1981) experimentally investigated the aerodynamic characteristics of an isolated rotor operating in ground effect at low advance ratios. Several conclusions were drawn from the study, including the fact that a recirculating flow was present at low speeds, as part of the wake flowed forward and upward. A well-defined elliptically-shaped horseshoe vortex was formed under the rotor at higher speeds, and contrary to theoretical predictions, the experimental results indicated a significant additional down-flow through the forward half of the rotor. It was also noted that the flow field associated with the ground vortex appeared steady whereas the recirculating flow was quite unsteady. Estimates of the ground vortex strength also indicated it was at least an order of magnitude stronger than the blade tip vortex.

Boyd and Kusmarwanto (1983) measured the ground vortex in greater detail, noting that the geometry of the ground vortex is heavily influenced by forward flight, and if the forward velocity is sufficiently low the "rotor wake is able to travel forward into the wind before rolling up into the vortex and being swept downstream". The authors conclude that an increase in rotor height and forward flight velocity rapidly degraded the beneficial effects of the ground seen by the rotor. The advent of Computational Fluid Dynamics (CFD) and non-invasive measurement techniques such as PIV enabled aerodynamic features to be measured quantitatively. A study

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7The advance ratio is the ratio of the freestream air speed to that of the rotor tip speed.
of the ground vortex structure at low advance ratios was undertaken by Ganesh and Komerath (2006) and flow visualisation, hot-wire measurements and PIV were used to conduct a quantitative analysis. It was noted that the ground vortex strength was four times that of the tip vortex, and that the blade tip vorticity was entrained into the ground vortex. Experiments conducted by Nathan and Green (2012) assessed the ground vortex formation under conditions more representative of full-scale operations. The wind tunnel in use was fitted with a rolling road, and tests were conducted using both a stationary ground plane, and with the rolling road speed matched to the wind speed. Nathan and Green (2012) noted that the rolling road had a significant effect on the wake structure, with the observed ground vortex reduced in size and closer to the rotor than in the case of a stationary ground plane.

1.3 Brownout Flow Mechanics

1.3.1 Sediment Uplift

Environmental conditions are the root cause of the brownout phenomenon given aircraft parameters are fixed and brownout events can be caused by any airframe. As such it is assumed that the onset of any event which results in loss of visibility in the cockpit due to the entrainment of ground particles is dictated by the properties of the particles themselves. The geological term saltation, which refers to particle transport by fluids, is applied in the context of brownout to describe the movement of particles across the ground surface. Saltation models have been used to investigate how particles are disturbed and subsequently entrained by the rotor wake. Investigations which account for the two-way interaction between the fluid and the particles are referred to as dual-phase studies.

The study undertaken by Phillips and Brown (2008) coupled CFD with a particle transport model and analysed two different rotor configurations under conditions representative of landing manoeuvres. The authors noted two features that played a primary role in the characteristics of the dust cloud: the ground vortex and regions of recirculatory flow. Although considered a preliminary analysis, the work highlights the inherent complexity of accurately modelling brownout conditions and the importance of the particle transport model.

The work presented by D’Andrea (2009) utilises a numerical approach to the analysis of brownout conditions. The research is of particular interest as it is one of the few papers in open literature published by an Original Equipment Manufacturer (OEM), in this case AugustaWestland. A physics based model was used to investigate the differences between rotor configurations. D’Andrea concluded that results of the first-level assessment supported anec-
dotal evidence that tandem and tilt-rotor configurations suffered more severely from brownout effects than single rotor configurations (for reference, rotor configurations are defined in figure 1.7). This conclusion is to be expected, as both tandem and tilt-rotor configurations typically demonstrate higher disk loading and downwash velocities, along with increased flow complexity due to interference effects between the two rotors when compared to conventional single rotor configurations. D’Andrea noted that larger and stronger ground vortex structures were identified within the recirculation regimes and near the fuselage greater levels of flow unsteadiness existed. Of particular interest is the explicit mention that the EH-101 is less susceptible to brownout conditions than other aircraft; however, the evidence provided is purely anecdotal and no explanation is offered as to what features of the aircraft are responsible for the improved performance.

The dual-phase flow environment was investigated by Johnson et al. (2009) using a sub-scale rotor model installed above a sediment bed. The results presented included both flow visualisation and PIV, and the key mechanism to determining the concentration of entrained particles was identified as the merging between adjacent wake vortices. Compared to sediment uplift of a single vortex, the uplift of particles by vortex merging increased the height above the ground plane that the particles were transported, which in turn enabled entrainment back through the rotor. It was also observed that larger particles, while not easily uplifted, went on to further agitate other particles on the surface via bombardment mechanisms which in turn caused smaller particles to become suspended in the rotor outwash.

The work of Sydney et al. (2011) extended the investigation of Johnson et al. (2009) using a similar experiment setup and measurement techniques. Sydney et al. identify six fundamental uplift and transport mechanisms responsible for development of brownout dust clouds. Presented in figure 1.8 are the six mechanisms, which include creep, saltation and saltation bombardment, unsteady pressure loading, vortex induced trapping, re-ingestion bombardment and secondary suspension. Creep refers to the movement of particles across the sediment bed, and vortex induced trapping is the mechanism by which particles are captured and mobilised by the individual blade tip vortices. These results highlight the complexity of sediment uplift, in particular the fact that the mechanisms can occur simultaneously and result in a cascade effect which rapidly causes suspension of a large number of particles. Sydney et al. also note that the sediment uplift and transport occurs in waves. Although not explicitly stated, it is likely these accumulations are a function of aperiodicity in the rotor downwash, and represent locations of vortex merging. The importance of particle size was also identified, as test cases with larger average particle sizes within the sediment bed beneath the rotor did not exhibit the

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8 Also known as the AW101, the EH-101 is a medium-lift military helicopter with a conventional rotor configuration.
Conventional (single) Rotor Configuration

Tandem Rotor Configuration

Tilt Rotor Configuration

*Figure 1.7 Helicopter rotor configurations*
full range of sediment transport and uplift mechanisms. Larger particles continued to form a saltation layer at the surface, but significantly fewer particles were uplifted and suspended by the vortex flow. For the particle sizes tested, those below 20µm were seen to yield long-term suspension, with short-term suspension sustained by particles 20 – 70µm. This finding is consistent with operational reports that only specific geographic locations are likely to result in the formation of dense dust clouds, indicating that particle size is a critical parameter in determining the likely severity of brownout conditions.

The role of particle modelling for accurate simulation was investigated by Jasion and Shripton (2012), and Syal and Leishman (2013). Jasion and Shripton (2012) used a Lagrangian entrainment model and show that as a function of distance from the rotor, three different boundary layer zones exist, each exhibiting different physics. Three different particle sizes were assessed; 10µm, 300µm and 500µm, and the dominant particle forces identified. It was found that weight controlled the largest particles and cohesion controlled the particle dynamics at the smallest scale. Drag was identified as the dominant aerodynamic force, and wall-bounded lift was found to be sufficient to entrain medium-sized particles. Syal and Leishman (2013)
coupled a model for bombardment ejection to a Lagrangian solver in order to better capture the mechanics of sediment transport and uplift during simulation. It is noted that in practice the mobilisation of particles under shear stress alone is difficult, and that bombardment is a key mechanism that explains why measurements taken during full-scale testing find brown-out clouds to be composed mainly of small particles. The movement of the blade-tip vortices across the sediment bed was found to be a primary mechanism for bombardment ejection. The blade tip vortices persist in the flow field much longer when the rotor is IGE, due to vortex stretching and re-intensification of vorticity, which in turn increases their propensity to agitate particles at the ground plane. Syal and Leishman (2013) also make an interesting point relating to the identified flow mechanics of bombardment ejection and the subsequent importance of operating environment. It was found that there was a critical particle size that generated the greatest surface crater during the saltation process, which then exposed a large number of smaller particles to uplift and entrainment mechanisms. The critical size was found to be a function of both the flow-field and the sediment bed, and it was suggested as a reason for the differing dust cloud geometries seen at full-scale under what are ostensibly the same rotor operations. Syal and Leishman (2013) subsequently note that natural variability in sediment beds cause large challenges in prediction of accurate brownout conditions.

The sub-scale experiments of Lee et al. (2008), Johnson et al. (2009) and Sydney et al. (2011) were designed to match full-scale rotor behaviour by way of disk loading. No studies could be found that investigated sediment uplift behaviours as a function of either disk loading or Reynolds (Re) number. The rationale behind the choice of particle sizes used during the aforementioned experiments was not explicitly stated by any of the authors, with no direct parallel being drawn to full-scale measurements. Although it is difficult to confirm that the sub-scale experiment results can be generalised, the simulation undertaken by Jasion and Shripton (2012), and Syal and Leishman (2013) indicate that there is consistency in the flow features and sediment uplift processes at full-scale when compared to the sub-scale experiments. More detailed discussion of the effect of Reynolds number on the blade tip vortex is given by Ramasamy and Leishman (2007), where a vortex model was developed and validated against rotor tip vortex measurements. Consistent with experimental observations, the model showed that the temporal core growth rate increased with an increase in vortex Reynolds number. The investigation highlighted the importance of vortex filament strain and diffusion as two interdependent processes, but did not extend to analysis within the context of ground plane interactions.

There are very few reports of full-scale brownout testing available in open literature, but the results of Cowherd (2007), Murowchick (2006) and Bourne et al. (2014a) identify soil samples taken from areas known to consistently produce brownout conditions, and a large
percentage of each sample is made up of very fine particles representing sizes under $350\mu m$. The work of Rauleder and Leishman (2012) investigated differences between single-phase and dual-phase results where all other experiment conditions were held constant. It was found that a two-way coupling between phases did occur, with evident differences in turbulence intensity close to the ground plane. The common trends between single- and dual-phase flows were an increase in turbulence intensity with an increase in wall-normal distance, and a decrease in turbulence intensity with radial distance once the maximum value had been reached. The differences were that near the sediment bed the turbulence properties showed greater spatial excursions in the carrier-phase, and that for the same distance from the surface the dual-phase experiment yielded higher overall turbulence intensities. It was determined that the presence of resuspended particles in the flow altered the characteristics of the carrier-phase in the dual-phase flow environment and that the two-way coupling of the phases changed the distributions in the components of the Reynolds stress tensor. Rauleder and Leishman (2012) also note that the onset of sediment motion was not associated with the local action of the coherent vortex structures, but rather with the high levels of turbulent stresses induced by the vortex motion. As such, it can be surmised that the changes to the flow field when considering differences between single- and two-phase flows are most critical for sediment uplift processes, but it is not suggested that the large-scale carrier-flow structures are significantly altered. It is therefore assumed that the particles themselves do not significantly alter the flow field and are simply following the flow structures generated by the rotor. From an operational perspective the most intuitive change that could be affected is a change in the local air density as a result of the large number of particles in the flow field, however the highest dust concentrations reported by Cowherd (2007) do not change the air density beyond standard operating conditions.

The sediment transport and uplift mechanisms described by Sydney et al. (2011), Syal and Leishman (2013) and Rauleder and Leishman (2012) are accepted as the near-wall flow dynamics that result in particles being disturbed from the ground plane and ejected into the air. It is also assumed, on the basis of data presented by Cowherd (2007), Murowchick (2006) and Bourne et al. (2014a), that the particles which are small enough to be uplifted and suspended in the rotor wake will be entrained by the flow structures without significantly altering the characteristics of the flow.
1.3.2 Toroid Flow Structures

For cases of true vertical descent and hover IGE, where there is no aircraft drift, forward speed or ambient wind, the ground vortex does not develop. Instead, the blade tip vortices dominate the flow structure, creating the distinctive flow pattern seen in figure 1.2, with the strength of the vorticity dictated by aircraft characteristics and the descent rate. Viewed from above, the dust cloud formed in nil wind conditions looks like a toroid. The fluid mechanics underlying this flow structure are not well understood, specifically with regard to the persistent nature of the toroid structure and the associated region of clear air near the aircraft fuselage. It is unclear how the global flow field develops, in particular whether the toroid structure is purely a cumulative result of particles disturbed under the mechanisms described in Section 1.3.1 or whether under certain conditions a large-scale coherent flow structure is present.

The reference to the wave-like uplift of particles by Sydney et al. (2011) is consistent with aperiodicity of vortex filaments that dominate the rotor downwash. At the full scale, Wong and Tanner (2010) and Tanner (2011) used photogrammetric measurements to analyse the dust cloud generated by a helicopter in brownout conditions. The analysis of Tanner (2011) shows large-scale column-like structures in the brownout flow field, as shown in figure 1.9. During forward flight in brownout conditions the column-like structures are congruous with flow field aperiodicity and vortex merging, with the global flow field dominated by the ground vortex that is described in Section 1.2.2.
Figure 1.9 Large-scale column-like flow structures as identified by Tanner (2011). Shown is a false-colour image generated during the photogrammetric analysis and highlights the boundary of the dust cloud (green line) along with the dust cloud structures (grey lines), and features of the foreground surface (blue lines).
1.4 Objectives and Outline

The aim of this study is to better understand the underlying flow mechanics associated with so-called dust donuts, which are represented by a clearly defined large-scale toroid structure. To this end the following research questions are addressed:

1. Can the interaction of vortex rings with solid surfaces provide insight into the flow structures that underlie the dust donuts?

2. Can wake structures consistent with the geometry of the dust donuts be identified in sub-scale rotor experiments?

3. If such wake structures can be identified, can ground-based trip-strips or active flow deflectors alter the geometry of the wake in a manner likely to improve visibility for aircrew?

In Chapter 2 the problem is first simplified to the investigation of vortex-wall interactions using CFD in order to identify the tendency of these structures towards recirculatory behaviour, and to examine the flow pattern generated at the wall. Chapters 3 - 6 extend the analysis to sub-sale rotor experiments in order to investigate large-scale wake structures IGE. The experimental studies investigate the hypothesis that the large-scale toroid structure is generated by a large-scale coherent flow structure, referred to here as global recirculation. Finally, Chapter 7 presents an investigation into the effect of active flow deflectors on the rotor wake and whether the slipstream boundary can be moved further outboard away from the rotor centreline.
Chapter 2

Numerical Study of Vortex Ring / Wall Interactions

Part of this chapter has been published in the Journal of Fluids Engineering, please refer to Bourne et al. (2017). Results have also been presented at the 20th Australasian Fluid Mechanics Conference, please refer to Bourne et al. (2016).

2.1 Vortex Ring Simulations

Investigation of the fundamental flow behaviour that drives the development of brownout conditions will enable a more thorough understanding of the phenomenon. In this way vortex rings are first used to investigate the flow conditions at the wall that result from the impact of vortical structures. For the case of wall-normal impact the vortex ring is investigated as a possible representation of the large-scale "dust donut" type structures that were introduced in Section 1.3.2. In this study the vortex-wall interaction is used to investigate the tendency of the flow towards recirculatory behaviour, and to look at the flow pattern generated near the wall.

The analysis is then extended to the case of oblique impacts and multiple vortex rings. Although a significant simplification to the helical downwash generated by a helicopter rotor, vortex ring interactional dynamics provide insight into the fundamental flow features and phenomena that underlie the unsteady and highly complex flow field.
2.1.1 Literature Review

The study of vortex rings represents a field of research which has its genesis in the works of Reynolds (1876) and Rogers (1858). Since then, there has been a significant amount of theoretical and experimental analysis undertaken, which is well captured in the reviews of Shariff and Leonard (1992), Lim and Nickels (1995) and Meleshko (2010). Of particular interest to this study are the interactional dynamics between thin vortex rings and solid surfaces, as such flow mechanics can be considered representative of a helicopter rotor wake impinging on the ground.

The interaction between vortex rings and orthogonal solid surfaces is well studied and results in a number of relatively complicated flow phenomena, as is described by Saffman (1992). With sufficiently high Reynolds number the response as a vortex ring approaches a no-slip wall includes vortex stretching, unsteady separation in the boundary layer flow, formation of a secondary ring, rebound of the primary vortex ring, and subsequent interaction between the primary and secondary vortex rings. Experimental and numerical studies investigating the flow behaviour of isolated vortex rings impacting a no-slip wall with trajectories normal to the wall include Walker et al. (1987), Swearingen et al. (1995), Orlandi and Verzicco (1993), Chu et al. (1993), Archer et al. (2009), Cheng et al. (2010) and Cheng et al. (2014); and reviews are provided by Verzicco and Orlandi (1996) and Lim and Adhikari (2015).

The available literature relating to oblique interactions between vortex rings and no-slip surfaces is more limited. The experimental work of Lim (1989) focused on the role of the no-slip boundary in the formation of bi-helical vortex lines. It was observed that as the vortex ring approached the inclined wall, the segment of the ring closest to the wall experienced a higher rate of vortex stretching. The varying rate of vortex stretching around the circumference of the vortex ring resulted in variation in the size of the vortex core, subsequently leading to the formation of bi-helical vortex lines as shown in figure 2.1. Although the angle of incidence of the wall was varied between 0º and 90º, only the results at a wall angle of 51.5º were presented. Lim (1989) noted that the 51.5º test condition best accentuated the flow phenomena being investigated.

The work of Orlandi and Verzicco (1993) used a numerical approach, which solved the Navier-Stokes equations in Cartesian coordinates using the fractional-step method, to further investigate the experimental data of Walker et al. (1987). The primary purpose of the investigation was to identify the cause of ejection of a so-called "new" ring at the wall (in addition to the secondary vortex) that was observed during the experiments of Walker et al. (1987). The study concluded that the physical mechanism causing the additional new ring was vortex pairing. A similar numerical approach was used by the same authors to investigate the experiment results of Lim (1989). Although the qualitative observations of Lim were confirmed, the
authors noted further analysis was required before conclusions could be drawn regarding the dynamics of vortex lines. Their preliminary hypothesis suggested that the asymmetric pressure field acted to drive fluid around the vortex ring from the impact point to that farthest from the wall.

The study undertaken by Liu (2002) also numerically investigated the work of Lim (1989), using a hybrid Eulerian-Lagrangian algorithm. The numerical analysis did not fully support the experimentally-derived hypothesis regarding primary ring compression arising as a result of convergence of packets of bi-helical vortex lines. Rather, Liu (2002) proposes that the flow mechanism underlying features identified experimentally by Lim (1989) is more similar to the hypothesis of Verzicco and Orlandi (1994) with fluid migrating away from the point of first impact with the wall.

The more recent study of Cheng et al. (2010) provides a systematic numerical analysis of an isolated vortex ring impacting a flat wall across a range of angles of incidence and Reynolds numbers. The comprehensive analysis quantified the effects of both impact angle and Reynolds number on the evolution of the flow structures during oblique wall impacts, and three flow regions were identified. The first was for low Reynolds numbers\(^1\) (<100) where secondary vortex rings were not observed; the primary ring dissipated without generating additional vortical structures. The second flow region was defined as moderate Reynolds numbers (>100) and small angles of incidence (0° ≤ θ < 20°). In this region secondary vortex rings were generated during the vortex-wall interaction, and at higher Reynolds numbers tertiary rings were also observed. The interactions between primary and secondary vortex rings caused azimuthal instabilities in the secondary ring, resulting in the development of small, "hairpin-like" vortex structures. It is noted that the essential features of the flow were not altered due to the asymmetry associated with the non-zero angle of incidence. The third region of flow, categorised as moderately high Reynolds numbers, though not explicitly defined, and high angles of incidence (θ > 20°), resulted in a vorticity gradient being generated across the diameter of the vortex ring between the end of the ring in closest proximity to the wall, and the end of the ring furthest away. In this case the structure of the secondary vortex wrapped around the primary vortex and both structures bounced off the wall before a tertiary vortex could be generated. At large angles of incidence, not explicitly defined, the large vorticity gradient generated across the primary vortex diameter resulted in break-up of the primary structure upon impact with the wall.

For the case of multiple vortex rings impacting a wall, the work of Ghosh and Baeder (2011) is one of the few examples available in literature. The study sought to numerically

\(^1\)Where Cheng et al. (2010) define Reynolds number based on the translational speed of the vortex ring and its initial radius: \(Re = \frac{2\omega r_0}{v}\)
investigate two types of multi-vortex behaviour at $\theta = 0^\circ$. The first was the phenomenon known as "leapfrogging" (refer Cheng et al. (2015)), which occurs between co-rotating vortex rings in free space, and the second was the interaction of multiple vortex rings with a wall. Of greatest interest to this study is the latter, whereby a constant succession of vortex rings approached a wall, which can be considered an approximation to a rotor wake. Two test cases are presented in the work of Ghosh and Baeder (2011), both at a circulation-based Reynolds number$^2$ of 1250. The first examined an initial separation between rings of a single vortex radius, the second a separation distance of half the vortex radius. In both cases it was observed that the primary vortex structures at the wall were pushed radially outwards by the trailing vortex. The trailing vortex also interacted with the trajectory of the secondary vortices at the wall. Diffusion and the interaction between opposing velocity fields of the successive vortex rings was also seen to result in core distortion and tearing of the secondary vortex structures. The available literature did not include the following, which are of interest to this study.

- Analysis of interaction between vortex rings and solid surfaces at higher Reynolds numbers. Detailed analysis available in literature focuses on low and moderate Reynolds numbers (100-500), with very few studies including Reynolds numbers greater than 1000. Of these studies, the higher Reynolds number test cases are not discussed in the same detail as those at lower Reynolds numbers. In this study Reynolds numbers of 585 and 1170 are used to compare and contrast the interaction between vortex rings and solid surfaces.

- Interaction between two vortex rings and oblique solid surfaces. Oblique interaction between vortex rings and solid surfaces is more comparable to the helical wake generated by a helicopter rotor. Although it remains a significant simplification to the full-scale wake, investigation of oblique impacts can provide insight into fundamental flow structures present during vortex-wall interactions.

- The wall shear stress distribution and the change in wall-normal flow conditions during the impact of vortex rings with solid surfaces. The agitation of ground-based particles and subsequent uplift is the issue underlying brownout. The wall shear stress distribution and the geometry of wall-normal flow structures can aid in interpretation of conditions likely to lead to particle agitation and uplift.

$^2\text{Re}_\Gamma = \frac{\Gamma}{\nu}$
Figure 2.1 Bi-helical vortex lines as described by Lim (1989): arrows indicate vorticity vectors. Image (a) shows the vortex ring, image (b) shows the vortex ring as it moves in closer proximity to the wall, image (c) the vortex lines closest to the wall winding around the circumferential axis of the vortex ring at a faster rate than those further from the wall, and images (d) - (f) show the propagation of the bi-helical vortex lines.
2.2 Objectives

To further the analysis and understanding of vortex ring interactional behaviours in more complex environments, this study first seeks to replicate the single vortex ring findings of Cheng et al. (2010) before assessing the case of multiple vortex rings at $\theta = 0^\circ$ and $\theta = 20^\circ$. Of particular interest are the ring-ring interactions initiated after oblique impact with a no-slip surface, and the subsequent effect on flow conditions at the wall. The simulations aim to:

- identify the effect of Reynolds number on the flow field,
- identify the effect of oblique impacts on flow conditions near the wall, and
- investigate the vortex-vortex interaction, in addition to the vortex-wall interaction, for the case of two vortex rings.
2.3 Numerical Model

2.3.1 Governing Equations and Numerical Approach

This study was undertaken using the open source CFD software OpenFOAM\(^3\) (refer Weller et al. (1998)), release 2.3.x. The full Navier-Stokes equations for incompressible flows were solved in the computational domain, which consists of the conservation of mass,

\[
\nabla \cdot \mathbf{u} = 0,
\]

and the conservation of momentum,

\[
\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \mathbf{u}) = -\frac{1}{\rho} \nabla p + \nabla \cdot v \mathbf{D}_{\text{MS}} + \mathbf{F},
\]

where the divergence \( \mathbf{C} = \nabla \cdot (\mathbf{u} \mathbf{u}) \) is the convective term, \( \mathbf{P} = -\frac{1}{\rho} \nabla p \) is the pressure gradient term, \( \mathbf{D}_{\text{MS}} = \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \) is the rate-of-strain tensor, \( v \) is the kinematic viscosity, and \( \mathbf{F} \) is the explicit body force term. The divergence of the rate-of-strain tensor \( \nabla \cdot v \mathbf{D}_{\text{MS}} \) is also known as the viscous diffusion term. Taking the divergence from both sides of equation 2.2 leads to the Poisson equation for pressure,

\[
\nabla^2 p = -\nabla \cdot \mathbf{C}.
\]

The system of Partial Differential Equations (PDE) is solved using the standard Pressure Implicit with Splitting of Operator (PISO) algorithm, refer Ferziger and Peric (2002), available in the standard OpenFOAM distribution. The flow simulation is advanced in time using the implicit second order accurate backward differencing scheme. The time increment is chosen to maintain the Courant number below unity during the simulation. The Finite Volume Method (FVM) is used to spatially discretise the convective and diffusive terms in the governing equations. Using this method, the solution domain is divided into a set of discrete volumes (or cells) \( \delta V_i \) which fills the entire domain without overlap. Solutions to the governing equations are then sought for each of these discrete volumes at each time step. Using the FVM, the convective term is discretised using Gauss divergence theorem as follows:

\[
\nabla \cdot (\mathbf{u} \mathbf{u}) = \sum_f \varphi_f \mathbf{u}_f,
\]

where \( \varphi_f = \mathbf{u}_f \cdot \mathbf{S} \) is the convective flux through each control volume bounding face \( f \), and \( \mathbf{S} \) is the face area normal vector. The convective flux term is evaluated explicitly based on

\(^3\)http://www.openfoam.com [March 2017]
the solution at the current time step. The central differencing scheme is used to interpolate the cell-centred velocity to the face centre. The diffusive terms in both the momentum and Poisson equations can be expressed as a divergence of a gradient term which expands out to a second order Laplacian term. For example, the simplified viscous diffusion term can be discretised using the Gauss divergence term theorem as follows:

\[ \nu \nabla^2 \mathbf{u} = \sum_f \nu \mathbf{S}_f \cdot (\nabla \mathbf{u})_f, \]  

(2.5)

where the term \( \mathbf{S}_f \cdot (\nabla \mathbf{u})_f \) is called the diffusive flux and is evaluated based on the velocity gradient at each face. The central differencing scheme is again used to interpolate the velocity gradient evaluated at the cell centres to the face centre. Using the FVM, the discretised equations, including the time derivative, are assembled into a linear system of equations, which can be described in a matrix form as follows:

\[ [\mathbf{A}] \cdot \mathbf{u} = \mathbf{B}, \]  

(2.6)

where matrix \([\mathbf{A}]\) is a sparse block matrix containing the set of coefficients arising from the discretisation process, vector \(\mathbf{u}\) is the solution vector, and vector \(\mathbf{B}\) contains the pressure gradient term, body force term and the boundary conditions. The linearised system of equations (2.6) are solved for a set of boundary conditions using the Preconditioned Bi-Conjugate Gradient Method (PBiCG). A Diagonal Incomplete L-U decomposition method is used to precondition matrix \([\mathbf{A}]\) to minimise computational cost. The coupling between the momentum and pressure equations are solved using a segregated approach employed in the PISO algorithm. Please refer to Ferziger and Peric (2002) for full discussion of the PISO algorithm and PBiCG method.

### 2.3.2 Vortex Ring Initialisation

The vortex ring is initialised in the flow field by introducing a time-dependent body force term \( \mathbf{F} \) in equation 2.2 at the start of the simulation. A vortex ring model based on the equations developed by Sullivan et al. (2008) has been used in this study. Sullivan et al. (2008) develop their vortex ring model based on experimental parameters and the so-called "slug model". The slug model, as described by Didden (1979), assumes a cylindrical "slug" of fluid is ejected from a vortex generator with a velocity \( u_0 \) at the exit, which then rolls up to form a vortex ring. The flux of vorticity at the nozzle forms the basis for the slug model.

The experiment parameters used by Sullivan et al. (2008) to determine vortex characteristics are based on a piston-nozzle arrangement and require the definition of the following
variables:

\(l_{\text{piston}}, t_{\text{piston}}\): piston stroke length and stroke time

\(r_{\text{nozzle}}\): radius of the nozzle

From these inputs the following relationships are defined; radius of the vortex ring

\[
 r_{\text{vortex}} = \sqrt[3]{\frac{3r_{\text{nozzle}}^2l_{\text{piston}}}{4\gamma}}, \tag{2.7}
\]
circulation of the vortex ring,

\[
 \Gamma = \frac{r_{\text{nozzle}}^2l_{\text{piston}}^2}{r_{\text{vortex}}^2}, \tag{2.8}
\]
and ejection impulse from the piston

\[
 I = \rho \Gamma \pi r_{\text{vortex}}^2. \tag{2.9}
\]

These derived relationships, although empirical, emphasise the key role of the vortex formation process with respect to vortex characteristics but cannot be applied to test cases where the formation number, defined as \(L/2r_{\text{nozzle}}\), is greater than 4. The momentum source term \(F_{\text{MS}}\) is derived based on the ejection impulse \(I\) per unit control volume and is implemented in a pre-defined cylindrical region of radius \(R_{\text{nozzle}}\), which has a thickness of one cell. This zone is called the vortex initialisation region, and represents the local region over which the momentum source is applied. The model assumes that the momentum imparted to the fluid by the piston movement is approximately equal to the impulse of the ring. The piston movement is modelled incrementally based on the simulation time step:

\[
 \Delta l_{\text{piston}} = u_{\text{piston}} \times \Delta t_{\text{sim}}, \tag{2.10}
\]
where \(\Delta l_{\text{piston}}\) refers to the incremental movement of the virtual piston, and \(\Delta t\) is the simulation time step. The incremental value of \(L_{\text{piston}}\) is then used to calculate the radius of the vortex ring, as per equation 2.7 and then the vortex ring circulation, as per equation 2.8. Thus, the momentum source \(F_{\text{MS}}\) during the formation of the vortex ring is given as:

\[
 F_{\text{MS}} = \sum_i \frac{1}{\delta V_i} (\rho_i \Delta \Gamma \pi \Delta r_{\text{vortex}}^2) \cdot \mathbf{x}_i, \tag{2.11}
\]
where the subscript $i$ represents the index of the cells included in the vortex ring initialisation region, $\hat{x}$ is a unit vector in the direction of the vortex ring travel, and the symbol $\Delta$ indicates the cumulative result based on the current simulation time step. The source term $\mathbf{F}_{MS}$ ceases to exist when $\Delta l_{piston} = l_{piston}$ and $time = t_{piston}$. The use of a momentum source to establish the vortex ring proves a suitable technique for vortex ring initialisation, ostensibly negating the requirement for direct modelling of a vortex generator. Furthermore, the technique offers the benefit of allowing the physics involved in the vortex ring formation to be captured when solving the governing equations.

Dimensionless parameters for time $t_{ND}$, velocity $u_{ND}$, vorticity $\omega_{ND}$ and wall shear stress $\tau_{ND}$ are defined as follows:

\[
t_{ND} := \frac{(t - t_1)}{r_1}, u_{ND} := \frac{u}{u_1}, \omega_{ND} := \frac{\omega}{\omega_1}, \tau_{ND} := \frac{\tau}{1/2 \rho u_1^2}.
\] (2.12)

In order to account for the differing mesh geometries arising from inclination of the wall plane, the initial conditions were set to the point at which the vortex centre point was $2.75R_{vortex}$ from the ground plane. This yields $t_1, r_1, u_1$ and $\omega_1$ as initial values for time, vortex radius, velocity and vorticity. For consistency with literature the definition of Reynolds number (refer equation 2.13) includes values of $u_0$ and $r_0$, which represents the translational speed and radius of the vortex ring at the point of formation. These values are illustrated schematically in figure 2.2.

\[
Re = \frac{2u_0r_0}{v}.
\] (2.13)

Strouhal number is defined as:

\[
St = \frac{f_{vortex}r_0}{u_0},
\] (2.14)

where $f_{vortex}$ is the vortex ring generation frequency. Distances presented in x, y and z are normalised by $r_0$ to yield $X_{ND}, Y_{ND}$ and $Z_{ND}$.
2.3.3 Computational Setup

The computational domain is a rectangular box of size $20r_{vortex} \times 20r_{vortex}$ in the wall-parallel direction, and $15r_{vortex}$ in the wall-normal direction, as shown in figure 2.3. The domain was meshed using non-uniformly spaced structured hexahedral Cartesian grid as shown in figure 2.4. The grid expansion ratio in the x-z plane was 2.5 and no expansion was applied in the y-direction. The grid points in the three cardinal directions are 374, 374 and 155 respectively for the case where the wall angle is zero ($\theta = 0^\circ$). The final mesh comprised of a total of 21 million computational cells, increasing to 40 million when the domain size was increased to account for the inclined wall ($\theta = 20^\circ$). A symmetry boundary condition was applied to all domain boundaries, except the wall boundary which was modelled as a no-slip boundary. Numerical artefacts were not observed at the domain boundaries and analysis of vortex characteristics such as circulation, propagation velocity and vorticity indicated that the domain size was appropriate for the test conditions. The analysis of Cheng et al. (2010), Liu (2002) and Orlandi and Verzicco (1993) also show that the effect of finite domain size is negligible when the domain dimensions are greater than $10r_{vortex}$. 

![Figure 2.2 Parameters for non-dimensionalization](image-url)
For each test case the vortex rings were initialised at a distance no greater than $5r_{vortex}$ from the wall on a symmetrical mesh with zero skew, and allowed to fully develop across a distance of approximately $1.5r_{vortex}$. For the test cases with an inclined wall, a second mesh zone was introduced to model the angled boundary, which introduced skew in the axial direction. Analysis of the vortex characteristics as compared to results generated using a straight mesh showed only minor differences in vortex geometry and propagation velocity (<5%). As such, the elevated numerical error introduced by the skewed mesh is not deemed significant.

A mesh resolution study was undertaken with the numerical model set to match the experiment conditions of Chu et al. (1995), at $\theta = 0^\circ$ and $Re \approx 1000$. Results are shown in figure 2.5, with Mesh A representing approximately 3 million cells, Mesh B 13 million cells and Mesh C 32 million cells. The increasing mesh resolution increased the accuracy of the result.
with the obvious cost of computational time. The CPU time for Mesh A was 96 hours, Mesh B 224 hours and Mesh C 480 hours\textsuperscript{4}. In all cases the simulation time-step was set to maintain a Courant number less than 1.

Vortex geometry, peak vorticity and propagation velocity were compared between each mesh resolution. The vortex propagation and radial expansion upon contact with the wall can be seen in figure 2.5. Taking into account the practical cost to computational time and accuracy of results as compared to experiment data, a mesh resolution halfway between Mesh B and Mesh C was chosen.

\textbf{Figure 2.5} Vortex core trajectory of wall impact at $\theta = 0^\circ$

\textsuperscript{4}Using 32 cores from a system equipped with Opteron 6282SE CPUs (2.6GHz)
2.4 Validation

In order to validate the implementation of the Sullivan equations a number of test cases were investigated using the momentum source vortex model implemented within OpenFOAM. The first was a comparison against the data presented by Dabiri and Gharib (2004), where vortex measurements were captured using time-resolved PIV and the vortex trajectory was identified from the location of peak vorticity. The vortex was generated in a water tank using a piston arrangement and allowed to propagate without impediment. Given the detailed description of experiment procedure and parameters provided by the authors, the test conditions were straightforward to replicate with the momentum source vortex model. Comparison was made against the baseline test case, where the vortex generator was set to a formation number\(^5\) of 2.

Presented in figure 2.6 is the trajectory of the vortex ring as measured by Dabiri and Gharib (2004), along with the OpenFOAM simulation result. The OpenFOAM data does not include the initial stages of simulation when the momentum source is active, as it effectively represents the vortex mid-formation. As such, the numerical results are effectively allowed a settling time, with initial conditions taken at the point at which the momentum source ceases to drive the flow. Figure 2.6 shows that there is good agreement between the simulation and experiment results, with a similar trend for the vortex propagation rate. The percentage difference between curves in the initial stages is approximately 33%, decreasing to 2.8% at the end of the OpenFOAM simulation.

A comparison was also undertaken between the vorticity results of the Dabiri and Gharib (2004), baseline test case (formation number = 2), and the OpenFOAM vortex model. Shown in 2.7 is the vorticity profile of the vortex ring at experiment time \(t=3.54s\) (3.6s for the OpenFOAM simulation). As can be seen there is good agreement in both the trend and magnitude of results. An interesting point to note is the asymmetry in the vorticity peaks of the experiment results. It would be expected that a vortex ring generated under ideal conditions, without any asymmetry in its formation and clear of any influence from test section walls / free surfaces, should have symmetry in the magnitude of its vorticity. The OpenFOAM results yield the expected symmetry, however it is difficult to ascertain the root cause of the discrepancy in the experiment results. The issue is not explicitly mentioned by the authors, although it is likely the asymmetry is due to the inherent difficulty of precise measurement, coupled with typical experiment errors introduced by the vortex generator. The innate instability of vortex ring structures also compounds the issue as features such as Kelvin Waves can make vortex core measurements difficult. When considering peak values presented in figure 2.7, the difference in the "positive" vorticity peak is 0.84%, but this increases to 14.5% for the "negative" peak.

\(^5\)Formation number is defined as \(l_{\text{piston}}/d_{\text{cylinder}} = 2\), where \(l_{\text{piston}}\) refers to the total piston stroke length and \(d_{\text{cylinder}}\) is the cylinder exit diameter.
2.4 Validation

Figure 2.6 Vortex trajectory comparison against the results of Dabiri and Gharib (2004)

Figure 2.7 Vorticity profile comparison against the results of Dabiri and Gharib (2004)

An additional parameter which can be used to compare the experimental results of Dabiri and Gharib (2004), with the OpenFOAM vortex model, is by calculating circulation from the vorticity plots. In order to estimate circulation from the vorticity graphs presented in figure 6a of Dabiri and Gharib (2004), it is possible to integrate the area under the curve. Only one half of each graph is considered at a time, as the opposing signs of the vorticity peaks will
ostensibly lead to a net result of zero. For the results presented in figure 2.7, the percentage difference in circulation was 1.11% for the "positive" peak, and 1.2% for the "negative" peak. This results confirms the good correlation between the OpenFOAM vortex model and the experiment results of Dabiri and Gharib.

Presented in Figure 2.8 is a comparison of the vortex propagation velocity decay. Three data sets are presented: that of Dabiri and Gharib (2004), Maxworthy (1977) and the OpenFOAM model. A logarithmic decay is expected for the vortex propagation velocity, and all three data sources show such behaviour. The original work presented by Maxworthy (1977) predicted a -1 power-law decay in the vortex ring propagation velocity. This trend is not matched by the experimental data for Dabiri and Gharib, with the authors noting this is likely due to differences in the experiment setup. Similarly, the OpenFOAM result does show logarithmic decay, but it is more similar to the trend of Dabiri and Gharib than the -1 power-law decay of Maxworthy (1977). The slope of the curve for the test case of Dabiri and Gharib (2004) is -0.29, with the OpenFOAM curve slope -0.17. With respect to the current validation task, the result of the OpenFOAM vortex model is considered reasonable in comparison to the experimental data.

Given the test cases of greatest interest to this study involve interaction with ground planes, validation was also undertaken against data from experiments that investigated the behaviour of vortices impacting surfaces. The first data set, taken from Chu et al. (1995), provided the
trajectory of the vortex core location with respect to a solid wall. OpenFOAM initial conditions were set up to match the Reynolds number\(^6\) of the experiment \((R_{ed} = 1000)\), and data was non-dimensionalised by the initial vortex diameter. Presented in Figure 2.5 is the comparison between the OpenFOAM vortex model and the data presented by Chu et al. (1995). There is good correlation to the profile of the vortex trajectory.

The second data set taken from experiments of vortex-surface interactions is that from Chu et al. (1993). The experiment looked to assess the interaction of vortices with free surfaces, in this case the water/air interface, as distinct from the wall model implemented in OpenFOAM. The vortex rings were generated in a water tank and moved vertically toward each surface. Both a solid surface and free surface were investigated, with the vortices generated within four diameters of the surface in order to maintain azimuthal stability. The vortex core trajectory results are only presented for the free surface (water-air) case, but despite this difference, there is very good correlation between results, as shown in Figure 2.9. Such a similar result despite the inherent difference to the OpenFOAM wall model is due to the fact there is only marginal differences in the effective boundary conditions when the water-air interface represents a difference in density of an order of magnitude. Further examination of the results presented by Chu et al. (1993) confirmed that very similar trends were observed when comparing vortex impacts between free- and fixed-surfaces. Qualitatively the flow structures were consistent and the deformation of the free surface as a result of the vortex impact was (at maximum) 3% of the vortex diameter. As such, although there are fundamental differences between the properties of the surfaces with which the vortex is colliding when comparing experiment and computational results, the differences at \(R_{ed} = 1000\) are not so significant as to negate the use of the data set for validation purposes.

\(^6\)Where Chu et al. Chu et al. (1995) define Reynolds number based on the translational speed of the vortex ring and its initial diameter: \(Re_d = \frac{U_{d0}}{v}\)
The OpenFOAM vortex model has been compared against three different experimental data sets. Good correlation was shown against the experiment results published by Dabiri and Gharib (2004), Chu et al. (1993) and Chu et al. (1995). All key trends demonstrated in literature were captured by the momentum source vortex model as implemented in OpenFOAM, indicating that the physics of each test case was appropriately replicated numerically. Overall the correlation between computational and experiment results was deemed sufficient.
2.5 Single Vortex Ring / Wall Interaction

When a single vortex ring approaches a wall with a wall-normal trajectory it begins to expand radially. The diameter of the vortex core shrinks, but increases in vorticity magnitude due to vortex stretching. A boundary layer is generated as a result of the induced radial flow due to the no-slip condition at the wall (refer Lim (1989)). The boundary layer at the wall grows and intensifies before eventually separating and generating what is known as the secondary vortex, which has an opposite direction of rotation to the vortex ring. Presented in figure 2.10 is an illustration of key flow features and critical points that develop as a vortex ring moves towards a wall.

The vortex ring is visualised by a \( \lambda_2 \) (refer Jeong and Hussain (1995)) iso-surface, and vorticity magnitude contour lines and the global velocity flow field trends are illustrated in the wall-normal direction. The global velocity flow field is characterised by the circulation distribution generated by the vortex ring, and results in a radially expanding flow at the ground plane that is then entrained upward and back toward the centre of the vortex ring. The saddle points highlight the change in direction of the flow field between the radially expanding flow and the far-field quiescent flow that is also entrained toward the vortex. The vorticity contour lines show the boundary layer being generated at the wall due to the proximity of the vortex ring.

Wall shear stress contour lines and direction of the wall shear stress distribution are also shown in figure 2.10. The degenerate bifurcation line (refer Perry and Chong (1987)) is coincident with the saddle points and shows the point of transition between the radially expanding flow and the far-field quiescent flow entrained toward the vortex. The shear stress distribution highlights the near-wall changes in flow conditions as vortex ring impinges upon the wall and the secondary vortex develops.

Figure 2.10 Key flow features and critical points as a vortex ring approaches a wall
2.5.1 Test Case Parameters

The vortex rings were generated at Reynolds numbers 585 and 1170, calculated as per equation 2.15, where $\nu$ is the kinematic viscosity of the fluid:

$$Re = \frac{2u_0r_0}{\nu}. \quad (2.15)$$

For the purposes of this study, $u_0$ and $r_0$ represent the initial state of the vortex ring corresponding to the time at which the momentum source is no longer active. All results have been non-dimensionalised in order to enable direct comparison between test cases. To enable direct comparison between test cases given the variation in the domain geometry for varying $\theta$, the vortex radius ($r_1$), translational velocity ($u_1$), vorticity ($\omega_1$) and simulation time ($t_1$) were measured when the vortex ring centre point was $2.75r_{vortex}$ from the wall (refer figure 2.2). Dimensionless parameters were subsequently defined for velocity ($u_{ND}$), vorticity ($\omega_{ND}$), shear stress at the wall ($\tau_{ND}$) and time ($t_{ND}$):

$$u_{ND} = \frac{u}{u_1}; \quad \omega_{ND} = \frac{\omega}{\omega_1}; \quad \tau_{ND} = \frac{\tau}{1/2u_1^2}; \quad t_{ND} = \frac{(t - t_1)u_1}{r_1}.$$
2.6 Orthogonal Impact of a Single Vortex Ring

For the case where $Re = 585$ and $\theta = 0^\circ$, the vortex structures are visualised in figures 2.11 and 2.12 using $\lambda_2$ iso-surfaces Jeong and Hussain (1995) and vorticity contour lines. Results show the vortex ring impinging upon the wall and the development of the secondary vortex, as described in section 2.5. Once separated from the wall the secondary vortex moves around the outside of the vortex ring (referred to as the primary vortex to distinguish it from the secondary structure) and upward, away from the wall. The primary vortex ring continues to move upward and expand radially after rebounding from the wall, before moving back toward the ground plane. Such motion is consistent with the results of Cheng et al. (2010) and Chu et al. (1995). Results also show the boundary layer at the wall continuing to develop under the influence of the primary vortex, as a tertiary vortex structure is initiated by the same mechanisms that generated the the secondary vortex (refer $t_{ND} = 4.40$).

The time evolution of the velocity flow field is presented in 2.13 and shows the interaction of the flow entrained by the vortex as it approaches the wall. The velocity flow field in the wall-normal plane shows consistency with the large-scale toroid-like structures outlined in Section 1.3.2. As the vortex ring approaches the wall the flow is pushed radially outward along the ground plane before turning upward and becoming entrained back toward the middle of the vortex.

Figure 2.14 shows wall-normal velocity contour plots sampled at $0.2r_{vortex}$ above the wall. It is the flow in this region which is likely to drive motion of ground-based particles. The wall-normal velocity components, visualised as both contour and surface plots, show the velocity component that contributes to the global recirculation of the flow. The wall-normal velocity contour plots of figure 2.14 highlight the regions where the flow is moving into the wall, a characteristic likely to promote agitation of ground-based particles, and regions where the flow is moving vertically away from the wall which is a condition likely to promote particle entrainment and recirculation. It should be noted that positive values of velocity indicate a direction away from the wall. Although the near-wall flow field is not dominated by the wall-normal velocity component, there is evidence of flow field trends that are consistent with the toroid flow structure outlined in Section 1.3.2. The surface plots of the wall-normal velocity, presented in figure 2.15, provide a topological perspective with the wall-normal velocity profile and highlights the velocity fields of opposing direction prevalent around the circumference of the vortex ring. The transition between positive and negative wall-normal velocity is relatively steep. As the vortex ring impact with the the wall progresses, the upflow away from the wall becomes more prevalent as the secondary structure is formed and the primary ring rebounds from the solid surface.

Shown in figure 2.16 is the distribution of shear stress magnitude at the wall. An isotropic
node (refer Delery (2001)) is located at the vortex ring centre point and as the vortex ring approaches the wall, degenerate bifurcation lines identify the switch in direction of the shear stress distribution at the wall, as introduced in figure 2.10. The outermost bifurcation line corresponds to the transition between radial flow along the wall and that being entrained back toward the centre of the vortex ring and is a result of changes in the boundary layer under the ongoing influence of the primary vortex. The secondary vortex is opposite in sign to the primary vortex ring and generates additional bifurcation lines in the wall shear stress distribution as it develops. The subsequent switching in flow direction between the middle and outer bifurcation lines shows the interactional effect between the flow following the primary vortex structure and that of the secondary vortex. From this result it is evident that the development of the boundary layer at the wall and subsequent ejection of a secondary vortex causes transient variation in the direction of the wall shear stress distribution.

\[
\begin{align*}
\text{Figure 2.11} & \quad \lambda_2 \text{ iso-surfaces single vortex ring: wall angle } \theta = 0^\circ, \text{ Re } = 585
\end{align*}
\]
Figure 2.12 $\lambda_2$ iso-surfaces with vorticity contours - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 585$
Figure 2.13  Wall-normal velocity field - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 585$
2.6 Orthogonal Impact of a Single Vortex Ring

Figure 2.14 Near-wall, wall-normal velocity contour plots - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 585$

$t_{ND} = 3.30$
$t_{ND} = 4.00$
$t_{ND} = 4.70$
$t_{ND} = 5.40$
$t_{ND} = 6.10$
$t_{ND} = 6.80$
Figure 2.16  Wall shear stress distribution - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 585$
2.6 Orthogonal Impact of a Single Vortex Ring

Figure 2.15  Near-wall, wall-normal velocity surface plots - single vortex ring: wall angle $\theta = 0^\circ$, Re = 585
The impact of a vortex ring with a flat wall at $Re = 1170$ shows similar mechanisms of wall-interaction for the case where $Re = 585$. The most significant effect of the increase in Reynolds number is the presence of azimuthal instability and its subsequent effects on both the primary and secondary vortex structures. Presented in figures 2.17 and 2.18 are $\lambda_2$ iso-surfaces and vorticity contour plots. Instead of generating a secondary vortex with a smooth toroidal structure, the azimuthally-varying structure of the primary vortex ring yields a secondary ring structure that quickly develops into so-called "hairpin loops" that wrap around the primary vortex structure. Such hairpin-like structures results are also reported by Lim (1989), Verzicco and Orlandi (1994), and Cheng et al. (2010). Once the secondary vortex structure has developed the hairpin-like structures, interaction with the primary vortex ring fluctuates azimuthally, further increasing the azimuthal variation of vorticity. Despite the azimuthal variation in the geometry of both primary and secondary vortex rings, the development of the core structure is consistent with results at $Re = 585$. Approaching the wall the vortex core is circular, but once vortex stretching mechanisms have begun as a result of wall interaction, the core first becomes elliptic and before transitioning to a teardrop profile during interaction with the secondary vortex structure.

Presented in figure 2.19 is the development of the global velocity flow field. Radially expanding flow is entrained back towards the core of the primary vortex in a manner consistent with global flow recirculation. The flow pattern generated by the secondary vortex is confined to the region close the structure, and yields flow opposing the direction of the primary vortex circulation. This counter-rotating flow produces greater variation in flow direction inboard of the vortex cores, but the recirculation associated with the primary vortex dictates the global motion of the radial flow.

The wall-normal velocity near to the wall is presented as a contour plot in figure 2.20. With an increase in Reynolds number the azimuthal variation in the velocity flow field is clearly evident in both flow directions. The circumferential fluctuation in the vortex ring structure manifests as azimuthal variation in the wall-normal velocity component. As the primary and secondary vortex rings break down, the peak wall-normal velocity components are greater than for $Re = 585$. The interaction between the primary and secondary vortex structures can be seen in the discontinuities that develop around the circumference of the vortex ring as the secondary structure develops hairpin loops. The wall-normal velocity surface plots presented in figure 2.21 provide topological visualisation of the variation in azimuthal peak values around the circumference of the vortex ring. The fluctuations in the peak values around the circumference of the vortex ring are consistent with the azimuthal instability introduced by the increase in Reynolds number.

The wall shear stress distribution, and associated flow features, are shown in figure 2.22
and are consistent with the results seen at $Re = 585$ but with increased azimuthal fluctuation. The centre of the vortex ring can be identified by a node and the degenerate bifurcation lines show the position where the direction of the wall shear stress distribution changes. As the vortex ring’s impact with the wall progresses, additional bifurcation lines identify the region associated with development of the secondary vortex. As the vortex ring structures break down, there is increased asymmetry in the wall shear stress distribution, which is indicative of conditions likely to agitate ground-based particles.

![Diagram of vortex ring structures](image)

*Figure 2.17* $\lambda_2$ iso-surfaces single vortex ring: wall angle $\theta = 0^\circ$, $Re = 1170$
Figure 2.18 $\lambda_2$ iso-surfaces with vorticity contours - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 1170$
2.6 Orthogonal Impact of a Single Vortex Ring

Figure 2.19  Wall-normal velocity field - single vortex ring: wall angle θ = 0º, Re = 1170

\[ t_{ND} = 3.30 \]
\[ t_{ND} = 3.90 \]
\[ t_{ND} = 4.70 \]
\[ t_{ND} = 5.25 \]
\[ t_{ND} = 6.10 \]
\[ t_{ND} = 6.60 \]
**Numerical Study of Vortex Ring / Wall Interactions**

\[ t_{ND} = 3.30 \]

\[ t_{ND} = 3.90 \]

\[ t_{ND} = 4.70 \]

\[ t_{ND} = 5.25 \]

\[ t_{ND} = 6.10 \]

\[ t_{ND} = 6.60 \]

*Figure 2.20* Near-wall, wall-normal velocity contour plots - single vortex ring: wall angle \( \theta = 0^\circ \), \( Re = 1170 \)
2.6 Orthogonal Impact of a Single Vortex Ring

Figure 2.21  Near-wall, wall-normal velocity surface plots - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 1170$
Numerical Study of Vortex Ring / Wall Interactions

$t_{ND} = 3.30$

$t_{ND} = 3.90$

$t_{ND} = 4.70$

$t_{ND} = 5.25$

$t_{ND} = 6.10$

$t_{ND} = 6.60$

Figure 2.22  Wall shear stress distribution - single vortex ring: wall angle $\theta = 0^\circ$, $Re = 1170$
As a preliminary approximation to the toroid flow structure generated by a rotor wake the interaction of a single vortex ring with a wall yields the following trends, which are outlined in figure 2.23. As the vortex ring approaches the solid surface (a), the direction of the flow near the wall is predominantly into the wall and parallel to the wall as the recirculating flow is driven along the ground plane. During impact with the wall (b) the upflow increases in magnitude, subsequently increasing the magnitude of the recirculating flow. As the primary vortex structure rebounds and moves away from the wall (c), the magnitude of the upflow and radial flow near the wall are of similar magnitude.

*Figure 2.23 Orthogonal impact of a single vortex ring with a solid surface: key flow directions*

Analysis of the flow near to the wall shows characteristics likely to lead to agitation and potential entrainment of ground-based particles, namely the outflow and upflow generated as the ring makes first contact then rebounds. The increase in azimuthal fluctuation seen with increase Reynolds number is also a feature likely to promote the agitation of ground-based particles. The transient variation in the wall shear stress distribution is further evidence of the increase in azimuthal fluctuation which would lead to increased agitation of ground-based particles.
2.7 Oblique Impact of a Single Vortex Ring

The impact between a vortex ring and an inclined solid surface may be considered representative of simplified rotor wake flow structures. As presented in Section 1.2, the rotor wake downwash is helical (refer figure 1.1), which may be modelled at a basic level as a series of discrete vortex rings. Taking into account the typical pitch of the rotor wake, which for a medium size troop lift helicopter is around 12-15°, refer Bourne et al. (2014a), along with the results of Cheng et al. (2010) which indicated that at wall angles up to 20° primary, secondary and tertiary vortex structures could develop, the ground plane was inclined by 20°. For the case of oblique impacts the vortex ring is considered less an approximation to the global flow field structure, and more a representation of how structures within the rotor wake may interact with the ground plane.

When the ground plane is inclined to \( \theta = 20° \), one side of the vortex ring impacts the wall before the other causing asymmetry in both the vorticity of the core, and also the subsequent evolution of the major flow structures. Presented in figures 2.24 and 2.25 are \( \lambda_2 \) iso-surfaces overlaid with the vorticity magnitude contours calculated along the vortex midline. It can be seen that rather than being uniformly distributed around the primary vortex core, the secondary vortex is initialised at the point of first impact, which then grows into a circular structure that evolves alongside the progression of the impact of the primary vortex ring with the wall. This is consistent with the underlying mechanism driving creation of the secondary vortex, insofar as the boundary layer at the wall only separates to form the secondary vortex once sufficient energy is imparted from the primary vortex ring.

There is discernible skew in the motion of the secondary vortex with respect to the primary vortex structure. The contact and rebound from the wall of the primary vortex occurs at a different rate to the development of the secondary vortex, and as such the core of the secondary vortex is not aligned with the core of the primary vortex during its development. This accentuates the changes in core geometry of the primary vortex as it undergoes vortex stretching and radial expansion, as the influence of the secondary vortex is not symmetric. Unlike the orthogonal impact at \( \theta = 0° \), the structure of the primary vortex ring warps azimuthally in response to the oblique wall impact.

The evolution of velocity in the wall-normal plane is shown in figure 2.26. The oblique impact significantly changes the global flow field as the fluid entrainment pattern of the radial flow becomes dominated by the low-side outwash moves upward and above the vortex ring centre point before moving back downward to the high-side of the vortex ring. Only a small percentage of the outwash moves up along the wall, with the majority being quickly re-entrained by the high-side vortex structure.

With the ground plane inclined to \( \theta = 20° \), the progressive nature of the impact of the
vortex ring is clearly evident from the wall-normal velocity contour plots presented in figure 2.27. The wall-normal velocity component shows azimuthal variation in peak values as the primary structure interacts with the wall. The wall-normal velocity surface plots, presented in figure 2.28, show the geometry of the azimuthal fluctuation and it is interesting to note that the peak velocity away from the wall is greater than the peak velocity into the wall at the vortex structures break down.

The distribution of wall shear stress magnitude for $\theta = 20^\circ$ is shown in figure 2.29 and is markedly different from the case of an orthogonal impact. Given the asymmetry of the vortex ring contact with the wall, the shear stress distribution is not symmetrical as the vortex impact progresses. Unlike the distribution seen in figure 2.16 for $\theta = 0^\circ$ the shear stress magnitude generated during an oblique impact yields two node points, the first located at the centre point of the primary vortex, the second at the interface between the primary and secondary vortex structures (refer $t_{ND} = 3.00$ and $t_{ND} = 3.70$). The outboard node is a consequence of the skew in the alignment between the primary vortex and the secondary vortex, which results in the low-side of the secondary vortex sustaining a higher vorticity magnitude in closer proximity to the ground plane when compared to the high-side (refer figure 2.24, $t_{ND} = 4.20$). The non-uniform distribution in vorticity is also highlighted by the geometry of the bifurcation lines. At the high-side the boundary layer is weaker than the low-side given the evolution of secondary vortex is further progressed than for the low-side. This feature is in opposition to the vorticity gradient sustained by the primary vortex ring, but shows that the near-wall flow characteristics are dominated by the behaviour of the boundary layer, which is to be expected.
Figure 2.24 \( \lambda_2 \) iso-surfaces single vortex ring: wall angle \( \theta = 20^\circ \), \( Re = 585 \)
2.7 Oblique Impact of a Single Vortex Ring

\[ t_{ND} = 2.05 \]
\[ t_{ND} = 2.30 \]
\[ t_{ND} = 3.00 \]
\[ t_{ND} = 3.70 \]
\[ t_{ND} = 4.35 \]
\[ t_{ND} = 5.05 \]
\[ t_{ND} = 5.70 \]
\[ t_{ND} = 6.40 \]
\[ t_{ND} = 7.10 \]

**Figure 2.25** $\lambda_2$ iso-surfaces with vorticity contours - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 585$
$t_{ND} = 2.05$

$u_{ND}$

$t_{ND} = 2.30$

$u_{ND}$

$t_{ND} = 3.00$

$u_{ND}$

$t_{ND} = 3.70$

$u_{ND}$

$t_{ND} = 4.35$

$u_{ND}$

$t_{ND} = 5.00$

$u_{ND}$

**Figure 2.26**  Wall-normal velocity field - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 585$
2.7 Oblique Impact of a Single Vortex Ring

$t_{ND} = 2.05$

$t_{ND} = 2.30$

$t_{ND} = 3.00$

$t_{ND} = 3.70$

$t_{ND} = 4.35$

$t_{ND} = 5.00$

*Figure 2.27* Near-wall, wall-normal velocity contour plots - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 585$
Figure 2.28 Near-wall, wall-normal velocity surface plots - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 585$
2.7 Oblique Impact of a Single Vortex Ring

Figure 2.29  Wall shear stress distribution - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 585$

$t_{ND} = 2.05$
$t_{ND} = 2.30$
$t_{ND} = 3.00$
$t_{ND} = 3.70$
$t_{ND} = 4.35$
$t_{ND} = 5.00$
Shown in figures 2.30 and 2.31 are the $\lambda_2$ iso-surface and vorticity contour plots for $Re = 1170$ at a wall angle of $\theta = 20^\circ$. The high-side impact initiates generation of the secondary vortex while the primary ring begins to rebound. During the progressive contact with the wall, the deformation seen in the $\lambda_2$ iso-surfaces of the primary vortex ring are indicative of vortex stretching and interaction with the secondary vortex. Similarly to the case at $\theta = 0^\circ$ the azimuthal instability propagates to hairpin vortices in the secondary vortex, a result which is consistent with the findings of Cheng et al. (2010) and Verzicco and Orlandi (1994). Both primary and secondary structures yield complex geometry post-impact and deteriorate rapidly. There is also a greater degree of interaction between the primary and secondary vortex structures than results at $Re = 585$.

The global velocity is presented in figure 2.32 and is similar to the result for $Re = 585$. As a consequence of the wall angle, the radial flow is skewed towards the high-side of the wall, with the radial flow from the low-side being entrained above the vortex core and toward the high-side of the primary vortex. The wall-normal velocity contour plots are presented in figure 2.33. Compared to the results at $Re = 585$, the asymmetry of the contour plots is amplified by the increase in azimuthal fluctuation resulting from the increased Reynolds number. The breakdown of the primary and secondary vortex ring structures, along with the development of the hairpin structures, yields peak wall-normal velocities greater than the results at $\theta = 0^\circ$. The wall-normal velocity component is presented as a surface in figure 2.34, which highlights the azimuthal fluctuation of the peak wall-normal velocity. As the hairpin structures develop and break down, the fluctuation becomes more localised as the minutiae of the degrading vortex structures define the key characteristics of the flow field.

As for the oblique wall impact at $Re = 585$ the wall shear stress distribution, presented in figure 2.35, shows the effect of flow field generated by the vortex ring structures. An isotropic node identifies the centre of the primary vortex ring, and asymmetrical bifurcation lines highlight the oblique nature of the impact. As for the case at $Re = 585$, a second node and additional bifurcation lines are generated at the secondary vortex ring progressively develops.

Overall, the results at both $Re = 585$ and $Re = 1170$ showed good consistency with the experimental work of Chu et al. (1995) and Liu (2002), and the numerical study of Cheng et al. (2010). The wall-normal pressure distributions presented by Cheng et al. (2010) enable a more complete understanding of the interaction between flow structures in the near-wall region, but such results do not enable full analysis of azimuthal variation in the flow. The shear stress magnitude distributions (presented in figure 2.29 and figure 2.35) provided insight into the azimuthal flow variation as a result of a single vortex ring impact. Although representing transient flow conditions the distribution of shear stress magnitude shows that flow direction at the wall is not uniform. The bifurcation lines show both radial and azimuthal variation in
2.7 Oblique Impact of a Single Vortex Ring

the flow direction, which can also be seen in the flow patterns of the near-wall velocity. Such transient variation is considered likely to lead to conditions conducive to brownout events.

\[
\begin{align*}
& t_{ND} = 1.65 & t_{ND} = 2.20 & t_{ND} = 3.00 \\
& t_{ND} = 3.55 & t_{ND} = 4.35 & t_{ND} = 4.90 \\
& t_{ND} = 5.70 & t_{ND} = 6.30 & t_{ND} = 7.10
\end{align*}
\]

*Figure 2.30* \(\lambda_2\) iso-surfaces single vortex ring: wall angle \(\theta = 20^\circ\), \(Re = 1170\)
Figure 2.31 λ₂ iso-surfaces with vorticity contours - single vortex ring: wall angle θ = 20°, Re = 1170
2.7 Oblique Impact of a Single Vortex Ring

Figure 2.32  Wall-normal velocity field - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 1170$
Numerical Study of Vortex Ring / Wall Interactions

$t_{ND} = 2.95$

$t_{ND} = 3.50$

$t_{ND} = 4.35$

$t_{ND} = 4.90$

$t_{ND} = 5.70$

$t_{ND} = 6.25$

Figure 2.33  Near-wall, wall-normal velocity contour plots - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 1170$
2.7 Oblique Impact of a Single Vortex Ring

Figure 2.34  Near-wall, wall-normal velocity surface plots - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 1170$
Figure 2.35  Wall shear stress distribution - single vortex ring: wall angle $\theta = 20^\circ$, $Re = 1170$
2.7 Oblique Impact of a Single Vortex Ring

2.7.1 Vorticity Evolution

Results presented by Cheng et al. (2010) show the temporal evolution of vorticity for \( Re = 100 \) and \( Re = 500 \). A similar analysis is presented in the top image of figure 2.36 for the change in peak vorticity at the primary vortex ring core at \( Re = 585 \) on approach to both the flat and inclined walls. The wall impact point for each curve is marked with an open circle. The trends shown in figure 2.36 are consistent with those presented by Cheng et al. and clearly identify the effect of the sloped wall. The wall-normal impact shows a symmetrical variation in the vortex ring vorticity. As the vortex ring approaches the wall vorticity increases, before decreasing post-impact. Maximum vorticity occurs as the secondary vortex ring is ejected form the boundary layer.

When \( \theta = 20^\circ \), the high-side impact causes a local increase in vorticity while the low-side of the primary vortex ring continues to decrease progressively until it reaches sufficient proximity to the wall to undergo vortex stretching. The high-side impact shows a sharper increase in vorticity, as is expected. The difference in peak vorticity after interaction with the inclined wall is a result of the vorticity gradient that is generated around the circumference of the primary ring. As noted by Lim (1989) and Cheng et al. (2010) a vorticity gradient occurs between the high-side and low-side of the vortex ring, strengthening the vorticity of the high-side at the expense of the low-side.

Cheng et al. (2010) do not present analysis of temporal velocity evolution for \( Re = 1000 \), and detailed discussion of their results at \( Re > 500 \) is limited. Presented in the lower image of figure 2.36 is the development of vorticity with time at \( Re = 1170 \), for both \( \theta = 0^\circ \) and \( \theta = 20^\circ \). The point of wall impact is marked by open circles. Due to the azimuthal fluctuations exhibited by the primary vortex ring, there is fluctuation in the vorticity of the ring as it approaches the ground plane. Although it does not appear that the instability is propagating in an azimuthal sense, the geometry of the structure varies and grows azimuthally. Despite the pre-impact fluctuation in vorticity, it is still possible to identify the change in vorticity as a result of wall interaction, as the increase is larger than the periodic variation. The fluctuation continues post-impact in both cases and is likely a result of the asymmetrical interaction between the primary vortex and the hairpin structures of the secondary vortex.

While the vorticity evolution for the wall-normal impact shows the expected symmetry, when \( \theta = 20^\circ \) there is an interesting result at \( t_{ND} = 3.80 \), the point marked by open black squares in the lower image of figure 2.36. The vorticity gradient generated around the circumference for a vortex ring as a result of an oblique wall impact is expected to yield an increase in vorticity at the high-side of the vortex, and a corresponding decrease at the low-side of the ring. In this case there is a simultaneous post-impact peak at both ends of the ring, a feature which can be attributed to a combination of the azimuthal vorticity fluctuation coupled with
the increased vorticity of the secondary vortex generated at the low-side impact point. Referring to the $t_{ND} = 3.80 \lambda_2$ iso-surface and vorticity contour plots in figure 2.31, it can be seen that strength of vortex core at the low-side does degrade more rapidly than the high-side, and conversely it can be seen that the low-side secondary vortex retains a higher amount of vorticity as the high-side portion of the structure begins to degrade to hairpin-like structures. It is this azimuthal variation that is a key driver in the peak fluctuations of the near-wall velocity flow fields and wall shear stress distributions.

![Figure 2.36](image_url)  
*Figure 2.36*  Time evolution of vorticity at the core of the primary vortex ring for $Re = 585$ (top) and $Re = 1170$ (lower)
When considering that a rotor wake may be approximated as a series of vortex rings, the analysis of Section 2.7 is extended to investigate the case of two vortex rings impinging upon a wall. The second vortex ring was generated at a separation distance equal to the radius of the lead vortex ring, which corresponds to a Strouhal number of 0.48. From the results of Cheng et al. (2015) it was determined that conditions of this study would result in vortex leapfrogging, whereby the trailing vortex (S2) would contract under the influence of the fluid entrainment of the lead vortex (S1) at the same time as the lead vortex is slowed by the induced velocity of the trailing vortex. If the two vortices are left to develop in quiescent fluid they eventually arrive at sufficiently close proximity to initiate a leapfrog motion, where the trailing vortex moves through the centre of the lead vortex. This study did not seek to investigate leapfrogging flow mechanisms, but focused on the interaction between the two vortex structures and the wall. The separation distance between vortex rings ($r_0$) ensured the trailing vortex would not leapfrog the lead vortex prior to wall impact. Identical source term parameters were used for both the lead vortex and the trailing vortex ring, and the contraction of the trailing ring under the influence of the lead vortex can be seen in the results.

At $Re = 585$ and $\theta = 0^\circ$, the interaction between primary and secondary vortices of both the lead and trailing vortex rings is visualised using both $\lambda_2$ iso-surfaces and vorticity contour plots, as shown in figures 2.37 and 2.38. The impact of the first vortex ring (S1) with the wall yields the same result as discussed in Section 2.7. A secondary vortex is formed as the primary ring impacts the wall, and the two structures then rebound. The impact of the trailing vortex (S2) with the wall follows the same flow mechanics in the initial phase, however the boundary layer remains energised from the first collision, which leads the trailing vortex to develop a more energetic secondary vortex. The proximity between the vortical structures of the leading vortex and those subsequently developed by the trailing structure results in interference and merging. The secondary vortex generated by the leading vortex is positioned above the associated primary structure as the trailing vortex impacts the wall. As such, both the lead vortex and the trailing vortex ring, and the contraction of the trailing ring under the influence of the lead vortex can be seen in the results.

Presented in figure 2.39 is the evolution of the global velocity flow field. It is evident that the flow structures generated by successive impacts of S1 and S2 yield a much more complicated flow pattern. The secondary vortex generated by S2 has the effect of reversing the recirculation direction of the expanding flow in the region outboard of the vortex core, and
the merged primary structure dominates the recirculation pattern inboard of the S2 secondary vortex.

Figure 2.40 shows the wall-normal velocity component and it can be seen that the presence of the trailing vortex S2 increases the magnitude of the velocity into the wall. The increase in peak velocity, as compared to the case of a single vortex ring, is a result of the proximity of the trailing vortex and its wake to the primary vortex structure. Presented in figure 2.41 are surface contour plots of the out-of-plane velocity, which show the transition from a single-peak to a double-peak profile as the trailing vortex approaches and impacts the wall (refer $t_{ND} = 3.90$ and $t_{ND} = 4.40$). The peak magnitude of the velocity component into the wall is greater than that away from the wall, however it does not show the same double-peak trend as for the velocity away from the wall. The effect of the trailing vortex is to concentrate the flow into the wall in the central region, but the interference between the S1 and S2 primary structures and the subsequent development of the boundary layer and secondary vortex structures generates a "ripple" in the peak velocities away from the wall. The wall shear stress distribution is shown in figure 2.42. The central isotropic node is consistent with results for a single vortex ring impact, however the impact of S2 has the expected effect of increasing directional changes in the wall shear stress distribution.
2.8 Orthogonal Impact of Two Vortex Rings

Figure 2.37 $\lambda_2$ iso-surfaces two vortex rings: wall angle $\theta = 0^\circ$, $Re = 585$

$t_{ND} = 2.50$

$t_{ND} = 3.00$

$t_{ND} = 3.30$

$t_{ND} = 3.85$

$t_{ND} = 4.40$

$t_{ND} = 4.70$

$t_{ND} = 4.95$

$t_{ND} = 5.50$

$t_{ND} = 6.10$
Figure 2.38 $\lambda_2$ iso-surfaces with vorticity contours - two vortex rings: wall angle $\theta = 0^\circ$, Re = 585
2.8 Orthogonal Impact of Two Vortex Rings

\[ t_{ND} = 3.30 \]
\[ t_{ND} = 3.90 \]
\[ t_{ND} = 4.40 \]
\[ t_{ND} = 5.00 \]
\[ t_{ND} = 5.20 \]
\[ t_{ND} = 6.10 \]

*Figure 2.39  Wall-normal velocity field - two vortex rings: wall angle \( \theta = 0^\circ \), Re = 585*
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$t_{ND} = 3.30$

$t_{ND} = 3.90$

$t_{ND} = 4.40$

$t_{ND} = 5.00$

$t_{ND} = 5.20$

$t_{ND} = 6.10$

Figure 2.40  Near-wall, wall-normal velocity contour plots - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 585$
2.8 Orthogonal Impact of Two Vortex Rings

![Near-wall, wall-normal velocity surface plots - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 585$](image)

**Figure 2.41** Near-wall, wall-normal velocity surface plots - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 585$
Figure 2.42  Wall shear stress distribution - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 585$
Presented in figures 2.43 and 2.44 are the $\lambda_2$ iso-surfaces and vorticity contour plots for $Re = 1170$ and $St = 0.48$. The increase in Reynolds number shows similar overall trends to those outlined in Section 2.6, most notably the increase in azimuthal fluctuation of vorticity in both the lead (S1) and trailing (S2) vortex. As for the case of a single vortex ring, the orthogonal impact of the S1 with the wall generates a secondary vortex structure that moves alongside and above the primary vortex. The S1 secondary vortex then contracts to a position inside the primary structure as the hairpin-like vortices develop. The presence of S2 maintains a larger amount of energy in the boundary layer at the wall, which results in the ejection of a tertiary vortex from the S1 impact. A weaker version of the same structure can be seen in the vorticity contour plots at $Re = 585$, refer figure 2.38, but there is insufficient energy in the boundary layer for the tertiary vortex structure to fully develop at the lower Reynolds number.

The impact of the S2 with the wall results in similar flow mechanisms as those described for $Re = 585$. With the boundary layer at the wall already energised from the impact of the S1, a stronger secondary vortex is generated by the primary structure of S2. This secondary vortex then merges with the tertiary vortex generated by S1, as shown at time $t_{ND} = 5.80$ in figure 2.44. The primary structures of both S1 and S2 are in close proximity as the S2 structures rebound from the wall, and they rapidly coalesce and merge. The secondary vortex generated by the S1 develops into hairpin vortex structures that interact with the merged primary structure. This interaction leads to degradation and decay of the primary structure. The vortex ring generated by the merge of the S1 tertiary vortex and the S2 secondary vortex moves alongside and above the primary structure, but it does not contract nor develop the hairpin vortices as per the S1 secondary vortex. Although azimuthal fluctuation is evident along the circumference of the ring, the interaction between the primary structure and the hairpin vortices constrain further development as the large scale structures in the flow field begin to degrade.

The evolution of the global velocity flow field, shown in figure 2.45, highlights the distortion in the flow field as a result of the increased azimuthal fluctuation. At $Re = 1170$ the recirculation of the radial flow is dictated by the merged primary vortex structure. Flow opposing this global motion is prevalent in local regions surrounding the secondary and tertiary structures. In particular, the degradation of the hairpin-like structures inboard of the primary structure leads to both radial and azimuthal fluctuation in the flow near the wall.

The wall-normal velocity components near to the wall are presented as contour plots in figure 2.46. Although there is consistency in the general trends seen for the result of a single vortex ring, the impact of two vortex rings increases the azimuthal variation in the velocity distribution. The development of the hairpin vortex structures can also be identified (refer $t_{ND} = 6.10$ and $t_{ND} = 6.60$), which correspond to higher peak velocities as the vortex structures of S1 and S2 interact and break down. Shown in figure 2.47 is the surface plot of the wall-
normal velocity component, which highlights the variation in azimuthal fluctuation and the concentration of flow into the wall near the vortex ring centre points. As the trailing vortex S2 impinges upon the wall, the double-peak in the velocity away from the wall is evident, as for the case at $Re = 585$. As the vortex structures break down the erratic fluctuation of the near-wall velocity field is clearly evident.

Presented in figure 2.48 is the wall shear stress distribution, which shows increased azimuthal variation when compared to the case of a single vortex ring. The trailing vortex yields an increased number of bifurcation lines as the primary and secondary structures interact (refer $t_{ND} = 5.25$). The increased fluctuation in the flow direction very close to the wall is indicative of conditions likely to lead to the agitation of ground-based particles.
2.8 Orthogonal Impact of Two Vortex Rings

$t_{ND} = 2.50$
$t_{ND} = 3.00$
$t_{ND} = 3.30$

$t_{ND} = 3.85$
$t_{ND} = 4.70$
$t_{ND} = 5.00$

$t_{ND} = 5.25$
$t_{ND} = 6.10$
$t_{ND} = 6.60$

Figure 2.43 $\lambda_2$ iso-surfaces two vortex rings: wall angle $\theta = 0^\circ$, $Re = 1170$
Figure 2.44 $\lambda_2$ iso-surfaces with vorticity contours - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 1170$
2.8 Orthogonal Impact of Two Vortex Rings

Figure 2.45  Wall-normal velocity field - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 1170$

$t_{ND} = 3.30$  
$t_{ND} = 3.90$  
$t_{ND} = 4.70$  
$t_{ND} = 5.25$  
$t_{ND} = 6.10$  
$t_{ND} = 6.60$
Figure 2.46  Near-wall, wall-normal velocity contour plots - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 1170$
2.8 Orthogonal Impact of Two Vortex Rings

Figure 2.47  Near-wall, wall-normal velocity surface plots - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 1170$
Figure 2.48 Wall shear stress distribution - two vortex rings: wall angle $\theta = 0^\circ$, $Re = 1170$
2.9 Oblique Impact of Two Vortex Rings

Presented in figures 2.49 and 2.50 are the $\lambda_2$ iso-surfaces and vorticity contour plots for $Re = 585$. The two vortices can be seen on approach to the wall, with the radius of the trailing vortex constrained by the wake of the lead vortex. Also evident is the wake structure of the trailing vortex. When a single vortex ring is generated, the wake structure is much weaker than the vortex ring itself and is typically not included in flow visualisation. For the case of two vortex rings, the constraint to the growth of the trailing vortex given its proximity to the lead vortex yields greater magnitudes of circulation, and hence a more energetic wake. This increased strength in the wake of the trailing vortex can be seen in the $\lambda_2$ iso-surface and vorticity visualisations, and is considered an inherent feature of the test case.

When the lead vortex, S1, impacts the inclined wall a secondary vortex is initiated at the high-side. The secondary vortex then progressively develops around the circumference of the lead vortex as the oblique interaction with the wall continues. By the time the primary vortex structure of the lead vortex has impinged upon the wall at the low-side, the secondary structure at the high side has moved around the above the primary structure. The oblique nature of the impact creates variation in the vorticity distribution around the circumference of both primary and secondary vortex structures. As the trailing vortex, S2, approaches the wall it interacts with the pre-energised boundary layer that persists from the interaction with the lead vortex. Owing to the interaction with the lead vortex wake, the trailing vortex has a smaller diameter and reduced vorticity upon impact with the wall. The trailing vortex does not persist as an individual primary structure; instead it rapidly merges with the primary structure of the lead vortex. The secondary vortex generated by S2 develops outside the merged primary vortex structure and does not directly interact with the secondary vortex of S1. The S1 secondary vortex retains its circumferential asymmetry as it develops, with the high-side of the structure collapsing back toward the ground plane.

The global velocity flow field is shown in figure 2.51 and is consistent with the general trend shown for the case of a single vortex ring. Rather than being entrained back toward the centre of the vortex, the flow expanding from the low-side is entrained toward the high-side of the vortex ring. This asymmetry is then further amplified as the trailing vortex, S2, impinges upon the wall. The wall-normal velocity contour plots are presented in figure 2.52. Compared the case of a single vortex ring, there is greater variation in the velocity near the vortex centre as the trailing vortex S2 impinges upon the wall and interacts with the structures of the lead vortex S1. The asymmetry in the wall-normal velocity components can be clearly identified in the surface plots of figure 2.53. Shown in figure 2.54 is the wall shear stress distribution. The impact of the trailing vortex acts to increase the number of bifurcation lines present in the wall shear stress distribution.
Figure 2.49 $\lambda_2$ iso-surfaces two vortex rings: wall angle $\theta = 20^\circ$, $Re = 585$
2.9 Oblique Impact of Two Vortex Rings

Figure 2.50 $\lambda_2$ iso-surfaces with vorticity contours - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 585$
Numerical Study of Vortex Ring / Wall Interactions

$t_{ND} = 2.55$

$t_{ND} = 3.00$

$t_{ND} = 3.30$

$t_{ND} = 3.70$

$t_{ND} = 3.95$

$t_{ND} = 4.35$

**Figure 2.51** Wall-normal velocity field - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 585$
Figure 2.52  Near-wall, wall-normal velocity contour plots - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 585$
Figure 2.53  Near-wall, wall-normal velocity surface plots - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 585$
2.9 Oblique Impact of Two Vortex Rings

Figure 2.54  Wall shear stress distribution - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 585$
Presented in figures 2.55 and 2.56 are the $\lambda_2$ iso-surfaces and vorticity contour plots for $Re = 1170$. The increase in Reynolds number sees an increase in the azimuthal distribution of vorticity around the circumference of both S1 and S2, and finer scale structures in the wake region. Similar flow mechanisms occur to the $Re = 585$ test case as the lead vortex impacts the inclined wall. A secondary vortex is asymmetrically generated as the impact of the primary structure progresses, and a tertiary structure also begins to form owing to the increased energy of the impact. As the secondary vortex develops it displays the characteristic hairpin vortices. At the high-side, the impact of the trailing vortex results in ejection of a secondary vortex from the boundary layer. The S2 primary structure quickly coalesces with the primary structure of S1. At the low-side the S2 impact yields a secondary vortex, but a combination of the slope of the wall and proximity to the disintegrating S1 structures means that the S2 structures stay in close proximity to the wall.

The global velocity flow field is shown in figure 2.57 and is consistent with the general trend shown for the case of a single vortex ring. Presented in figure 2.58 are the wall-normal velocity contour plots. The presence of S2 increases the asymmetry and azimuthal fluctuation of the velocity components. The development of hairpin vortices and the subsequent interaction between the structures generated by S1 and S2 can be identified from the peaks in the wall-normal velocity contours (refer $t_{ND} = 5.70 - t_{ND} = 7.10$). The double-peak feature in the flow away from the wall can be seen in the surface plots of figure 2.59 (refer $t_{ND} = 4.35$ and $t_{ND} = 4.90$), and is consistent with the results seen in Section 2.8. The peaks merge to form a single pronounced region of flow away from the wall before the S1 and S2 vortex structures degrade under the influence of the hairpin vortices. The wall shear stress distribution is shown in figure 2.60, and highlights both the asymmetry and azimuthal fluctuation generated by the impact of the trailing vortex.

For both test cases the interaction of two vortex rings with an inclined wall yields similar flow mechanisms to that of a single vortex. The oblique impact generated asymmetry in both the primary and secondary structures, and there was significant interaction between flow structures at both the high- and low-side impact points. The increase in Reynolds number had the effect of increasing the variation in azimuthal distribution of vorticity. Although a larger number of individual flow structures persisted at $Re = 1170$, the breakdown of those structures was more rapid and there was increased complexity in the geometry of the flow field near the wall. In both cases the fluctuation of the vortical flow structures represents conditions conducive to the agitation of ground-based particles.
2.9 Oblique Impact of Two Vortex Rings

Figure 2.55 $\lambda_2$ iso-surfaces two vortex rings: wall angle $\theta = 20^\circ$, $Re = 1170$
Figure 2.56 $\lambda_2$ iso-surfaces with vorticity contours - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 1170$
2.9 Oblique Impact of Two Vortex Rings

$\tau_{ND} = 3.55$

$\tau_{ND} = 4.35$

$\tau_{ND} = 4.90$

$\tau_{ND} = 5.71$

$\tau_{ND} = 6.25$

$\tau_{ND} = 7.10$

Figure 2.57  Wall-normal velocity field - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 1170$
Numerical Study of Vortex Ring / Wall Interactions

$t_{ND} = 3.55$  \hspace{1cm}  $t_{ND} = 4.35$

$t_{ND} = 4.90$  \hspace{1cm}  $t_{ND} = 5.70$

$t_{ND} = 6.25$  \hspace{1cm}  $t_{ND} = 7.10$

Figure 2.58  Near-wall, wall-normal velocity contour plots - two vortex rings: wall angle $\theta = 20^\circ$, Re = 1170
2.9 Oblique Impact of Two Vortex Rings

Figure 2.59  Near-wall, wall-normal velocity surface plots - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 1170$
Numerical Study of Vortex Ring / Wall Interactions

$t_{ND} = 3.55$

$t_{ND} = 4.35$

$t_{ND} = 4.90$

$t_{ND} = 5.70$

$t_{ND} = 6.25$

$t_{ND} = 7.10$

Figure 2.60  Wall shear stress distribution - two vortex rings: wall angle $\theta = 20^\circ$, $Re = 1170$
2.10 Chapter Summary

The numerical model results are shown to compare favourably with both experimental and numerical data published in open literature, which indicates that the numerical model has appropriately captured the physics involved in the interaction between isolated vortex rings and solid surfaces. For the case of a single vortex ring impinging on a wall the results are consistent with previous observations and the analysis is extended to higher Reynolds number test cases. For a single vortex ring impacting a solid surface it was found that:

• The primary effect of Reynolds number on the large-scale flow structured was an increase in azimuthal fluctuation, as evidenced by the properties of the primary vortex structure and the subsequent development of the hairpin vortex structures from the secondary vortex.

• The azimuthal fluctuation was further amplified by the highly asymmetric nature of the oblique wall impact.

• When comparing the global velocity flow field pattern generated during wall-normal (θ = 0°) and oblique (θ = 20°) impacts, only the wall-normal impact generated a flow field consistent with a large-scale toroid structure.

• The wall shear stress distribution provided insight into the transient flow patterns generated at the wall during impact of the vortex ring, and for both θ = 0° and θ = 20° the progressive development of the boundary layer yielded conditions likely to agitate ground-based particles.

Introducing a second vortex into the flow field did not alter the essential features of the vortex ring / wall interaction, however the increased energy of the boundary layer, along with the subsequent proximity of the large-scale structures resulted in rapid merging of vortices. It was found that:

• As for the single vortex case, the increase in Reynolds number promoted azimuthal fluctuation in vorticity.

• At increased Reynolds number the secondary vortex generated by the lead vortex ring developed hairpin vortices, but the secondary vortex generated by the trailing vortex retained greater stability.

• Recirculation was prevalent in the global velocity flow field, and the entrainment profile was altered by both the wall angle and the impact of the second vortex ring.
• The flow patterns that arise during vortex ring interactions with a wall are consistent with conditions likely to lead to the agitation of ground-based particles.

• The global recirculation of the velocity field is congruous with a flow pattern required for particle uplift.

It is acknowledged that the test cases presented in this chapter are a significant simplification to the helical downwash generated by a helicopter rotor, however vortex ring interactional dynamics provide insight into the fundamental flow features and phenomena that underlie the unsteady and highly complex flow field. To extend the analysis further and better replicate conditions associated with full-scale operations, sub-scale experiments were subsequently undertaken.
Chapter 3

Experimental Study of Rotor Wake In Ground Effect

3.1 Global Recirculation Hypothesis

The structure of the brownout toroid, as discussed in Section 1.3.2, shows similarity to flow structures in the global velocity flow field during vortex/wall interactions. It is hypothesised that for the case of true hover IGE, it is possible for a "global recirculation" flow structure to exist, which perpetuates the toroidal flow structure. The rotor wake behaviour most likely to cause such flow structures would be a persistent up-flow, whereby some percentage of the radially-expanding wake turns back towards the rotor disk rather than following the ground plane. This hypothesis was proposed after flight trial data showed that the toroidal dust clouds persisted throughout the landing manoeuvre, and were not simply a transient flow pattern.

3.2 Literature Review

To date, the most comprehensive study of brownout dust cloud particle concentrations and associated particle characterisation is that undertaken by Cowherd (2007). Testing was conducted at the Yuma Proving Grounds (YPG) in Arizona as part of the U.S. Army Sandblaster 2 project. The soil moisture of the YPG samples was found to be 1.3-2.3% with a default silt content of 12%, where silt is defined as particles smaller than 75μm. Soil samples taken from the YPG test area were compared with samples taken from operational areas where brownout conditions are prevalent, with the determination that the particle size and shape characteristics were similar. Cowherd noted that with regard to brownout dust cloud formation, the rotor downwash acted to impinge on the soil surface and that subsequent exposure of particles to
the rotor outwash resulted in the particles becoming airborne. Although there was no way for sediment uplift mechanisms to be investigated under the trial conditions, results are broadly consistent with the results of Sydney et al. (2011) and Syal and Leishman (2013). The Sandblaster 2 report also refers to a "clear out" zone directly beneath the helicopter, which seems likely to indicate the formation of a ground vortex. Cowherd notes that the dust generated by the helicopter in the hover taxi\(^1\) mode is pushed out laterally by the downwash flow of cleaner air from above the rotor disk. Such a description is consistent with the ground vortex flow structure presented in Section 1.2.2.

Although there is only a relatively small amount of brownout flight trial imagery in the public domain, most notably that published by Wong and Tanner (2010) and Tanner (2011), it is clear that the dust clouds generated during brownout events have geometries and propagation rates specific to the aircraft type. In addition, there are features of the cloud formation and motion that show coherence at a very large scale. The large-scale columns identified by Wong and Tanner (2010) during low-speed forward flight indicate that the brownout dust clouds are composed of flow mechanics across a range of scales. Although sediment uplift mechanisms are responsible for the volume of dust agitated at the ground surface and uplifted into the flow, larger-scale flow structures also exist. The studies currently available in open literature do not make mention of flow mechanisms underlying large-scale brownout structures at hover.

When brownout was identified as a significant operational issue sub-scale experiments were undertaken by a number of institutions to investigate the phenomenon. Reports of preliminary investigations were presented by Whitehouse et al. (2009) and Whitehouse et al. (2010), however more detailed analysis of dual-phase conditions is presented by Johnson et al. (2009) and Sydney et al. (2011). Both of these experiments focused on investigation sediment uplift mechanisms, and the work of of Syal and Leishman (2013) applied the laboratory results to full-scale numerical investigations.

Lakshminarayan et al. (2013) numerically investigated micro-scale rotors operating in ground effect, replicating the experiment conditions of Lee et al. (2008). Their results were consistent with experiment data, and also congruous with the findings of Mula et al. (2012). Analysis confirmed the rotor wake to be highly aperiodic and the blade tip vortices were shown to have increasing instability as they decay. Aside from the wave-like uplift of particles, Sydney et al. (2011) do not make further reference to large-scale flow patterns that may be considered characteristic of a sustained toroid. Similarly, there is no discussion of large-scale structures revealed as part of the investigations undertaken by Lee et al. (2008) or Johnson et al. (2009).

Although anecdotal evidence of dust donuts is provided by Cowherd (2007) it has not been

\(^1\)The hover taxi manoeuvre refers to low level, low speed forward flight IGE.
possible to identify definitive analysis of the phenomenon in any publication at either full- or sub-scale. The available literature does not include:

- analysis of dust donuts beyond qualitative description of flight trial observations,
- analysis of large-scale flow structures which could underlie formation of dust donuts, or
- the conditions under which dust donuts can be repeatably observed.

### 3.3 Objectives

Extending the numerical investigation of Chapter 2, which assessed the interaction of vortex rings with solid surfaces, the flow field generated by a sub-scale rotor IGE was analysed experimentally. Compared to the CFD study, the experiment better replicated conditions associated with full-scale operations; most notably the generation of a helical rotor downwash, which enabled direct investigation of the rotor wake interaction with the ground plane. The experiment aims were to:

- assess the flow field generated by the rotor across a range of test conditions in order to identify large-scale structures which could be considered consistent with the global recirculation hypothesis,
- investigate the conditions under which large-scale structures could be formed,
- identify the flow features underlying large-scale structures, and
- investigate the effect of flow deflectors.

### 3.4 Experiment Overview

In order to investigate the global recirculation hypothesis a sub-scale rotor was placed in a ground effect hover condition. The rotor wake was analysed at several different thrust settings and the effect of ground-based trip-strips on large-scale flow structures was also investigated. Different thrust conditions were achieved by varying the rotational speed of the rotor (RPM) and changing the blade properties, details of which are provided in table 3.1. The sub-scale blades used for Stages I - III had a NACA0012 aerofoil section and radius of 70mm, without twist or taper. Each blade was fabricated as a single piece at fixed collective pitch ($\alpha$) as shown in the figure 3.1. The sub-scale blade used for Stage IV had the same NACA0012 aerofoil section, but had a radius of 110 mm and was set to a collective pitch angle of 15°.
The experiment was broken into four stages:

- Stage I: Investigation of large-scale flow structures in the rotor wake flow field using stereo PIV,

- Stage II: Investigation of large-scale wake structure using planar PIV (increased field of view),

- Stage III: Investigation of the effect of ground-based trip-strips using planar PIV,

- Stage IV: Investigation of the effect of flow deflectors on the region of flow near the rotor centre line.

<table>
<thead>
<tr>
<th>Blade Designation</th>
<th>Chord Length (mm)</th>
<th>Pitch Angle (°)</th>
<th>Rotor Speed (RPM)</th>
<th>Rotor Height (y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>15</td>
<td>12°</td>
<td>200, 250, 300, 500, 1000</td>
<td>0.75D, 1D</td>
</tr>
<tr>
<td>B2</td>
<td>20</td>
<td>12°</td>
<td>200, 300</td>
<td>0.75D, 1D</td>
</tr>
<tr>
<td>B3</td>
<td>20</td>
<td>15°</td>
<td>200, 250, 300, 500</td>
<td>0.75D, 1D</td>
</tr>
</tbody>
</table>

*Table 3.1 Sub-scale rotor blade designation*

*Figure 3.1 Schematic of sub-scale rotor (B1) used for Stage I - III experiments*
3.5 Experiment Design

Whilst brownout is inherently a two-phase flow problem, comprising of the air-wake generated by the helicopter rotor and the motion of the dust particles entrained at the ground plane, the scope of this study was restricted to a single-phase investigation of the air-wake generated beneath an isolated rotor. Results published by Syal and Leishman (2013) indicated that the dust particle size most likely to become suspended in the rotor wake were those below 20\textmu m, with particles below 100\textmu m also contributing to dust cloud formation. These results were confirmed by analysis of soil samples in areas prone to brownout conditions (refer Murowchick (2006), Cowherd (2007) and Bourne et al. (2014a)) which showed a large number of particles in the sub-100\textmu m range. When considering the size of the particles with respect to the size of the rotor, there is a difference of 4 - 5 orders of magnitude, indicating that the particles are likely to behave as passive scalars. Whilst the dust does change the viscosity of the air as the cloud is generated, it is assumed that the particles do not significantly alter the characteristics of the rotor wake (refer Section 1.3.1). As such, it was deemed acceptable to consider the rotor wake structure representative of the path that small particles would follow if they were entrained. Given the focus of this investigation are the so-called dust-donuts, which present as large-scale flow structures, further study of near-wall sediment uplift mechanisms will not be undertaken. It is assumed that if the particles are small enough they will be entrained by the flow, regardless of the sediment uplift mechanism at play.

Following is an overview of each experiment undertaken. Full details of each stage are provided in the relevant chapter, as noted in the summaries below.

3.5.1 Stage I

The first stage of the investigation into the global recirculation flow structure assessed the large-scale flow structures generated as a result of interaction between the rotor wake downwash and the ground plane. Rotor thrust and height above the ground plane were varied to study their effect on large-scale flow structures. Owing to the inherent difficulty in matching full-scale conditions at laboratory scale, the approach use by Lee et al. (2008) and Sydney et al. (2011) was adopted. The maximum rotational frequency investigated (1000 RPM) was chosen to be the same order of magnitude as the full-scale blade loading coefficient\(^2\). Stage I is presented in Chapter 4.

\(^2\)The blade loading coefficient is given by \( \frac{C_T}{\sigma} \), where \( C_T \) is the thrust coefficient and \( \sigma \) is the rotor solidity

\[ \sigma = \frac{\text{total blade area}}{\text{rotor disk area}} \]
3.5.2 Stage II

Informed by the results of Stage I, the second stage of the experiment focused on the test conditions identified as those which yielded large-scale recirculation structures. The field of view was increased in order to study the flow structures in greater detail and to assess the persistence of the global recirculation structure. Stage II is presented in Chapter 5.

3.5.3 Stage III

The third stage of the investigation looked to assess the stability of the global recirculation structure. Ground-based trip-strips were installed in order to determine whether the formation and position of the large-scale recirculation structure could be influenced by ground-based objects. Two trip-strip profiles were tested, and are illustrated in Figure 3.2. The first (TS1) was a rounded cross-section and the second (TS2) had a square profile. Each had a diameter of 300 mm (2.1D), with the height of the cross-section 1.67% of the ring diameter. An illustration of the installation is provided in Figure 3.3. The flow field generated by blades B1 and B2 was investigated with focus on identification of global recirculation flow features. Stage III is presented in Chapter 6.

Figure 3.2 Ground-based trip strip profiles: curved-edge TS1 (top) and square TS2 (bottom)
3.5.4 Stage IV

The final experiment was an analysis of the region of flow inboard of the rotor wake slipstream and an investigation into the effect of flow deflectors. The intent of the deflectors was to push the trajectory of the rotor tip vortices further outboard, and by doing so potentially increase the region of clear air inboard of the rotor wake slipstream, ostensibly representing the zone where the cockpit would be located. The effect of both passive and active deflectors was investigated. Illustrations of each deflector type are provided in figures 3.4 and 3.5. Stage IV is presented in Chapter 7.
Figure 3.4 Passive deflectors

Figure 3.5 Active deflectors
3.6 Flow Field Measurement: Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a non-invasive measurement technique whereby quantitative measurement of instantaneous and mean velocity can be captured across a full plane. A schematic representation of the key elements of a PIV process is outlined in figure 3.6, showing both the equipment and analysis required to yield quantitative results. The PIV technique relies on the presence of "seed" or "tracer" particles that are sufficiently small so as to follow the fluid without altering the characteristics of the flow. Within the flow field a region of interest is illuminated by a thin light sheet from dual-pulse laser, where the time delay between pulses ($\Delta t_{laser}$) is chosen based on the properties of the flow field. The light scattered by the seed particles during each laser pulse is captured by a digital camera. Having prescribed the time delay between laser pulses and measuring the particle displacement between image pairs ($\Delta x$) by cross-correlating successive images, the velocity field can be calculated from the simple relationship ($\Delta t_{laser}/\Delta x$).

![Figure 3.6 PIV measurement process](image-url)
3.6.1 Experiment Apparatus

The experiments were conducted in the Defence Science and Technology (DST) Group Low Speed Wind Tunnel (LSWT) using both two-dimensional, two-component (2D-2C) planar PIV; and two-dimensional, three-component (2D-3C) stereoscopic PIV (SPIV). Given only the hover condition was being examined, and therefore no wind tunnel operation was required, the working section (refer figure 3.7) was isolated from the rest of the LSWT using removable panels which enabled seeding densities to be well-controlled throughout the experiment. Shown in figure 3.8 is the general layout of the test section during experiments, indicating the camera positions and the region of interest. Further detail of the rig configurations is provided in figures 3.9 and 3.10.

The region of interest was illuminated using a New Wave Solo PIV 200XT Nd:YAG dual-pulse laser. The laser was fitted with a spherical lens (focal length $\geq 2000\,\text{mm}$) to reduce the width of the beam and a cylindrical lens (focal length $= -20\,\text{mm}$) to increase the beam height. The resulting thickness of the laser sheet was 2 mm. Images were acquired using 11 MP TSI PowerViewTM Plus CCD camera(s), fitted with lenses appropriate to each experiment setup (further detail is provided in Section 3.8). The CCD cameras have a pixel resolution of 4008 x 2672, a pixel size of 9 $\mu\text{m}$ x 9 $\mu\text{m}$ and a frame rate of 2.07 Hz in frame straddling mode. Data acquisition was undertaken using the TSI Insight 4G software. The PIV seed particles were Di-2-EthylHexyl-Sebacate (commonly referred to as DEHS) droplets generated using a 6-jet TSI Laskin nozzle Laskin (1948), with a nominal diameter of 1$\mu\text{m}$.

Figure 3.7 Schematic of the DST LSWT working section
3.6 Flow Field Measurement: Particle Image Velocimetry

Figure 3.8 PIV camera arrangement in the DST LSWT

Figure 3.9 Rig configuration for Stage I - III experiments
### 3.6.2 Planar PIV

The 2D-2C PIV measurements enabled calculation of the two in-plane velocity components as outlined in Section 3.7. Calibration of the camera to the position of the region of interest was achieved by focusing on a target\(^3\) within the field of view that spanned the full width of the image. Data obtained from the calibration image was then used as input to the TSI Insight 4G software for data processing.

\(^3\)Two targets were used, one a ruler and the other a purpose-built strip with regularly spaced markings that could be affixed directly to the rig assembly.
3.6 Flow Field Measurement: Particle Image Velocimetry

3.6.3 Stereoscopic PIV

The 2D-3C SPIV technique enables measurement of all three velocity components. From the image pairs captured the velocity components are calculated using perspective projection of the two-component particle motions. In a similar manner to Lee et al. (2016), the SPIV configuration used a symmetrical camera arrangement as per figure 3.11. The perspective projection within the laser sheet thickness of local particle displacement ($\Delta x$, $\Delta y$, $\Delta z$) is also shown in the figure 3.11 illustration. At viewing angle $\theta_l$, the magnification of each camera lens is:

$$ M_l = \frac{d_l}{d_{0,l}}, $$

where $d_l$ is the distance between the lens plane and the image plane and $d_{0,l}$ is the distance to the object. To achieve optimal focusing across the full CCD, the image planes were angled by $\theta_{s,l}$ to meet the Scheimpflug condition (refer Scheimpflug (1904) and Prasad and Jensen (1995)):

$$ \theta_{s,l} = \tan^{-1} \left[ M_l \tan(\theta_l) \right]. $$

The local velocity vector $\vec{U}_{xyz}$ can then be determined from perspective projection of recorded particle images (refer Raffel et al. (2007)) by the particle displacement between successive laser pulses ($\Delta t$):

$$ \vec{U}_{xyz} = \frac{\Delta x \vec{i} + \Delta y \vec{j} + \Delta z \vec{k}}{\Delta t}, $$

where $\vec{i}$, $\vec{j}$ and $\vec{k}$ are unit vectors in the $x$, $y$ and $z$ directions.
The calibration process for SPIV is significantly more involved than the planar PIV procedure. To ensure high quality images with sharp focus corner-to-corner, there must be precise alignment between the cameras, laser and region of interest. The SPIV images were calibrated with a two-sided, 705 mm by 400 mm TSI target\(^4\) that was sufficiently large to encompass the full region of interest. Given the geometry of the test rig apparatus, it was not possible for the calibration target and model to be co-located. To overcome this issue the laser was first aligned to a specified position on the rotor assembly, before the rig was removed and the calibration target installed. The target was then aligned to the laser sheet, and calibration images acquired using the TSI Insight 4G software. The target was subsequently removed from the test area and the rotor assembly returned to its original position. To achieve a good calibration over the required FOV Camera 1 had a viewing angle ($\alpha$) of $53^\circ$ and Camera 2 had a viewing angle of $53^\circ$. Although not a perfectly symmetrical arrangement, the difference in angle was minimal and simply a result of the optical constraints associated with the wind tunnel test section.

\(^{4}\)A matte-black plate with uniformly spaced white dots.
3.6.4 PIV Image Processing

In practice the images captured by the digital camera are divided into sections known as Interrogation Windows (IW). These smaller areas are then processed using statistical image cross-correlation in order to compute the in-plane displacement of the seed particles. The cross-correlation and velocity calculation is repeated across each IW to map the velocity over the full measurement plane. For a detailed description of the PIV technique, please refer to Raffel et al. (2007). Full details of each experiment setup, the associated calibration procedures and data processing are provided in Section 3.8.

All data was processed using the TSI Insight 4G software, and an overview of the processing pipeline is provided in Appendix A. The particle displacement was calculated within each IW using a two-pass recursive algorithm, and each vector in the resulting vector field was validated and filtered to eliminate spurious vectors. Such invalid vectors could be caused by experiment conditions such as low density of seed particles, significant out-of-plane particle motion, steep velocity gradients or high levels of noise in the recorded image. A global velocity range filter was implemented using a neighbourhood size of $3 \times 3$ pixels and a displacement tolerance of 2 pixels. Bi-linear interpolation was then used to replace any vector identified as invalid. According to Liang et al. (2003), the spurious vector count should be less than 5% of the total number of measured vectors for well-optimised PIV experiment. In the same manner as Manovski et al. (2013), if a single velocity vector field contained yielded a spurious vector count of more than 5% it was not included in the ensemble average. At least 99% of all images acquired were used to calculate the ensemble average.
3.7 PIV Derived Quantities

Several flow quantities can be calculated from the velocity field data generated by planar PIV measurements, including turbulence intensity, Reynolds stress, out-of-plane vorticity and spatial velocity gradients. Data captured during both 2D-3C stereo and 2D-2C planar experiments has temporal functional dependence, which also carries over to the derived quantities. The same method as presented by Manovski et al. (2013) was used to calculate the PIV derived quantities, and what follows here is a brief description of each.

3.7.1 Velocity

The individual components of the fluid velocity may be calculated at each x,y point in the flow at time t, from the in-plane displacements \( \Delta X \) and \( \Delta Y \) by:

\[
    u(x,y,t) = \frac{\Delta X \times M}{\Delta t},
\]

and

\[
    v(x,y,t) = \frac{\Delta Y \times M}{\Delta t},
\]

where \( M \) is the image magnification and \( \Delta t \) is the time separation between successive image pairs. In the case of SPIV, the out-of-plane displacement can be calculated in a similar manner:

\[
    w(x,y,t) = \frac{\Delta Z \times M}{\Delta t}.
\]

3.7.2 Mean Velocity

Calculated from \( N \) velocity realisations, the mean velocity at each point in the flow, x,y, is defined as:

\[
    \bar{u}(x,y) \equiv \left\langle u(x,y,t) \right\rangle = \frac{1}{N} \sum_{n=1}^{N} u(x,y,t_n)
\]

where \( \langle . \rangle \) denotes the expected value over \( N \) realisations. Therefore the mean velocity components calculated from the PIV measurements are:

\[
    \bar{u}(x,y), \bar{v}(x,y).
\]
3.7 PIV Derived Quantities

3.7.3 Turbulent Quantities

The velocity fluctuating components were calculated as follows:

\[ u'(x, y, t) = u(x, y, t) - \bar{u}(x, y), \] (3.9)

\[ v'(x, y, t) = v(x, y, t) - \bar{v}(x, y), \] (3.10)

and

\[ w'(x, y, t) = w(x, y, t) - \bar{w}(x, y). \] (3.11)

The turbulence strengths, or root-mean-square (RMS) of the velocity fluctuation, are defined as:

\[ u_{RMS}(x, y) = \sqrt{u'^2(x, y)} \] (3.12)

and

\[ v_{RMS}(x, y) = \sqrt{v'^2(x, y)} \] (3.13)

and the turbulence intensities:

\[ \frac{u_{RMS}(x, y)}{u_{tip}} \] (3.14)

and

\[ \frac{v_{RMS}(x, y)}{u_{tip}}, \] (3.15)

where \( u_{tip} \) is the rotor blade tip speed.
3.8 Experiment Setup and Data Processing

The rotor wake flow field was quantitatively measured using both stereo and planar PIV. SPIV enabled a more comprehensive analysis of the flow field as all three components of velocity were measured, however equipment and installation limitations meant it was not possible to increase the field of view. As such, the SPIV test cases were used to undertake a preliminary investigation of the large-scale flow features and inform progression to the larger field of view that was possible with a planar PIV setup. A Hall Effect sensor was mounted to the rotor shaft (refer figures 3.9 and 3.10) and used to trigger the PIV data acquisition at a blade azimuth angle of 90° relative to the camera FOV, which ensured the blade was clear of the recorded image. The maximum acquisition rate of the PIV equipment (2Hz) was below the nominal operational speeds of the rotor (3 - 17 Hz), and as such the results were phase-averaged.

The time between laser pulses, $\Delta t$, was individually tailored to each test case and chosen in order to investigate large-scale flow structures. As with any complex flow field, flow structures exist across a range of time scales and each has its own optimal $\Delta t$ value. For this investigation $\Delta t$ was chosen based on the motion of the large-scale flow features, rather than the progression of the individual blade tip vortices. The blade tip vortices can be clearly identified in several of the instantaneous images, however the experiment was not designed to capture the high speed flow features. It was anticipated that any large-sale structures, should they exist, would have a different time scale and hence optimal $\Delta t$ to the blade tip vortices.

3.8.1 Stage I: Stereo PIV

Experiment setup for the 2D-3C Stereo PIV yielded a reproduction ratio\(^5\) of 7.9 and a spatial resolution of 70.86 $\mu$m/pixel. Based on the requirement that the maximum particle displacement be less than 25% of the initial IW size of 32 $\times$ 32 pixels, the time interval between laser pulses was determined individually for each test case. The data was processed through a two-pass recursive algorithm using 50% grid spacing overlap. The first pass IW was 32 $\times$ 32 pixels, and the resultant particle image displacement distance then applied to the second pass with an IW size of 16 $\times$ 16 pixels. Offsetting the IW by the particle image displacement distance increases the signal-to-noise ratio, as lost pairs due to in-plane motion are reduced. Spurious vectors were removed using a global velocity range filter, a mean filter using a neighbourhood size of 3 $\times$ 3 pixels and a displacement tolerance of 2 pixels for each test case. Vectors identified as invalid were replaced with interpolated points using bi-linear interpolation. Data convergence was assessed using running averages of the velocity components. All results

\(^5\)The reproduction ratio (RR) is the inverse of the magnification (M): $RR = \frac{1}{M}$
stabilised within the first 500 samples indicating sufficient convergence in the statistical parameters could be established from the number of vector fields recorded for each test case. If a single velocity vector field contained yielded a spurious vector count of more than 5% it was not included in the ensemble average. To reduce measurement uncertainty, between 1000 – 3000 image pairs were captured for each test case and at least 99% of all images acquired were used to calculate the ensemble average.

### 3.8.2 Stage II: Planar PIV

The 2D-2C planar PIV setup yielded a reproduction ratio of 15.1 and a spatial resolution of 136 μm/pixel. As for the SPIV experiments, the time interval between laser pulses (\(\Delta t\)) was determined individually for each test case and the data was processed through a two-pass recursive algorithm using 50% grid spacing overlap. The 2D data set was processed with a first pass IW of 32 × 32 pixels, reducing to 16 × 16 pixels second pass. As previously, the vector fields were validated via a global and local velocity range filter. Data convergence was assessed using running averages of the velocity components. All results stabilised within the first 500 samples indicating sufficient convergence in the statistical parameters could be established from the number of vector fields recorded for each test case. If a single velocity vector field contained yielded a spurious vector count of more than 5% it was not included in the ensemble average. To reduce measurement uncertainty, between 1000 – 2000 image pairs were captured for each test case and at least 99% of all images acquired were used to calculate the ensemble average.

### 3.8.3 Stage III: Planar PIV

A similar experiment setup was used to Stage II, which yielded a reproduction ratio of 15.1 and a spatial resolution of 136 μm/pixel. Based on the requirement that the maximum particle displacement be less than 25% of the initial IW size of 32 × 32 pixels, the time interval between laser pulses was determined individually for each test case. The data was processed through a two-pass recursive algorithm using 50% grid spacing overlap. The first pass IW was 32 × 32 pixels, and the resultant particle image displacement distance then applied to the second pass with an IW size of 16 × 16 pixels. All results stabilised within the first 500 samples indicating sufficient convergence in the statistical parameters could be established from the number of vector fields recorded for each test case. If a single velocity vector field contained yielded a
spurious vector count of more than 5% it was not included in the ensemble average. To reduce measurement uncertainty, between 1000 - 2000 image pairs were captured for each test case and at least 99% of all images acquired were used to calculate the ensemble average.

3.8.4 Stage IV: Planar PIV

The offset distance to the PIV camera with the rotor aligned to the tunnel centre-line was approximately 1400 mm, which resulted in a reproduction ratio of 6.7 and a spatial resolution of 60.3 μm/pixel. For test cases with a plan view, the reproduction ratio was 5.9, with a spatial resolution of 52.85 μm/pixel. Based on the requirement that the maximum particle displacement be less than 25% of the initial interrogation window (IW) size of 64 × 64 pixels, the time interval between laser pulses (Δt) was either 30 or 50 μs, depending on the test case. The data was processed through a two-pass recursive algorithm using 50% grid spacing overlap. The first pass IW was 64 × 64 pixels, and the resultant particle image displacement distance then applied to the second pass with an IW size of 32 × 32 pixels. All results stabilised within the first 500 samples indicating sufficient convergence in the statistical parameters could be established from the number of vector fields recorded for each test case. If a single velocity vector field contained yielded a spurious vector count of more than 5% it was not included in the ensemble average. To reduce measurement uncertainty, 3000 image pairs were captured for each test case and at least 99% of all images acquired were used to calculate the ensemble average.
3.9 Flow Symmetry

The rotor wakes were assessed at distances above the ground plane \((Z_{ND})\) of 0.75D and 1D, where D is the rotor diameter. As noted in Chapter 1 ground effect is most pronounced at rotor heights below 1D, and as such rotor heights at or below 1D are the focus of the study. It was assumed that the dominant features of the rotor wake were symmetrical beneath the rotor, and as such the PIV region of interest could be limited to one half of the full flow field. To establish the validity of this assumption, data was captured with the region of interest centred beneath the rotor. Shown in figure 3.12 and 3.13 are the phase-averaged mean velocity magnitude and \(v\)-component velocity contour plots, non-dimensionalised by the rotor tip speed. The height above the ground plane \((Z)\) and distance along the ground plane \((X)\) are non-dimensionalised by the rotor diameter \((D)\). Also included in figures 3.12 and 3.13 is a graphic representing the indicative position of the rotor, which is positioned outside the field of view.

It can be seen that there is symmetry in the flow beneath the rotor, and that the "slip-streams" created on either side of the rotor disk are of the same magnitude. The overall shape of the down wash when comparing either side of the rotor disk is also consistent. The variation seen between the left and right hand sides of the rotor wake is to be expected given the highly unsteady nature of the flow field, and the overall result is considered a satisfactory demonstration of flow symmetry.
Figure 3.12 Mean velocity magnitude contour plot overlaid with streamlines: Flow symmetry check

Figure 3.13 v-component velocity contour plot: Flow symmetry check
3.10 Experiment Error and Measurement Uncertainty

For the experiments undertaken as part of Stage I - Stage III limitations associated with mechanical components of the rotor rig meant that there was minor fluctuation in the rotor RPM up to +/-5%, despite the use of a feedback controller. As a source of experimental error it was deemed acceptable, but is a factor that may contribute to flow structure instabilities. For the Stage IV investigation, the two main sources of experimental error were the rotor RPM and the output of the active deflectors. Both these error sources are discussed in further detail in Chapter 7. PIV measurement uncertainty was calculated using the approach described by Kostas (2002). A summary of key values is provided in table 3.2, where $\epsilon_{\text{displacement}}$ is the error associated with the particle displacement, $\epsilon_{\Delta t}$ is the timing error, $\epsilon_{\text{scale}}$ is the error in the measurement of the image scale factor, $\epsilon_u$ is the error in the calculated velocity value, $\epsilon_{\bar{u}}$ is the error in the calculated mean velocity value and $\epsilon_{\sigma_u}$ is the error associated with calculation of the RMS velocity. Full details of the measurement uncertainty calculations are presented in Appendix B.

<table>
<thead>
<tr>
<th>Stage I - II</th>
<th>$\epsilon_{\text{displacement}}$ (%)</th>
<th>$\epsilon_{\Delta t}$ (%)</th>
<th>$\epsilon_{\text{scale}}$ (%)</th>
<th>$\epsilon_u$ (%)</th>
<th>$\epsilon_{\bar{u}}$ max (%)</th>
<th>$\epsilon_{\sigma_u}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIV: 200 RPM</td>
<td>2.17</td>
<td>$2.62 \times 10^{-4}$</td>
<td>0.419</td>
<td>2.21</td>
<td>2.21</td>
<td>0.0253</td>
</tr>
<tr>
<td>SPIV: 300 RPM</td>
<td>1.53</td>
<td>$3.46 \times 10^{-4}$</td>
<td>0.419</td>
<td>1.59</td>
<td>1.59</td>
<td>0.0253</td>
</tr>
<tr>
<td>SPIV: 500 RPM</td>
<td>1.18</td>
<td>$4.21 \times 10^{-4}$</td>
<td>0.419</td>
<td>1.25</td>
<td>1.25</td>
<td>0.0253</td>
</tr>
<tr>
<td>SPIV: 1000 RPM</td>
<td>2.60</td>
<td>$2.00 \times 10^{-3}$</td>
<td>0.419</td>
<td>2.64</td>
<td>2.64</td>
<td>0.0253</td>
</tr>
<tr>
<td>Planar PIV: 200 RPM</td>
<td>2.91</td>
<td>$2.31 \times 10^{-4}$</td>
<td>0.805</td>
<td>3.02</td>
<td>3.02</td>
<td>0.0438</td>
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<tr>
<td>Planar PIV: 300 RPM</td>
<td>2.42</td>
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<td>2.55</td>
<td>2.55</td>
<td>0.0438</td>
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<table>
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<tr>
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<tr>
<td>Baseline</td>
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<td>0.23</td>
<td>0.37</td>
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<td>0.0253</td>
</tr>
<tr>
<td>Deflector, V1</td>
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<td>$1.33 \times 10^{-3}$</td>
<td>0.23</td>
<td>0.54</td>
<td>0.542</td>
<td>0.0253</td>
</tr>
<tr>
<td>Deflector, V2</td>
<td>1.39</td>
<td>$1.33 \times 10^{-3}$</td>
<td>0.23</td>
<td>0.54</td>
<td>0.542</td>
<td>0.0253</td>
</tr>
</tbody>
</table>

Table 3.2 PIV Measurement Uncertainty
3.11 Analysis Methods

3.11.1 Proper Orthogonal Decomposition

The proper orthogonal decomposition (POD) approach was introduced by Lumley (1967) within the context of fluid mechanics, and provides an objective method by which coherent structures within a turbulent flow may be identified and visualised. No a priori knowledge of the flow field is required, instead a sum of weighted, linear basis functions or modes ($\varphi_m$) are decomposed from the original velocity field. Two different POD approaches are commonly used, referred to as classical POD and snapshot POD (refer Sirovich (1987)). Classical POD is typically applied to data sets with high temporal resolution but poor spatial resolution, such as hot-wire or laser Doppler anemometry techniques, where as snapshot POD is generally applied to data sets with high spatial resolution but reduced temporal resolution, which typically includes PIV and numerical simulations such as Direct Numerical Simulations or Large Eddy Simulations. Classical POD will not be discussed here, but further detail can be found in Sirovich (1987) and Cordier and Bermann (2003).

The modes generated during a snapshot POD analysis are representative of the most probable realisations of the input data. For the case of PIV data this corresponds to identification of the flow structures which comprise the flow field, specifically the Coherent Structures\(^6\) (refer Lumley (1981)) that have the largest projection onto the flow field. Highly complex flows may be comprised of a number of structures, and owing to the nature of their interaction the individual structures themselves may be difficult to identify. The most energetic modes resulting from a POD analysis are characteristic of the dominant flow structures, with the majority of the total kinetic energy in the flow typically represented by the first few POD modes. Caution should be exercised when assessing non-dominant POD modes as the flow structures seen in the low energy modes may not be representative of real flow structures. For a given flow structure to become prominent as a POD mode, it must have consistency in its characteristics and location in each snapshot. Further detail relating to POD and its applications can be found in Berkooz et al. (1993), Chatterjee (2000), Liang et al. (2002), Meyer et al. (2007) and Cavar and Meyer (2012).

Following is an overview of the snapshot POD method implemented in this study, which is taken from the mathematical method outlined by Chen et al. (2012). The fundamental premise of POD is to decompose a set of velocity distributions, $V^{(k)} = (u, v)^{(k)}_{i,j}$, known as snapshots, into a linear combination of $M$ spatial basis functions ($\varphi_m$), referred to as POD modes.

\(^6\)A Coherent Structure, as defined by Lumley (1981), is: the deterministic function which is best correlated on average with the realizations $\tilde{u}(\tilde{X})$. 
modes, and corresponding coefficients $c_m^{(k)}$, where $i, j$ is the velocity distribution index and $k$ is the snapshot index. As such,

$$V^k = \sum_{m=1}^{M} c_m^{(k)} \phi_m,$$

(3.16)

with the constraint that the basis functions are orthonormal to each other. The $u$—and $v$—components of velocity are then re-ordered into a single row matrices, $U$ and $V$, as follows

$$U = \begin{bmatrix} U^{(1)} \\ U^{(2)} \\ \vdots \\ U^{(K)} \end{bmatrix} = \begin{bmatrix} u_{i=1,j=1}^{(1)} & u_{i=1,j=2}^{(1)} & \cdots & u_{i=1,j=I}^{(1)} & u_{i=1,j=J}^{(1)} \\ u_{i=1,j=1}^{(2)} & u_{i=1,j=2}^{(2)} & \cdots & u_{i=1,j=I}^{(2)} & u_{i=1,j=J}^{(2)} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ u_{i=1,j=1}^{(K)} & u_{i=1,j=2}^{(K)} & \cdots & u_{i=1,j=I}^{(K)} & u_{i=1,j=J}^{(K)} \end{bmatrix},$$

(3.17)

where $K$ is the total number of snapshots and $I \times J$ is the total number of grid points in the velocity field. The spatial correlation matrix for velocity distributions is then defined as

$$C = \frac{1}{K} (UU^T + VV^T).$$

(3.18)

The POD technique aims to find a sequence of orthonormal basis functions, also referred to as POD modes, which represent the coherent structures in such a way that the following function is minimised

$$\sum_{k=1}^{K} \| V^{(k)} - \sum_{m=1}^{M} c_m^{(k)} \phi_m \|^2 \rightarrow min,$$

(3.19)

subject to

$$(\phi_i, \phi_j) = \delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}. $$

(3.20)

This minimisation is realised by solving the eigenvalue problem of correlation matrix $C$,

$$C \beta_m = \lambda_m \beta_m.$$

(3.21)

The basis functions are obtained by projecting $U$ and $V$ onto the eigenvector $\beta_m$ with subsequent normalisation. The coefficients of each mode are then computed by projecting the
original velocity fields onto the computed basis functions. The $K \times M$ coefficient matrix, $c_{m}^{(k)}$

$$c_{m}^{(k)} = \begin{bmatrix}
c_{1}^{(1)} & c_{2}^{(1)} & \cdots & c_{M}^{(1)} \\
c_{1}^{(2)} & c_{2}^{(2)} & \cdots & c_{M}^{(2)} \\
\vdots & \vdots & \ddots & \vdots \\
c_{1}^{(K)} & c_{2}^{(K)} & \cdots & c_{M}^{(K)}
\end{bmatrix} \quad (3.22)$$

contains the amplitude that the corresponding basis function contributes to a particular mode, $m$, in each column, and the amplitude that corresponds to a particular snapshot, $k$, in each row.

As per Kostas (2002) the same assumptions are applied regarding the accuracy and convergence of the POD technique. Breuer and Sirovich (1991) found that for a sample size of 400 (i.e. $M = 400$) with noise levels of $10^{-2}$ the eigenvalues were accurate for mode numbers up to 50, whereas the eigenfunctions diverged from the true solution for mode numbers less than 50. The PIV data sets captured for this study had a minimum sample size of $M = 1000$, with random noise levels of approximately 1.5%. Taking these parameters into account the eigenvalues and eigenfunctions generated in the first 10 modes are regarded as accurate. Full discussion and further detail of the effect of random noise and ensemble size within POD calculations can be found in Breuer and Sirovich (1991).

### 3.11.2 Vortex Identification

Although taking the shape of a standing vortex, the global recirculation is considered distinct from the blade tip vortices. Given the inherent unsteadiness and aperiodicity of a rotor wake, identification of individual blade tip vortices is generally only possible when assessing instantaneous snapshots of the flow. Although the blade tip vortices are shed each revolution and convect downwards in a relatively consistent manner, their exact azimuthal position varies with time in both a horizontal and vertical sense. When instantaneous PIV images are ensemble averaged to assess the mean flow field, the individual blade tip vortices become a "smear" as a result of the variation in position of the vortex cores. This occurs even when the data acquisition is phase locked, highlighting the inherent unsteadiness in the rotor wake flow field. Such mean flow results are considered typical of ensemble-averaged rotor wake flow fields generated by PIV techniques (refer Lee et al. (2008)). The smear associated with the convection of the blade tip vortices beneath the rotor and subsequent radial motion along the ground plane is seen in both the SPIV and planar PIV results, and is considered to typify motion of the individual vortices. This feature is distinct from the global recirculation structure, which is considered akin to a "roll-up" of the flow rather than a large-scale individual vortex.
somehow borne of the interaction between blade tip vortices\textsuperscript{7}.

To further investigate properties of the global recirculation, specifically with regard to preliminary analysis that indicated the structure meandered both vertically and radially, instantaneous vector fields were individually assessed. For most test cases, 1000 images took 20 minutes to acquire, meaning regular oscillation of the flow feature could be captured. In order to quantify the range of motion of the flow structure, a simple vortex identification method was used to process the instantaneous images that made up each ensemble. Taken from Holmen (2012), the technique applies a signum\textsuperscript{8} operation, as shown in equation 3.23, to the vector field and identifies points in the flow field where vortex core is likely to be present. A brief description of the method is as follows:

1. A signum operation is applied to the PIV vector field
2. At each point on the vector field, four surrounding vectors are assessed (first in \( u \) and then in \( v \))
3. If the sum of the signum values of the surrounding vectors is zero, a vortex core is likely to be present (refer left image of figure 3.14)

\[
\text{sgn}(x) := \begin{cases} 
-1 & \text{if } x < 0 \\
0 & \text{if } x = 0 \\
+1 & \text{if } x > 0 
\end{cases} 
\] (3.23)

To account for the fact a portion of each PIV snapshot included regions of flow that were close to still air, and likely to return false-positives, a second iteration followed, assessing an additional four points one position further outboard to those initially analysed. Checks were also included to account for the case where shear flow may return a false positive, as shown in the right image of figure 3.14.

\textsuperscript{7}It should be noted that the instantaneous images are unlikely to capture the individual blade tip vortices. Generally, it is not possible for an individual PIV setup to simultaneously capture fast and slow moving flow structures due to the inherent constraints of the \( \Delta t \) variable, which is the user-defined time between laser pulses (refer Section X for further detail). When considering a rotor wake downwash, it is expected that the blade tip vortices will move faster than the larger-scale, lower-speed global recirculation, so in this case it was not possible for a single \( \Delta t \) value to consistently capture both flow features.

\textsuperscript{8}A signum function extracts the sign of a real number.
Figure 3.14 Images taken from Holmen (2012) showing results which will return positive for vortex identification. On the left is vortical flow, on the right a false positive likely to result from shear motion.
Chapter 4

Experiment Results - Stage I

Part of this chapter has been presented at the 40th European Rotorcraft Forum, please refer to Bourne et al. (2014b).

To investigate the global recirculation hypothesis, the rotor wakes of B1 (15mm chord, 12° pitch angle) and B3 (20mm chord, 15° pitch angle) were assessed at distances above the ground plane ($Z_{ND}$) of 0.75D and 1D, where D is the rotor diameter. B1 and B3 were chosen in the first instance as they represented the lowest and highest thrust conditions from the variation in blade parameters. Full results are presented in Appendix C and include the mean velocity magnitude contour plot for each test case, along with the corresponding turbulence intensities. Both the vertical distance above the ground plane and the horizontal axis, representing the distance from the rotor shaft centre-line, has been non-dimensionalised by the rotor diameter. For reference, the location of the rotor Tip Path Plane\(^1\) (TPP) is also included as a dashed line in all figures, as the rotor itself falls outside the field of view. All velocities have been non-dimensionalised by the rotor tip speed associated with each each test case.

4.1 Out-of-Plane Velocity

The SPIV analysis enabled direct measurement of the out-of-plane velocity component, and an example is presented in table 4.1 for B1 operating at a rotor height of 1D. It should be noted that the primary interest of this study was the rotor outwash along the ground plane, rather than the downwash flow field which is comprised of the flow immediately below the rotor. As such, the maximum values presented refer to the peak velocities along the ground plane, the dominant component of which is in the $u$-component of velocity. It can be seen that the peak in-plane velocity component ($u$) is approximately double that of the other components.

\(^1\)The TPP describes the path of the helicopter blade tips during their rotation.
(v and w). This result is to be expected given the radial acceleration of the flow as the rotor downwash comes into contact with the ground plane. It also highlights the presence of swirl, represented by the w-component of velocity. The maximum values of the v- and w-components of velocity are of similar magnitude, indicating that when the rotor wake first impinges on the ground plane, which is where the maximal values occur, the vast majority of the wall-normal (v) velocity components of the downwash are converted to outwash. Subsequently, the u-component velocity of the radially expanding wake dominates the flow field.

| RPM | $U_{\text{mean}}|_{\text{max}}$ | $u_{\text{mean}}|_{\text{max}}$ | $v_{\text{mean}}|_{\text{max}}$ | $w_{\text{mean}}|_{\text{max}}$ |
|-----|-----------------|-----------------|-----------------|-----------------|
| 200 | 0.075           | 0.074           | 0.033           | 0.030           |
| 250 | 0.081           | 0.080           | 0.024           | 0.034           |
| 300 | 0.085           | 0.084           | 0.044           | 0.038           |
| 500 | 0.097           | 0.096           | 0.028           | 0.040           |
| 1000| 0.104           | 0.103           | 0.040           | 0.046           |

*Table 4.1 Maximum velocity magnitudes (ND) with increasing RPM*

### 4.2 Flow Structures at 200 RPM

Presented in figures 4.1 -4.3 are the mean velocity contour plots overlaid with streamlines and the v-component turbulence intensities for test cases that showed evidence of large-scale flow patterns which could be considered consistent with a region of global recirculation. At a rotor height of 0.75D the global flow field generated by B1 showed preliminary tendency toward up-flow. The v-component turbulence intensity does identify a clear “curl” of the flow back toward the rotor that indicates a large-scale upward trend is present in the flow, suggesting that global recirculation may be present but beyond the boundaries of the field of view. When the height above the ground plane was increased to 1D, a global recirculation zone was evident in the flow fields generated by B1 and B3. Results for the mean flow fields as well as the turbulence intensities show structures that are consistent with a large-scale vortical feature.

For full results please refer to Appendix C. Presented in figures C.1 - C.3 are the results for B1 at 0.75D above the ground plane, and in figures C.4 - C.6 the results for a rotor distance of 1D above the ground plane. Figures C.7 - C.9 present the results for B3 at 200 RPM and a distance of 1D above the ground plane.
4.2 Flow Structures at 200 RPM

**Figure 4.1** Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 0.75D, 200 RPM
Figure 4.2 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 1D, 200 RPM
Figure 4.3 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B3, 1D, 200 RPM
4.3 Flow Structures at 250 RPM

Shown in figures 4.4 - 4.6 are the mean velocity contour plots and associated streamlines generated by B1 and B3 at 250 RPM. At a rotor height of 1D from the ground plane, the B1 result shows a global recirculation flow structure. The mean velocity fields for B1 at 0.75D and B3 at 1D do not show clear trends toward up-flow, nor do the corresponding \( v \)-component turbulence intensities. As such, it must be surmised that there is no definitive evidence of large-scale flow structures that could be considered indicative of global recirculation. When taken together with the results at 200 RPM, there is some suggestion that large-scale structures may be present in the flow field, but beyond the field of view. The planar PIV setup undertaken in Stage II enabled a larger field of view to be captured in order to investigate the rotor wake flow structures at further distances from the rotor shaft.

For full results please refer to Appendix C. Presented in figures C.10 - C.12 are the results for B1 at a distance from the ground plane of 0.75D, with results at 1D presented in Figures C.13 - C.15. The results for B3 at 250 RPM at a rotor height of 1D above the ground plane are shown in figures C.16 - C.18.
Figure 4.4 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 0.75D, 250 RPM
Figure 4.5 Mean velocity magnitude contour plot overlaid with streamlines (top) and $v$-component turbulence intensities (bottom): B1, 1D, 250 RPM
Figure 4.6 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B3, 1D, 250 RPM
4.4 Flow Structures at 300, 500 and 1000 RPM

None of the results recorded at 300, 500 or 1000 RPM showed evidence of large-scale flow structures that could be considered indicative of global recirculation. Similarly for the test cases at 250 RPM it was not possible to discount the possibility of large-scale flow structures existing beyond the field of view, and as such further investigation was not undertaken using SPIV given the experiment setup for Stage II enabled a larger field of view to be captured. Please refer to sections 5.2 and 5.3 for further discussion of higher RPM results.

For the full set of SPIV results please refer to Appendix C. At 1D, the flow field generated at 300 RPM by B1 is presented in Figures C.19 - C.21, with B3 results shown in Figures C.22 - C.24. Shown in Figures C.25 - C.27 are results for B1 at 500 RPM, and the B3 flow fields presented in Figures C.28 - C.30. Figures C.31 - C.33 show the results for Blade 1 at 1000 RPM.

4.5 Investigation of Variation in Mean Flow Results

During the course of the experiment several test points were repeated in order to assess the persistence of the observed global recirculation flow structures. In some cases repetition of the test point did not yield the same mean velocity flow field, and such cases were referred to as a "State II" flow field. In this section further analysis is presented for the case of B3 operating at 200 RPM at a rotor height of 1D. The test point did not initially yield a global recirculation structure, but upon repetition a large-scale vortical structure was evident.

In order to investigate the variation in the mean velocity flow field results four separate data sets, designated Ensemble A - Ensemble D, were captured under the same operating conditions. No changes were made to the SPIV setup, nor to the experiment equipment, between the acquisition of each ensemble. Only one of the four, Ensemble C, yielded a mean velocity flow field that was consistent with a zone of global recirculation. The large-scale vortical structure did not appear to be transient, nor did it decay over time, but there was some evidence that the structure meandered both in the horizontal and vertical directions. Ensembles A, B and D were deemed State II results as the mean velocity flow fields did not show clear evidence of a large-scale vortical structure.
4.5.1 POD Analysis

The aim of implementing POD was:

- To ascertain whether the global recirculation structure was a single dominant structure.
  
  The most energetic modes resulting from a POD analysis are characteristic of the dominant flow structures, with the majority of the total kinetic energy in the flow typically represented by the first few POD modes. In this way, the first mode of a POD analysis generally shows the dominant flow structure, with subsequent modes identifying less energetic structures also present in the flow field. Given the variation in the results between ensembles, for what was ostensibly the same test condition, POD provided a method to assess whether the observed global recirculation zone was a single structure or whether it comprised of several different flow structures that when combined gave the impression of large-scale recirculation.

- To investigate differences underlying the mean flow results for each ensemble.
  
  POD also provided a technique to identify whether there were inherent differences in any of the flow structures underlying the mean flow result. By assessing the most energetic POD modes, it was possible to infer the contribution of smaller-scale flow structures to the global flow field.

4.5.2 Overview

Ensemble A did not show any clear sign of global recirculation or up-flow; Ensembles B and D showed an oblique pseudo-vortical flow structure that was suggestive of global recirculation but did not include a definitive up-flow; and Ensemble C showed a clearly formed large-scale vortex structure consistent with a zone of global recirculation, yet all cases were captured under the same test conditions. When considering the maximum magnitude of each of the three velocity components, as presented in table 4.2, there was no clear relationship between the speed of the flow and the development of large-scale vortical structures. Ensemble A showed the lowest in-plane maximum velocity, whereas Ensemble D had the highest average velocities of each test point. It is interesting to note that Ensembles B and C had similar peak velocities, but that the similarity did not carry over to the flow structure geometry. As such, it is difficult to infer fundamental differences between the test points based solely on the variation in peak velocities. To better understand the flow fields underlying each result, a POD analysis of the SPIV mean velocity flow fields was undertaken.
<table>
<thead>
<tr>
<th></th>
<th>$U_{\text{mean}}$</th>
<th>$u_{\text{mean}}$</th>
<th>$v_{\text{mean}}$</th>
<th>$w_{\text{mean}}$</th>
<th>Flow Field</th>
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</thead>
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<td>Ensemble A</td>
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<td>0.080</td>
<td>0.048</td>
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<tr>
<td>Ensemble B</td>
<td>0.106</td>
<td>0.105</td>
<td>0.037</td>
<td>0.045</td>
<td>State II Result</td>
</tr>
<tr>
<td>Ensemble C</td>
<td>0.098</td>
<td>0.097</td>
<td>0.037</td>
<td>0.042</td>
<td>Recirculation</td>
</tr>
<tr>
<td>Ensemble D</td>
<td>0.126</td>
<td>0.125</td>
<td>0.051</td>
<td>0.050</td>
<td>State II Result</td>
</tr>
</tbody>
</table>

*Table 4.2* Maximum velocity magnitude (ND) for each ensemble

As noted in the discussion of basic POD theory (refer Section 3.11.1), caution should be exercised when interpreting non-dominant POD modes as they may not be truly indicative of flow field if the structures in question are not of consistent size and position throughout the dataset. For the test cases that show structures indicative of global recirculation, the POD analysis offered insight into whether there was a large-scale structure generating such a flow field, or whether it was instead a combination of smaller-scale flow structures that resulted in a structure reminiscent of a standing vortex. For the test cases that did not show any tendency toward a global recirculation flow structure, the POD analysis revealed the combination of flow structures that comprised the global flow field.

For reference, the SPIV mean velocity contour plots for each case are presented in figure 4.7 and figure 4.8. Figures 4.9 and 4.10 present the corresponding contour plots of the first POD mode for each ensemble. It can be seen that the first POD mode of each ensemble correlates well to its respective mean velocity flow field. The consistency between the flow fields of figures 4.7 and 4.9, and figures 4.8 and 4.10, indicates that the mean flow calculated from the SPIV results represents the most energetic structure in the flow field. The POD analysis showed that the flow structures captured in the mean flow field were persistent across each image ensemble, and from this it can be inferred that the SPIV results presented the dominant features of each flow field. Shown in figures 4.11 - 4.14 are the second and third POD modes for each test case. The second and third modes represented much smaller percentages of the total kinetic energy of the flow, and although they must be interpreted with caution, the flow patterns presented are generally indicative of the smaller-scale structures associated with the motion of the blade tip vortices. Full POD results are shown in Appendix D.2, and include the energy associated with each of the first 10 POD modes, along with visualisation of the first three modes. Full results for the SPIV derived quantities of velocity magnitudes and turbulence intensity are presented in Appendix D.1.
4.5 Investigation of Variation in Mean Flow Results

Figure 4.7 SPIV mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles A and B)
**Figure 4.8** SPIV mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensemble C and D)
Figure 4.9 First POD mode mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles A and B)
Figure 4.10 First POD mode mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles C and D)
**Ensemble A**

**Ensemble B**

*Figure 4.11* Second POD mode mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles A and B)
Figure 4.12 Second POD mode mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles C and D)
4.5 Investigation of Variation in Mean Flow Results

Figure 4.13 Third POD mode mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles A and B)
**Ensemble C**

**Ensemble D**

*Figure 4.14 Third POD mode mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM, 1D (Ensembles C and D)*

### 4.5.3 Ensemble A: State II Result

The first POD mode of Ensemble A, shown in figure 4.9, accounted for 68.5% of the total kinetic energy of the flow. The flow pattern was consistent with the SPIV mean flow field of figure 4.7 and did not show any indication of up-flow or global recirculation. The second and third modes, shown in figures 4.11 and 4.13 respectively, represented 4.8% and 3.2% of the flow energy. The second and third POD modes were indicative of the position of the blade tip vortices as they impinged upon the ground plane. The strength of the individual blade tip vortices are maximal upon initial contact with the ground, although the inherent unsteadiness of the rotor wake results in fluctuation in the path of each individual vortex. Consequently, the second POD mode shows a smear of maximal velocity that represents the upper and lower bounds of individual blade tip vortices. A similar trend is shown in the third POD mode.
whereby the progressive position of the blade tip vortices is captured by two sets of local velocity maxima that are of opposite sign.

### 4.5.4 Ensemble B: State II Result

For Ensemble B, the first POD mode shows good agreement with the mean flow field result, and constituted 60.2% of the total kinetic energy in the flow. Although a large-scale vortical flow structure was identifiable, it appeared stretched, representing a more elliptical centre of rotation than what would be expected for a global recirculation zone. The second mode accounted for 4.8% of the flow energy and showed a flow structure consistent with the position of the blade tip vortices as they first interacted with the ground plane. The third POD mode, which represents 1.8% of the flow energy, also presented flow features consistent with the motion of the blade tip vortices along the ground plane. Interestingly, there was some weak evidence of large-scale vortical structures in both the mode one and mode two results. The mode three result shows weak recirculation further outboard than the weak recirculation in mode two. Summed together it is possible the change in location of the recirculation region, as driven by the progression of the blade tip vortices across the ground plane, results in the oblique structure identified in the first mode, which is ostensibly the mean flow result.

### 4.5.5 Ensemble C: Global Recirculation

The first POD mode of Ensemble C showed excellent agreement with the mean flow result with a clear large-scale structure consistent with global recirculation and clearly defined up-flow. The first POD mode represented 57% of the total flow kinetic energy. The second mode, making up 5.2% of the flow energy, showed a weak small-scale flow structure near the initial point of interaction between the blade tip vortices and the ground plane, representative of near-wall vortical flow. There was also a large-scale structure further outboard, which was consistent with a standing vortex feature. The third POD mode accounted for 2.6% of the flow energy and presented a flow structure consistent with the large-scale recirculation. The two local velocity maxima near the initial contact point between the rotor wake and the ground plane captured the position of the individual blade tip vortices. Radial expansion of the rotor wake could then be identified, along with a trend of global up-flow and recirculation; however the strength of the recirculation zone was not as pronounced as for the second mode.
4.5.6 Ensemble D: State II Result

For Ensemble D, the first POD mode contained 70.3% of the total flow energy and was consistent with the mean flow result. As for Ensemble B, the flow structure seen in the first mode of Ensemble D showed a large-scale elliptical vortical structure. Although there was some recirculation, there was no clearly defined up-flow. Mode two accounted for 2.7% of the flow energy and showed a small-scale vortical structure at the initial ground interface, making it likely to be a representation of the individual blade tip vortices interacting with the ground plane. There was also weak evidence of expanding radial flow that showed the same oblique geometry as the mode one result. The third POD mode, which constituted 1.5% of the flow energy, was similar to the mode three result for Ensemble B. The structure showed large-scale vortical motion that when taken in addition to the second mode suggested that the oblique feature of the first mode could be composed of flow features that show greater oscillation and instability when compared to Ensemble C.

4.5.7 Summary

The POD analysis provided insight into the variation in flow structures that comprised the mean flow result for each ensemble. The flow structures underlying the mean flow result, represented by the second and third POD modes, differed between test cases. Although it was not possible to definitively identify the root cause of the differences in the mean flow results, the flow features of the second and third POD modes represented flow structures consistent with the motion of the blade tip vortices. From this is may be inferred that it is the characteristics of the blade tip vortices that dictate the prevalence of the large-scale recirculation region. It was also likely that the inherent instability associated with the rotor wake flow field translated to instability in the formation of large-scale flow structures.

Overall, analysis of the State II results using the first three POD modes of each ensemble showed that:

- the flow field of Ensemble A did not exhibit features consistent with global recirculation,
- Ensembles B and D showed some evidence of up-flow in the lower energy POD modes but recirculation was not the dominant flow structure, and
- Ensemble C comprised flow features consistent with global recirculation.
4.6 Chapter Summary

The SPIV investigation yielded the following results.

- A large-scale flow structure consistent with the global recirculation hypothesis was identified in the rotor wake flow field at 200 RPM.

- The structure was not evident at rotor speeds above 200 RPM, however analysis indicated that some test cases showed a tendency toward up-flow. It was not possible to discount the fact that large-scale flow structures may be persistent beyond the field of view available with the SPIV setup.

- POD analysis showed that where present in the SPIV mean flow field results, the large-scale global recirculation structure had the highest kinetic energy of any identified flow structure. The first POD modes correlated strongly with the SPIV mean flow field, indicating that the large-scale structures were the dominant flow features. The second and third POD modes were representative of flow patterns generated by individual blade tip vortices as they impinged upon the ground plane.

The SPIV mean flow results showed large-scale flow structures consistent with the global recirculation hypothesis at 200 RPM, but limitations associated with the available field of view meant that further investigation would be undertaken with a planar PIV setup. Of particular importance was the measurement of all three velocity components, which was enabled by SPIV. The agreement between SPIV and 2D-2C planar PIV results was also able to provide justification for the use of 2D-2C planar PIV as a measurement technique given the complexity of the rotor wake flow field.
Chapter 5

Experiment Results - Stage II

Part of this chapter has been presented at the 40th European Rotorcraft Forum, please refer to Bourne et al. (2014b).

The SPIV results provided insight into the flow field generated by a rotor in ground effect hover, and confirmed the presence of a large-scale flow structure for a number of test conditions. The POD analysis presented in Section 4.5 confirmed that where the global recirculation was evident the flow structure was consistent with that presented in the SPIV mean flow fields, and not an unexpected combination of smaller-scale flow structures.

Analysis of the SPIV results indicated that a standing-vortex flow structure similar to that of the global recirculation hypothesis was evident at 200 RPM, and that it may also have been present at higher RPM test cases, however the field of view was a limiting factor when attempting to capture the structure in its entirety. Limitations of the experiment setup meant that the SPIV field of view could not be increased, so the investigation was transitioned to Stage II. An assessment of the magnitude of out-of-plane velocity components captured during the SPIV experiments, in combination with the flow characteristics of the test cases, justified the use of planar PIV for the analysis of the rotor wake outwash. It was acknowledged that the out-of-plane (swirl) component of velocity was not negligible, however, the flow component of greatest interest to this study is the wall-normal component, which was shown to be appropriately captured using 2D-2C PIV.

For each test case, the rotor wakes were assessed at distances above the ground plane (z) of 1D and 0.75D. Full results are presented in Appendix E, and include the in-plane mean velocity magnitude for each test case, along with the corresponding turbulence intensities. To confirm the SPIV findings B1 (15mm chord, 12° pitch angle) and B3 (20mm chord, 15° pitch angle) were tested at 200, 300 and 500 RPM, at a rotor height of 1D. The results, presented in figures E.37 - E.42, show that at 500 RPM there is no indication of up-flow or large scale
vortical structures. The vertical expansion of the rotor wake along the ground plane was a function of decreasing velocity and did not show evidence of a tendency toward up-flow and global recirculation.

5.1 Flow Structures at 200 RPM

The mean velocity contour plots for each test case are presented in figures 5.1 - 5.3, with full results presented in Appendix E. Table 5.1 presents the coordinates of the centre of the global recirculation region. For B1 at 200 RPM, at rotor heights of both the 0.75D and 1D, a global recirculation flow feature and up-flow is evident. At a rotor height of 0.75D the recirculation zone is centred at a height of 0.89D, and radial distance of 4.56R. With an increase in rotor height to 1D, the corresponding coordinates for the centre of recirculation are a height of 1.14D and radial location 5.96R. In both cases the recirculation centre point is above the height of the rotor, with the large-scale vortical structure closer to the rotor shaft for the 0.75D case. Interestingly the difference between the rotor height and the centre of the recirculation zone is the same (0.14D) for both the 0.75D and 1D results, showing that the global recirculation zone maintains a consistent offset from the rotor for B1 at 200 RPM. As anticipated, the maximum mean velocity magnitude is greater for the 0.75D case, where the rotor is closer to the ground plane and a higher radial velocity is expected. With respect to the global recirculation structure, both the $u$- and $v$-component turbulence intensity is larger for the 0.75D case, which is consistent with the trend for the mean velocity magnitude.

At 200 RPM both test cases for B2 show evidence of up-flow and global recirculation flow structures. The coordinates of the centre of the recirculation zone are 4.08R and 0.61D for the 0.75D test case, and 5.06R and 0.87D for the 1D test case. In both cases the height of the recirculation centre point is below the height of the rotor. When comparing the radial distance to the centre of the recirculation zone, the 0.75D results show the structure is closer to the rotor shaft than for the 1D case. Interestingly the velocity magnitude contour plots do not show a significant difference in magnitude between the 0.75D and 1D cases, other than the obvious difference in the geometry of the recirculation, however the 0.75D case does show increased turbulence intensity which is potentially be linked to the more compact nature of the recirculation structure.

When B3 is positioned at 0.75D there is a clear indication of up-flow, but the field of view is not large enough to definitively determine the presence of a global recirculation zone. Conversely, the 1D test case has a clearly identifiable region of recirculation, centred at 0.84D and 4.57R, which is below the height of the rotor and closer to the rotor shaft than the up flow
seen in the 0.75D test case at 5.41R. The velocity magnitudes for each test case are similar, with the 0.75D case showing higher radial velocity as expected. The turbulence intensity for the 1D case is greater than that of the 0.75D case, most likely owing to the geometry of the global recirculation structure evident in the field of view.

At 200 RPM there are progressive changes seen with increases to the blade pitch angle (12° B1 increasing to 15° B3), and increase in chord length (15mm B1 increasing to 20mm B3), both of which act to increase the thrust being produced by the rotor. Comparing B1 and B2 results, the increase in thrust lowered the centre of the global recirculation structure to a position below the rotor tip path plane and increased turbulence intensity. Comparing B2 and B3 results, the increase in thrust showed a significant increase in turbulence intensity, and whilst the 1D test case showed a stronger yet comparable global recirculation structure to the B2 result, it was not possible to definitively identify a vortical structure for the 0.75D Blade 3 test case. Although up-flow was present, which would indicate that the flow was likely to turn back toward the rotor, the full structure was outside the field of view.
Figure 5.1 Mean velocity magnitude contour plots overlaid with streamlines: B1, 200 RPM
5.1 Flow Structures at 200 RPM

Figure 5.2 Mean velocity magnitude contour plots overlaid with streamlines: B2, 200 RPM
Figure 5.3 Mean velocity magnitude contour plots overlaid with streamlines: B3, 200 RPM

<table>
<thead>
<tr>
<th>Blade Type</th>
<th>Rotor Height</th>
<th>Radial Distance (x/D)</th>
<th>Height (y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>2.28</td>
<td>0.89</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>2.98</td>
<td>1.14</td>
</tr>
<tr>
<td>B2</td>
<td>0.75D</td>
<td>2.04</td>
<td>0.61</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>2.53</td>
<td>0.87</td>
</tr>
<tr>
<td>B3</td>
<td>0.75D</td>
<td>3.0 (approx)</td>
<td>-</td>
</tr>
<tr>
<td>B3</td>
<td>1D</td>
<td>2.29</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 5.1 Global recirculation zone centrepoint coordinates, 200 RPM
5.2 Flow Structures at 300 RPM

Shown in figures 5.4 - 5.6 are the mean velocity contour plots calculated for test cases at 300 RPM, with full results presented in Appendix E. Table 5.2 presents the coordinates of the centre of the global recirculation region, where evident, for each test case. For B1 at 300 RPM and at a rotor height of 0.75D it is not possible to definitively locate the presence of global recirculation despite a clear indication of up-flow and overall flow characteristics indicative of a large-scale vortical structure. Recirculation is evident for B1 at a rotor height 1D, with the core of the structure located at 1.01D and 5.33R, which is effectively coincident with the rotor height above the ground plane. The turbulence intensity is greater for the 1D test case compared to results at 0.75D, which is consistent with the more tightly formed recirculation structure at 1D.

The B2 results at a rotor height of 0.75D show a large-scale flow structure that turns back toward the rotor disk, but rather than the relatively circular flow pattern seen at 200 RPM the flow field at 300 RPM results in a more oblique zone of recirculation. A core location for the global recirculation can still be identified, however the up-flow is more oblique. For B2 at a rotor height of 1D it is not possible to definitively locate a global recirculation zone, although there is some evidence of up-flow. The turbulence intensities for each test case are similar, although the 0.75D result does show higher values for both the \( u \)- and \( v \)-components. The global recirculation structure is clearly identifiable in the B3 results at a rotor height of 1D, with the centre of rotation located at 0.91D and 5.73R. When the height above the ground plane is decreased to 0.75D, it is not possible to identify a recirculation flow feature, although some up-flow is present. As expected the 1D test case shows a higher turbulence intensity owing to the presence of the large scale vortical flow structure.

Although two test points showed clear regions of global recirculation at 300 RPM, as shown by the streamlines in the mean velocity contour plot of figure 5.4, overall it appeared that the global recirculation zone was less robust under the increased thrust associated with the 100 RPM increase. Similarly to the SPIV results, a number of flow fields still displayed the characteristic up-flow that would be associated with a large-scale vortical structure, and it is possible that a further increase in the size of the field of view may have been able to identify global recirculation structures for those test cases.
Figure 5.4 Mean velocity magnitude contour plot overlaid with streamlines: B1, 300 RPM
Figure 5.5 Mean velocity magnitude contour plot overlaid with streamlines: $B_2$, 300 RPM
**Figure 5.6** Mean velocity magnitude contour plot overlaid with streamlines: B3, 300 RPM

### Table 5.2 Global recirculation zone centrepoint coordinates, 300 RPM

<table>
<thead>
<tr>
<th>Blade Type</th>
<th>Rotor Height</th>
<th>Radial Distance (x/D)</th>
<th>Height (y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>3.0 (approx)</td>
<td>-</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>2.67</td>
<td>1.01</td>
</tr>
<tr>
<td>B2</td>
<td>0.75D</td>
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<td>1D</td>
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<td>B3</td>
<td>0.75D</td>
<td>3.5 (approx)</td>
<td>-</td>
</tr>
<tr>
<td>B3</td>
<td>1D</td>
<td>2.87</td>
<td>0.91</td>
</tr>
</tbody>
</table>
5.3 Flow Structures at 500 RPM

There was no evidence of a global recirculation zone at 500 RPM, as shown in the results of B1 and B3 in figure 5.7. Given the lack of consistent results at 300 RPM, and no evidence of recirculation at 500 RPM, tests were not conducted at 1000 RPM. Although it is not possible to definitively determine whether the recirculation zone is outside the field of view, similar experiments by Lee et al. (2008), Sydney et al. (2011), Rauleder and Leishman (2012) and Sydney and Leishman (2013) also failed to report a large-scale recirculation structure. Instead their results showed the rotor wake expanding radially along the ground plane without any tendency for large-scale recirculation. Hence it appears more likely that the flow structure does not exist at higher RPM.

Given all test cases at 300 RPM showed some sign of the upflow indicative of a large-scale recirculating structure, it is likely that a larger field of view would have enabled the full structure to be captured. It is also likely that somewhere between 300 and 500 RPM the global recirculation feature "uncurls" and transitions to a radially expanding outwash. This would likely be caused by the strengthening of the blade tip vortices with increasing thrust, which would increase the strength of the radial component of the outwash. Unfortunately the further testing required to resolve this uncertainty was not possible due to resource constraints.
Figure 5.7 Mean velocity magnitude contour plot overlaid with streamlines: 500 RPM
5.4 Global Recirculation

Shown in table 5.3 are the coordinates of the core of the global recirculation feature, where evident, in the mean flow results. Comparing the results for B1 at 200 RPM, a 25% increase in the rotor height above the ground plane from 0.75D to 1D increased the height of the recirculation zone core by 25%, and moved it further outboard by 27%. The same change in rotor height for B2 increased the height of the recirculation zone core by 35%, and moved it outboard by 21%. The increase from 200 to 300 RPM represents an increase in thrust of approximately 40%. Results showed that the increase in downwash velocity moved the core location of the recirculation zone further inboard, as well as decreasing its height above the ground plane.

When considering the impact of varying blade characteristics on the location of global recirculation region, the increase in chord length between B1 and B2 is a 15% increase thrust, and the increase in collective pitch angle between B2 and B3 also yields a 30% increase in thrust. At a rotor height of 0.75D, the position of the core location of the recirculation region generated by B1 is further outboard by 11%, and 37% higher than for B2. At 1D the core location generated by B1 is also further from the rotor shaft than the large-scale flow structure generated by B2, with an increase in core height of 27% and increase in outboard location of 11%. Comparing B1 to B3 at 1D similar results were obtained, with the core of the recirculation structure generated by B1 further outboard by 26%, and higher by 30%. The same trend was also seen comparing B2 to B3 at a rotor height of 1D; however there was a marked reduction in the difference between the results. The mean flow generated B2 had a global recirculation region core located only 0.035% higher and 10% further outboard by than the B3 result. Overall, the increase in thrust associated with changes to the blade parameters acted to move the global recirculation zone core location closer to the rotor, and decrease its height above the ground plane.

The increase in thrust associated with the increase in RPM also acted to change the location of the recirculation zone core position. The B1 result followed previous trends, with the 200 RPM mean flow field showing a recirculation region core 11% further outboard and 12% closer to the ground plane when compared to the 300 RPM case. Conversely, the B3 results showed a reversed trend. At 300 RPM the core of the global recirculation zone was 23% further outboard, but only 0.08% higher than the 200 RPM case. The conflicting trends indicate that changes to recirculation region position are more variable with the 100 RPM increase, than for changes to blade properties and height above the ground plane. This result is not surprising given the increase in RPM from 200 to 300 represents the biggest change in thrust across all of the test cases.
Somewhat counter-intuitively an increase in thrust generally acted to bring the core of the recirculation region further inboard and closer to the ground plane for the test cases assessed. The exception was the B3 result at 1D, where the increase from 200 to 300 RPM resulted in the large-scale vortical structure being pushed higher and further outboard. Some care must be taken when interpreting these results, as although several test points were repeated and similar geometry of the recirculation zone noted, the State II results in Section D show that the large-scale vortical structure was not always persistent. As such, comparison of the mean flow structures can be taken as indicative of general trends, but the absolute variation between test cases is likely to fluctuate given the inherent unsteadiness in the rotor wake.

<table>
<thead>
<tr>
<th>200 RPM</th>
<th>(x/D)</th>
<th>(y/D)</th>
<th>300 RPM</th>
<th>(x/D)</th>
<th>(y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1, 0.75D</td>
<td>2.28</td>
<td>0.89</td>
<td>B1, 0.75D</td>
<td>3.0 (approx)</td>
<td>-</td>
</tr>
<tr>
<td>B1, 1D</td>
<td>2.98</td>
<td>1.14</td>
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<td>2.67</td>
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<tr>
<td>B2, 0.75D</td>
<td>2.04</td>
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<td>B3, 1D</td>
<td>2.29</td>
<td>0.84</td>
<td>B3, 1D</td>
<td>2.87</td>
<td>0.91</td>
</tr>
</tbody>
</table>

*Table 5.3 Coordinates of global recirculation core*
5.5 POD Analysis

A subset of the experimental test cases were analysed using POD in order to identify whether there were inherent differences in any of the underlying flow structures. Much as for the SPIV analysis, the aim of implementing POD was to ascertain whether the global recirculation flow structure was indeed a dominant single structure, or whether it comprised of several different flow structures that when combined gave the impression of large-scale recirculation. For each case the energy associated with the first 10 POD modes is presented in Appendix G, along with visualisation of the first three modes. As noted in the discussion of basic POD theory in Section 3.11.1, caution should be exercised when interpreting non-dominant POD modes as they may not be truly indicative of flow motion unless the structures in question are of consistent size and position throughout the dataset. Consequently, only the first three POD modes are analysed for each test case. For reference, figures 5.8 and 5.9 present the planar PIV in-plane mean velocity contour plots, and the first POD mode is shown in figures 5.10 and 5.11. Figures 5.12 to 5.15 present the second and third modes respectively. In all cases the rotor height is 0.75D.

5.5.1 200 RPM

For B1 at 200 RPM the first POD mode accounted for 63.7% of the total flow kinetic energy and yielded a similar flow structure to the PIV mean velocity flow field. In both cases the global recirculation zone can be clearly identified. The second mode, which comprised 4.2% of the total flow energy, showed a flow structure representative of the up-flow associated with a global recirculation zone. The difference between the location of the centre of recirculation in the first and second modes can be interpreted as evidence that the flow structure meanders with time. The third POD mode, which accounted for only 1.3% of the flow energy, appeared a weaker version of the mode two result.

POD mode 1 for B1 at 300 RPM represented 66.4% of the total flow energy, and replicated the flow structure seen in the PIV mean flow results. The dominant flow feature was consistent with a large-scale structure, and showed a clear tendency toward up-flow. As with the result at 200 RPM, the second mode showed a flow structure similar to the large-scale flow structure, although with significantly reduced magnitude. In this case mode two only accounted for 1.5% of the total flow energy. The third POD mode, making up 1.15% of the flow energy, showed evidence of the individual blade tip vortex position at the ground plane. Although a weak flow when compared to the mean result, the geometry of the structure is what would be expected for the averaged position of a blade tip vortex as it propagates along the ground plane. As
mentioned previously, due to the unsteady nature of the rotor wake the mean flow results tend to smear individual vortex structures into regions of local velocity maxima.

For B3 at 200 RPM the first POD mode accounted for 58.3% of the total flow kinetic energy, and was consistent with the PIV mean velocity flow field. It was possible to identify evidence of up-flow, but not recirculation. Interestingly, the second mode, which accounted for only 1.8% of the flow energy, did appear to show a global recirculation structure with a clearly identifiable core position, which was similar to the mode two results for B1. Given the second mode is of significantly lower energy than the first, the result should be interpreted with caution, but it could infer that global recirculation was present in some of the instantaneous snapshots, and that the overall flow structure meanders with time. The third POD mode, which constituted 1.45% of the flow energy, showed a flow pattern consistent with blade tip vortex interaction with the ground plane. Similarly to the B1 mode three result, the geometry of the structure is not a clearly defined vortex, but does show the hallmarks of distortion expected from an ensemble average.

5.5.2 300 RPM

The first POD mode for B3 at 300 RPM represented 66% of the total flow energy, and reflected the PIV mean velocity flow field results. There was no clear sign of recirculation, but up-flow was present. The second mode made up 1.2% of the flow energy and was indicative of blade tip vortex motion across the ground plane. A similar result was seen in the third POD mode, which accounted for 1.1% of the total flow energy, with a wave-like pattern of rotating flow along the ground plane. In all test cases the first POD mode was dominant, with subsequent modes representing a significantly smaller portion of the total flow kinetic energy. For test cases where a large-scale global recirculation structure was not evident in the mean flow field but where up-flow could be identified, the second POD mode yielded evidence of large-scale vortical structures in the underlying flow field. For these cases it is suggested that a large-scale region of recirculation was present in some portion of the instantaneous PIV flow fields, but that the structure meandered over time, most likely moving in and out of the field of view of the cameras. The mode two and mode three results also showed smaller-scale structures consistent with the motion of individual blade tip vortices along the ground plane.
Figure 5.8 PIV mean velocity magnitude contour plots, overlaid with streamlines: B1
Figure 5.9 PIV mean velocity magnitude contour plots, overlaid with streamlines: B3
Figure 5.10 Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 1, B1
**Figure 5.11** Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 1, B3
Figure 5.12 Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 2, B1
**Figure 5.13** Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 2, B3
Figure 5.14 Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 3, B1
Figure 5.15 Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 3, B3
5.6 Flow Structure Meandering

The POD analysis of the PIV results indicated it was likely that the large-scale global recirculation flow structures were meandering over time, and in some cases moving in and out of the field of view. Such oscillation would be consistent with the inherent unsteadiness of the rotor wake, but further analysis was required to confirm the POD result. Although the global recirculation structure resembles a standing vortex, it is formed by a curl in the flow associated with the motion of the blade tip vortices. The method used to approximate the centre of the large-scale recirculation structure is based on signum operations that look to identify areas of rotation in the flow Holmen (2012), as outlined in Section 3.11.2.

In order to account for the characteristics of the flow structures captured in the instantaneous PIV results, rather than the ensemble average, the location of the centre of recirculation was estimated by taking the mean of all the points that were identified as representing vortical motion. To address the issue of false positives arising from regions of flow that captured the blade tip vortices, the region of interest was confined to a height above the ground plane of 0.25D which captured the bulk of the rotor wake outwash in each image.

For test points where a large vortical structure was identified, an estimate for the core location was calculated for each instantaneous image. The results were then overlaid on the mean flow field to provide an illustration of the movement of the core across the ensemble average, as shown in figures 5.16 and 5.17. Individual variation in the vertical and horizontal positions are presented in separate plots in Appendix H to demonstrate the variation in core position, and are normalised by the smallest value in each respective dataset. Each dataset contained 1000 images, representing an acquisition interval of approximately 20 minutes. Where it was not possible to identify the global recirculation zone and associated position of the core of the vortical structure in an instantaneous image, the State II result returned was excluded from the final dataset. As such, the test cases present fewer than 1000 data points in total. The test cases discussed here are the same as those presented in Section 5.12. The rotor height for each case was 0.75D, as indicated by the dashed horizontal line in figures 5.16 and 5.17. Also shown in each plot is the location of the mean value of the instantaneous images, indicated by a light blue dot.
**Figure 5.16** Mean velocity magnitude contour plot overset with instantaneous estimates for location of global recirculation zone core: B1, 0.75D. The mean value of the instantaneous data is also shown.
Figure 5.17 Mean velocity magnitude contour plot overset with instantaneous estimates for location of global recirculation zone core: B3, 0.75D. The mean value of the instantaneous data is also shown.
5.6.1 B1, 200 RPM

The mean flow field generated by B1 operating at 200 RPM shows a large-scale vortical structure congruous with global recirculation. Analysis of the instantaneous images shows a recirculation centre-point skewed toward an inboard location which is not fully aligned with the mean flow centre of recirculation. This is most likely due to the associated strength of the flow, indicating that the instantaneous structures with greater flow velocities exhibited up-flow and large-scale vortical structures in positions more coincident with the mean flow result. The variation in the position of the estimated core locations suggests the large-scale flow structure does meander over time, and that the movement is relatively significant given the geometry of the structure. Both the horizontal and vertical variation in core location, presented in Figures H.1 and H.2 respectively, show oscillatory trends consistent with large-scale structure meandering. The horizontal component of the instantaneous estimates for core location show an overall increase, implying the structure moves outboard with time. Although there is a large amount of relatively high frequency fluctuation, the average initial position is approximately 0.57R closer to the rotor shaft than the average location in the final images of the ensemble. There also appears to be an underlying, long-period oscillation of lower-frequency fluctuation, which would suggest it may be regular motion. Such oscillation in the horizontal plane would be consistent with the expected instability of the rotor wake as the outwash expands radially and incorporates the effects of blade tip vortex interaction. The vertical component of the estimated core position does not show the same, long-period variation. The oscillation evident in the results shows a more consistent mean value throughout the dataset, without a clear cumulative trend either upward or downward.

5.6.2 B1, 300 RPM

Results for B1 operating at 300 RPM do not show a clearly defined large-scale vortex structure, but there is evidence of up-flow consistent with a global recirculation region. Although there is no clear recirculation zone evident in the mean flow field, the estimates for the position of a large-scale vortical structure core as shown in figure 5.16, fall in the location expected if the recirculation was present but larger than the field of view. This supposition is supported by the second mode of the POD analysis (refer figure 5.12), which indicates a recirculation zone is present in the flow despite the mean flow field result lacking definitive identification of a large-scale vortex structure. The variation in the horizontal and vertical components of the core location estimates, presented in figures H.3 and H.4, display oscillation consistent with
fluctuation in position of the large-scale flow structure. The horizontal variation in position does not show clear indication of a long-period oscillation, and shows less variation between final and initial positions when compared to the 200 RPM case. In the vertical, there appears to be an underlying long-period variation in the core position which implies there is a regular vertical fluctuation in the position of the large scale structure.

### 5.6.3 B3, 200 RPM

The mean flow field generated by B3 at 200 RPM does not conclusively show a zone of global recirculation, but a region of up-flow identified within the field of view. When the estimates for core location are plotted with respect to the mean flow, as shown in figure 5.16, vortical motion is identified inboard of the up-flow region which would be consistent with a large-scale vortex structure that moves beyond the field of view. This result is congruent with the second POD mode (see figure 5.13) which implies there is some recirculation present in the flow. Regular oscillation is evident in both the horizontal and vertical elements of the instantaneous estimates for core location, as shown in figures H.5 and H.6, which confirms the fluctuation of the large-scale structure with time. Neither component shows the long-period variation seen in the B1 results. In the horizontal, estimates for the core position show more erratic fluctuation than in the vertical case, and greater variation in the mean position over time. In contrast, there appears to be a relatively stable mean value in the vertical results, implying less variation in the average vertical position of the core.

### 5.6.4 B3, 300 RPM

At 300 RPM the B3 mean flow field shows less evidence of large-scale flow structure, although up-flow is still captured within the field of view. The points identified during analysis of the instantaneous images as representing vortical motion in the flow are clustered at the top boundary of the image as per 5.16, at a location just inboard of the initial up-flow. The POD analysis does not suggest any underlying flow structure to that presented in the mean flow field, and it must be concluded that if a large-scale vortex structure is indeed generated, it is beyond the field of view. Results of the estimates for core position in the horizontal and vertical, presented in figures H.7 and H.8, both show relatively consistent mean values for the large-scale structure location over time. There is significantly greater variation in the horizontal component of the position estimate, indicating that the structure captured within the field of
view does oscillate radially, but may not necessarily represent a large-scale vortex structure. It may instead be a reflection of the inherent unsteadiness of the rotor wake downwash and outwash, which fluctuates cyclically over time. Vortical motion captured by the instantaneous images may be a result of the relatively weak flow interaction at the boundary of the up-flow region, which would be expected to cause some swirl and rotation.

5.6.5 Variation in Core Location

Presented in Table 5.4 are the maximum horizontal and vertical variations in the instantaneous estimates for the core position of the global recirculation zone. For the B1 test cases, increasing RPM had the effect of increasing variation in the horizontal direction, whereas the vertical variation remained relatively consistent. For B1 the increase in thrust associated with increasing RPM saw greater movement in the radial position of the large-scale vortex structure. This result was not surprising given the horizontal position of the large-scale flow structure is driven by the momentum of the rotor outwash, where the dominant velocity is along the ground plane. As such, greater variation was expected in the horizontal position than in the vertical. At 300 RPM the up-flow associated with the large-scale recirculating structure was weaker than the 200 RPM case, potentially allowing for greater fluctuation in the structure’s position over time. With a weaker trend toward up-flow, the 300 RPM case would be more heavily influenced by the instabilities of the outwash as it expanded radially across the ground plane, which would in turn account for greater fluctuation in the horizontal position of the recirculation zone core. The difference between the horizontal variation between the 200 and 300 RPM test cases is approximately 20%, which given the similarity in vertical variation, essentially accounts for the bulk of the difference seen with the increase in RPM.

<table>
<thead>
<tr>
<th></th>
<th>Horiz. Variation (x/D)</th>
<th>Vert. Variation (z/D)</th>
<th>Mean (x/D)</th>
<th>Mean (z/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1, 200 RPM</td>
<td>1.04</td>
<td>0.62</td>
<td>3.00</td>
<td>1.03</td>
</tr>
<tr>
<td>B1, 300 RPM</td>
<td>0.87</td>
<td>0.33</td>
<td>3.50</td>
<td>1.06</td>
</tr>
<tr>
<td>B3, 200 RPM</td>
<td>0.88</td>
<td>0.44</td>
<td>2.27</td>
<td>0.91</td>
</tr>
<tr>
<td>B3, 300 RPM</td>
<td>1.04</td>
<td>0.40</td>
<td>2.99</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Table 5.4 Maximum variation in position of estimated core location and the corresponding mean values for each instantaneous dataset. In all cases the rotor height is 0.75D.

The B3 test cases show less variation with increasing RPM. Both the horizontal and ver-
tical variations in position of the large-scale recirculation zone show a change of approximately 12% with an increase from 200 to 300 RPM. Interestingly the 12% change corresponds to an increase in the horizontal variation, but a decrease in the vertical variation. Neither of the B3 mean flow results reveal a definitive region of global recirculation, although combined with the POD analysis there is greater evidence of a large-scale vortex structure present within the ensemble average of the 200 RPM test case. There is an increase the horizontal movement of the structure as the RPM is increased, but the difference is not as marked as for the B1 test cases.

Compared to the B1 results, the B3 flow fields show reduced strength the wake up-flow. The magnitude of the up-flow velocity reduces with increasing RPM, a trend which is consistent with B1. The percentage difference between the horizontal variation and vertical variation of core location for B3 is 68% at 200 RPM and 88% at 300 RPM. For B1 at 200 RPM the percentage difference between the horizontal and vertical variation in core location is 63%, increasing to 82% at 300 RPM. This similarity indicates that the relative variation in position of the large-scale flow structure is smaller for the 200 RPM test cases, and that the difference between horizontal and vertical variation in core position is consistent with an increase from 200 to 300 RPM. Regardless of the maximum values of the variation in the flow structure’s position, it is evident from the results in figure 5.16 that increasing RPM increases the horizontal movement in the structure over time, and that the vertical variation is more closely linked to the strength of the of the large-scale recirculation structure.

5.7 Transient Flow Field Patterns

The motion of the blade tip vortices is inherently aperiodic (refer Rauleder and Leishman (2012) and Mula et al. (2012)), a characteristic which promotes both azimuthal fluctuation in the rotor wake and unsteady motion of the blade tip vortices as they impinge upon the ground plane. The POD analysis indicated that the large-scale recirculation structures could be unsteady but it was not possible to definitively identify the flow mechanisms which were responsible for the large-scale structures. In order to further investigate the underlying flow mechanisms associated with the mean flow results, analysis was undertaken into the flow features evident in the instantaneous SPIV images.

5.7.1 Instantaneous PIV Results

To better understand the progression of the blade tip vortices as they impinged upon the ground plane in cases where the global flow field tended toward up-flow that curled back toward the
rotor disk, the instantaneous images were assessed for consistency with the POD analysis. Presented in figure 5.18 are a selection of instantaneous PIV images captured for B1 operating at 0.75D and 200 RPM. The full ensemble was made up of 1000 images, with image A the fourth image in the series, image B number 219, image C number 501, image D number 772 and image E number 995. In all cases a region of up-flow is evident, as is the tendency of the outwash to curl back toward the rotor. The instantaneous images also highlight the large-scale flow structure meandering, as radial oscillation of the large-scale flow feature can be seen throughout the ensemble.

**Figure 5.18** Instantaneous images: B1, 0.75D, 200 RPM
5.8 Chapter Summary

The analysis of the planar PIV results showed the following:

- Robust large-scale flow structures indicative of global recirculation conditions were present at 200 RPM for all test cases investigated.

- At 300 RPM a global recirculation zone could be identified for the B1 results, but the mean flow fields for B3 test points were not conclusive.

- No evidence of a large-scale structure was seen at 500 RPM.

- POD analysis confirmed the SPIV findings that, where present, the large-scale global recirculation structures were the dominant flow features. Underlying flow structures were consistent with the motion of individual blade tip vortices.

- Analysis indicated that the position of the recirculation zone core oscillated over time. This finding is consistent with the aperiodic nature of the motion of the blade tip vortices, whose interaction with the ground plane drive the development of the global recirculation flow structure.

- Increasing rotor thrust\(^1\) decreased the strength of the global recirculation region. Although the global recirculation zone was only identified over a limited thrust range, decreasing the strength of the global recirculation could potentially ameliorate the adverse effects of brownout by decreasing the strength of the large-scale flow structures which are capable of entraining particulates.

\(^{1}\)Increasing blade angle of attack and chord length, increasing RPM and increasing proximity of the rotor to the ground plane all acted to increase the rotor thrust.
Chapter 6

Experiment Results - Stage III

Part of this chapter has been presented at the 40th European Rotorcraft Forum, please refer to Bourne et al. (2014b).

To better understand the sensitivity of the flow structures to ground-based objects, circular metal "trip strips" were installed on the ground plane. For reference, an illustration of the trip strip profiles and installation with respect to the rotor assembly are presented in figures 6.1 and 6.2. Each trip strip had a diameter of 2.1D with the height of the cross-section 1.67% of the ring diameter. The diameter was chosen to be approximately coincident with the location of the rotor wake impingement upon the ground plane, being the point at which radial velocity is maximal and the effect of the trip-strip likely to be maximised. The height of the cross-section was representative of medium-sized obstacles likely to be seen during full-scale operations1, and the circular design was implemented to ensure a uniform interaction with the rotor wake. The geometry of the two cross-sections were chosen to assess the difference between sharp and smooth-edged objects. Given the persistence of the flow structure at 200 RPM and evidence of its decay with increasing thrust, the trip strips provided a mechanism for determining the robustness of the flow structures, particularly whether a ground-based impediment would act to promote or inhibit formation of the large-scale vortical flow. Full results are presented in Appendix F, which include the mean velocity magnitude contour plot for each test case, along with the corresponding turbulence intensities.

1For a typical full-scale rotor diameter of 16.3m this corresponds to obstacles approximately 0.75m high
Figure 6.1 Ground-based trip strip profiles: curved-edge TS1 (top) and square TS2 (bottom)

Figure 6.2 Ground-based trip strip installation: 2D view (top) and 3D view (bottom)
6.1 Flow Structures at 200 RPM

With the ground based trip-strips installed, B1 (15mm chord, 12° pitch angle) was tested at rotor heights of 0.75D and 1D with both the curved-edge (TS1) and square-edged (TS2) trip strips. B2 (20mm chord, 12° pitch angle) was also tested at 1D with TS1 and TS2. Presented in figures 6.3 to 6.8 are the mean velocity magnitude contour plots and \( v \)-component turbulence intensities for each test case. For reference, the radial location of the trip strip is indicated by a green dot in the mean velocity magnitude contour plots. It can be seen that the flow is deflected up and over the trip strip, however the deflection is not so large as to overcome the radial outwash and initiate up-flow. The effect of the curved-edge and square-edge trip strip profiles on the near-wall flow is similar, with no significant difference in the magnitude of the flow deflection, nor subsequent change to the overall flow profile. This result indicates that the near-wall flow structure is more dependent on the characteristics of the radial flow than on the geometry of the trip-strip profile for the cross-sectional sizes tested.

For B1 at a rotor height of 0.75D, a global recirculation zone is evident with both TS1 and TS2 installed. The recirculation zone persists when the rotor height is increased to 1D, as shown in figures 6.3 - 6.6. Turbulence intensity is greater at 0.75D when compared to the 1D test case, given the relative increased velocity of the flow and increased proximity of the global recirculation core to the ground plane. Unlike the B1 results, the global recirculation flow structure was only evident for B2 with TS1 installed. The B2 flow field for TS2 only showed initial tendency toward up-flow at the edge of the field of view, where the flow velocity was relatively low. The deflection of the flow field as it interacted with the trip-strips was less pronounced than for the B1 test cases, most likely due to the increased thrust associated with B2 and subsequent increase in outwash velocity. Consistent with previous results, the turbulence intensity was higher for the test condition where global recirculation was present, in this case where TS1 was installed.

Table 6.1 lists the coordinates of the centre point of the global recirculation zone for each test case, and it is evident that the global recirculation flow feature was persistent across all B1 test points. For B1 at 1D the centre of recirculation in the vertical direction was the same for both TS1 and TS2, whereas there is a difference of approximately 17% in the radial location. When comparing the 0.75D results, the difference in radial direction to the centre of the global recirculation zone was approximately 14%, increasing to 25% in the vertical. The TS1 result for B1 at 0.75D yielded a particularly tight structure for the global recirculation, but overall there were no major differences in the flow fields caused by difference in the geometry of TS1 and TS2.
Experiment Results - Stage III

<table>
<thead>
<tr>
<th>Blade Type</th>
<th>Rotor Height</th>
<th>Trip-Strip</th>
<th>Radial Distance (x/D)</th>
<th>Height (y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>-</td>
<td>2.28</td>
<td>0.89</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>TS1</td>
<td>2.06</td>
<td>0.60</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>TS2</td>
<td>2.35</td>
<td>0.82</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>-</td>
<td>2.98</td>
<td>1.14</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>TS1</td>
<td>2.54</td>
<td>0.92</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>TS2</td>
<td>2.97</td>
<td>0.91</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>TS1</td>
<td>3.02</td>
<td>1.03</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>TS2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 6.1 Global recirculation zone centre-point coordinates, 200 RPM*

*Figure 6.3 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 0.75D, 200 RPM, TS1*
6.1 Flow Structures at 200 RPM

Figure 6.4 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 0.75D, 200 RPM, TS2
Figure 6.5 Mean velocity magnitude contour plot overlaid with streamlines (top) and $v$-component turbulence intensities (bottom): B1, 1D, 200 RPM, TSI
Figure 6.6 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 1D, 200 RPM, TS2
Figure 6.7 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B2, 1D, 200 RPM, TSI
Figure 6.8 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B2, 1D, 200 RPM, TS2
6.2 Flow Structures at 300 RPM

Presented in figures 6.9 - 6.14 are the mean velocity contour plots and $v$-component turbulence intensities for test cases at 300 RPM with the trip-strips installed on the ground plane. As for the 200 RPM results, the radial location of the trip strip is indicated by a green dot in the mean velocity magnitude contour plots. Unlike the test cases at 200 RPM, only one of the 300 RPM test cases showed a clear region of global recirculation. At a rotor height of 0.75D with TS1 installed, the mean B1 global flow field yielded a large-scale recirculating pattern. In addition to a lack of large-scale recirculation zones, the mean flow results of both B1 and B2 at a rotor height of 1D also failed to show evidence of up-flow. These "State II" results are confirmed upon investigation of the $v$-component turbulence intensities, as there is no strong indication of flow recirculation in any case other than B1/TS1 at 0.75D. Although it is possible to identify vertical growth in the flow in all test cases from the results presented in figures 6.9 - 6.14, it should be noted that in all cases there exists a decrease in radial wake velocity as the outwash expands along the ground plane. As such, the low-velocity vertical regions seen for test cases that did not exhibit a global-recirculation type flow structure in the mean flow results are not likely to be indicative of up-flow.
Figure 6.9 Mean velocity magnitude contour plot overlaid with streamlines (top) and $v$-component turbulence intensities (bottom): B1, 0.75D, 300 RPM, TS1
Figure 6.10 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 0.75D, 300 RPM, TS2
Figure 6.11 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): BI, 1D, 300 RPM, TSI
Figure 6.12 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B1, 1D, 300 RPM, TS2
Figure 6.13 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B2, 1D, 300 RPM, TSI
Figure 6.14 Mean velocity magnitude contour plot overlaid with streamlines (top) and v-component turbulence intensities (bottom): B2, 1D, 300 RPM, TS2
6.3 Global Recirculation

In all test cases the effect of the trip strips on the radial velocity of the rotor wake was evident, as interference with a ground-based obstacle had the expected effect of inflecting the flow, increasing turbulence and decreasing the radial velocity. It was not possible to identify significant changes in the flow field as a result of the differences between the TS1 and TS2 profile geometries, however the introduction of the trip strips did appear to hinder formation of global recirculation for the 300 RPM test case. Although the trip strips impeded the radial flow of the downwash along the ground plane, it did not promote up-flow or the formation of a global recirculation structure. It is possible to conclude that the persistence of the large-scale recirculation structure at 200 RPM is not purely a function of the wake expansion rate in the radial direction.

Presented in table 6.2 are the test points at 200 RPM where a global recirculation region core could be identified, both for the isolated rotor and for test cases with the ground-based trip strips installed. For B1 at a rotor height of 0.75D there is consistency between the position of the global recirculation zone core for the isolated rotor test case, and the tests cases with the ground-based trip strips installed. The same is true of the B1 result at 1D, although the height of the large-scale vortical structure core is more elevated for the isolated rotor test case. In all, there is no marked difference between the global recirculation zone position in the wakes generated by B1, with and without the ground-based trip strips installed. At a rotor height of 1D, the B2 isolated rotor and TS1 test cases show evidence of a global recirculation zone, however this did not extend to the TS2 test case. Compared to the B1 results, there is greater variation in the location of the large-scale vortical structure with the introduction of the ground-cased trip strip in both the horizontal and vertical directions.

<table>
<thead>
<tr>
<th>Baseline</th>
<th>(x/D)</th>
<th>(y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1, 0.75D</td>
<td>2.28</td>
<td>0.89</td>
</tr>
<tr>
<td>B1, 1D</td>
<td>2.98</td>
<td>1.14</td>
</tr>
<tr>
<td>B2, 1D</td>
<td>2.53</td>
<td>0.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trip Strips Installed</th>
<th>(x/D)</th>
<th>(y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1, 0.75D, TS1</td>
<td>2.06</td>
<td>0.60</td>
</tr>
<tr>
<td>B1, 0.75D, TS2</td>
<td>2.35</td>
<td>0.82</td>
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<tr>
<td>B1, 1D, TS1</td>
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<td>0.92</td>
</tr>
<tr>
<td>B1, 1D, TS2</td>
<td>2.97</td>
<td>0.91</td>
</tr>
<tr>
<td>B2, 1D, TS1</td>
<td>3.02</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Table 6.2 Coordinates of global recirculation core at 200 RPM: baseline (left) and with trip-strips installed (right)
6.4 POD Analysis

A subset of the experimental test cases were analysed using POD in order to investigate the flow features underlying the mean flow result. Presented here is the POD analysis for the B1/TS1 combination at 200 RPM and a rotor height of 0.75D, and a rotor height of 1D at both 200 and 300 RPM. For reference, figure 6.15 shows the PIV-derived mean velocity contour plots for each test case and the corresponding first POD modes are presented figure 6.16. The velocity contour plots of the second and third POD modes are presented in figures 6.17 and 6.18. Full results for each test case are presented in Appendix G.

6.4.1 200 RPM

For B1 at 0.75D and 200 RPM with the curved-edge trip strip (TS1) installed, the first POD mode accounts for 58% of the total flow kinetic energy and correlates well to the mean flow result, with a clearly defined region of global recirculation. The second POD mode, which makes up 6.6% of the flow energy, shows the interaction of the large scale vortical structure with the region of ambient air, suggesting that there is some movement of the flow structure over time. The third POD mode reflects 2.13% of the total flow energy and is a weaker version of the mode two result.

Results for B1/TS1 at a rotor height of 1D and rotor RPM of 200, with TS1 installed, show that mode one represents 61% of the total flow energy and replicates the mean flow result. There is clear up flow and the centre of the recirculation region is also captured in the flow field. The second POD mode accounts for 2.7% of the flow energy, and shows a small-scale structure not dissimilar from the blade tip vortex structures evident at the ground plane in the isolated rotor test cases. The flow structure in this instance appears to rotate just inboard of the TS1 location, and is most likely representative of the interference between the ground-based trip strip and the rotor outwash. There is also a weak, large-scale structure in the flow field which appears to show confirmation of recirculation and interaction with ambient air. The third POD mode makes up 2.1% of the flow energy and shows a similar small-scale structure to the mode two result, just inboard of the trip strip. The large-scale structure identified in the flow field appears to be representative of global recirculation.
6.4.2 300 RPM

For B1/TS1 at 300 RPM and a rotor height of 1D, the first POD mode makes up 67.6% of the total energy of the flow and is consistent with the mean flow result. There is no clear evidence of global recirculation, and this supposition is supported by the second POD mode, which accounts for 1.6% of the flow energy and shows a small-scale rotational flow inboard of the ground-based trip strip, but no large-scale structure. The third POD mode accounts for 1.2% of the flow energy and very clearly shows the flow inflection over the ground-based trip strip. Similarly to mode two, there is no clear indication of a large-scale flow structure.

The POD analysis confirmed that in all cases assessed the dominant flow structure was that evident in the PIV mean flow field result, as the first POD mode of each test case reflected the same flow structure for each test case. In cases where there was some evidence of a global recirculation zone, such as up-flow without a definitive large-scale vortical flow, the second modes showed some evidence of recirculation. For these cases it is hypothesised that the global recirculation zone is present but meanders over time, and that the mean flow represents a position where the recirculation zone core is out of the field of view.
0.75D, 200 RPM

1D, 200 RPM

1D, 300 RPM

Figure 6.15 PIV mean velocity magnitude contour plots, overlayed with streamlines: B1/TS1
6.4 POD Analysis

0.75D, 200 RPM

1D, 200 RPM

1D, 300 RPM

Figure 6.16 Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 1, B1/TS1
**Experiment Results - Stage III**

*0.75D, 200 RPM*

*1D, 200 RPM*

*1D, 300 RPM*

**Figure 6.17** Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 2, B1/TS1
6.4 POD Analysis

$0.75D, 200\ \text{RPM}$

$1D, 200\ \text{RPM}$

$1D, 300\ \text{RPM}$

Figure 6.18 Mean velocity magnitude contour plots overlaid with streamlines: POD Mode 3, B1/TS1
6.5 Flow Structure Meandering

The analysis presented here was undertaken using the vortex identification method outlined in Section 3.11.2. The same B1/TS1 test cases were examined as for the POD analysis in the previous section. Presented in figure 6.19 are the estimated locations of the large-scale vortical structure core location across the instantaneous image ensemble, overlaid on the mean flow field for the relevant test case. Images on the left hand side are the TS1 results and images on the right hand side are the flow field results for the same rotor settings without any trip-strip installed. Full results for the TS1 test cases, which include variation in position of the core in both the horizontal and vertical directions across the instantaneous time series, are presented in Appendix H.

6.5.1 200 RPM

At 200 RPM and a rotor height of 0.75D, a region of global recirculation was evident in the mean velocity flow field. Compared to the test case with no trip-strip installed, the large-scale vortex structure generated with TS1 was of reduced magnitude. The installation of the trip-strip also appears to cause greater variation in the horizontal and vertical estimates for the recirculation zone core. Such fluctuation can be seen as indicative of the effect of decreasing the strength of the global recirculation. As the strength of the structure was reduced, its instability increased. Interestingly however, with the trip strip installed, the location of instantaneous estimates for core location was better aligned to the mean flow field result, potentially indicating that the trip strip regulated the position large-scale flow structure over time. Presented in figures H.9 and H.10 are the horizontal and vertical components of the core position estimates. In both cases the oscillation supported the fact that the large-scale flow structure meandered over time. The horizontal fluctuation showed some evidence of a long-period oscillation, with an overall increase in the outboard location of the flow structure across the ensemble. Similarly the vertical position of the core estimate gradually increased across the dataset, though in a slightly more linear fashion than the horizontal component, indicating that the height of the structure increased with time. When compared to the isolated rotor case (refer figures H.1 and H.2), the installation of the trip strip appeared to cause cumulative drift in position of the large-scale flow structure.

At 200 RPM and a rotor height of 1D a large-scale global recirculation structure was generated with TS1 installed. Although it is close to the upper bounds of the field of view, the result was sufficient to confirm the presence of a global recirculation region. The structure was
also identified within the first mode of the POD analysis (refer figure 6.16). Referring to figure 6.19, estimates for the location of the core of the vortical structure are positioned, as expected, inboard of the up-flow region and show less spread in the vertical direction when compared to the result without trip-strips installed. Figures H.11 and H.12 show the horizontal and vertical estimates for the core position across the ensemble of instantaneous images. The horizontal fluctuation showed regular, large displacement with some elements of long-period oscillation. There was an overall increase in the outboard location of the core position across the dataset, but it was not as pronounced as for previous results. In the vertical, the fluctuation shows less variation than the horizontal component, and maintained oscillation about a relatively regular mean value until late in the data acquisition period. There appeared to be an increase in unsteadiness in the last 200 frames, though it is difficult to account for the source of the increase in fluctuation.

### 6.5.2 300 RPM

At 300 RPM and a rotor height of 1D, the mean flow field did not show flow structures consistent with up-flow or recirculation that would be expected for a large-scale vortical structure; however, a weak vortical structure can be identified at the upper boundary of the mean flow result. Estimates for the core location of vortical motion across the instantaneous image ensemble, shown in figure 6.19, are concentrated in the same area of the flow field as the centre of recirculation would be expected to be located if the mean flow field results were extrapolated beyond the field of view. Although this cannot be considered definitive evidence of a large-scale vortical structure, it implies that some vortical motion is persistent throughout the dataset. Figures H.13 and H.14 show the horizontal and vertical estimates for the position of vortical flow. There is relatively high frequency fluctuation in both components of the core position, without any suggestion of underlying long-period oscillation or cumulative drift in the structure over time. Without any large-scale recirculation or up-flow structures within the field of view, the vortex identification is limited to areas of relatively weak flow. Similarly to the isolated rotor result with B3 at 300 RPM (refer figures 5.16, H.7 and H.8), the analysis may instead reflect the interaction of "ambient air" with the radially-expanding rotor outwash.
**Figure 6.19** Mean velocity magnitude contour plot overset with instantaneous estimates for location of global recirculation zone core: B1/TS1 (top), B1 baseline (lower)
6.5 Flow Structure Meandering

**B1, 1D, 200RPM (TS1)**

![Mean velocity magnitude contour plot overset with instantaneous estimates for location of global recirculation zone core: B1/TS1 (top), B1 baseline (lower).]

**B1, 1D, 200RPM (no trip strips)**

![Mean velocity magnitude contour plot overset with instantaneous estimates for location of global recirculation zone core: B1/TS1 (top), B1 baseline (lower).]

**Figure 6.20** Mean velocity magnitude contour plot overset with instantaneous estimates for location of global recirculation zone core: B1/TS1 (top), B1 baseline (lower)
6.5.3 Variation in Core Location

Presented in table 6.3 are the maximum horizontal and vertical variations in the instantaneous estimates for the core position of the global recirculation zone. The variation in the horizontal position of the vortex structure across the ensemble of instantaneous images is extremely similar to the test cases without the trip strip installed. This result suggests that the large-
scale flow structure generated at rotor height of 0.75D and 200 RPM is relatively robust and repeatable, with very consistent fluctuation in its horizontal position. Results for the vertical variation are less consistent as installation of the trip strip markedly increases the range of oscillation in the vertical position of the large-scale flow structure. One reason for this may be the increase in turbulence intensity in the vertical direction with the trip strip installed (refer figure F.3). Increased turbulence generally acts to decrease flow structure stability, which would result in greater fluctuation of the position of the flow structure with time. It follows that the percentage difference between horizontal and vertical variation of the structure’s core location is smaller for the TS1 case, than for the isolated rotor results.

<table>
<thead>
<tr>
<th>B1 / TS1</th>
<th>Horiz. Variation (x/D)</th>
<th>Vert. Variation (y/D)</th>
<th>Mean (x/D)</th>
<th>Mean (y/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75D, 200 RPM</td>
<td>0.49</td>
<td>0.41</td>
<td>2.02</td>
<td>0.67</td>
</tr>
<tr>
<td>1D, 200 RPM</td>
<td>0.37</td>
<td>0.45</td>
<td>2.50</td>
<td>1.03</td>
</tr>
<tr>
<td>1D, 300 RPM</td>
<td>0.64</td>
<td>0.26</td>
<td>3.67</td>
<td>1.07</td>
</tr>
</tbody>
</table>

*Table 6.3 Maximum variation in position of estimated core location, and the corresponding mean values for each instantaneous dataset: B1/TS1*

Increasing the rotor height to 1D decreases the associated variation in the flow structure’s core position. With clear evidence of up-flow and recirculation, there percentage difference between variation in the horizontal and vertical components is similar to the results without the trip strip installed; however, the overall values for the estimates of the flow structure oscillation are much smaller. Of all the test cases assessed, B1 operating at 200 RPM, 1D with TS1 installed shows the global recirculation structure with the least amount of fluctuation over time. With the blade installed at 1D, increasing the RPM to 300 yields estimates for a large-scale vortical structure core location that are likely based on the interaction of weak up-flow with ambient air, rather than vortical motion associated with global recirculation.
6.6 Operational Viability

The ground-based trip strips showed promise in their reduction of key flow parameters likely to contribute to the severity of brownout conditions. As such, they warrant further investigation given the relative ease with which such a structure could be deployed operationally. Further testing would need to take place at conditions that better replicate full-scale blade loading in order to assess whether the ground-based trip strips alter the flow in a manner that improves visibility for the aircrew. A parametric study to assess a range of cross-sectional geometries and diameters would be able to identify optimum sizing, and this could then be tested with a dual-phase laboratory experiment, or indeed at full-scale if such resources were available.

6.7 Chapter Summary

Installation of ground-based trip-strips to disturb the near-wall flow yielded the following results:

- For B1 at 0.75D the trip-strips did not significantly alter the global flow field. In all cases a large-scale recirculation structure could be identified and the change to the position of the global recirculation zone core was not significant.

- For B1 at 1D results were also qualitatively similar in structure to the baseline test case where trip strips were not installed. However, both TS1 and TS2 results yielded the same change to the horizontal position of the global recirculation core, but the TS1 result also showed a change to the vertical position of the core location.

- For B2 the introduction of TS1 increased both the vertical and horizontal location of the global recirculation zone core.

- Overall the results at 0.75D did not show the same sensitivity to the introduction of trip-strips as the results at 1D.

- Investigation of the movement of the large-scale global recirculation region indicated that the trip-strips decreased the in-plane velocities associated with the large-scale flow structure. Reducing the magnitude of the in-plane velocities associated with upflow and recirculation may act to reduce the severity of brownout conditions by reducing the strength of flow structures capable of entraining particulates.
Chapter 7

Experiment Results - Stage IV

Part of this chapter has been presented at the 18th Australasian Fluid Mechanics Conference, please refer to Bourne et al. (2012).

The final investigation assessed the potential of both passive and active defectors to influence the region of flow near to the fuselage. Inherent to this approach were the following presumptions relating to the flow field present during brownout conditions:

1. Maintaining a region of clear air close to the fuselage for the duration of a landing manoeuvre will increase the safety of operations.

2. The airflow inboard of the slipstream boundary generated by the blade tip vortices is a comparatively weak component of the rotor wake downwash, without distinct structure.

3. Influencing the rotor wake slipstream could influence the geometry and persistence of the region of clear air.
7.1 Smoke Flow Visualisation

7.1.1 Experiment Setup

A preliminary investigation was undertaken using smoke flow visualisation. A sub-scale rotor model with a rotor diameter of 1200 mm was mounted in the DST LSWT at 0.5D from the ground plane, a rotor height which maximised the ground effect condition. The rotor blades had a chord length of 50 mm and NACA0015 profile, without span-wise twist. In order to visualise the rotor wake structures, a light sheet was generated using a projector with the output beam constrained to pass through a single slit filter. A probe connected to an Aerotech smoke generator was positioned just above the blade tip, with its location optimised for clear visualisation of the blade tip vortices. To ensure that the region of interest was illuminated without obstruction, the ground plane was made of perspex to enable the light sheet to illuminate the ground plane beneath the rotor. For reasons of practicality, given the size of the rotor assembly and its supports, the ground plane was mounted above the rotor and the blade collective pitch set to -13°. This was the highest negative angle of attack achievable with the configuration and was chosen to maximise the thrust produced by the rotor. Figure 7.1 shows an image of the experiment setup as installed, and figure 7.2 provides a schematic of key apparatus positions in a conventional orientation.

Four deflectors were tested, three passive and one active. Each was fixed between the rotor and the ground plane as shown in figure 7.2. The rotor was positioned 0.5D above the ground plane and the deflectors installed 0.25D between the ground plane and the rotor, representing the indicative position of the underside of the airframe. Detailed in figure 7.3 are the profiles of the passive deflectors. Each had a radius of 600 mm (0.5D) with a thickness of 250 mm, and the profiles were chosen to assess the ability of basic geometry to radially deflect the flow. The active deflector, shown in figure 7.4, was constructed from two circular flat plates of 400 mm diameter, connected to a high-pressure compressed air supply. The flow rate of the compressed air was manually controlled by a valve, which was connected to a pressure gauge. $V_B$ refers to the airflow in the duct, and $V_X$ indicates the resulting radial flow. Given the size of the duct and the limitations of the available pressure of the compressed air supply, the system was set to the maximum available flow rate. At maximum pressure $V_X$ was measured using a handheld anemometer and found to be approximately 8 m/s at the outlet, dropping to 6 m/s at a radial distance of 50 mm, then decreasing by 1 m/s for every additional 50 mm.

Design of the deflectors was based on the simplest practical implementation given the test was considered an exploratory study to assess the merits of deflectors in general. Due to the

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1. 0.5D is considered the point at which a medium-lift helicopter would be very near to landing.
fact that the analysis was restricted to a qualitative assessment, the effect of the deflectors was measured by the change, if any, in the radial position of the blade tip vortices.

Figure 7.1 Equipment arrangement for flow visualisation study: image of experiment orientation without deflectors installed

Figure 7.2 Equipment arrangement for flow visualisation study: sketch of conventional orientation
7.1.2 Passive Deflectors

The blade tip vortices can be clearly identified in the baseline test case of figure 7.5 (image (a)). It should be noted that the rotor graphic is included for indicative position reference only, and is not to scale, and that the dashed line represents the position of the ground plane. The trajectory and location of the blade tip vortices is consistent with the behaviour of the rotor wake IGE (refer Section 1.2). The blade tip vortices are shed by the rotor and their radial position initially contracts toward the rotor centre line as they convect down toward the ground plane, before moving outboard as the rotor wake expands radially.

Results showed that all passive deflectors produced very little change in the flow structure of the blade tip vortices, as can be seen in images (b) - (c) of figure 7.5. Without being located in the direct path of the rotor wake slipstream, the deflectors were unable to alter the trajectory of the blade tip vortices. The interference between the deflectors and the rotor wake downwash...
was limited to the area inboard of the blade tips. Flow visualisation confirmed that the airflow near the rotor hub was weak and turbulent, and although there was interaction between the flow and the deflectors in this region, it was not sufficient to alter the motion of the blade tip vortices. It was concluded that the passive deflectors did not have a strong effect on the rotor wake blade tip vortices.

![Figure 7.5 Results of smoke flow visualisation: (a) baseline, (b) circular flat plate, (c) angled edge and (d) curved edge passive deflectors.](image)

### 7.1.3 Active Deflector

Presented in figure 7.6 is the baseline test case alongside the active deflector in operation. The active deflector is outside the field of view, and so for reference its vertical position is marked on image (b) along with the direction of the radial jet flow and the indicative location of the deflector. As previously the rotor image is not to scale, but indicative of the rotor radial position outside the field of view. Figure 7.6(a) shows the blade tip vortex flow structure prior to the operation of the active deflector. The deflector is behaving like a passive deflector in this instance, with negligible effect on the dominant features of the rotor wake. Figure 7.6(b) shows the flow structure with the active deflector operational. The alteration to the flow
structure is evident, as emphasised by the orange trend-lines outlining the trajectory of the blade tip vortices. After activation of the deflector, the radial position of the blade tip vortices was increased, providing the desired effect. The result was sufficiently encouraging so as to pursue a more quantitative analysis of the effect of active flow deflectors on the rotor wake, both with regard to the direction of the jet, and its location in respect to the rotor. To this end two active deflectors were designed for investigation using PIV.

![Figure 7.6](image_url) (a) Image of the test case with deflector installed but inactive and (b) with active deflector in operation. The trajectory of the blade tip vortices is highlighted by the orange line.

### 7.2 PIV Results

#### 7.2.1 Experiment Setup

The 2D-2C PIV experiments were undertaken with a small-scale two-bladed rotor in the DST LSWT. The rig assembly used to conduct the flow visualisation study yielded a field of view too large to be captured by the PIV equipment. As such, a smaller rotor assembly was constructed (refer figures 7.7 and 7.8) with blades of 110 mm radius, NACA0012 aerofoil profile and chord length of 20 mm, without twist or taper. The deflectors are detailed in figure 7.9. The first deflector (D1) was designed to produce a jet flow parallel to the outlet which would impinge upon the rotor wake in a near-orthogonal manner. During operation the deflector jet was drawn downwards under the influence of the rotor wake, however the primary interaction was maintained in the radial direction. The second deflector (D2) was designed such that the jet flow was angled toward the ground plane, and as such the interaction with the rotor wake downwash was more oblique, and focused more on the region of flow inboard of the rotor wake slipstream. Further detail of the deflector jets is provided in the following section.

The deflectors were attached to the ground plane in front of the rotor as per figure 7.7, where the variable $h$ specifies the distance between the rotor hub and the deflector. The rotor
position was kept fixed at 0.6D and the deflectors tested in two different positions beneath the rotor. The separation distance between the top of each deflector and the rotor hub was non-dimensionalised by the rotor diameter such that $h_1 = 0.11D$ and $h_2 = 0.20D$. For reasons of practicality the assembly was mounted in a vertical orientation in a similar manner to the experiments of Lee et al. (2008). As for the experiments detailed in Chapters 3 - 6, the laser was mounted overhead in the LSWT test section, which meant that the region of interest could be illuminated free of shadow from the rotor and the deflector. The camera position was unchanged to that shown in figure 3.8, and remained orthogonal to the laser light sheet. As previously, a Hall-Effect sensor was mounted to the rotor shaft and used to trigger the PIV data acquisition. The maximum acquisition rate of the equipment (2 Hz) was below the nominal operational speed of the rotor (30 Hz), and as such the results presented here are phase averaged. The rotational frequency was chosen to yield a blade loading coefficient of the same order of magnitude to full-scale rotors. Full details of the PIV setup and data processing are provided in Section 3.8. All distances are non-dimensionalised by the rotor diameter (D), and velocities non-dimensionalised by the blade tip speed. To reduce measurement uncertainty 3000 image pairs were acquired for each test point. Full results, which include mean velocity magnitude contour plots and $u-$ and $v-$component turbulence intensities are provided in Appendix I.
**Figure 7.7** Equipment setup: Active deflectors

**Figure 7.8** Rotor assembly for deflector study
7.2 PIV Results

7.2.2 Baseline and Deflector Flow

Figure 7.10 presents the mean velocity magnitude contour plot for in-plane velocity components of the baseline test case, with the same field of view as that used for the deflector tests. Two points of interest are noted on the image, the first is the focus point of the region of recirculation inboard of the rotor wake slipstream, annotated by a green marker. The second is the saddle point at the ground plane, annotated by a blue marker, which represents the point at which the flow inboard of the blade top vortices splits between flow moving inboard toward the rotor centre line, and flow moving radially outboard along the ground plane. The rotor wake flow structure is consistent with the results of the flow symmetry test (refer figures 3.12 and 7.10). In both cases there is no deflector installed between the rotor and the ground plane, so the inboard recirculation, although weak compared to the wake structure generated by the blade tip vortices, cannot be attributed to interference with the deflector pylon.

Presented in figures 7.11 and 7.12 are the results for each of the deflectors operating in isolation. Two different flow trajectories are generated by the differing deflector geometries. The first deflector (D1) yields a radially expanding jet inclined at 11° to the horizontal, which does not reach the ground plane within the field of view. The second deflector (D2) is directed downward at an angle of 65° to the horizontal, and upon contact with the ground plane moves in a radial direction. For D1 operating at $h_1$, the height of the jet outlet above the ground plane was 0.45D decreasing to 0.39D at $h_2$. With D2 operating at $h_1$, the height of the jet outlet above the ground plane was 0.44D decreasing to 0.37D at $h_2$. Both deflectors were also tested
at two different outlet velocities. The deflector jet velocities were non-dimensionalised by the rotor tip speed to yield values of $V_1 = 0.67$ and $V_2 = 0.77$, which corresponded to an increase in flow rate at the periphery of the deflector.

It should also be noted that in order to facilitate installation of the deflectors, support pylons connected the deflectors to the ground plane (refer figure 7.7). The support pylons introduced obstruction to the flow inboard of the blade tip vortices. Whilst it is not possible to determine the unobstructed flow pattern with the deflectors in operation, the baseline test case presented in figure 7.10 shows that the region of recirculation inboard of the rotor wake slipstream exists without the deflector installed. As such, the recirculation is determined to be an inherent feature of the rotor wake, and not a feature resulting from the obstruction.

**Figure 7.10** Mean in-plane velocity magnitude contour plot overlaid with streamlines: Baseline
7.2 PIV Results

Figure 7.11 Mean in-plane velocity magnitude contour plot: Deflector 1 operating in isolation at $V_2$ when installed at $h_2$

Figure 7.12 Mean in-plane velocity magnitude contour plot: Deflector 2 operating in isolation at $V_2$ when installed at $h_2$
7.2.3 Deflector 1

Presented in figure 7.13 are the mean velocity magnitude vector field plots for D1 at a separation distance of $h_1$, operating at both $V_1$ and $V_2$. The corresponding results for D1 installed at a separation distance of $h_2$ is presented in figure 7.14. The position of the focus point of the recirculation is annotated with a green marker in each figure, with a blue marker indicating the position of the saddle point at the ground plane. As previously, results are non-dimensionalised by the rotor tip speed and the rotor diameter.

When considering the difference between the contour plot and flow pattern of the baseline test case (refer figure 7.10) and those where D1 is operating (refer figures 7.13 and 7.14), it can be seen that the presence of the jet has two immediate effects. The first is an increase to the magnitude of the velocity of the rotor wake slipstream. This is to be expected given the jet flow is directed in the same radial direction to the expansion of the rotor wake. This increase in velocity magnitude also extends to the region of flow inboard of the slipstream boundary, where the introduction of D1 sees an increase in the peak magnitude of the inboard flow. Differences in the flow structure, as highlighted by the streamlines in each figure, show that the effect of D1 is to yield a more pronounced recirculation feature.

The central coordinates for the inboard recirculation zone for each test case are presented in table 7.1. Compared to the baseline case, introduction of the jet flow from D1 at $h_1$ pushed the region of recirculation further outboard. When operating at $V_1$ the radial position of the recirculation focus point moved further outboard by 13%. At $V_2$ the increase was 25%. The deflector also had the effect of increasing the height of the recirculation zone centre coordinate, yielding an increase of 39% for the case of $V_1$, and 38% for $V_2$. Given the nature of the radial flow from D1 (refer figure 7.11), it is expected that the interference between the jet flow and rotor wake downwash would have greater impact on the radial position of the inboard recirculation than the vertical location. When the distance between the rotor and the deflector is increased to $h_2$, there is a greater change to the position of the inboard recirculation region. Compared to the baseline case, at $V_1$ the centre of the recirculation region is moved outboard by 28% and is increased in height by 36%. At $V_2$ the increases are 51% and 30% respectively.

With the deflector mounted at distance $h_1$ beneath the rotor hub the radial location of the inboard recirculation zone varies by 12% between $V_1$ and $V_2$. The introduction of the radial jet near the top of the rotor slipstream has a consistent effect on the change to the location of the inboard recirculation region. When the distance between the rotor hub and the deflector is increased to $h_2$, greater difference is seen between the $V_1$ and $V_2$ results, with a 19% increase in the radial location of the inboard recirculation region. Considering the position of the ground-based saddle point, introduction of D1 beneath the rotor only had a marginal effect on the location of the saddle point of the flow at the ground plane. With D1 operating at $h_1$ the saddle
point was moved further outboard by 5% at both $V_1$ and $V_2$. At $h_2$ the saddle point was again moved outboard by 5% when operating at $V_1$, but this increased to 7% when operating at $V_2$.

It can be surmised that the introduction of a jet with a predominantly radial flow direction has the effect of moving key flow features further outboard. Increasing velocity of the jet flow increased the radial position of the inboard recirculation zone at both separation distances. The key difference between jet locations is the point of impingement with the rotor wake, insofar as at $h_1$ the jet interacts with the wake at a point higher than the region of maximum downwash velocity. At $h_2$ the jet impinges on the wake very near the region of maximum downwash velocity. It can be seen that D1 has greater effect interacting with the wake nearer its maximal magnitude.

<table>
<thead>
<tr>
<th>Focus Point</th>
<th>$x/D$</th>
<th>$y/D$</th>
<th>Saddle Point</th>
<th>$x/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0.147</td>
<td>0.164</td>
<td>Baseline</td>
<td>0.40</td>
</tr>
<tr>
<td>D1, $V_1$, $h_1$</td>
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<tr>
<td>D1, $V_1$, $h_2$</td>
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<td>D1, $V_2$, $h_2$</td>
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<td>0.221</td>
<td>D1, $V_2$, $h_2$</td>
<td>0.43</td>
</tr>
</tbody>
</table>

*Table 7.1 Coordinates of the inboard recirculation region focus point (left) and saddle point (right)*
Figure 7.13 Mean in-plane velocity magnitude contour plot overlaid with streamlines: Deflector 1, $h_1 - V_1$ (top) and $V_2$ (lower)
Figure 7.14 Mean in-plane velocity magnitude contour plot overlaid with streamlines: Deflector 1, $h_2$ - $V_1$ (top) and $V_2$ (lower)
7.2.4 Deflector 2

The jet of the second deflector (D2) was angled down toward the ground plane, as per figure 7.12. Compared to the D1 test cases (refer figures 7.13 and 7.14) the D2 jet impinges upon the rotor wake at a more oblique angle with the intent to influence the flow structure closer to the ground plane, rather than near the region of peak vertical velocity. Compared to the baseline test case (refer figure 7.10) the effect of D2 on the flow structure inboard of the rotor wake slipstream is significant. Whereas D1 promoted the region of inboard recirculation, D2 eliminates the structure. As previously, the deflector’s support pylon introduces an obstruction to inboard region of flow, however the effect appears less pronounced when compared to D1 results. This is likely due to the fact that the D2 flow promotes radial flow, and as such the magnitude of the flow velocity moving inboard is reduced compared with the flow moving radially outward.

Table 7.2 presents the location of the saddle point at the ground plane (annotated by a blue marker in each figure), that is, the point at which the radial flow changes direction from moving back towards the rotor centre line (inboard) to expanding radially outward (outboard). At a separation distance of $h_1$, the introduction of D2 beneath the rotor alters the geometry of the inboard boundary of the rotor wake slipstream, as shown in figure 7.15. The flow inboard of the rotor wake slipstream is pushed radially outward, with a reduced component of the flow moving back toward the rotor centre line. For the baseline test case the flow inboard of the rotor wake slipstream boundary turns back inboard at a radial location of approximately 0.40D. With D2 in operation at $h_1$ this value decreases to 0.12 at $V_1$ and 0.08 at $V_2$.

When the separation distance between the deflector and the rotor hub is increased to $h_2$ there is a different change to the flow pattern inboard of the rotor wake slipstream, as can be seen in figure 7.16. At $h_1$ the flow broadly followed the same trajectory as the baseline test case, but rather than generating a region of recirculating flow inboard of the rotor wake slipstream, the flow instead tended towards radial expansion upon impact with the ground plane. For the case of $h_2$, the interference effect of the deflector support pylon is more significant. The deflector jet flow continues to promote a change in direction of the inboard flow region toward radial expansion, however the flow that does turn back towards the rotor centre line is subsequently drawn up toward the D2 outlet after impinging on the deflector support pylon. It is acknowledged that this flow pattern is an interference effect, but the net effect of the deflector within the inboard region can still be determined as one which promotes flow away from the rotor centre line.

Overall the effect of D2 is to alter the flow structure inboard of the rotor wake slipstream such that a region of recirculation does not form. Instead, the flow more closely follows the global trajectory of the rotor wake, with a larger percentage of flow inboard of the slipstream
boundary moving radially outward upon contact with the ground plane. In all cases the point at which the flow changes direction back toward the rotor centre line is decreased compared with the baseline.

<table>
<thead>
<tr>
<th></th>
<th>(x/D)</th>
</tr>
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<tbody>
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<td>D1, (V_2, h_2)</td>
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</tbody>
</table>

*Table 7.2 Position of flow saddle point at the ground plane*
Figure 7.15 Mean in-plane velocity magnitude contour plot overlaid with streamlines: Deflector 2, $h_1 - V_1$ (top) and $V_2$ (lower)
Figure 7.16 Mean in-plane velocity magnitude contour plot overlaid with streamlines: Deflector 2, $h_2$. $V_1$ (top) and $V_2$ (lower)
7.3 Operational Viability

Unlike the ground-based trip strips, the implementation of an active deflector to full-scale aircraft would be complex. Disregarding the non-trivial technical and regulatory requirements of integrating such a device, the fundamental issue is the required strength of the jet as compared to the induced velocity generated by the rotor. In the experiments presented here the velocity of the deflector jet and the maximal velocity of the rotor wake downwash are comparable. Such deflector velocities were chosen to highlight the maximal effect that could be achieved, however a more detailed analysis would be required to determine what flow rate and velocities could be attained in an operational context. Further studies could focus on the minimum jet velocity required to achieve positive effects in a brownout context, and then assess in further detail the viability of scaling-up such a design. In theory such designs could be tested on smaller test-beds such as remote controlled helicopters, as this would also identify whether active deflectors introduce any change to the aircraft performance and/or controllability.
7.4 Chapter Summary

Investigation of the potential of flow deflectors to modify the flow near to the rotor centre line showed that passive deflectors did not significantly alter the flow field. Introduction of active flow deflectors beneath the rotor yielded the following changes to the flow field:

- D1 moved the inboard recirculation region further away from the rotor centre line and also increased the height of the recirculation zone focus point.

- Increases in the D1 jet velocity, and also in the separation between D1 and the rotor hub, moved the recirculation zone focus point further outboard.

- D2 altered the flow structure of the zone inboard of the rotor wake slipstream, with the recirculation zone replaced by flow that tended toward radial expansion upon contact with the ground plane. Such a change has the potential to reduce the tendency of ground-based particles to move back toward the rotor centre line, which could result in improved visibility for air crew.

- Increasing the jet velocity of D2 increased the percentage of inboard flow that moved outward along the ground plane.

- Increasing the separation distance between D2 and the rotor hub changed the flow structure near to the deflector support pylon.

- Results show encouraging trends in the modification of the inboard wake flow structure, however further testing would be required to assess the feasibility of such designs at full-scale.
Chapter 8

Summary and Conclusions

The objective of this study was to investigate the global flow fields generated by vortex ring structures and rotor wakes as they impinged upon solid surfaces so as to better understand the development of large-scale flow structures. Of particular interest were the mechanisms that underlie flow structures which could be observed as toroids and their effect on the flow near to the surface. The study also sought to assess how the region of flow near to the centre line of the rotor may be influenced using ground-base trip strips and flow deflectors, given the flow beneath a rotor is dominated by the behaviour of the blade tip vortices. To achieve these aims a numerical investigation into the interaction between vortex rings and solid surfaces was undertaken, followed by experiments analysing the wake structure of a sub-scale rotor in ground effect.

8.1 Principal Results: Vortex Ring / Wall Interaction

A review of the literature relating to the interaction of vortex rings with solid surfaces revealed that publications relating to high Reynolds number were limited, as were studies focusing on wall impacts of multiple vortex ring structures. For the case of a single vortex ring impinging on a wall the results of this study are consistent with previous observations and extend analysis of higher Reynolds number test cases. It was found that:

- **The primary effect of Reynolds number on the large-scale flow structured was an increase in azimuthal fluctuation.** An increase in azimuthal variation in the distribution of vorticity around the vortex circumference was evident in the primary vortex, and the subsequent development of hairpin vortex structures from the secondary vortex also highlighted the azimuthal fluctuation in the vortex ring structure.

- **The azimuthal fluctuation was further amplified by the highly asymmetric nature**
of the oblique wall impact. The progressive impact with the wall increased the variation in vorticity distribution around the circumference of the vortex ring, leading to a more rapid breakdown of the vortex structures.

- The wall shear stress distribution provided insight into the transient flow patterns generated at the wall during impact of the vortex ring. For both the orthogonal wall impact ($\theta = 0^\circ$) and oblique wall impact ($\theta = 20^\circ$) the nature of the development of the boundary layer at the wall yielded conditions likely to agitate ground-based particles. Such conditions are typified by the frequently changing direction of flow along bifurcation lines which resulted from the interaction between vortex structures. For test cases at higher Reynolds number and also for cases of oblique wall impact, the frequency of flow direction changes was increased.

- The global flow field recirculation pattern consistent with a large-scale toroid structure was only evident for an orthogonal wall impact. When the vortex ring approached the inclined wall the velocity profile promoted a highly asymmetric global flow field that entrained fluid from the low-side to the high-side, rather than a recirculation back toward the centre point of the vortex ring.

Introducing a second vortex into the flow field did not alter the essential features of the vortex ring / wall interaction, however the increased energy of the boundary layer, along with the subsequent proximity of the large-scale structures resulted in rapid merging of vortices. It was found that:

- The increase in Reynolds number promoted azimuthal fluctuation in vorticity. As for the single vortex case, the increase in Reynolds number promoted azimuthal fluctuation in vorticity.

- At increased Reynolds number the secondary vortex generated by the lead vortex ring during an orthogonal impact developed hairpin vortices, but the secondary vortex generated by the trailing vortex retained greater stability. Although both primary vortex structures showed increase azimuthal variation in their vorticity distribution, the merging of primary structures and location of the secondary vortex generated by the lead vortex, meant that the secondary vortex generated by the trailing vortex did not rapidly form hairpin structures. Although the structure shows azimuthal variation in vorticity, it is more stable than the secondary structure generated by the lead vortex ring.

- Recirculation was prevalent in the global velocity flow field, and the entrainment profile was altered by both the wall angle and the impact of the second vortex ring.
The presence of the second vortex ring in the flow field did not markedly change the global velocity flow field, and results are consistent with the single vortex ring results. For the case of orthogonal impact with a wall the velocity flow field shows fluid entrainment back toward the centre of the vortex ring, which is consistent with a toroid-like flow pattern, however the oblique impact yielded an asymmetric entrainment from the low-side to the high-side.

- **The flow patterns that arise during vortex ring interactions with a wall are consistent with conditions likely to lead to the agitation of ground-based particles.** The wall shear stress distributions highlight the increase in frequency of flow direction changes near the wall with the impact of a second vortex ring, and the fluctuation in wall normal velocity is also increased compared to the case of a single vortex ring impact.

- **The global recirculation of the velocity field is congruous with a flow pattern required for particle uplift.** Despite the differences in the recirculation profile between the orthogonal and oblique test cases, the direction of the global flow is consistent with that required for particle uplift.

## 8.2 Principal Results: Rotor Wake / Ground Plane Interaction

Results of the sub-scale experiment show that a large-scale flow structure consistent with the global recirculation hypothesis could be repeatedly generated at 200 RPM, however, the structure rapidly degraded with increasing RPM. As such, the global recirculation flow structure was only observed at rotational frequencies that yielded blade loading coefficients an order of magnitude smaller than that expected for full-scale operations. Therefore, it cannot be inferred that the global recirculation hypothesis applies to flow fields generated at full scale.

- **The large-scale global recirculation flow structure is persistent and robust at 200 RPM.** Repetition of test conditions using both 2D-3C SPIV and 2D-2C PIV showed that the global recirculation flow structure could be repeatedly generated at 200 RPM.

- **The global recirculation structure is a genuine large-scale structure observed in the mean flow field.** A POD analysis confirmed that the global recirculation flow structure was a large-scale structure and not a composition of smaller structures.

- **The strength and location of the core of the global recirculation region is dependent on the rotor thrust.** The structure and position of the global recirculation region...
Summary and Conclusions

showed variation based on rotor thrust.

- **The global recirculation structure reduces in stability with increasing thrust.** Variation to the rotor thrust did yield global recirculation flow structures at 300 RPM, but results indicated there may be more than one stable state to the global flow field as thrust increased, as shown by the POD results.

- **The global recirculation structure was inherently unsteady and fluctuated with time.** An analysis of the position of the global recirculation structure’s core showed that it oscillated in both the vertical and radial directions, which is consistent with the inherently unsteady nature of rotor wakes in general. The oscillation did not show a cumulative change to the mean position, rather that the core of the large-scale structure oscillated about a stable mean.

- **Ground-based trip strips did not significantly promote or inhibit the formation of the global recirculation zone.** The ground-based trip-strips altered the location of the core of the recirculation zone compared to the baseline results, but there was no significant change the flow structure itself.

- **The large-scale flow structure that is consistent with the global recirculation zone hypothesis is a structure specific to the test conditions between 200 - 300 RPM.** The recirculation zone could not be identified at test conditions above 300 RPM, and further investigation would be required above 500 RPM.

8.3 Principal Results: Flow Deflectors

Introduction of active flow deflectors beneath the rotor yielded the following changes to the flow field:

- **Deflector 1 changed the location of the inboard recirculation region.** The jet flow introduced by Deflector 1 increased the height and radial position of the focus point of the inboard recirculation region. Increases in the deflector jet velocity, and also in the separation between Deflector 1 and the rotor hub, moved the recirculation zone centre point further outboard.

- **Deflector 2 altered the flow structure of the zone inboard of the rotor wake slipstream.** With Deflector 2 in operation, the zone of inboard recirculation was replaced by a flow pattern that tended toward radial expansion upon contact with the ground plane. Increasing the jet velocity of Deflector 2 increased the percentage of inboard
flow that moved outward along the ground plane. Such an alteration to the flow field has the potential to reduce the tendency of ground-based particles to move back toward the rotor centre line, which could result in improved visibility for air crew.

8.4 Suggestions for Future Work

While several aspects of this study have been extensively investigated, other elements would benefit from further exploration. Due to resource and time constraints it was not able to pursue every avenue of investigation available, and some aspects would be considered an extension of the work undertaken here.

- **Vortex ring / wall interactions at high Reynolds numbers.** Investigating the interaction between vortex rings and solid surfaces at higher Reynolds numbers is likely to provide further insight into the fundamental flow mechanics that underlie the interaction.

- **Vortex ring / wall interactions with swirl.** The available literature relating to swirling vortex ring interaction with solid surfaces is limited. This is a particularly interesting test case as the presence of swirl is likely to promote a more elaborate flow environment with more complex flow mechanics.

- **Rotor wake analysis with tomographic PIV.** The ability to volumetrically investigate a rotor wake flow experimentally would provide significant advantages to the conclusions which could be drawn relating to the interaction between blade tip vortices and solid surfaces. The resources required for tomographic PIV are significant, and at present practical constraints exist to the achievable size of the flow volume that can be captured. The inherently unsteady nature of rotor wake structures makes them an ideal candidate for detailed investigation.

- **Operational viability of ground-based trip strips and active flow deflectors.** Further work could be undertaken in the form of parametric studies and detailed design to properly determine the feasibility of ground-based trip strips and active flow deflectors for operational application. Future studies could include dual-phase experiments to better assess the level to which visibility in the cockpit is compromised.
References


A. Betz. The ground effect on lifting propellers. NACA Technical Memorandum 836, National Advisory Committee for Aeronautics, August 1937.


References


T. Scheimpflug. Improved method and apparatus for the systematic alteration or distortion of plane pictures and images by means of lenses and mirrors for photography and for other purposes. British Patent No. 1196, 1904.


Appendix A

PIV Processing

All PIV data processing was undertaken using the TSI Insight 4G software, and an outline of the processing pipeline is provided in figure A.1. Informed by previous experiments which made use of the same equipment and processing methods to this study (refer Manovski et al. (2013)), image pre-processing was applied prior to batch processing of each image ensemble. Image pre-processing encompasses a range of methods used to improve the correlation signal of PIV processing algorithms, and several techniques are outlined by Raffel et al. (2007). The motivation for the use of these techniques is to improve the particle contrast within each image such that there is similar contribution in the correlation function from all particle images. This study used a method known as background subtraction, which aims to reduce the effect of laser flare and take into account stationary image features which can include aberrations such as dead pixels and defects on surfaces within the field of view. The background image was calculated as a minimum intensity image using the Minimum Intensity Image Generator within the Insight 4G processing tool. The minimum intensity images were calculated using all frames of each ensemble, and yielded two separate images for each test point, one for Frame A and one for Frame B (refer figure 3.6: image from pulse 1 / image from pulse 2). These minimum intensity images were then subtracted from each image of the ensemble as the first stage of data processing.

A post-processing stage was also applied to validate each vector in the vector field and eliminate bad vectors. Such invalid vectors can be caused by experiment conditions such as low density of seed particles, significant out-of-plane particle motion, steep velocity gradients or high levels of noise in the recorded image. The values applied using the global velocity range filter were determined by assessing a small subset of images from each ensemble, typically 10 - 20 frames chosen at random but covering the full time span of the ensemble acquisition. From each ensemble subset maximum and minimum u- and v-velocity components were identified. These maximum and minimum values were then applied as global validation,
with maximum displacement set to $\Delta x = \Delta y = 0.25$. Local validation was applied using a median test with a neighbourhood size of $3 \times 3$ pixels and a displacement tolerance of 2 pixels. Bi-linear interpolation was then used at the vector conditioning stage to replace any vector identified as invalid.

According to Liang et al. (2003), the spurious vector count should be less than 5% of the total number of measured vectors for well-optimised PIV experiment. If a single velocity vector field contained yielded a spurious vector count of more than 5% it was not included in the ensemble average. In this case spurious vectors included both invalid and interpolated vectors, and each ensemble typically included a good vector percentage greater than 99% with fewer than 1% spurious vectors. At least 99% of all images acquired at each test point were used to calculate each ensemble average, which in combination with the small percentage of spurious vectors gave good confidence in the quality of the processed data.

**Figure A.1 PIV processing pipeline**

Appendix B

PIV Measurement Uncertainty

Errors in PIV measurements stem from a range of sources within the experiment. Issues involving particle seeding (low density, blooming), large velocity gradients, loss of particle pairs due to high out-of-plane motion, noisy images and equipment misalignment are some of the principal contributors.

B.1 Velocity

As per Kostas (2002), the error in the velocity measurement calculated from the PIV images was defined as

\[ \varepsilon_u = \sqrt{\left( \frac{\delta_u}{\bar{u}} \right)^2} = \sqrt{\left( \frac{\delta_{Ax}}{\Delta X} \right)^2} + \left( \frac{\delta_{scale}}{scale} \right)^2 + \left( \frac{\delta_{At}}{At} \right)^2, \]  

(B.1)

where \( \delta_{Ax} \) denotes the uncertainty associated with particle displacement, \( \delta_{scale} \) represents the error associated with determining the image scale factor and \( \delta_{At} \) denotes the timing error. The error in displacement was determined from the minimum resolvable displacement of the processing algorithm, which was found by Manovski et al. (2013) to be 0.05 pixels. The scale and timing errors were also taken from Manovski et al. (2013) owing to the commonality of test equipment and processing techniques. The scale error \( \delta_{scale} \) was found to be 4.1 pixels and the timing error \( \delta_{At} \), based on the laser and synchroniser performance, was 4 ns. Table B.1 provides a summary of the errors for each test case associated with the velocity measurement. The velocity error is referenced to the blade tip velocity \( (U_{tip}) \) for consistency with the non-dimensionalisation of the PIV data. Identical errors are assumed for the remaining velocity components.
Table B.1 PIV Error: Velocity

B.2 Mean Derived Quantities

As noted by Kostas Kostas (2002), confidence interval estimates in mean measurements can be calculated from the theory of random variable analysis (refer Taylor (1982) and Grant and Owens (1990)) due to the fact that PIV velocity fields conform to a normal distribution and are statistically independent.

B.2.1 Mean Velocity

For a given confidence interval the mean flow velocity may be estimated from $n$ individual fields as per:

$$\bar{u} \pm \gamma_c \frac{\sigma}{\sqrt{n}}, \quad (B.2)$$

where $\sigma$ is the standard deviation and $\gamma_c$ is the confidence coefficient. Given that $\sigma$ refers to an infinite sample size, a t-distribution may be used in conjunction with the standard deviation of the sample ($\sigma_n$) with an appropriately adjusted $\gamma_c$. The smallest sample size captured during this study was 1000 images, which is sufficiently large so as to render the t-distribution identical to the normal distribution. For a confidence interval of 95% and $n = 1000$, $\gamma_c = 1.96$ for both a normal- and t-distribution. When referenced to the blade tip velocity, the error in
the mean velocity is given by:

$\bar{u} = \frac{\gamma \sigma_u}{U_{tip} \sqrt{n}}$.

(B.3)

The ratio $\sigma_u/U_{tip}$ represents the turbulent intensity and can be used to calculate the maximum uncertainty in the mean flow measurements. The PIV measurement error, $\epsilon_u$ must also be incorporated to account for the measurement error in each individual sample. Thus, the mean velocity values have both the statistical and measurement error applied:

$\bar{u} \pm (\epsilon_{\bar{u}} + \epsilon_u)$.

(B.4)

Presented in table B.2 is the measurement uncertainty for mean velocity for each test case.

### B.2.2 RMS Velocity

Kostas (2002) notes that the RMS velocity may be expressed as:

$u_{RMS} = \sigma_u \pm \frac{\gamma \sigma}{\sqrt{2n}}$.

(B.5)

By the assumption that $\sigma_u \approx \sigma$ the error is independent of the standard deviation of the sample and is simply a function of sample size and confidence coefficient (refer Taylor
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<th>Stage I - II</th>
<th>M</th>
<th>$\varepsilon_{\sigma_v}$(%)</th>
</tr>
</thead>
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<tr>
<td>SPIV: 200 RPM</td>
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<td>SPIV: 300 RPM</td>
<td>3000</td>
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<tr>
<td>SPIV: 500 RPM</td>
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<td>1.25 %</td>
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<tr>
<td>Planar PIV: 200 RPM</td>
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<tr>
<td>Planar PIV: 300 RPM</td>
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<td>2.55 %</td>
</tr>
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<table>
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</tr>
<tr>
<td>Deflector, V2</td>
<td>3000</td>
<td>0.54 %</td>
</tr>
</tbody>
</table>

*Table B.3 PIV Error: RMS Velocity*

(1982)), the equation for RMS velocity error can be reduced to:

$$
\varepsilon_{\sigma_v} = \frac{\gamma_c}{\sqrt{2n}}.
$$

(B.6)

Shown in table B.3 is the calculated RMS velocity error for each test case.
Appendix C

Stereo PIV Results: Isolated Rotor

C.1 Test Case Summary

Listed in table C.1 is a description of the test cases investigated using 2D-3C SPIV.

<table>
<thead>
<tr>
<th>Blade Designation</th>
<th>Rotor Height</th>
<th>Rotor RPM</th>
<th>Global Recirculation / Up-Flow</th>
</tr>
</thead>
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<tr>
<td>B1</td>
<td>0.75D</td>
<td>200</td>
<td>Up-Flow</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>200</td>
<td>Global Recirculation</td>
</tr>
<tr>
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<td>1D</td>
<td>250</td>
<td>Global Recirculation</td>
</tr>
<tr>
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</tr>
<tr>
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<td>-</td>
</tr>
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<td>Global Recirculation</td>
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<td>-</td>
</tr>
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<td>B3</td>
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<td>-</td>
</tr>
<tr>
<td>B3</td>
<td>1D</td>
<td>500</td>
<td>-</td>
</tr>
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*Table C.1 SPIV test cases*
C.2 200 RPM

C.2.1 Blade 1

*Figure C.1* Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 200 RPM, 0.75D

*Figure C.2* Turbulence intensity (u-component): Blade 1, 200 RPM, 0.75D
Figure C.3 Turbulence intensity (v-component): Blade 1, 200 RPM, 0.75D

Figure C.4 Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 200 RPM, 1D
**Figure C.5** Turbulence intensity (u-component): Blade 1, 200 RPM, 1D

**Figure C.6** Turbulence intensity (v-component): Blade 1, 200 RPM, 1D
C.2 200 RPM

C.2.2 Blade 3

Figure C.7 Mean velocity magnitude contour plot overlaid with streamlines: Blade 3, 200 RPM, 1D

Figure C.8 Turbulence intensity (u-component): Blade 3, 200 RPM, 1D
Figure C.9 Turbulence intensity (v-component): Blade 3, 200 RPM, 1D
C.3 250 RPM

C.3.1 Blade 1

*Figure C.10* Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 250 RPM, 0.75D

*Figure C.11* Turbulence intensity (u-component): Blade 1, 250 RPM, 0.75D
Figure C.12 Turbulence intensity (v-component): Blade 1, 250 RPM, 0.75D

Figure C.13 Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 250 RPM, 1D
Figure C.14 Turbulence intensity (u-component): Blade 1, 250 RPM, 1D

Figure C.15 Turbulence intensity (v-component): Blade 1, 250 RPM, 1D
C.3.2 Blade 3

Figure C.16 Mean velocity magnitude contour plot overlaid with streamlines: Blade 3, 250 RPM, 1D

Figure C.17 Turbulence intensity (u-component): Blade 3, 250 RPM, 1D
Figure C.18 Turbulence intensity (v-component): Blade 3, 250 RPM, 1D
C.4 300 RPM

C.4.1 Blade 1

\textbf{Figure C.19} Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 300 RPM, 1D

\textbf{Figure C.20} Turbulence intensity (u-component): Blade 1, 300 RPM, 1D
Figure C.21 Turbulence intensity (v-component): Blade 1, 300 RPM, 1D
C.4.2 Blade 2

**Figure C.22** Mean velocity magnitude contour plot overlaid with streamlines: Blade 3, 300 RPM, 1D

**Figure C.23** Turbulence intensity (u-component): Blade 3, 300 RPM, 1D
Figure C.24 Turbulence intensity (v-component): Blade 3, 300 RPM, 1D
C.5 500 RPM

C.5.1 Blade 1

*Figure C.25* Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 500 RPM, 1D

*Figure C.26* Turbulence intensity (u-component): Blade 1, 500 RPM, 1D
Figure C.27 Turbulence intensity (v-component): Blade 1, 500 RPM, 1D
C.5.2 Blade 2

*Figure C.28* Mean velocity magnitude contour plot overlaid with streamlines: Blade 3, 500 RPM, 1D

*Figure C.29* Turbulence intensity (u-component): Blade 3, 500 RPM, 1D
Figure C.30 Turbulence intensity (v-component): Blade 3, 500 RPM, 1D
C.6 1000 RPM

C.6.1 Blade 1

*Figure C.31* Mean velocity magnitude contour plot overlaid with streamlines: Blade 1, 1000 RPM, 1D

*Figure C.32* Turbulence intensity (u-component): Blade 1, 1000 RPM, 1D
Figure C.33 Turbulence intensity (v-component): Blade 1, 1000 RPM, 1D
C.7 Individual Velocity Components

C.7.1 200 RPM

*Figure C.34* Mean velocity magnitude contour plot (u-component): Blade 1, 1D, 200 RPM

*Figure C.35* Mean velocity magnitude contour plot (v-component): Blade 1, 1D, 200 RPM
Figure C.36 Mean velocity magnitude contour plot (w-component): Blade 1, 1D, 200 RPM
C.7.2 250 RPM

Figure C.37 Mean velocity magnitude contour plot (u-component): Blade 1, 1D, 250 RPM

Figure C.38 Mean velocity magnitude contour plot (v-component): Blade 1, 1D, 250 RPM
Figure C.39 Mean velocity magnitude contour plot (w-component): Blade 1, 1D, 250 RPM
C.7.3 300 RPM

Figure C.40 Mean velocity magnitude contour plot (u-component): Blade 1, 1D, 300 RPM

Figure C.41 Mean velocity magnitude contour plot (v-component): Blade 1, 1D, 300 RPM
Figure C.42 Mean velocity magnitude contour plot (w-component): Blade 1, 1D, 300 RPM
C.7.4 500 RPM

Figure C.43 Mean velocity magnitude contour plot (u-component): Blade 1, 1D, 500 RPM

Figure C.44 Mean velocity magnitude contour plot (v-component): Blade 1, 1D, 500 RPM
Figure C.45 Mean velocity magnitude contour plot (w-component): Blade 1, 1D, 500 RPM
C.7.5 1000 RPM

**Figure C.46** Mean velocity magnitude contour plot (u-component): Blade 1, 1D, 1000 RPM

**Figure C.47** Mean velocity magnitude contour plot (v-component): Blade 1, 1D, 1000 RPM
Figure C.48 Mean velocity magnitude contour plot (w-component): Blade 1, 1D, 1000 RPM
Appendix D

Stereo PIV: State II Results

D.1 SPIV Derived Quantities

D.1.1 Ensemble A

Figure D.1 Mean velocity magnitude contour plot overlaid with streamlines: Ensemble A
**Figure D.2** Mean velocity magnitude contour plot (u-component): Ensemble A

**Figure D.3** Mean velocity magnitude contour plot (v-component): Ensemble A
Figure D.4 Mean velocity magnitude contour plot (w-component): Ensemble A

Figure D.5 Turbulence intensity (u-component): Ensemble A
Figure D.6 Turbulence intensity ($v$-component): Ensemble A
D.1 SPIV Derived Quantities

D.1.2 Ensemble B

Figure D.7 Mean velocity magnitude contour plot overlaid with streamlines: Ensemble B

Figure D.8 Mean velocity magnitude contour plot (u-component): Ensemble B
Figure D.9 Mean velocity magnitude contour plot (v-component): Ensemble B

Figure D.10 Mean velocity magnitude contour plot (w-component): Ensemble B
Figure D.11 Turbulence intensity (u-component): Ensemble B

Figure D.12 Turbulence intensity (v-component): Ensemble B
D.1.3 Ensemble C

Figure D.13 Mean velocity magnitude contour plot overlaid with streamlines: Ensemble C

Figure D.14 Mean velocity magnitude contour plot (u-component): Ensemble C
**Figure D.15** Mean velocity magnitude contour plot (v-component): Ensemble C

**Figure D.16** Mean velocity magnitude contour plot (w-component): Ensemble C
Figure D.17 Turbulence intensity (u-component): Ensemble C

Figure D.18 Turbulence intensity (v-component): Ensemble C
D.1.4 Ensemble D

**Figure D.19** Mean velocity magnitude contour plot overlaid with streamlines: Ensemble D

**Figure D.20** Mean velocity magnitude contour plot (u-component): Ensemble D
Figure D.21 Mean velocity magnitude contour plot (v-component): Ensemble D

Figure D.22 Mean velocity magnitude contour plot (w-component): Ensemble D
Figure D.23 Turbulence intensity (u-component): Ensemble D

Figure D.24 Turbulence intensity (v-component): Ensemble D
D.2 POD Analysis

D.2.1 Ensemble A

Figure D.25 Relative energy of POD modes: Ensemble A
Figure D.26  First POD mode: Ensemble A

Figure D.27  Second POD mode: Ensemble A
Figure D.28 Third POD mode: Ensemble A
D.2 POD Analysis

D.2.2 Ensemble B

![Relative energy of POD modes: Ensemble B]

*Figure D.29* Relative energy of POD modes: Ensemble B
Figure D.30 First POD mode: Ensemble B

Figure D.31 Second POD mode: Ensemble B
Figure D.32 Third POD mode: Ensemble B
D.2.3 Ensemble C

Figure D.33 Relative energy of POD modes: Ensemble C
**D.2 POD Analysis**

**Figure D.34** First POD mode: Ensemble C

**Figure D.35** Second POD mode: Ensemble C
Figure D.36 Third POD mode: Ensemble C
D.2.4 Ensemble D

![Bar chart showing relative energy of POD modes for Ensemble D.](image)

*Figure D.37 Relative energy of POD modes: Ensemble D*
Figure D.38 First POD mode: Ensemble D

Figure D.39 Second POD mode: Ensemble D
Figure D.40 Third POD mode: Ensemble D
Appendix E

Planar PIV Results: Isolated Rotor

E.1 Test Case Summary

Listed in table E.1 is a description of the test cases investigated using 2D-2C planar PIV.

<table>
<thead>
<tr>
<th>Blade Designation</th>
<th>Rotor Height</th>
<th>Rotor RPM</th>
<th>Global Recirculation / Up-Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>200</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>300</td>
<td>Up-Flow</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>200</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>300</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>0.75D</td>
<td>200</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B2</td>
<td>0.75D</td>
<td>300</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>200</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>B3</td>
<td>0.75D</td>
<td>200</td>
<td>Up-Flow</td>
</tr>
<tr>
<td>B3</td>
<td>0.75D</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>B3</td>
<td>1D</td>
<td>200</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B3</td>
<td>1D</td>
<td>300</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B3</td>
<td>1D</td>
<td>500</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table E.1 Planar PIV test cases*
E.2 200 RPM

E.2.1 Blade 1

Figure E.1 Mean velocity magnitude contour plot: Blade 1, 200 RPM, 0.75D

Figure E.2 Turbulence intensity (u-component): Blade 1, 200 RPM, 0.75D
Figure E.3 Turbulence intensity (v-component): Blade 1, 200 RPM, 0.75D

Figure E.4 Mean velocity magnitude contour plot: Blade 1, 200 RPM, 1D
**Figure E.6** Turbulence intensity (v-component): Blade 1, 200 RPM, 1D

**Figure E.5** Turbulence intensity (u-component): Blade 1, 200 RPM, 1D
E.2.2 Blade 2

Figure E.7 Mean velocity magnitude contour plot: Blade 2, 200 RPM, 0.75D

Figure E.8 Turbulence intensity (u-component): Blade 2, 200 RPM, 0.75D
Figure E.9 Turbulence intensity (v-component): Blade 2, 200 RPM, 0.75D

Figure E.10 Mean velocity magnitude contour plot: Blade 2, 200 RPM, 1D
Figure E.11 Turbulence intensity (u-component): Blade 2, 200 RPM, 1D

Figure E.12 Turbulence intensity (v-component): Blade 2, 200 RPM, 1D
E.2.3 Blade 3

Figure E.13 Mean velocity magnitude contour plot: Blade 3, 200 RPM, 0.75D

Figure E.14 Turbulence intensity (u-component): Blade 3, 200 RPM, 0.75D
Figure E.15 Turbulence intensity (v-component): Blade 3, 200 RPM, 0.75D

Figure E.16 Mean velocity magnitude contour plot: Blade 3, 200 RPM, 1D
Figure E.17 Turbulence intensity (u-component): Blade 3, 200 RPM, 1D

Figure E.18 Turbulence intensity (v-component): Blade 3, 200 RPM, 0.75D
E.3 300 RPM

E.3.1 Blade 1

Figure E.19 Mean velocity magnitude contour plot: Blade 1, 300 RPM, 0.75D

Figure E.20 Turbulence intensity (u-component): Blade 1, 300 RPM, 0.75D
Figure E.21 Turbulence intensity (v-component): Blade 1, 300 RPM, 0.75D

Figure E.22 Mean velocity magnitude contour plot: Blade 1, 300 RPM, 1D
Figure E.23 Turbulence intensity (u-component): Blade 1, 300 RPM, 1D

Figure E.24 Turbulence intensity (v-component): Blade 1, 300 RPM, 1D
Planar PIV Results: Isolated Rotor

**E.3.2 Blade 2**

*Figure E.25* Mean velocity magnitude contour plot: Blade 2, 300 RPM, 0.75D

*Figure E.26* Turbulence intensity (u-component): Blade 2, 300 RPM, 0.75D
Figure E.27 Turbulence intensity (v-component): Blade 2, 300 RPM, 0.75D

Figure E.28 Mean velocity magnitude contour plot: Blade 2, 300 RPM, 1D
Figure E.29 Turbulence intensity (u-component): Blade 2, 300 RPM, 1D

Figure E.30 Turbulence intensity (v-component): Blade 2, 300 RPM, 1D
E.3.3 Blade 3

Figure E.31 Mean velocity magnitude contour plot: Blade 3, 300 RPM, 0.75D

Figure E.32 Turbulence intensity (u-component): Blade 3, 300 RPM, 0.75D
Figure E.33 Turbulence intensity (v-component): Blade 3, 300 RPM, 0.75D

Figure E.34 Mean velocity magnitude contour plot: Blade 3, 300 RPM, 1D
Figure E.35 Turbulence intensity (u-component): Blade 3, 300 RPM, 1D

Figure E.36 Turbulence intensity (v-component): Blade 3, 300 RPM, 1D
E.4  500 RPM

E.4.1  Blade 1

Figure E.37 Mean velocity magnitude contour plot: Blade 1, 500 RPM, 1D

Figure E.38 Turbulence intensity (u-component): Blade 1, 500 RPM, 1D
Figure E.39 Turbulence intensity (v-component): Blade 1, 500 RPM, 1D
E.4.2 Blade 3

Figure E.40 Mean velocity magnitude contour plot: Blade 3, 500 RPM, 1D

Figure E.41 Turbulence intensity (u-component): Blade 3, 500 RPM, 1D
Figure E.42 Turbulence intensity (v-component): Blade 3, 500 RPM, 1D
Appendix F

Planar PIV Results: Ground-Based Trip Strips

F.1 Test Case Summary

Listed in table F.1 is a description of the test cases with ground-based trip strips installed.

<table>
<thead>
<tr>
<th>Blade Designation</th>
<th>Rotor Height</th>
<th>Rotor RPM</th>
<th>Trip-Strip Installed</th>
<th>Global Recirculation / Up-Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>200</td>
<td>TS1</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>200</td>
<td>TS2</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>300</td>
<td>TS1</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>0.75D</td>
<td>300</td>
<td>TS2</td>
<td>-</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>200</td>
<td>TS1</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>200</td>
<td>TS2</td>
<td>Global Recirculation</td>
</tr>
<tr>
<td>B1</td>
<td>1D</td>
<td>300</td>
<td>TS1</td>
<td>-</td>
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<tr>
<td>B1</td>
<td>1D</td>
<td>300</td>
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<tr>
<td>B2</td>
<td>1D</td>
<td>200</td>
<td>TS1</td>
<td>Global Recirculation</td>
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<td>B2</td>
<td>1D</td>
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<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>300</td>
<td>TS1</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>1D</td>
<td>300</td>
<td>TS2</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table F.1 Planar PIV test cases: ground-based trip-strips*
F.2 200 RPM

F.2.1 Blade 1

Figure F.1 Mean velocity magnitude contour plot: Blade 1, 200 RPM, 0.75D, TS1

Figure F.2 Turbulence intensity (u-component): Blade 1, 200 RPM, 0.75D, TS1
Figure F.3 Turbulence intensity (v-component): Blade 1, 200 RPM, 0.75D, TSI
Figure F.4 Mean velocity magnitude contour plot: Blade 1, 200 RPM, 0.75D, TS2

Figure F.5 Turbulence intensity (u-component): Blade 1, 200 RPM, 0.75D, TS2
Figure F.6 Turbulence intensity (v-component): Blade 1, 200 RPM, 0.75D, TS2
Figure F.7 Mean velocity magnitude contour plot: Blade 1, 200 RPM, 1D, TS1

Figure F.8 Turbulence intensity (u-component): Blade 1, 200 RPM, 1D, TS1
Figure F.9 Turbulence intensity (v-component): Blade 1, 200 RPM, 1D, TS1
Figure F.10 Mean velocity magnitude contour plot: Blade 1, 200 RPM, 1D, TS2

Figure F.11 Turbulence intensity (u-component): Blade 1, 200 RPM, 1D, TS2
Figure F.12 Turbulence intensity (v-component): Blade 1, 200 RPM, ID, TS2
F.2.2 Blade 2

**Figure F.13** Mean velocity magnitude contour plot: Blade 2, 200 RPM, 1D, TS1

**Figure F.14** Turbulence intensity ($u$-component): Blade 2, 200 RPM, 1D, TS1
Figure F.15 Turbulence intensity (v-component): Blade 2, 200 RPM, ID, TSI
Figure F.16 Mean velocity magnitude contour plot: Blade 2, 200 RPM, 1D, TS2

Figure F.17 Turbulence intensity (u-component): Blade 2, 200 RPM, 1D, TS2
**Figure F.18** Turbulence intensity ($v$-component): Blade 2, 200 RPM, 1D, TS2
F.3  300 RPM

F.3.1 Blade 1

Figure F.19 Mean velocity magnitude contour plot: Blade 1, 300 RPM, 0.75D, TS1

Figure F.20 Turbulence intensity (u-component): Blade 1, 300 RPM, 0.75D, TS1
Figure F.21 Turbulence intensity (v-component): Blade 1, 300 RPM, 0.75D, TS1
**Figure F.22** Mean velocity magnitude contour plot: Blade 1, 300 RPM, 0.75D, TS2

**Figure F.23** Turbulence intensity (u-component): Blade 1, 300 RPM, 0.75D, TS2
Figure F.24 Turbulence intensity (v-component): Blade 1, 300 RPM, 0.75D, TS2
Figure F.25 Mean velocity magnitude contour plot: Blade 1, 300 RPM, 1D, TS1

Figure F.26 Turbulence intensity (u-component): Blade 1, 300 RPM, 1D, TS1
Figure F.27 Turbulence intensity (v-component): Blade 1, 300 RPM, ID, TSI
Figure F.28 Mean velocity magnitude contour plot: Blade 1, 300 RPM, 1D, TS2

Figure F.29 Turbulence intensity (u-component): Blade 1, 300 RPM, 1D, TS2
Figure F.30 Turbulence intensity (v-component): Blade 1, 300 RPM, ID, TS2
F.3.2 Blade 2

**Figure F.31** Mean velocity magnitude contour plot: Blade 2, 300 RPM, 1D, TS1

**Figure F.32** Turbulence intensity (u-component): Blade 2, 300 RPM, 1D, TS1
Figure F.33 Turbulence intensity (v-component): Blade 2, 300 RPM, ID, TSI
Figure F.34 Mean velocity magnitude contour plot: Blade 2, 300 RPM, 1D, TS2

Figure F.35 Turbulence intensity (u-component): Blade 2, 300 RPM, 1D, TS2
Figure F.36 Turbulence intensity (v-component): Blade 2, 300 RPM, ID, TS2
Appendix G

POD Results

G.1 Isolated Rotor: Blade 1, 0.75D

G.1.1 200 RPM

Figure G.1 Relative energy of POD modes: Blade 1, 200 RPM, 0.75D
Figure G.2 First POD mode: Blade 1, 200 RPM, 0.75D

Figure G.3 Second POD mode: Blade 1, 200 RPM, 0.75D
Figure G.4 Third POD mode: Blade 1, 200 RPM, 0.75D
G.1.2 300 RPM

Figure G.5 Relative energy of POD modes: Blade 1, 300 RPM, 0.75D
G.1 Isolated Rotor: Blade 1, 0.75D

Figure G.6 First POD mode: Blade 1, 300 RPM, 0.75D

Figure G.7 Second POD mode: Blade 1, 200 RPM, 0.75D
Figure G.8 Third POD mode: Blade 1, 200 RPM, 0.75D
G.2 Isolated Rotor: Blade 3, 0.75D

G.2.1 200 RPM

Figure G.9 Relative energy of POD modes: Blade 3, 200 RPM, 0.75D
Figure G.10 First POD mode: Blade 3, 200 RPM, 0.75D

Figure G.11 Second POD mode: Blade 3, 200 RPM, 0.75D
Figure G.12 Third POD mode: Blade 3, 200 RPM, 0.75D
G.2.2 300 RPM

Figure G.13 Relative energy of POD modes: Blade 3, 300 RPM, 0.75D
Figure G.14 First POD mode: Blade 3, 300 RPM, 0.75D

Figure G.15 Second POD mode: Blade 3, 300 RPM, 0.75D
Figure G.16 Third POD mode: Blade 3, 300 RPM, 0.75D
G.3 Ground-Based Trip Strips: Blade 1, TS1

G.3.1 200 RPM, 0.75D

Figure G.17 Relative energy of POD modes: Blade 1, 200 RPM, 0.75D, TS1
Figure G.18 First POD mode: Blade 1, 200 RPM, 0.75D, TS1

Figure G.19 Second POD mode: Blade 1, 200 RPM, 0.75D, TS1
Figure G.20 Third POD mode: Blade 1, 200 RPM, 0.75D, TS1
G.3.2 200 RPM, 1D

Figure G.21 Relative energy of POD modes: Blade 1, 200 RPM, 1D, TSI
Figure G.22 First POD mode: Blade 1, 200 RPM, 1D, TS1

Figure G.23 Second POD mode: Blade 1, 200 RPM, 1D, TS1
Figure G.24 Third POD mode: Blade 1, 200 RPM, 1D, TSI
G.3.3 300 RPM, 1D

*Figure G.25* Relative energy of POD modes: Blade 1, 300 RPM, 1D, TS1
Figure G.26 First POD mode: Blade 1, 300 RPM, 1D, TS1

Figure G.27 Second POD mode: Blade 1, 300 RPM, 1D, TS1
Figure G.28 Third POD mode: Blade 1, 300 RPM, 1D, TS1
Appendix H

Vortex Identification

H.1  Isolated Rotor: Blade 1, 0.75D

H.1.1  200 RPM

Figure H.1 Estimated recirculation region core - horizontal position: Blade 1, 200 RPM, 0.75D
Figure H.2 Estimated recirculation region core - vertical position: Blade 1, 200 RPM, 0.75D
H.1 Isolated Rotor: Blade 1, 0.75D

H.1.2 300 RPM

**Figure H.3** Estimated recirculation region core - horizontal position: Blade 1, 300 RPM, 0.75D

**Figure H.4** Estimated recirculation region core - vertical position: Blade 1, 300 RPM, 0.75D
H.2 Isolated Rotor: Blade 3, 0.75D

H.2.1 200 RPM

Figure H.5 Estimated recirculation region core - horizontal position: Blade 3, 200 RPM, 0.75D

Figure H.6 Estimated recirculation region core - vertical position: Blade 3, 200 RPM, 0.75D
H.2 Isolated Rotor: Blade 3, 0.75D

H.2.2 300 RPM

**Figure H.7** Estimated recirculation region core - horizontal position: Blade 3, 300 RPM, 0.75D

**Figure H.8** Estimated recirculation region core - vertical position: Blade 3, 300 RPM, 0.75D
H.3 Ground-Based Trip Strips: Blade 1, TS1

H.3.1 200 RPM, 0.75D

Figure H.9 Estimated recirculation region core - horizontal position: Blade 1, 200 RPM, 0.75D, TS1

Figure H.10 Estimated recirculation region core - vertical position: Blade 1, 200 RPM, 0.75D, TS1
H.3.2 200 RPM, 1D

Figure H.11 Estimated recirculation region core - horizontal position: Blade 1, 200 RPM, 1D, TS1

Figure H.12 Estimated recirculation region core - vertical position: Blade 1, 200 RPM, 1D, TS1
H.3.3 300 RPM, 1D

Figure H.13 Estimated recirculation region core - horizontal position: Blade 1, 300 RPM, 1D, TS1

Figure H.14 Estimated recirculation region core - vertical position: Blade 1, 300 RPM, 1D, TS1
Appendix I

Planar PIV Results: Active Deflectors

I.1 Baseline

*Figure I.1* Mean velocity magnitude contour plot overlaid with streamlines: Baseline
Figure 1.2 Turbulence intensity (u-component): Baseline

Figure 1.3 Turbulence intensity (v-component): Baseline
I.2 Deflector 1

I.2.1 $h_1 (0.11D), V_1 (0.67V_{tip})$

Figure I.4 Mean velocity magnitude contour plot overlaid with streamlines: $D1, V_1, h = 25$ mm
**Figure 1.5** Turbulence intensity (u-component): $D1, V_1, h = 25$ mm

**Figure 1.6** Turbulence intensity (v-component): $D1, V_1, h = 25$ mm
I.2 Deflector 1

I.2.2 $h_1 (0.11D), V_2 (0.77V_{tip})$

*Figure I.7* Mean velocity magnitude contour plot overlaid with streamlines: $D1, V_2, h = 25\ mm$
Figure I.9 Turbulence intensity (v-component): \( D1, V_2, h = 25 \text{ mm} \)

Figure I.8 Turbulence intensity (u-component): \( D1, V_2, h = 25 \text{ mm} \)
I.2.3 \( h_2 (0.20D), V_1 (0.67V_{tip}) \)

*Figure I.10* Mean velocity magnitude contour plot overlaid with streamlines: \( D_1, V_1, h = 45 \text{ mm} \)
Figure 1.12 Turbulence intensity (v-component): $D_1, V_1$, $h = 45$ mm

Figure 1.11 Turbulence intensity (u-component): $D_1, V_1$, $h = 45$ mm
I.2.4  $h_2 \, (0.20D), \, V_2 \, (0.77V_{tip})$

*Figure I.13* Mean velocity magnitude contour plot overlaid with streamlines: $D1, \, V_2, \, h = 45 \text{ mm}$
Figure I.15 Turbulence intensity (v-component): $D1, V_2, h = 45 \text{ mm}$

Figure I.14 Turbulence intensity (u-component): $D1, V_2, h = 45 \text{ mm}$
I.3 Deflector 2

I.3.1 $h_1 (0.11D), V_1 (0.67V_{tip})$

Figure I.16 Mean velocity magnitude contour plot overlaid with streamlines: $D2, V_1, h = 0.23R$
Figure I.18 Turbulence intensity (v-component): D2, V1, h = 0.23R

Figure I.17 Turbulence intensity (u-component): D2, V1, h = 0.23R
I.3.2 $h_1 (0.11D), V_2 (0.77V_{tip})$

*Figure I.19* Mean velocity magnitude contour plot overlaid with streamlines: $D_2, V_2, h = 0.23R$
Figure I.21 Turbulence intensity (v-component): $D_2, V_2, h = 0.23R$

Figure I.20 Turbulence intensity (u-component): $D_2, V_2, h = 0.23R$
I.3 Deflector 2

I.3.3 $h_2 (0.20D), V_1 (0.67V_{tip})$

**Figure I.22** Mean velocity magnitude contour plot overlaid with streamlines: $D_2, V_1, h = 0.41R$
Figure I.24 Turbulence intensity (v-component): $D_2, V_1, h = 0.41R$

Figure I.23 Turbulence intensity (u-component): $D_2, V_1, h = 0.41R$
I.3.4 \( h_2 (0.20D), V_2 (0.77V_{tip}) \)

**Figure I.25** Mean velocity magnitude contour plot overlaid with streamlines: \( D_2, V_2, h = 0.41R \)
Figure I.27 Turbulence intensity ($v$-component): $D_2, V_2, h = 0.41R$

Figure I.26 Turbulence intensity ($u$-component): $D_2, V_2, h = 0.41R$
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