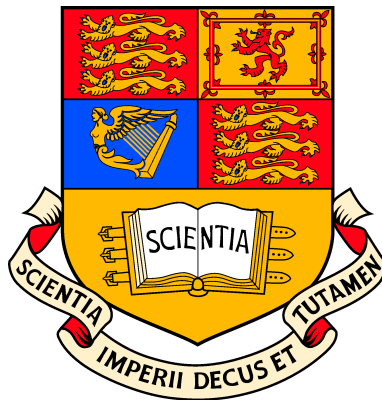


Experimental Study of the Vortex System Generated by a Formula 1 Front Wing

by

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Declaration

I declare that all of the work that is contained within this thesis has been undertaken by the author.

Signed.....

Date.....

Abstract

This thesis describes the research undertaken on the behaviour of the vortex system generated by a Formula 1 front wing, as it travels about a rotating wheel. This has been realised by investigating the flow structure downstream of a 50% wind tunnel model using flow visualisation, total pressure wake surveys, hot-film anemometry and PIV.

The characteristics of the vortex system have been obtained by examining the flow from the wing and endplate without the wheel. This has shown that the wake consists of four co-rotating vortices which interact and merge together. By modifying the ride height of the wing the relative strengths of the vortices are affected resulting in subtle differences to the downstream merging process.

The introduction of the wheel substantially affects the vortex system. To analyse its influence the behaviour of a single trailing vortex has been examined as it passes about the wheel. Observations have shown that the trajectory of the vortex is strongly dependant on its initial position and strength ahead of the wheel.

With the wheel included, the flow structure generated by the Formula 1 front wing is dominated by the interaction between two vortices. The relative strength and separation of these two structures is affected by both the ride height of the wing and the influences of the rotating wheel. As a result the flow structure formed downstream is dependant on the amount of merging which has taken place.

This research has shown that the flow downstream of a Formula 1 front wing is strongly affected by the merging characteristics of the trailing vortex system. Hence by careful consideration of the placement and strength of the vortices it is possible to change the structure of the flow.

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Nomenclature

Roman

X	Lateral Axis
Y	Streamwise Axis
Z	Vertical Axis
U	Velocity component aligned with the X-Axis
V	Velocity component aligned with the Y-Axis
W	Velocity component aligned with the Z-Axis
U_θ	Tangential velocity
U_x	Axial velocity
b	Separation between vortex centres
r	Radius
c	Chord
h	Gap between trailing edge of footplate and ground plane (used to define ride height)
D	Wheel diameter
t	Time

Greek

α	Angle of incidence
Γ	Circulation
ω	Vorticity
ϕ	Swirl angle

Subscripts

y	Streamwise
c	Core
o	Total (e.g. Γ_0 =total circulation)
mp	Mainplane
fp	Flap
∞	Freestream

Abbreviations

Re	Reynolds number
CFD	Computational fluid dynamics
RANS	Reynolds averaged Navier-Stokes
PIV	Particle image velocimetry
MS	Model scale
FS	Full scale
SD	Standard Deviation

Chapter 1

Introduction

1.1 Race-Car Aerodynamics

Many race-car teams have invested significant time and effort into aerodynamic research and development due to the considerable performance gains that can be obtained from the application of aerodynamics to motorsport. A measure of the performance of a race-car is that of the maximum lateral acceleration. A graph of this performance parameter during the twentieth century is shown in Figure 1.1. As can be seen from the trend in this figure, the application of aerodynamics to the field of motorsport became popular during the latter part of the 1960's and during the 1970's (Flefl & Singer 1998). Prior to this period the aerodynamic design of a race-car (such as a Formula 1 car), was limited to improving the cars performance by careful streamlining of the chassis and controlling cooling flows (Wright 1983).

During the mid part of the century, there was a significant increase in the performance of race-cars due to the phenomenon of downforce. Downforce or negative lift, is the force that is generated by a wing when inclined at a negative angle of attack (Katz 2006). Downforce increases the performance of a race-car by supplementing the mechanical grip produced by the tyres, thus increasing the wheel load and improving both handling and driving stability (Flefl & Singer 1998). The first application of downforce was achieved by the 1967 Chaparral 2F racing car which had inverted wings. The success of this innovation ensured downforce producing

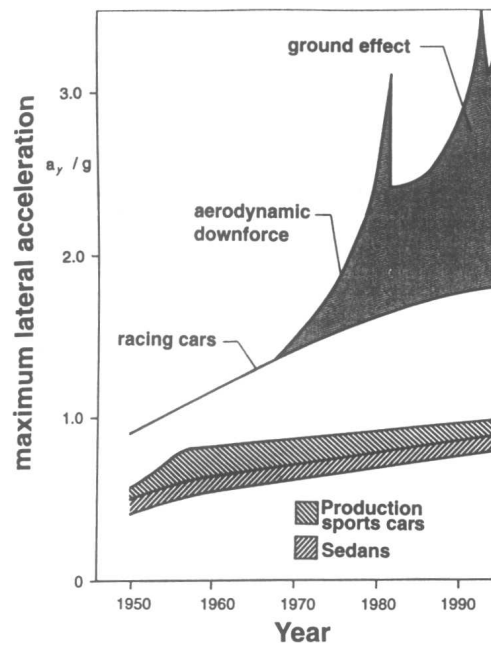


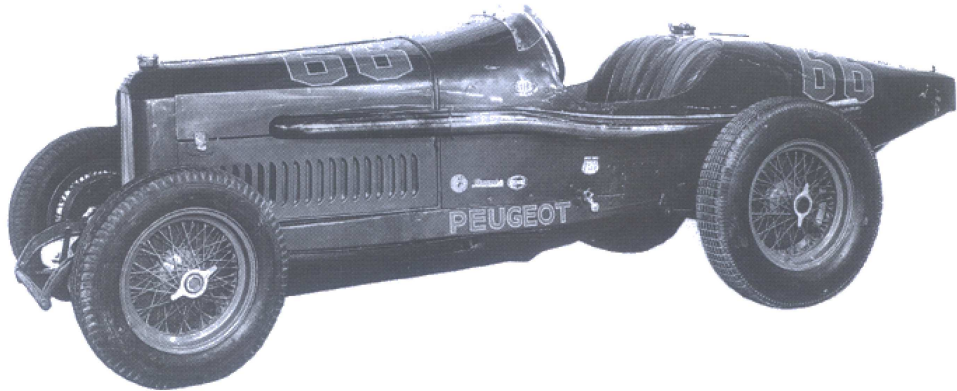
Figure 1.1: A graph showing the development in maximum cornering acceleration with time (Flefl & Singer 1998)

wings on race-cars would be common from that day on (Katz 2006).

Once the potential performance gains resulting from race-car aerodynamics had been realised during the 1960's, the subsequent development in the area was rapid (Zhang, Toet, & Zerihan 2006). The next major step-forward was the introduction of ground effect (Flefl & Singer 1998). Ground effect can be generally defined as the aerodynamic consequences of operating a lifting surface in close proximity to the ground (Wright 2001). The Lotus 79 Formula 1 racing car was the first race-car to utilise ground effect, which it achieved by having a venturi shaped underbody thereby generating suction with the ground. (Flefl & Singer 1998).

Modern Formula 1 teams now utilise advanced techniques in wind tunnels to improve the aerodynamics of their race-cars. Consequently, the chassis of a modern car has become very complicated with many complex aerodynamic features. This can be seen in Figure 1.2, where a modern Formula 1 car bears little resemblance to the race winning Indy 500 car of 1916 and Figure 1.3 which highlights the various aerodynamic components on a modern Formula 1 car.

To summarise, the utilisation of aerodynamics to improve the performance of a



(a) The 1916 Indy 500 Peugeot winning car (Katz 1995)



(b) The 2006 McLaren MP21 (www.mclaren.com visited on 10/07/06)

Figure 1.2: Two race-cars of different eras, showing the drastic differences in appearance due to the progress made in race-car aerodynamics

race-car can be achieved in any of the following ways (Flefl & Singer 1998):

- Augmentation of mechanical grip by aerodynamic downforce to increase cornering speeds
- Reduction of aerodynamic drag to raise maximum attainable velocity
- Control of aerodynamic forces to improve car balance and hence handling characteristics
- Control of internal flow to enhance the cars cooling and engine aspiration

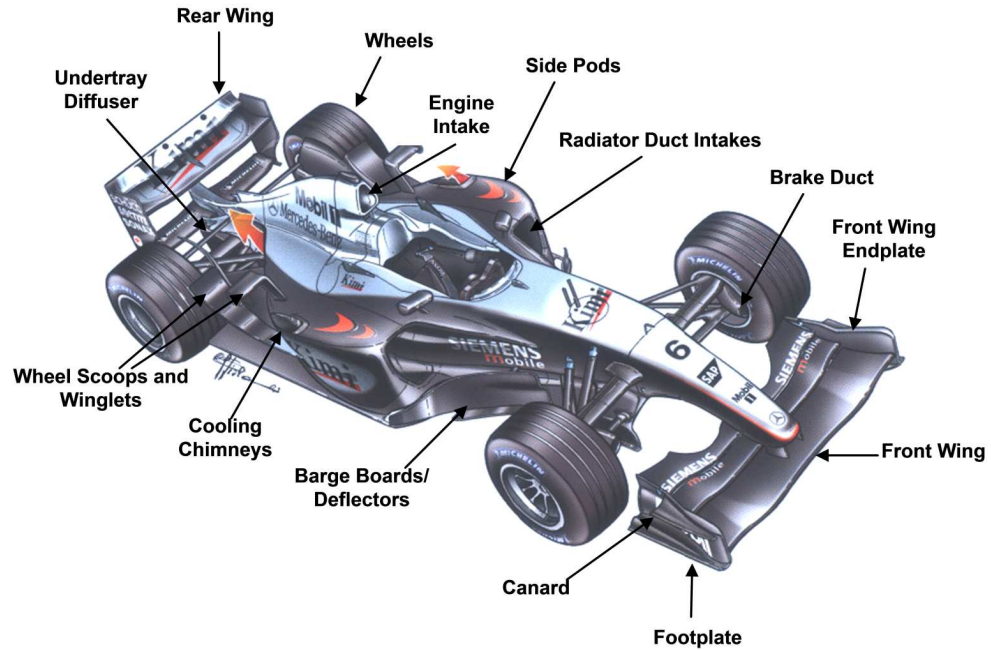


Figure 1.3: Schematic of a modern Formula 1 car highlighting the various aerodynamic components (Piola 2005)

1.2 Front Wing Aerodynamics

As discussed above, the performance of a race-car can be greatly enhanced by the production of downforce. As such, the main design objective for a front wing is to generate as much downforce as possible. However, as a consequence of its location as the most upstream aerodynamic component, it is extremely important that the production of negative lift by the front wing is not at the detriment of other components downstream (Wright (2001) and Zhang, Toet, & Zerihan (2006)). Moreover, due to the distance of the front wing from the cars centre of pressure, the downforce produced by the front wing is a major parameter in setting the aerodynamic balance of the car and hence its handling characteristics.

On a modern race-car, a large proportion of the generated downforce originates from underneath the chassis. Consequently it is undesirable to extract large amounts of energy from this air. Hence, there is a trend of loading up the outer portions of the wing so that the losses that are generated in this area, can be directed away from the major downforce producing components downstream (Wright 2001).

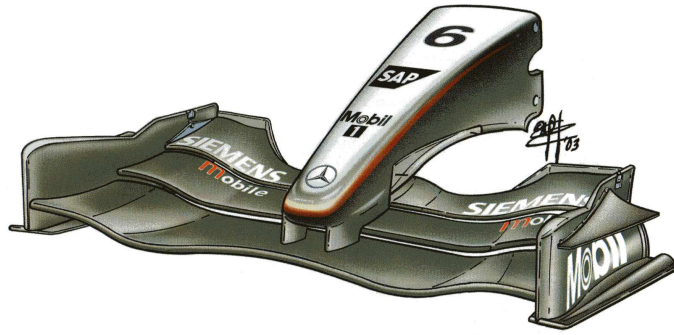


Figure 1.4: A pictorial representation of a typical Formula 1 front wing and endplate taken from Tremayne (2004)

In order to follow this trend, the endplates found on the outboard edges of the front wing are often extremely complicated (see Figure 1.4), and their lifting surfaces generally result in a multiple trailing vortex system. It is this trailing vortex system that will form the basis for this project, the motivation of which is discussed in the following section.

1.3 Project Motivation

The wake downstream of a Formula 1 front wing consists of a trailing vortex system originating from the endplates. This system usually consists of several co-rotating vortical structures which after having been shed from the endplate, immediately encounter the presence of the front wheels (see Figure 1.3). One of the governing rules of Formula 1 dictates that the car must have four large exposed wheels. The aerodynamics of the flow about these wheels is complicated, and not only must the vortices navigate about these large bluff bodies, but they must also encounter the strong cross-flows which further complicate the flow in this region (Agathangelou & Gascoyne (1998) and Wright (2001)).

All of these factors contribute to a complicated flow structure inboard and downstream of the front wheel. These structures can result in an undesirable region of energy loss, which may affect the performance of the car.

Therefore, the behaviour of the front wing wake inboard and downstream of

the wheel, provides the main motivation for this experimental project. By gaining further knowledge about how the vortex system behaves and interacts with the flow about the wheel, then hopefully performance gains can be made in the future.

In the next chapter the literature relevant to this problem will be reviewed and the specific aims and objectives of the project will be presented.

Chapter 2

Review of Relevant Literature

2.1 Introduction to Review

As Katz (2006) has stated, due to the very specific application and the corresponding competitive nature of the motorsport industry, the results of research that has been conducted into race-car aerodynamics have generally been kept confidential and consequently little has been published.

Therefore the research into the aerodynamics of a front wing trailing vortex system, navigating about a wheel, has been broken down into the following smaller sections in which literature is more readily available:

1. Vortical Structures

As discussed in Section 1.2, the front wing of a Formula 1 car operates in ground effect and produces a substantial amount of downforce. However, this research project is primarily focussed on the behaviour of its trailing vortex system as it passes around the wheel. Therefore the front wing and endplate can be thought of as a vortex generator and hence it is necessary to review the literature on the fundamental flow physics of such structures.

2. Vortical Behaviour

Once the multiple trailing vortex system has been shed from the front wing, the vortices may interact with one another as they travel downstream. They

may also pass close to the solid boundary formed by the ground plane and their initial strength or the presence of the wheel may provoke a breakdown in the structure of the vortices. Hence the literature associated with the behaviour of vortices due to such influences, has been examined to provide a useful background for this research.

3. Wheel Aerodynamics

The presence of the large, rotating wheel in close proximity to the trailing edge of the front wing and endplate ensures that it has a drastic influence on the flow in the region. The flow about an isolated wheel is known to be complex from the reasonable amount of literature on the subject. This has been reviewed to provide an understanding into the influence of the wheel on the front wing's trailing vortex system.

Finally, once the relevant literature has been reviewed and discussed, it is possible to state the overall aims and objectives of this research project and this is completed at the end of the chapter.

2.2 Vortical Structures

Over the years, swirling flows have been observed in many different applications. Perhaps the most obvious is that of the natural world. One such example of this can be seen in Figure 2.1, showing hurricane Katrina as viewed from a satellite. This 'naturally occurring vortex' wrecked havoc and destruction in and around the Gulf of Mexico during the month of August 2005 (http://en.wikipedia.org/wiki/Hurricane_Katrina_viewed_on_21/07/06). There are also many more examples of naturally occurring vortices including: tornadoes, typhoons and whirlpools.

The presence of vortices is also extremely common in the field of aeronautics, where knowledge of their behaviour is of paramount importance. Also, as the motor-sport industry has employed aerodynamics to enhance the performance of race-cars, vortices are present in this application and therefore play an important role. As a consequence of their presence in many varied applications, the study of vortices has

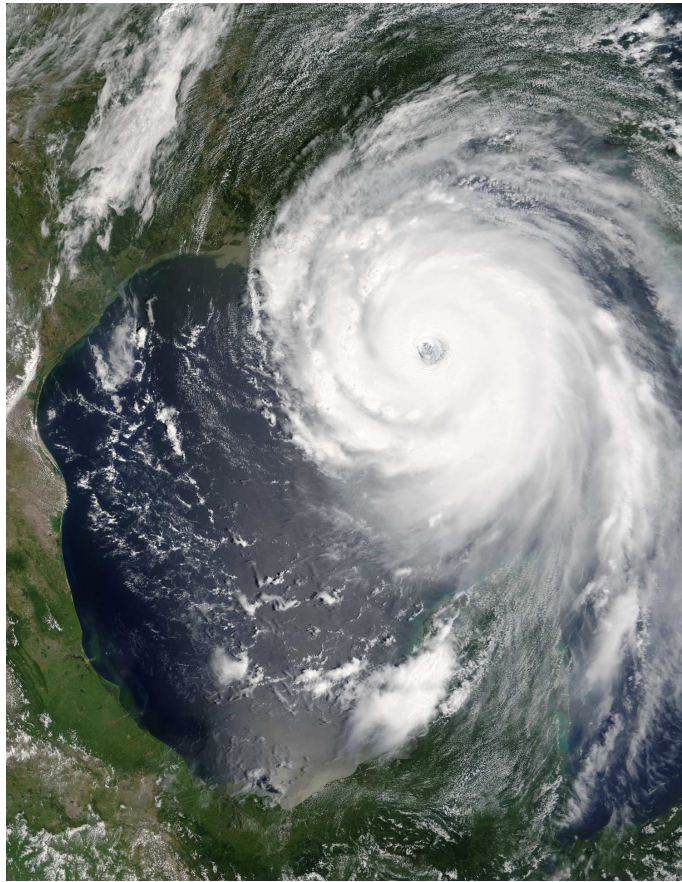


Figure 2.1: Hurricane Katrina as viewed from a satellite is just one example of a naturally occurring vortex (taken from www.nasa.gov visited on 10/07/06)

received extensive attention for many decades. The main results of which will be reviewed in this section.

2.2.1 Definition of a Vortex

In complex flows the question as to what constitutes a vortex has long been a source of contention to researchers, despite the considerable work that has been undertaken in this area. At present there is no universally accepted, rigorous, definition of a vortex, which completely describes their physical characteristics (Jeong & Hussain 1995).

In the past many definitions have been proposed. The majority of these refer to attributes of a vortex such as; pressure minimum in a core, closed or spiralling

streamlines or a threshold vorticity level (Jeong & Hussain 1995). Unfortunately, these statements do not uniquely define every known vortical flow and sometimes may indicate the erroneous presence of a vortex. In his discussion on fluid vortices, Green (1995a) proposes a non-rigorous definition that a “fluid vortex is a region of concentrated vorticity.” Although this has several deficiencies, it does loosely describe what can be seen physically.

The most widely accepted condition for locating the core of a vortex was proposed by Jeong & Hussain (1995) in their paper on the identification of a vortex. In this paper, they propose a mathematical condition based on the Navier-Stokes equations, which focusses on the presence of a pressure minimum, formed without the contribution from unsteady, irrotational straining and viscous terms. This condition can be obtained by examining the symmetric and asymmetric components of ∇u which are S and Ω respectively (as defined by Equations 2.1 and 2.2 below).

$$S_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad (2.1)$$

$$\Omega_{ij} = \frac{1}{2}(u_{i,j} - u_{j,i}) \quad (2.2)$$

By considering the individual components which can create a local pressure minimum and by ignoring those which are not as a consequence of vortical motion (those from unsteady, irrotational straining and viscous terms), the symmetric part of the gradient of the Navier-Stokes equations can be reduced to that shown in Equation 2.3.

$$\Omega_{ik}\Omega_{kj} + S_{ik}S_{kj} = \frac{-1}{\rho}p_{i,j} \quad (2.3)$$

Since the occurrence of the pressure minimum requires two positive eigenvalues of the tensor $p_{i,j}$, a vortex core can be defined as a connected region with two negative eigenvalues of $S^2 + \Omega^2$. If λ_1, λ_2 and λ_3 are the eigenvalues of this expression and $\lambda_1 \geq \lambda_2 \geq \lambda_3$ then this definition of the vortex core can be reduced to the region in which $\lambda_2 < 0$.

In their paper Jeong & Hussain (1995) evaluate the suitability of this condition in certain conditions where previous definitions have erroneously found a vortex (for example, a wall bounded shear layer). They conclude that this mathematical condition appears to be the most successful method for locating a vortex core.

However when the presence of a valid vortex is known, the more basic definitions of the vorticity threshold or closed spiraling streamlines may be more suitable due to their simplicity.

2.2.2 The Formation of a Vortex

As stated in Section 2.2.1, a vortex can be thought of as a region of concentrated vorticity. Although this definition was introduced previously, it was not necessary to elaborate further on the concept of vorticity. However vorticity is an extremely important property of the flow necessary for the generation of a vortex and as such needs to be introduced at this point.

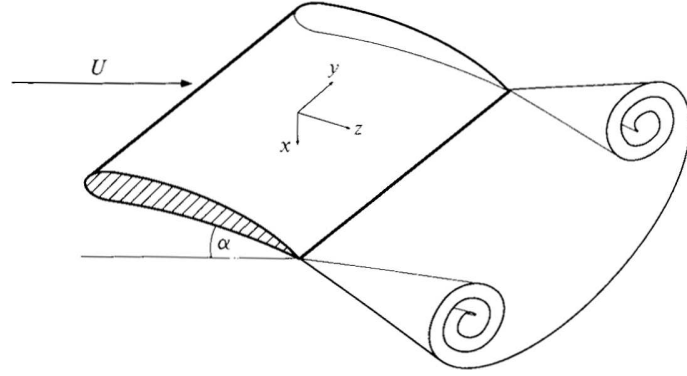
The mathematical definition of vorticity is that it is the curl of the velocity vector and as such, physically it is related to the angular velocity in the flow (Anderson 1991). Vorticity is generated as a consequence of flow passing over a surface in a favourable pressure gradient (where $\frac{\partial P}{\partial x} < 0$). Vorticity is generated by the viscous forces acting near the surface (Green 1995a) and when the flow terminates at a body or separates from the surface in an adverse pressure gradient (where $\frac{\partial P}{\partial x} > 0$), the vorticity originally generated in the boundary layer is transported away from the surface. Vortices can be interpreted as the structures which form due to the rolling up of this separation surface (Delery 1994). This separation can occur on both conventional planform wings and delta wings (high sweep and low aspect ratio), in each case forming a trailing vortex system. The formation of a vortex on these two types of wing will now be discussed.

2.2.2.1 Tip Vortex Formation From a Rectangular Planform Wing

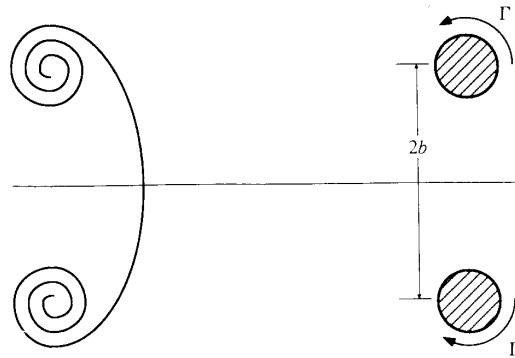
Tip vortices are generated whenever a lifting surface terminates in a fluid (Green 1995b). The streamwise vorticity contained within a tip vortex which was generated

on the lifting surface, is shed as a continuous vortex sheet (Phillips 1981).

Inviscid theory states that a vortex sheet which is generated on a finite lifting wing will roll-up as a consequence of its own induced velocity as shown schematically in Figure 2.2(a) (Saffman (1992), Moore & Saffman (1973) and Saffman & Baker (1979)). During the roll-up process the spirals continuously tighten as the distance



(a) Vortex sheet roll-up



(b) Intermediate and asymptotic stages of vortex sheet roll-up

Figure 2.2: The roll-up of an inviscid vortex sheet into two trailing vortices of equal strength (Saffman 1992)

between neighbouring turns becomes smaller and smaller (Saffman & Baker 1979). Consequently, the sheet between the two spirals becomes increasingly thinner as the vortex sheet is stretched (Saffman 1992). Viscosity acts to diffuse the discrete spiral structure in the innermost spirals and hence the theoretical discontinuities in the tangential and axial velocity distributions due to the piecewise steps from one spiral to another, are smoothed out (Moore & Saffman 1973). It is this merged region

within the spiral structure which is termed a trailing vortex (Phillips 1981). This roll-up process leaves the two discrete tip vortices shown in Fig 2.2(b). According to Green (1995b) this roll-up process is reasonably rapid, occurring with 2-3 chords downstream of the trailing edge. Roll-up is deemed complete when there is little change in the tangential velocity and circulation of the vortex with downstream distance (Green 1995b).

Another, more intuitive explanation for the formation of a tip vortex is given by Batchelor (1967) and Anderson (1991). They base the reasons for the generation of a trailing vortex system on a finite wing from the pressure imbalance that exists at the wing tip. This pressure imbalance arises due to the consequences of a lifting surface. The differences in curvature of the aerofoil cross-section of a lifting-wing creates a suction surface and a pressure surface (Batchelor 1967). For a finite wing, at some point these two surfaces must meet and this occurs at the tip. At the tip the pressure difference leads to a tendency for the flow to accelerate in a circular fashion, curling the flow about the tip (Batchelor (1967) and Anderson (1991)). This behaviour can be seen schematically in Figure 2.3 for a conventional positive lift producing wing (note that for a downforce producing wing, such as found on a race-car, the wing is inverted and hence the suction acts on the lower surface).

Either of these two explanations is sufficient to describe the trailing vortices shed from a rectangular planform wing such as those seen experimentally from Figure 2.4.

2.2.2.2 Tip Vortex Formation From a Delta Wing

A delta wing also produces a trailing vortex system. In similarity to a rectangular planform wing, the pressure difference at the tips, provokes the flow in the region to curl around the wing (Anderson 1991). However, if the leading edge of the delta wing is sharp (or if sufficiently blunt, when a certain angle of attack has been reached), then the formation of the vortex is enhanced by a shear layer created as a consequence of the separation of the flow along the leading edge (Althaus, Brücker, & Weimer 1995). This leads to two vortices dominating the flow over the delta wing as can be seen in Figure 2.5. These vortices can be very strong with axial velocities

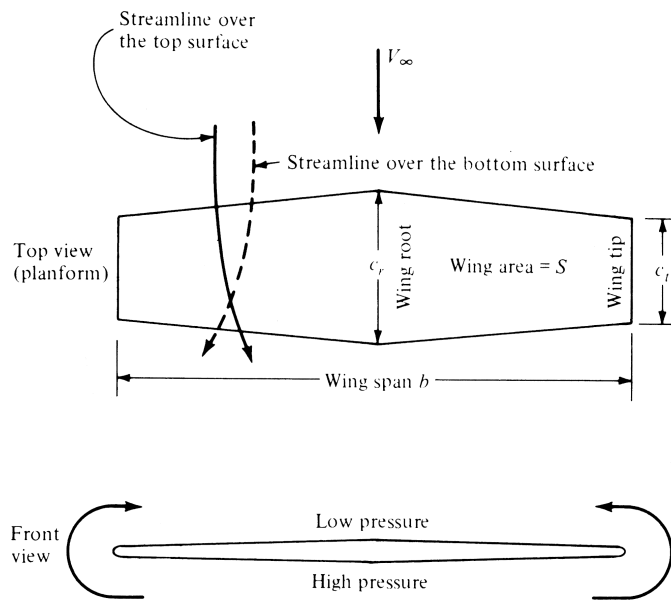


Figure 2.3: A schematic of the flow about a conventional wing and the formation of the tip vortices due to the pressure imbalance at the tips (Anderson 1991)

as large as four or five times the freestream velocity (Gursul 2005). Hence additional suction is generated as a result of the very low pressures in the core and the lift on the wing due to these vortices can be increased by as much as 60 % (Althaus, Brücker, & Weimer 1995). As a consequence of their structure, delta wing vortices can be prone to vortex breakdown. This phenomenon is discussed later in Section 2.3. The next section will discuss the structure of a vortex.

2.2.3 Structure of an Isolated Vortex

In the previous two sections, the various definitions of a vortex have been reviewed and discussions on how a vortex is formed during the roll-up process have been made. Once roll-up has been completed then a trailing vortex without any external influences can be approximately considered as axisymmetric (Saffman 1992). Consequently an isolated vortex has a tangential velocity and circulation distribution varying only with the distance from the axis. In this section these will be examined and also the axial velocity will be discussed.

Perhaps the simplest model for the tangential velocity about a vortex is that

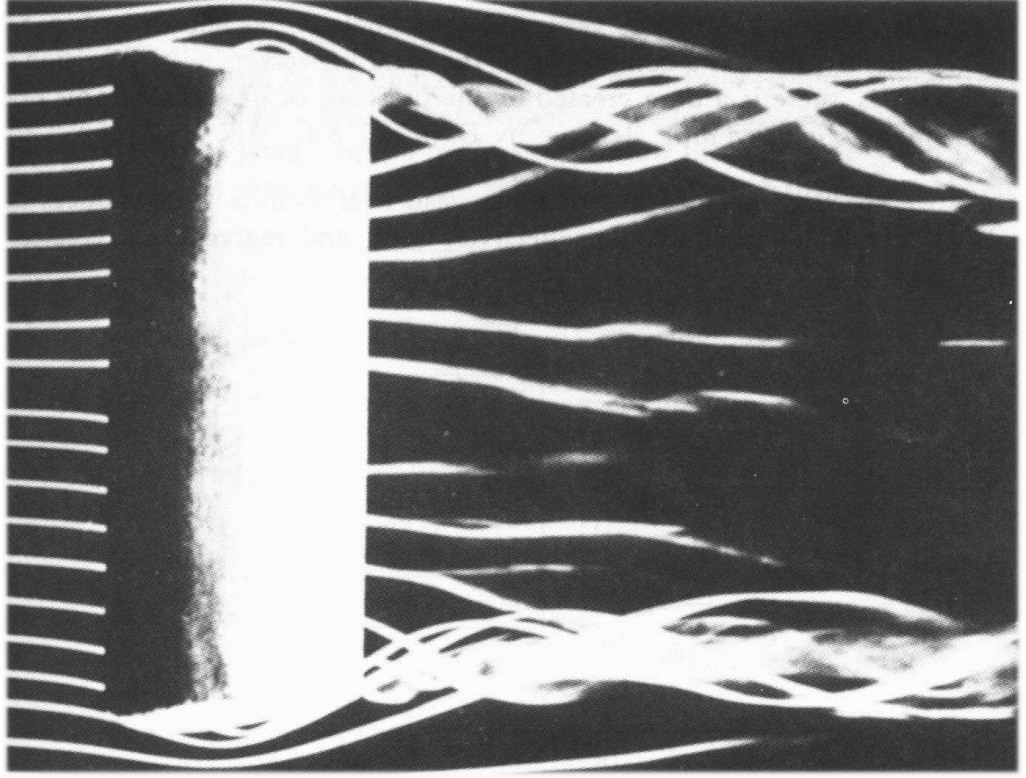


Figure 2.4: Wing tip vortices shed from a rectangular planform wing, made visible by smoke filaments (Anderson 1991)

known as the Rankine vortex. This two-dimensional model assumes that inside the core of the vortex, fluid rotates as a solid body and outside of the core the flow is essentially irrotational (Green 1995a). Equation 2.4 makes this statement mathematically (taken from Green (1995a)).

$$U_{\theta}(r, \theta, z) = \begin{cases} \frac{\Gamma_0}{2\pi r_c^2} r & r \leq r_c \\ \frac{\Gamma_0}{2\pi r} & r > r_c \end{cases} \quad (2.4)$$

where Γ_0 is the total circulation of the vortex and r_c is the radius of the core. This expression produces the non-dimensional tangential velocity and non-dimensional circulation shown by the red data series displayed in Figures 2.6(a) and 2.6(b) respectively. As can be seen from this figure, the Rankine vortex model has an inherent discontinuity in the rate of change of velocity with radius at the edge of the vortex core. This is not physically correct and hence, other vortex models have been

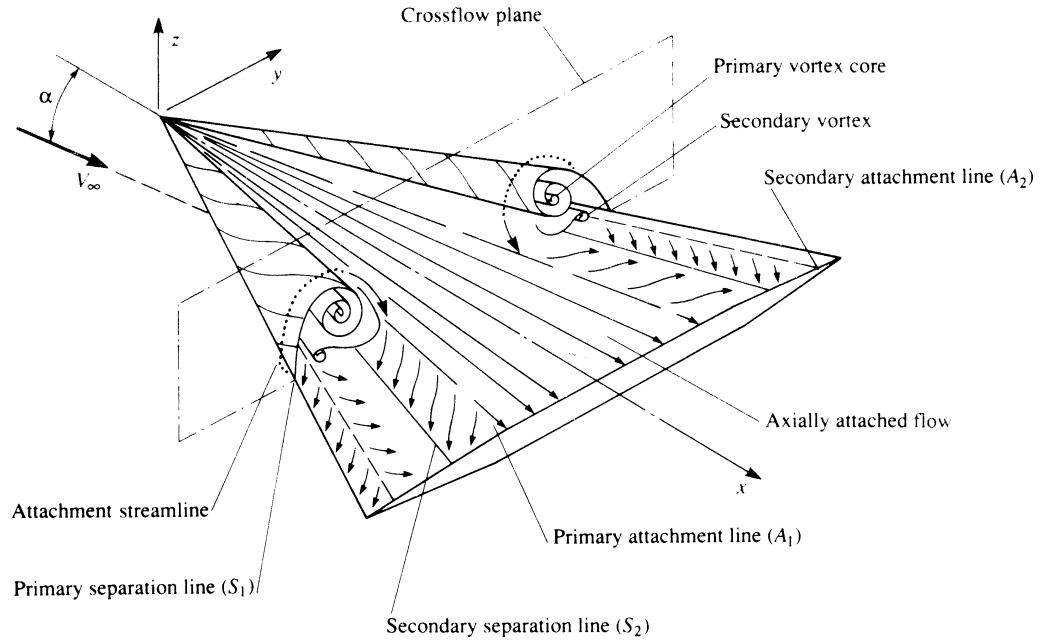


Figure 2.5: Schematic of the flow over a delta wing at an angle of attack taken from Anderson (1991)

produced.

A vortex model which takes into account viscosity is the Lamb-Oseen model (Lamb (1932) and Batchelor (1967)). This is an exact solution of the Navier-Stokes equations given two-dimensional laminar flow and circular streamlines. Hence this model is a more physical representation of a vortex. The exact solutions for the vorticity, circulation and tangential velocity are given in Equations 2.5, 2.6 and 2.7 respectively (Saffman 1992), where ν is the kinematic viscosity and t is a measure of the time.

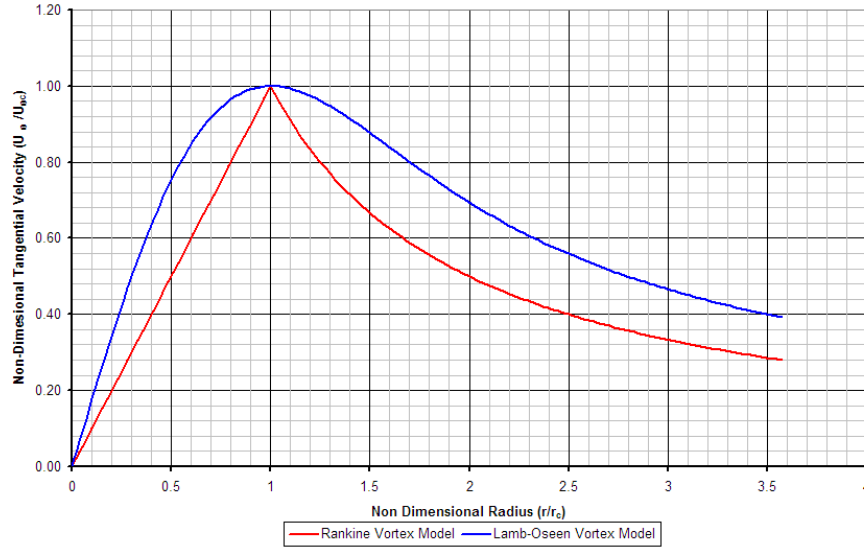
$$\omega = \frac{\Gamma_0}{4\pi\nu t} e^{-\frac{r^2}{4\nu t}} \quad (2.5)$$

$$\Gamma = \Gamma_0 \left(1 - e^{-\frac{r^2}{4\nu t}}\right) \quad (2.6)$$

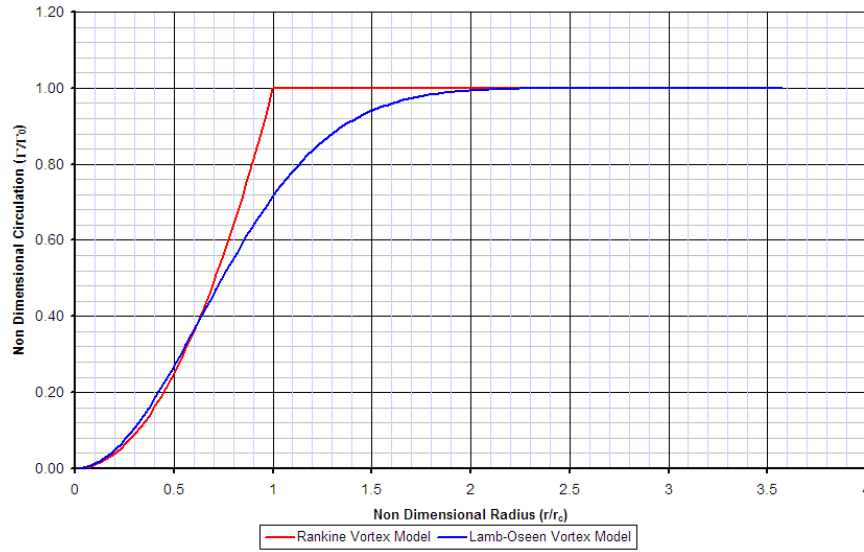
$$U_\theta = \frac{\Gamma}{2\pi r} = \frac{\Gamma_0}{2\pi r} \left(1 - e^{-\frac{r^2}{4\nu t}}\right) \quad (2.7)$$

This model results in a tangential velocity and circulation distribution without a singularity at the edge of the vortex core and is plotted in Figure 2.6 as the blue data series.

So far, the models that have been examined do not take into account the axial velocity, as they are two dimensional axisymmetric models. From the discussion



(a) Non-Dimensional Tangential Velocity Plotted with Non-Dimensional Radius



(b) Non-Dimensional Circulation Plotted with Non-Dimensional Radius

Figure 2.6: Comparison of the circulation and tangential Velocity for both the Rankine and Lamb-Oseen Vortex Models

in Section 2.2.2.2 it is known that low pressure exists within the core. Batchelor (1964) stated that this was a consequence of the need to balance the large centrifugal forces which are present in the vortex core and has also been viewed experimentally

(such as that shown in Figure 2.7). The low pressures found in the core, accelerate

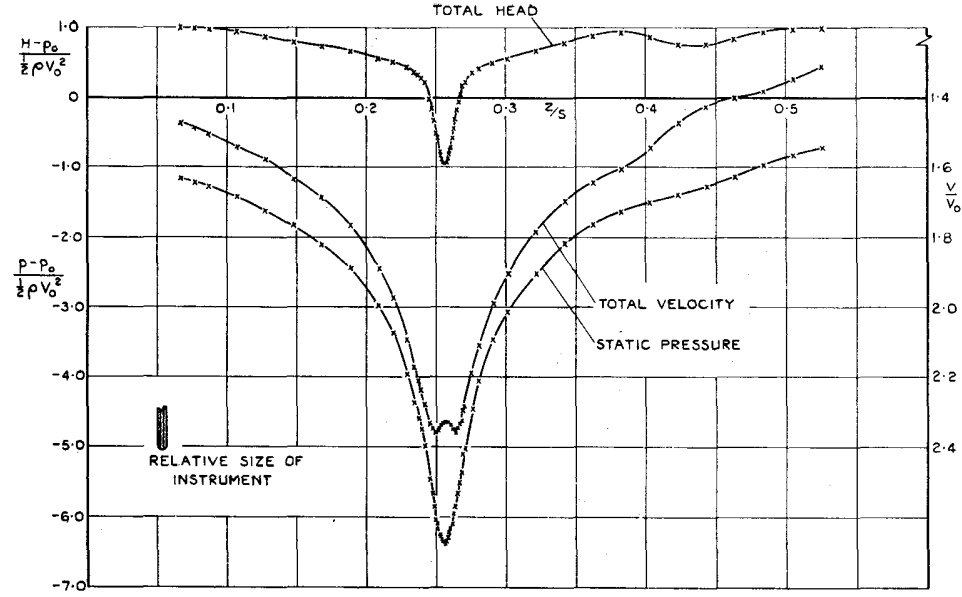


Figure 2.7: Experimental pressure and velocity distributions through the axis of a delta wing vortex (Earnshaw 1962)

incoming fluid to produce a favourable pressure gradient and hence an axial velocity which is greater than that of the freestream (Devenport, Rife, Liapis, & Follin 1996). Such vortices where the axial velocity is greater than the freestream are termed ‘*jet-like*’ vortices and are found in intense vortices such as those over wings at high incidences and delta wings (Delery 1994). According to Batchelor (1964), the high axial velocity in these vortices is due to the separated shear layer constantly feeding vorticity into the vortex core with chordwise distance. Conversely, vortices where there is a axial velocity deficit are termed ‘*wake-like*’ and it is this sort of axial velocity which is found in trailing vortices formed from a standard planform wing at moderate angles of attack (Delery 1994).

There are several vortex models which take into account the distribution of axial velocity through the core. One of the most commonly used is that of the Batchelor Vortex (Batchelor 1964), which is also an exact solution of the Navier-Stokes equations. The mathematical expressions for this model are given below in

Equation 2.8 (Devenport, Rife, Liapis, & Follin 1996). This model is similar to the two-dimensional Lamb-Oseen vortex with the inclusion of an axial velocity.

$$U_{\theta} = U_{\theta c} \left(1 + \frac{0.5}{\alpha} \right) \frac{r_c}{r} \left[1 - e^{-\frac{\alpha r^2}{r_c^2}} \right] \quad (2.8)$$

$$U = U_x e^{-\frac{\alpha r^2}{d^2}} \quad (2.9)$$

where $\alpha = 1.25643$, $U_{\theta c}$ is the peak tangential velocity, U_x the centreline axial velocity (relative to the freestream), r_c is the core radius and d is a radial scale for the axial profile.

Many experimental investigations have been performed on the structure of a tip vortex. Perhaps the most comprehensive of these is that carried out by (Devenport, Rife, Liapis, & Follin 1996). They used a four-wire hot wire probe to obtain the velocity components and streamwise vorticity of a tip vortex behind a rectangular planform wing. Whilst performing this study they found that it was necessary to address the problem of vortex wandering or vortex meander. Vortex wandering is defined as the random displacement of the vortex core and has been viewed in tip vortices from both rectangular planform wings and delta wings (Gursul & Xie 1999). There is some uncertainty over the source of these fluctuations. Devenport, Rife, Liapis, & Follin (1996) suggested that the slow lateral movement of the vortex core is an inherent feature of wind tunnel generated vortices. Gursul & Xie (1999) examined this phenomenon further and concluded that the experimentally obtained velocity fluctuations of the vortex core (see Figure 2.8), were a direct result of shear layer instabilities. They found that at low Reynolds numbers, the core did not meander. Yet past a critical Reynolds number the fluctuation in the position of the vortex core began. This behaviour correlated with the presence of small vortical structures generated by the Kelvin-Helmholtz instability (see Figure 2.9), and are thought to be the source of the oscillations. It is noted that the statement made by Devenport, Rife, Liapis, & Follin (1996) that the wandering was due to some wind tunnel effect could be valid, with such devices as electric motors and fans common to tunnels being a source of excitement for the Kelvin-Helmholtz instabilities.

Once the effect of meandering had been noted, Devenport, Rife, Liapis, & Follin (1996) removed the component due to vortex wandering and presented their results

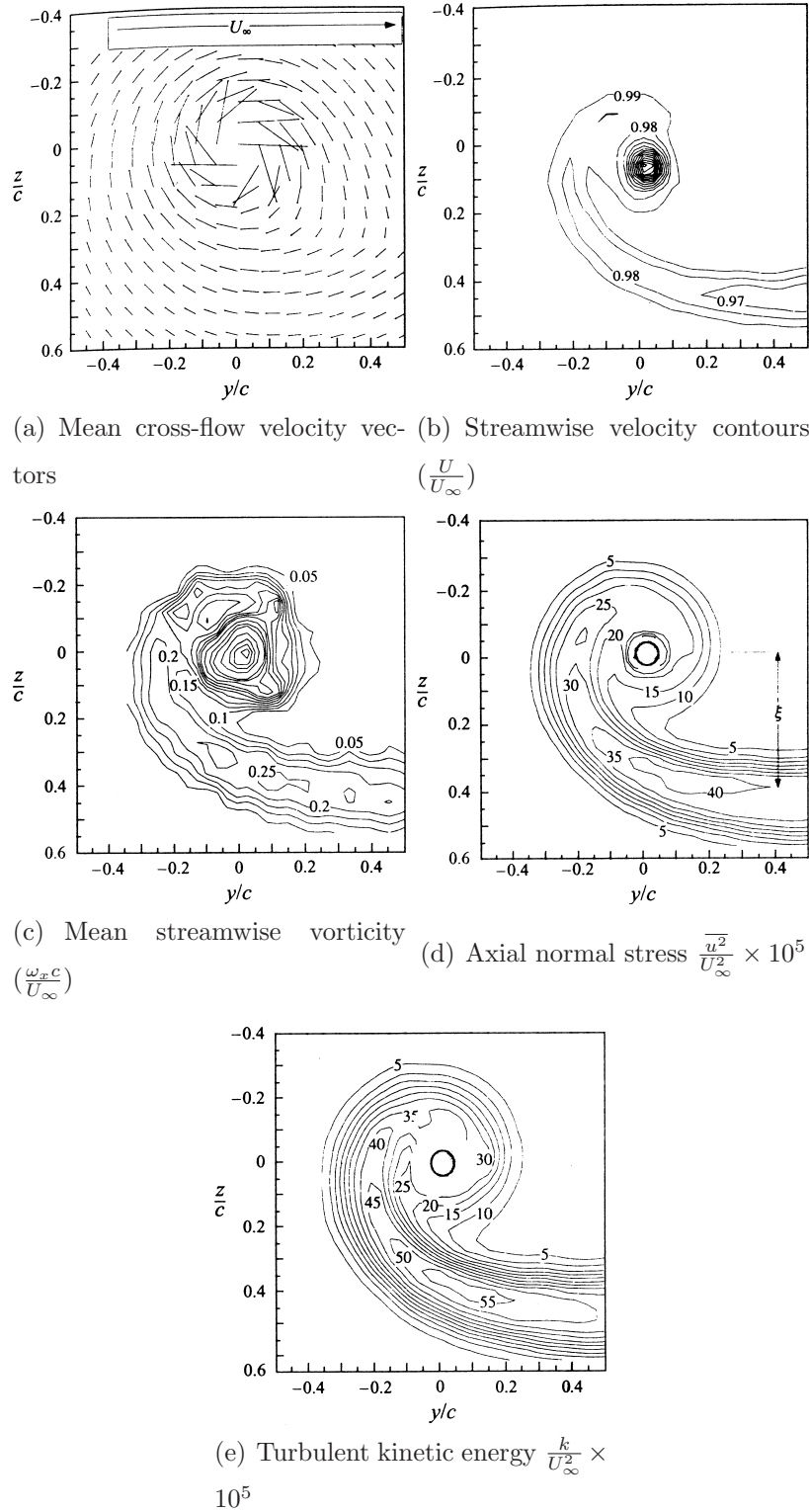


Figure 2.10: Experimental plots of a trailing vortex ten chord lengths behind a rectangular planform wing with a Reynolds number of 5.3×10^5 (Devenport, Rife, Liapis, & Follin 1996)

Follin (1996) has an axial velocity deficit and is therefore wake-like.

2.3 Vortex Behaviour

So far in this chapter the definition, formation mechanisms and structure of an isolated vortex have been discussed. However, in a great deal of applications vortices are commonly influenced by interactions with other bodies which may cause their behaviour to be different to that of an isolated vortex. This is certainly true for the case of race-car front wings as the trailing vortex usually consists of multiple cores which interact with one another. The influence of the ground plane is also felt by the vortex system as is the presence of the wheel which may make the vortices prone to breakdown. These influences will be discussed in this section.

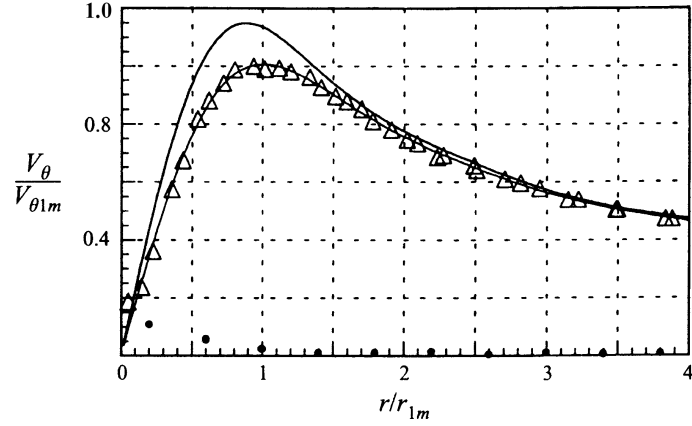
2.3.1 Vortex Interactions

2.3.1.1 Interaction with Other Vortices

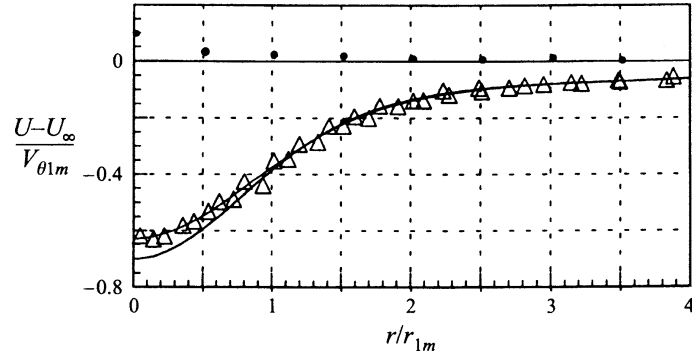
When multiple vortices are located close together in a flow, they may interact with one another. The interaction of one vortex on another may consist of a change in position of the vortices due to the velocity that the vortices will induce on one another. If vortices of like sign become sufficiently close then the viscous mechanism of merging may take place. These two sorts of interactions will be discussed in this section.

The effect of the induced velocity field felt by one vortex due to another may be modelled by inviscid arguments if the vortices are sufficiently far apart. The vortices can be treated as irrotational point vortices and potential theory applied. Here potential theory assumes that a flow is inviscid, irrotational and incompressible. Based on these assumptions the flow field about an isolated point vortex can be described by the same irrotational relationship which is used for the flow outside of the core of a Rankine vortex (Equation 2.4, where r is now the distance from the one core to another).

Using this relationship Batchelor (1967) stated that a single vortex within a



(a) Tangential Velocity



(b) Axial Velocity

Figure 2.11: Experimental plots of the tangential and axial velocities within a tip vortex 30 chord lengths downstream of a rectangular planform wing from Devenport, Rife, Liapis, & Follin (1996) (Triangles are measured velocities, thin lines are profiles to those points, thick lines are profiles corrected for wandering and the dots are the uncertainty due to the correction procedure)

system of point vortices will move with a velocity due to the sum of the induced velocities of all the other vortices, as given below in Equations 2.10 and 2.11.

$$\frac{dx_j}{dt} = -\frac{1}{2\pi} \sum_{i(\neq j)} \frac{\Gamma_i(y_j - y_i)}{r_{ij}^2} \quad (2.10)$$

$$\frac{dy_j}{dt} = \frac{1}{2\pi} \sum_{i(\neq j)} \frac{\Gamma_i(x_j - x_i)}{r_{ij}^2} \quad (2.11)$$

where r_{ij} is the separation distance between vortices i and j . The vortices in the system rotate about a ‘centre of vorticity’ (X,Y), as defined by Batchelor (1967) in Equations 2.12 and 2.13 below.

$$X = \frac{\sum_i x_i \Gamma_i}{\sum_i \Gamma_i} \quad (2.12)$$

$$Y = \frac{\sum_i y_i \Gamma_i}{\sum_i \Gamma_i} \quad (2.13)$$

A few examples of the behaviour of two vortices according to this model can be seen in Figure 2.12. Of special interest is the case shown in Figure 2.12(c), where there are two point vortices of equal strength, which due to the induced velocity from one another, both move vertically upwards. This case represents the trailing vortex found behind an inverted wing, such as is common to race-car applications.

The phenomenon of merging occurs when two co-rotating vortices (of the same sense of rotation), come within a critical distance of one another (Meunier, Dizès, & Leweke 2005). The actual process of merging consists of the sharing of a substantial amount of vorticity from each core resulting in a single vortex (Meunier, Dizès, & Leweke 2005), and usually occurs after a certain amount of orbiting. Figure 2.13 shows an example taken from an experiment of a co-rotating vortex pair undergoing merging. Vortex interactions between counter-rotating vortices does also occur in many applications. However, for the application relevant to this research, all of the vortices that are shed from the endplate of the front-wing will be of the same sense of rotation. Hence only the case of merging between co-rotating vortices will be examined.

In essence, vortex merging is a two dimensional problem (Meunier, Dizès, & Leweke 2005). Consequently it has received a large amount of attention from re-

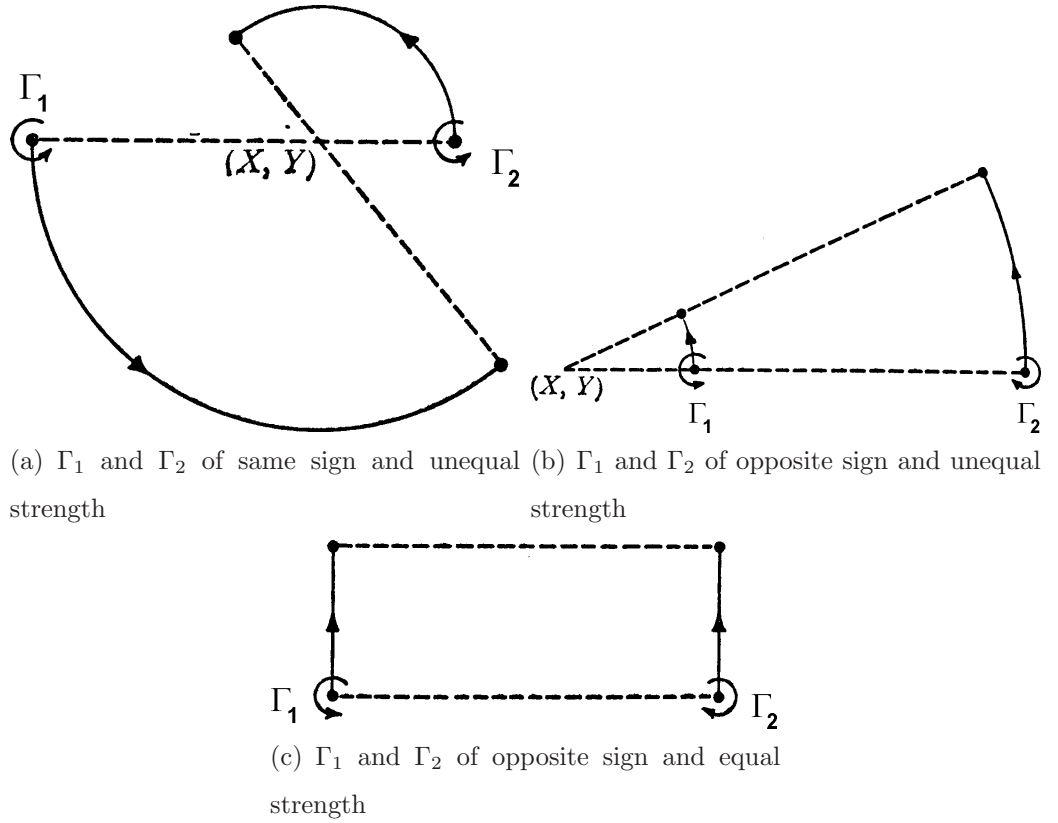


Figure 2.12: Motion of two point vortices with various signs and relative strengths according to the point vortex model (Batchelor 1967)

searchers due to the fact that it has both a fundamental and physical significance (Brandt & Nomura 2006). Fundamentally, vortex merging of co-rotating vortices is an elementary vortex interaction which is present in the dynamics of many shear and turbulent flows. It plays a key role in applications such as aircraft wakes, where

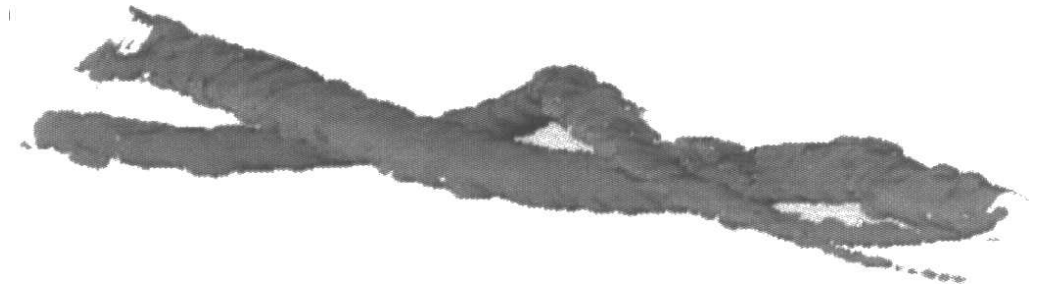


Figure 2.13: An experimental isovorticity plot ($\omega = 4.5s^{-1}$) of a co-rotating vortex pair undergoing merging taken from A L Chen & Savas (1999)

the vortices from the many high-lift devices merge together and generate the potentially serious effect known as wake-hazard. Accordingly, there has been a significant amount of numerical, experimental and theoretical literature published on the subject (Brandt & Nomura (2006), Cerretelli & Williamson (2003), A L Chen & Savas (1999) and Meunier, Dizès, & Leweke (2005)).

An extremely good analysis of the physical mechanism of vortex merging is that by Cerretelli & Williamson (2003). In their paper they build on the hypothesis originally put forward by Melander, Zabusky, & McWilliams (1988) and split the process of vortex merging into four distinct stages. The vorticity fields associated with the first two stages of a co-rotating vortex pair are shown in Figure 2.14.

In the first stage, the two vortices are essentially axisymmetric and the velocity that they induce on each other causes the vortices to rotate about one another as predicted by the irrotational point vortex model discussed previously. Whilst maintaining the separation distance between the two cores during this phase, termed the *first diffusive stage* (see Figure 2.15), the vortices spread by viscous diffusion. This leads to an increase in the core size of each vortex, governed by the following law; $r_c = \sqrt{4\nu t}$. (Meunier, Dizès, & Leweke 2005). Once the radii of the vortex cores exceed a critical value the relatively slow evolution of viscous diffusion is abruptly modified (Meunier, Dizès, & Leweke 2005), and the *convective stage* commences. During this part of the process the vortices deform substantially and vortex filaments are formed at the edges of the pair (see (c) and (d) in Figure 2.14). This is termed the ‘heart of the merging process’ by Cerretelli & Williamson (2003), as the separation distance between the two vortices is drastically reduced (refer to Figure 2.15). Many researchers have applied various methods (numerical, theoretical and experimental), for defining the value of this critical core radius at which this stage occurs (Meunier, Dizès, & Leweke 2005). Most have defined this value as a function of the separation distance and have found values between $0.2 \leq (a/b)_c \leq 0.326$ (where a is the radius of the vortex core and b is the separation distance). Meunier, Dizès, & Leweke (2005) noted that the variance comes from the discrepancy in the various vorticity profiles chosen to represent the vortices and hence define the core radius. They concluded that if the core size was defined using the angular momentum (J) as

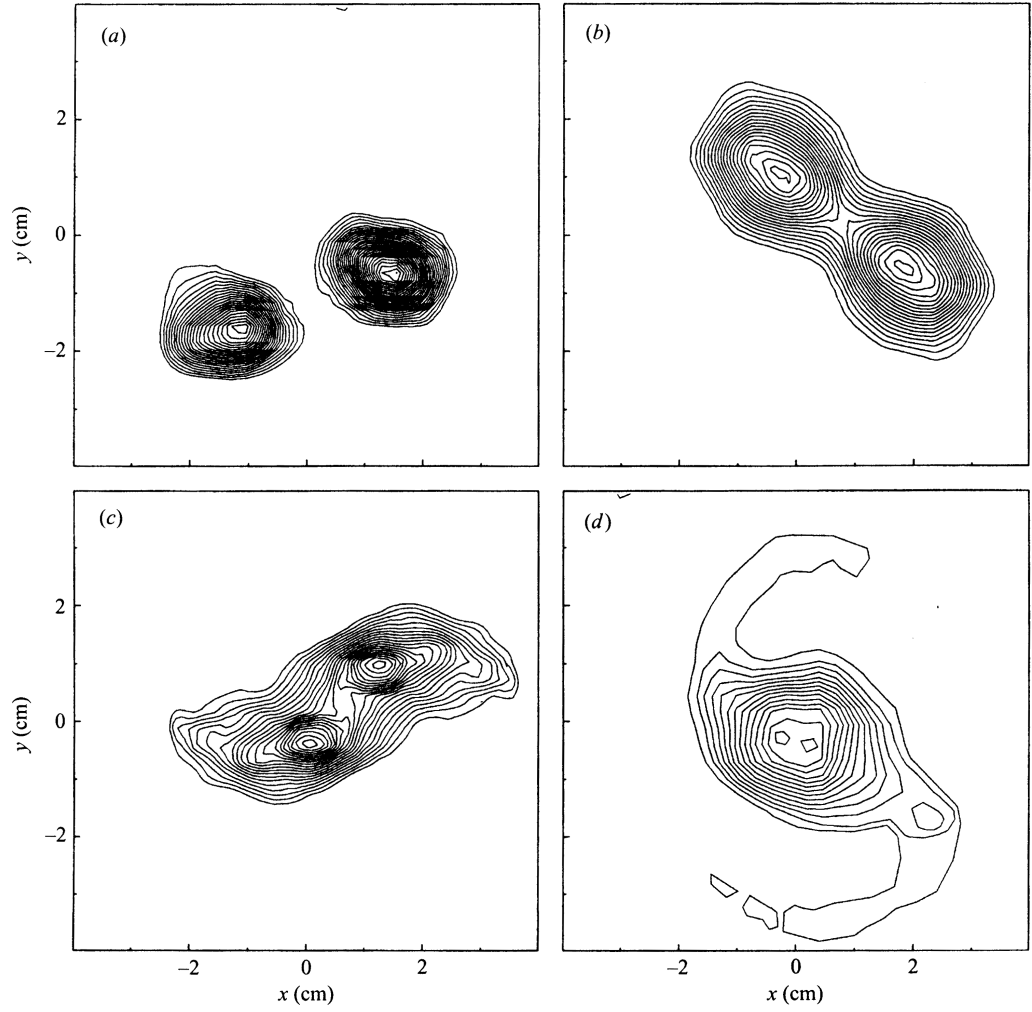


Figure 2.14: Vorticity contours of two co-rotating vortices of equal strength, during merging taken from an experimental study (Cerretelli & Williamson 2003). In (a) and (b) the merging process is in the diffusive stage, while (c) and (d) show the convective merging stage. Contour levels are in steps of $\Delta\omega = 0.05s^{-1}$, with the lowest contour being $\omega = 0.15s^{-1}$.

shown in Equation 2.14 (where x_c and y_c are the cartesian coordinates of the vorticity centroid), then the critical core size ratio collapses to a value of $(a/b)_c = 0.22$.

$$a^2 = \frac{J}{\Gamma} = \frac{\int_S [(x - x_c)^2 + (y - y_c)^2] \omega(x, y) dS}{\Gamma} \quad (2.14)$$

Cerretelli & Williamson (2003) define the third part of the merging process as the *second diffusive stage*. This is a relatively short stage and is where the separation between the two cores tends to zero (see Figure 2.15). Hence once this process has been completed, the vortices can be defined as ‘fully merged.’ At the start

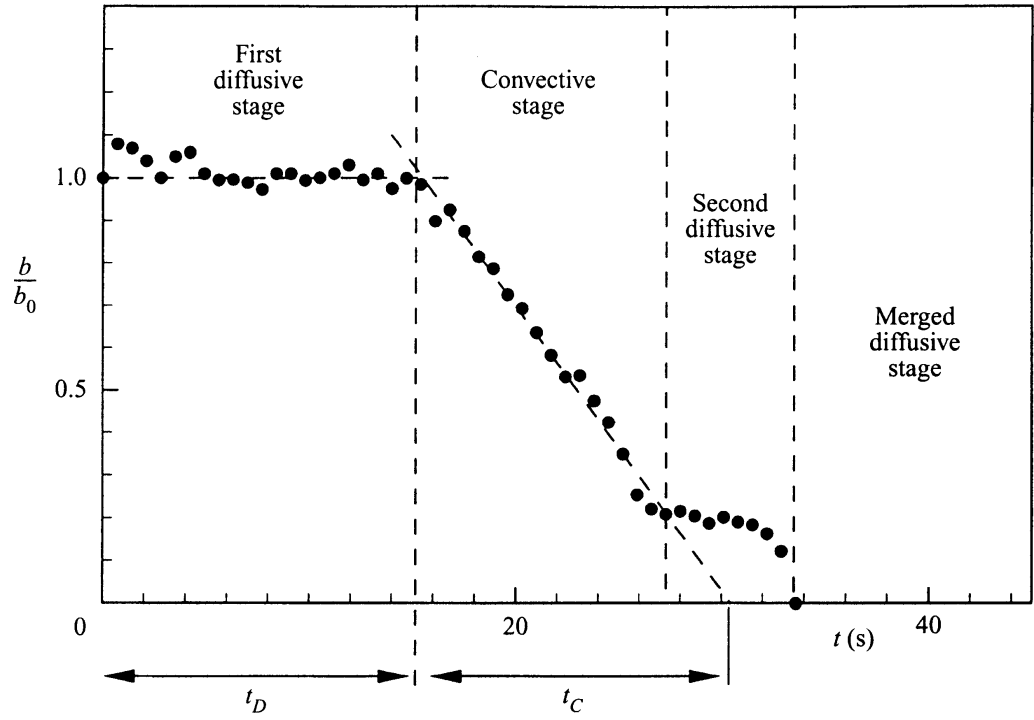


Figure 2.15: A graph showing the reduction in the normalised separation distance between the two vortex cores with time (non-dimensionalised by the initial separation), taken from Cerretelli & Williamson (2003)

of this stage the small separation distance between the two cores ensures that the induced velocities are not sufficient to bring the distance to zero. Instead, Cerretelli & Williamson (2003) suggest that this process is achieved through diffusion.

Once the separation distance has been reduced to zero and the vortex cores have ‘merged,’ the *merged diffusive stage* commences. During this final stage the deformed elliptical core, resulting from the previous stages, becomes axisymmetric. Once this has taken place, the merging process is complete and the final structure is that of a single axisymmetric vortex with an enlarged core (Cerretelli & Williamson 2003).

In order to understand fully the process of vortex merging, it is necessary to examine further the flow physics involved in the convective stage. To achieve this, Cerretelli & Williamson (2003) and Melander, Zabusky, & McWilliams (1988) utilise a frame of reference which rotates with the flow. Figure 2.16 shows results of this, with the vorticity of the co-rotating pair of Figure 2.14 superimposed on the stream-

lines and separatrices of the rotating frame. Cerretelli & Williamson (2003) defines the *inner core region*, *inner recirculation region* and the *outer recirculation region* as per Figure 2.16 (a). In the inner core region, the flow rotates with the sense of the vortex. In the inner recirculation region the fluid can travel about both of the cores with the sense shown in the figure. However, in the outer recirculation region the flow rotates about the vortices in an opposite sense to that of the cores.

The behaviour of the flow in these regions can highlight the mechanisms that cause the vortices to merge. In the first diffusive stage shown in Figure 2.16 (a), the cores enlarge and vorticity begins to diffuse from the inner recirculation region into the outer. As this process continues into the convective stage, (Figures 2.16 (b) and (c)), this diffusion of vorticity into the outer recirculation regions causes deformation of the cores and vortex filaments are formed at the upper left and lower right of the merging vortices. These structures are a result of the flow behaviour in each of these regions. The vortex filaments contain anti-symmetric vorticity which induces a velocity field on to the cores and pushes them together (Cerretelli & Williamson 2003). The definition of anti-symmetric vorticity arises from the decomposition of the vorticity field into its symmetric and antisymmetric components as shown below in Equations 2.15 and 2.16.

$$\omega(x, y) = \frac{1}{2}[\omega(x, y) + \omega(x, -y)] + \frac{1}{2}[\omega(x, y) - \omega(x, -y)] \quad (2.15)$$

$$\omega(x, y) = \omega_S(x, y) + \omega_A(x, y) \quad (2.16)$$

where ω_S and ω_A are the symmetric and anti-symmetric components of the vorticity field ($\omega(x, y)$) respectively.

As the merging process continues (Figures 2.16 (d) and (e)), the inner region expands and recaptures some of the anti-symmetric vorticity of the filaments, which reduces this induced velocity. Hence the vortex diffusion mentioned earlier is required to finally bring the separation distance to zero. The process concludes with the symmetric vortex seen in Figure 2.16 (f).

The discussions on vortex merging so far have been on vortex merging of two equal strength co-rotating vortices. However, it is unlikely that the vortices that are

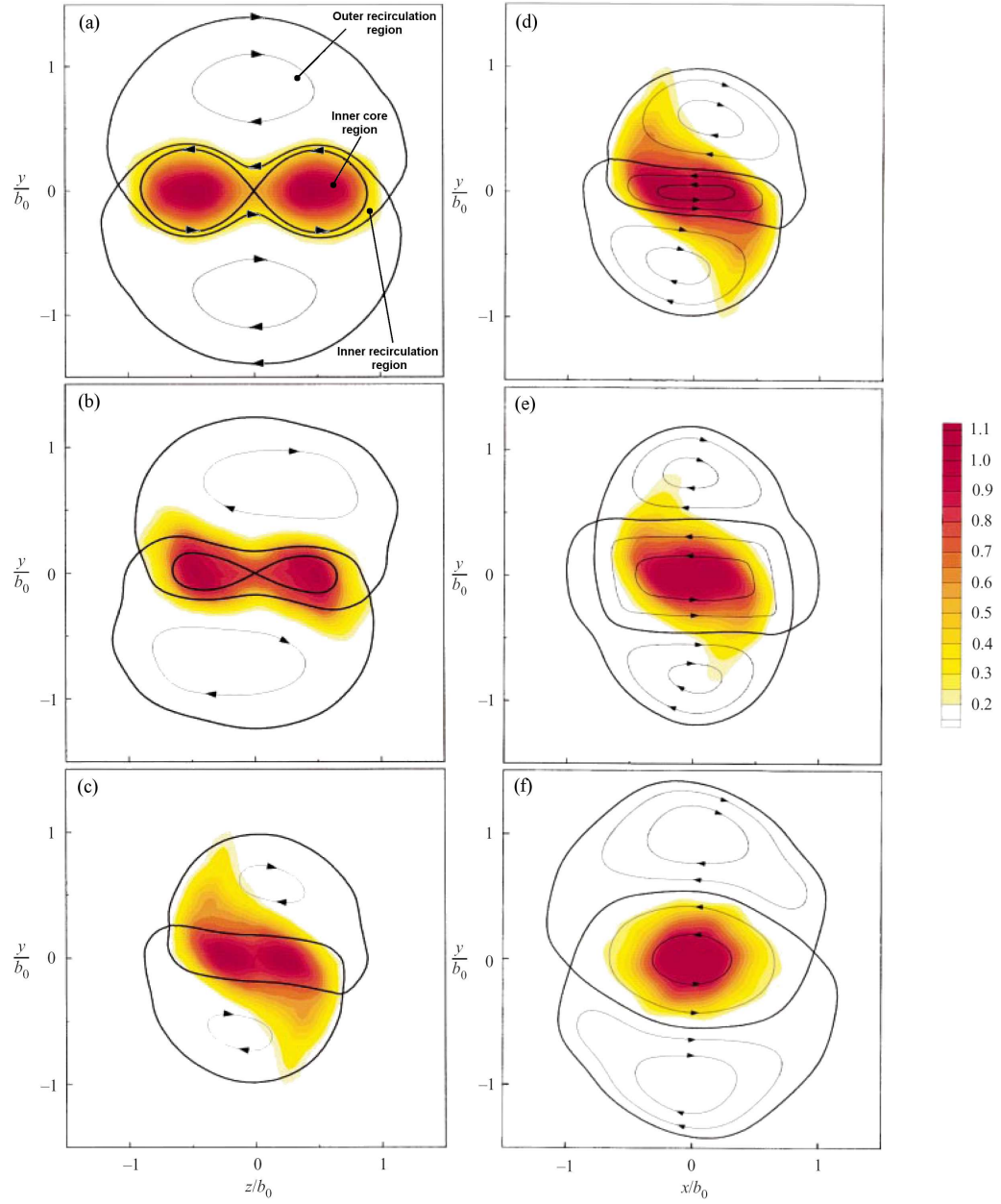


Figure 2.16: The vorticity field of a co-rotating vortex pair superimposed on the separatrices of the co-rotating stream function (the vorticity levels have dimensions of s^{-1}) (Cerretelli & Williamson 2003)

shed from a Formula 1 front wing are all going to be of equal strength. Hence it is necessary to examine briefly the behaviour of unequal vortex merging.

Trieling, Velasco Fuentes, & van Heijst (2005) examine the interaction of two unequal co-rotating vortices experimentally by performing flow visualisations. The resulting images are presented in Figure 2.17. The flow visualisation in these exper-

iments consisted of utilising dye injected into the cores of the vortices to examine their merging behaviour. This is based on the premise that the concentration of the dye is indicative of the vorticity distribution of the vortices. However, some differences may arise as vorticity diffuses much faster than dye (Trieling, Velasco Fuentes, & van Heijst 2005).

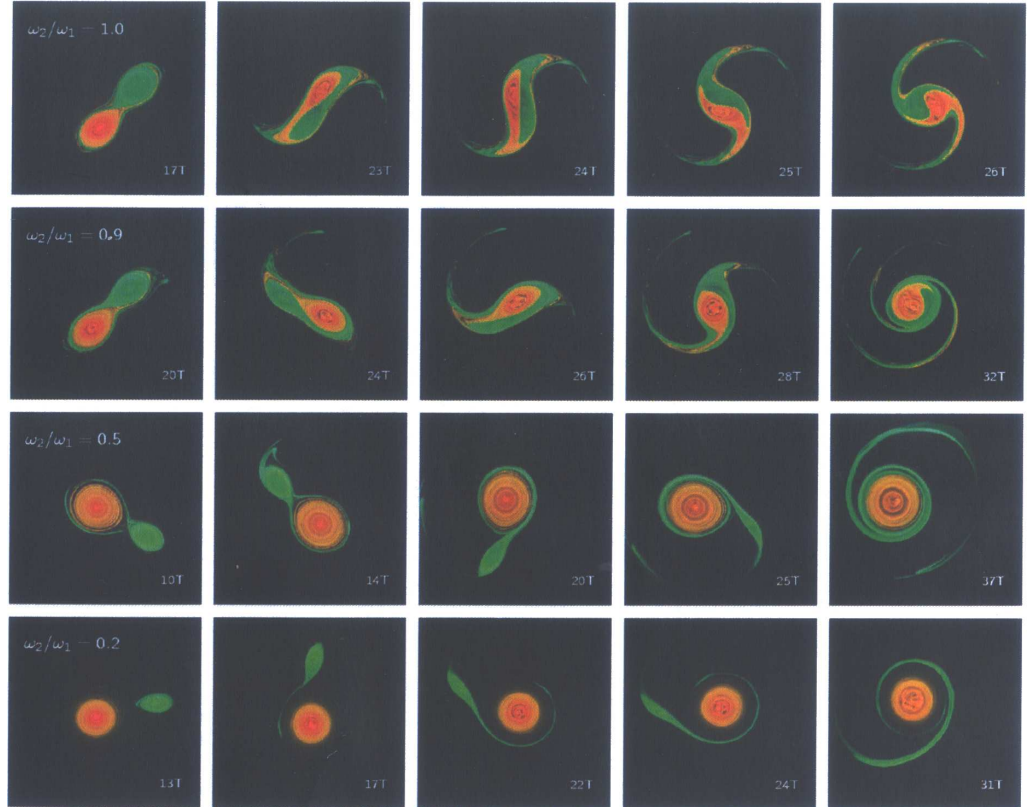


Figure 2.17: Dye visualisation of two co-rotating vortices showing the merging process for unequal initial ratios of maximum vorticity. Note the stronger and weaker vortices are visualised with red and green dye respectively (Trieling, Velasco Fuentes, & van Heijst 2005)

With these restrictions in mind, it is possible to make some observations of the behaviour of unequal strength vortex merging. The first set of images show the result of the merging of two equal vortices and it can be seen that they act as has been described above, with the resulting structure consisting of a single vortex containing approximately equal amounts of dye (vorticity) from each vortex.

When the vortices are only slightly unequal ($\omega_2/\omega_1=0.9$), the resulting structure

of the process is similar to that of the equal case, with a single large vortex core. However the exchange of vorticity is mostly attributed to the weaker vortex (identified by the green dye). Consequently the final merged core contains more of the dye from the stronger vortex (Trieling, Velasco Fuentes, & van Heijst 2005). As the inequality in vortex strength is increased ($\omega_2/\omega_1=0.5$ and $\omega_2/\omega_1=0.2$), the weaker vortex is torn apart with its vorticity wrapping about the stronger vortex which appears to be almost unaffected.

2.3.1.2 Interaction with Solid Boundaries

When a vortex is a sufficient distance away from a wall, so that the effects of viscosity can be ignored, its resulting behaviour can be adequately described by the method of images. This classical method first suggested by Lamb (1932), models the effect of the solid boundary on the wall by placing a vortex of equal yet opposite strength at an equal distance on the other side of the boundary. The image is shown in Figure 2.18 and it ensures that the boundary is a streamline of the flow (hence there is no flow across it (Barlow, Rae, & Pope 1999)).

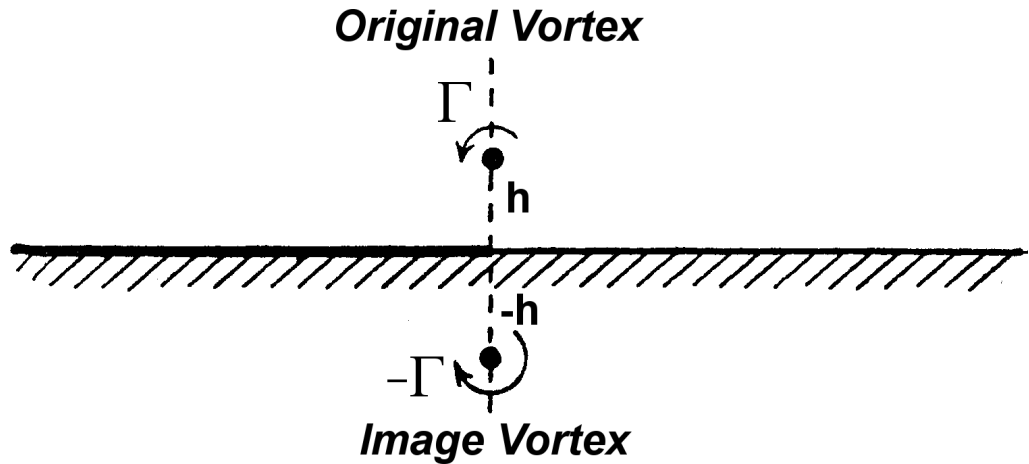


Figure 2.18: Diagram of the use of an image vortex to represent the effects of the solid boundary on the original vortex, adapted from Milne-Thomson (1952)

Once this system is established, then the theory of rectilinear line vortices (point vortices), laid out in Section 2.3.1.1, which describes the motion imparted on one

vortex by another, can be utilised to explain the influence of the solid boundary. Hence in the situation shown in Figure 2.18, the vortex would be displaced to the right (due to the induced velocity from the image vortex) as a consequence of the solid boundary.

Unfortunately, the method of images is based on potential flow theory and hence does not include the effects of viscosity. As discussed in Section 2.2.2, in a viscous fluid the no-slip condition at a solid boundary will generate additional vorticity. Hence if a vortex is located close to such a boundary, then secondary vorticity may be produced and the two patches of vorticity may interact with one another. This inherent limitation of the utilisation of the method of images to describe the behaviour of a vortex close to a boundary was highlighted by Harvey & Perry (1971) and Barker & Crow (1977) (amongst others), when examining the consequences of the trailing vortices in the wake of an aircraft during landing.

After examining flight test data performed by Dee & Nicholas (1968), Harvey & Perry (1971) noticed that the path of the vortices deviated from the theoretical solution when in close proximity to the ground. They observed that after initially descending towards the ground, the vortices tended to ‘rebound’ away from the boundary. They performed experiments to examine this interaction, using a total pressure probe and a moving ground plane to simulate the ground boundary condition. Total pressure is a useful tool for examining this situation as its value decreases in regions of high-shear such as boundary layers, vortex sheets and cores (Harvey & Perry 1971).

From the resulting data, Harvey & Perry (1971) noticed that a patch of secondary vorticity could be formed when a vortex aligned with the freestream, passes close to a solid boundary. The influence of this secondary vorticity induced a motion on the primary vortex which caused the primary vortex to move away from the surface. This is shown schematically in Figure 2.19. Harvey & Perry (1971) hypothesised that this phenomenon was a consequence of the cross-flow that exists around the vortex core due to rotation of the fluid. This cross-flow is a maximum directly beneath the core and therefore a suction peak is formed at this point (Figure 2.19(a)). Consequently, the cross-flow must negotiate an adverse pressure gradient past this location and

if the vortex is close enough to the ground, then the pressure gradient may be sufficient to invoke separation (2.19(b)). Hence, flow may detach from the ground plane and form a concentration of vorticity which is of the opposite sense to the primary vortex. Further downstream this forms a secondary vortex and its induced velocity acting on the primary core causes this initial vortex to displace away from the ground plane (Figure 2.19(c)).

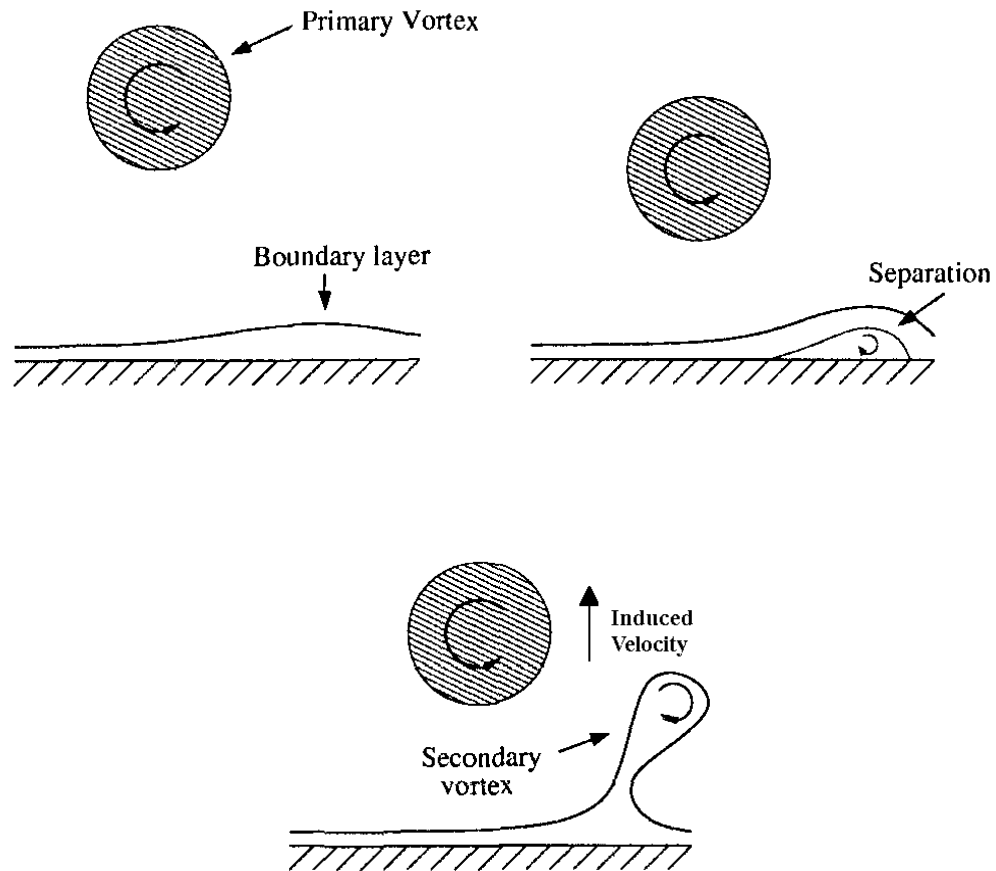


Figure 2.19: The production of secondary vorticity as a consequence of the viscous interaction between a vortex (whose axis is aligned with the direction of the freestream) and a solid boundary (Puel & de Saint Victor 2000)

Other researchers such as Puel & de Saint Victor (2000), have furthered the work of Harvey & Perry (1971) and noticed that the secondary vorticity may contain up to 25% of the intensity of the primary vortices. Their numerical studies showed that

this secondary vortex orbits about the primary vortex thus causing it to loop and hence rebound again thus generating a looping trajectory.

The experiments of Harvey & Perry (1971) were limited to Reynolds number $Re_\Gamma = \Gamma/\nu \leq 1.17 \times 10^5$. According to Türk, Coors, & Jacob (1999), for the vortices found in an aircraft wake, the Reynolds number is more likely to be of the order of $Re_\Gamma = 10^7 - 10^8$. The results of their numerical calculations showed that multiple vortices can be formed from the secondary vorticity thereby increasing the complexity of the vortex dynamics.

Most of the results of Harvey & Perry (1971) were obtained with a moving ground plane but they also noticed the same qualitative trajectories occurring as a result of the secondary vorticity, when a stationary ground plane was used. However the quantitative effect of this phenomenon was reduced in this case. Due to the unrealistic conditions of this case for aircraft and road vehicles, little literature has been published which addresses this point directly (Garrood 2004). However, it is known that the boundary conditions on a stationary plane are different to that of a moving plane and hence differences in secondary vorticity production may occur. Indeed, the time-averaged data produced by Cutler & Bradshaw (1993a) and Cutler & Bradshaw (1993b), from the vortices of a delta wing interacting with a stationary solid boundary confirm the generation of secondary vorticity. However, their data show that this patch of secondary vorticity quickly becomes entrained into the cores of the primary vortices and hence the ‘rebound’ effect does not occur as this vorticity does not form a secondary vortex.

The interaction of vortices with other external factors may cause a catastrophic change in structure. The literature associated with the phenomenon of vortex breakdown, will be examined in the next section.

2.3.2 Vortex Breakdown

An early observation of vortex breakdown was made by Peckham & Atkinson (1957), concerning the leading edge vortices over a delta wing. The flow over a delta wing is dominated by two strong leading edge vortices (see Section 2.2.2) and their presence

enhances the lift of the wing. At high angles of attack, breakdown of these intense vortices can occur leading to a dramatic loss in lift. Figure 2.20 shows two different types of vortex breakdown as seen by Lambourne & Bryer (1962) during a flow visualisation study of a delta wing. Due to the dramatic changes that the occurrence of vortex breakdown can have on an aircraft's performance, a great deal of research has been undertaken on this phenomenon (summarised by the reviews of Hall (1972), Leibovich (1978), Delery (1994) and Lucca-Negro & O'Doherty (2001)).

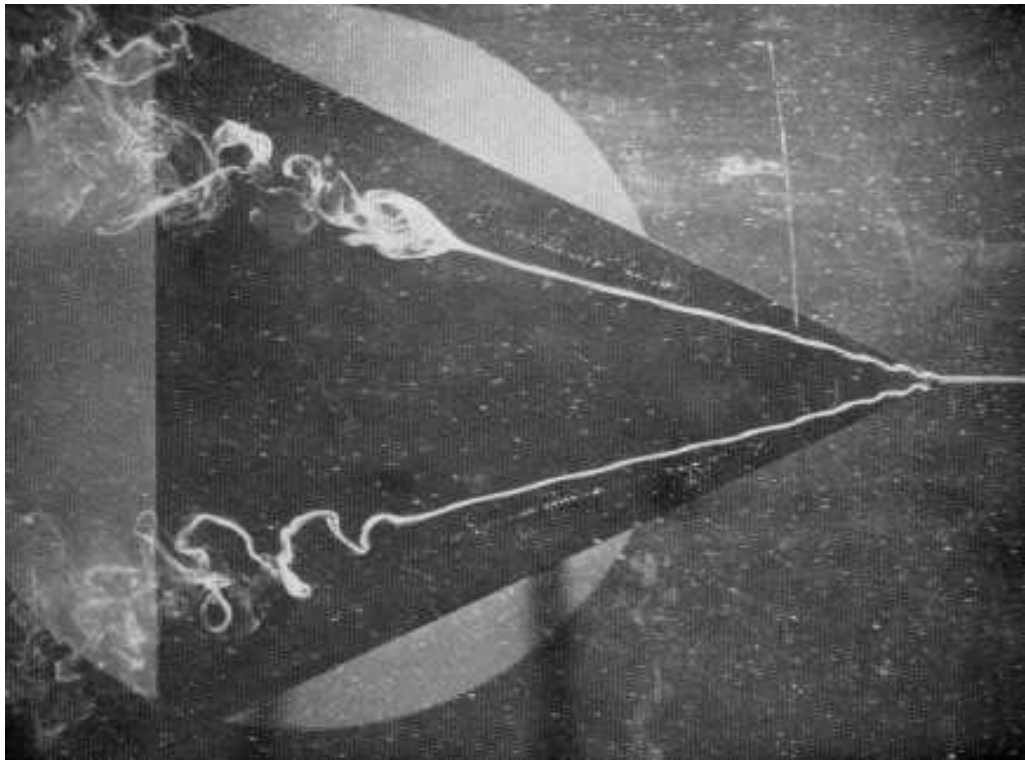


Figure 2.20: Flow visualisation of vortex breakdown over a delta wing as visualised by Lambourne & Bryer (1962). Note this image shows two different types of breakdown (bubble-type at the top and spiral beneath it)

2.3.2.1 Definition of Breakdown

Several different definitions of vortex breakdown have been proposed and can be found in the literature. The earliest was by Harvey (1962) who described this phenomenon as ‘an intermediate stage between the two basic types of rotating flow, that is those that do and those that do not exhibit axial velocity reversal.’ This

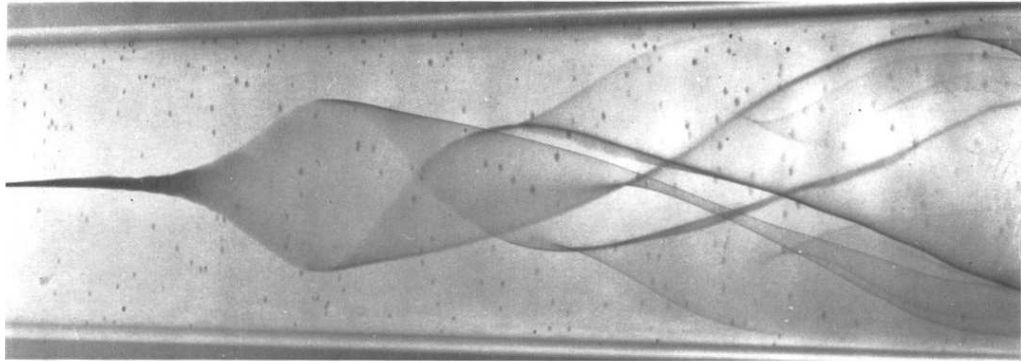
definition picks up on two important consequences of vortex breakdown. That of an abrupt change in structure of the core of swirling flow (Benjamin 1962), and that of a reduction in the axial velocity. A latter definition of breakdown was proposed by Leibovich (1978) which built on the earlier definition by Harvey (1962) and made it more specific, by saying that it is ‘a disturbance characterised by the formation of an internal stagnation point on the vortex axis, followed by a reverse flow in a region of limited axial extend.’ In fact it is the existence of a stagnation point on the centre-line of the structure which is universally accepted as the characteristic feature of the breakdown (Delery 1994).

2.3.2.2 Flow Structure

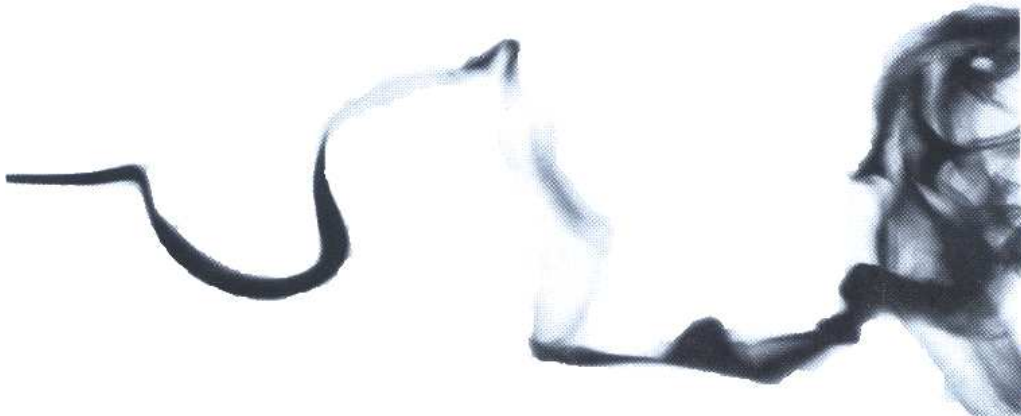
A large amount of research has been undertaken to try and understand what structure the flow forms when breakdown occurs, and how this can be initiated or modified by various flow parameters (a good review of which is that of Lucca-Negro & O’Doherty (2001)). These two aspects will be discussed in the next two sections.

Six different types of vortex breakdown have been observed by Faler & Leibovich (1977), by performing dye visualisations of a vortex in water. However, these different structures are only slight variations on three individual structures as were found by Sarpkaya (1971a) and Sarpkaya (1971b). These three structures are termed the *double-helix*, *spiral* and *bubble-type breakdown* and can be seen in Figure 2.21. These observations were obtained by producing a vortex from guide vanes, in a slightly diverging cylindrical tube and visualising the resulting structure with dye particles injected into the core of the vortex. The three different structures were observed as the volume flow rate, and swirl were varied. The flow rate changes the Reynolds number and in common with other previous experiments utilising similar apparatus, Sarpkaya (1971a) defined the Reynolds number based on the diameter of the pipe, Re_{tube} . Unfortunately as Lucca-Negro & O’Doherty (2001) discussed, if the Re_{tube} is increased by raising the flow rate within the tube, then the size of the vortex core can decrease. Therefore if the circulation of the vortex is kept constant then core vorticity will intensify (Althaus, Brücker, & Weimer 1995). Due to this undesirable coupling, Lucca-Negro & O’Doherty (2001), suggested that it would be more ap-

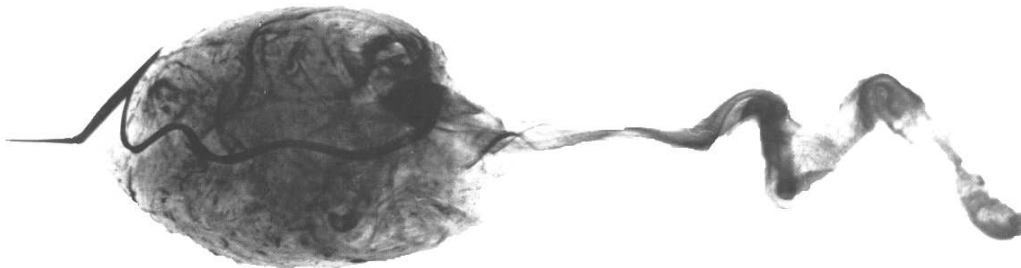
propriate to use the core diameter as the characteristic length, Re_{core} . This would also make the resulting observations more applicable to other situations (other than a pipe) where breakdown may occur. Unfortunately, the majority of the published literature has used the Reynolds number based on the tube and so these anomalies should be kept in mind when discussing the effect of Reynolds number on vortex



(a) Double-Helix



(b) Spiral breakdown



(c) Bubble breakdown

Figure 2.21: Flow visualisation of the three main forms of vortex breakdown as observed in the experiments of Sarpkaya (1971a)

breakdown.

Sarpkaya (1971a) and Faler & Leibovich (1977) found that the double-helix form of breakdown (Figure 2.21(a)) only occurred when the volume flow rate (and hence Re_{tube}) was low. Therefore, its applicability to many real-life applications is minimal. This is true for the application of race-car front wings and hence it is not deemed appropriate to discuss its structure or behaviour further.

As the flow rate is increased (higher Re_{tube}), the dominant characteristic forms of vortex breakdown are the bubble and spiral-type (Leibovich (1984) and Lucca-Negro & O'Doherty (2001)). It is these two structures that have been visualised on delta wings such as that seen in Figure 2.20.

A visualisation of the spiral-type breakdown can be seen in Figure 2.21(b). This flow phenomenon is characterised by a rapid deceleration of the flow along the swirl axis, which causes stagnation. After this stagnation there is an abrupt kink in the core which is followed by a spiraling of the flow. The flow persists for one or two turns before breaking up into large-scale turbulence (Lucca-Negro & O'Doherty 2001).

According to Sarpkaya (1971a), bubble-type breakdown is characterised by a nearly axisymmetric region of reversed flow with a stagnation point at the forward end. Leibovich (1984) likened this structure to a body of revolution placed in the flow. The interior of this bubble consists of reversed flow with fluid exchange occurring between the internal and outer flow. Downstream of the bubble the core appears greatly expanded and a 'spiral-tail' can be observed at the rear (Lucca-Negro & O'Doherty 2001) (see Figure 2.21(c)).

The appearance of these two different types of structure is dictated by several different parameters which will be examined next.

2.3.3 Factors Affecting Vortex Breakdown

In order for breakdown to occur Hall (1972) states that the swirl of the vortex must be high. If the angle of swirl ϕ is defined as in Equation 2.17 (where U_θ and U_x are the tangential and axial components of velocity respectively), then he states that

the maximum angle of swirl is usually greater than 40° upstream of breakdown. This statement is based on various observations. However, many different criteria for vortex breakdown have been suggested based on theoretical, experimental or numerical arguments (see Delery (1994) or Lucca-Negro & O'Doherty (2001) for an overview). Delery (1994) discussed and compared the many theories and found that they could all be reduced to a single criteria based on the swirl parameter, S , as defined in Equation 2.18 (where $U_{x(ext)}$ is the axial velocity outside of the core).

$$\phi = \tan^{-1} \left(\frac{U_\theta}{U_x} \right) \quad (2.17)$$

$$S = \frac{\Gamma_0}{r_{core} U_{x(ext)}} \quad (2.18)$$

He suggested that if this parameter is less than or equal to a value $S \leq S_\star$ where $S_\star \approx 1.37$, then the vortex will have a slow and steady evolution and not breakdown. However, if this value is reached or exceeded then vortex breakdown is likely to occur. It is interesting to note that this value equates to a swirl value of $\phi \approx 50^\circ$ (Delery 1994), which satisfies the observation made by Hall (1972) previously.

An adverse pressure gradient will instigate the deceleration of a flow and can be provided by an external pressure gradient, or by divergence in the flow (Hall 1972). By making approximations of a slender vortex, neglecting viscous effects and utilising the Navier-Stokes equations, Delery (1994) suggested that the relationship between the adverse pressure gradient felt along the axis of the vortex and that experienced outside is that of Equation 2.19 (where α is a proportionality constant).

$$\left(\frac{\partial p}{\partial x} \right)_{(axis)} - \left(\frac{\partial p}{\partial x} \right)_{r_{core}} \sim \alpha \rho \frac{\Gamma_0^2}{r_{core}^3} \quad (2.19)$$

This shows that the effect of the external adverse pressure gradient is amplified as the vortex axis is approached. This effect is also augmented for vortices of high swirl. Consequently, a mild adverse pressure gradient or divergence in the flow may be sufficient to promote a large retardation in velocity on the axis of the vortex thereby causing breakdown.

Once breakdown has occurred, changes in either the swirl or the pressure gradient can affect the form of the breakdown. Leibovich (1984) states that once there

is enough swirl in the flow, at a sufficient Reynolds number ($Re_{tube} \approx 3000$), then spiral breakdown is the type of breakdown which occurs. As swirl is increased, the mean location of breakdown moves upstream. Further increasing the swirl initiates the bubble breakdown which also causes the breakdown location to move back downstream. Leibovich (1984) goes on to state that there is a range of swirl values whereby the flow alternates between the two types of breakdown with the corresponding breakdown position oscillating. Once higher swirls are reached and a constant bubble-type breakdown is established, in similarity to the behaviour of the spiral-type breakdown, the position of vortex breakdown moves upstream with further increases in swirl. This sequence of events was also discussed by Hall (1972) and is summarised in Figure 2.22.

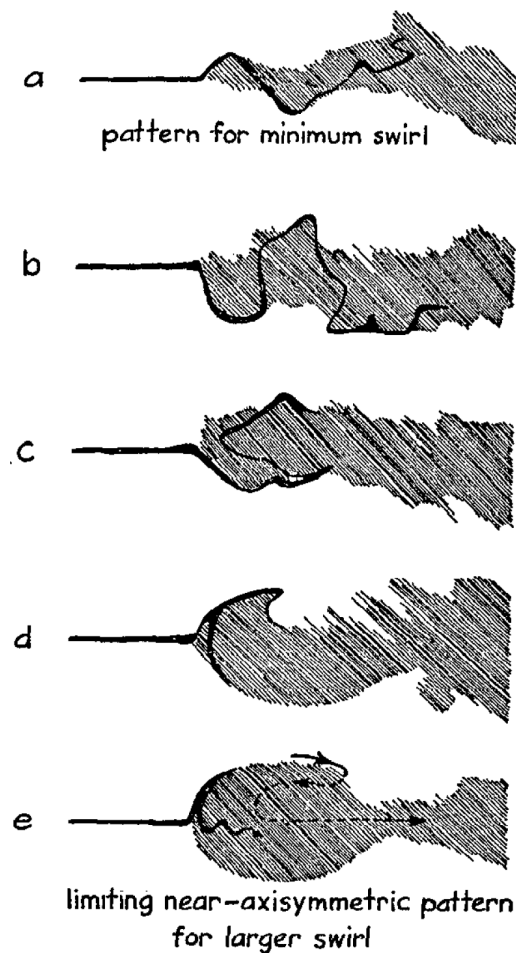


Figure 2.22: Variation in breakdown structure with increasing swirl (based on photographs of Sarpkaya (1971a)) taken from Hall (1972)

Several researchers who examined the flow in vortex tubes (Sarpkaya (1971b), Faler & Leibovich (1977) and Escudier & Zehnder (1982)) examined the effect of modifying the flow rate into the tube, hence modifying the Reynolds number. Delery (1994) summarised the results of their observations by stating that in similarity to the above conclusions of Leibovich (1984) with regard to increasing swirl at a fixed Reynolds number, that a similar behaviour was obtained if the swirl was maintained and the Reynolds number increased. With this observation Leibovich (1984) noted it was unlikely that this variance with Reynolds number was due to a viscous activity in the breakdown mechanism. Rather that the vortex tube produces a vortex whose core size varies with this parameter. Hence the changes in the breakdown behaviour would have been a consequence of the modifications in the peak swirl and core vorticity associated with the change in core size.

Hence the occurrence, the form and the location of vortex breakdown is governed by a balance between the magnitude of the swirl, the external pressure gradient and the degree of divergence. However, from the literature reviewed in this section, it can be concluded that the vortex breakdown is not a simple balance (Hall 1972). Nevertheless, the overall pressure and velocity fields are extremely important.

In the next section, the likely occurrence of vortex breakdown in the vortex system shed from a race-car will be discussed including reviews of previous studies which have examined this relationship.

2.3.4 Application to Race-Cars

It is known that vortices with a high degree of swirl may be prone to breakdown and that if an adverse pressure gradient acts along the axis of the vortex then this can cause the structure to breakdown into either the bubble or spiral-forms. The front wing of a race-car operates in close proximity to the ground and produces large amounts of downforce. Therefore the vortices which are shed from the endplate will have a high swirl. Consequently vortices shed from the front-wing of a race-car may be prone to vortex breakdown. Several researchers have examined this application and their results will be reviewed in this section.

In their work on investigating the effect of the ground on an inverted front wing, Zhang & Zerihaan (2003) produced the graph shown in Figure 2.23 (where h/c is the height of the lowest point of the wing from the ground non-dimensionalised by the mainplane chord and C_L is the negative lift coefficient). It can be seen from this

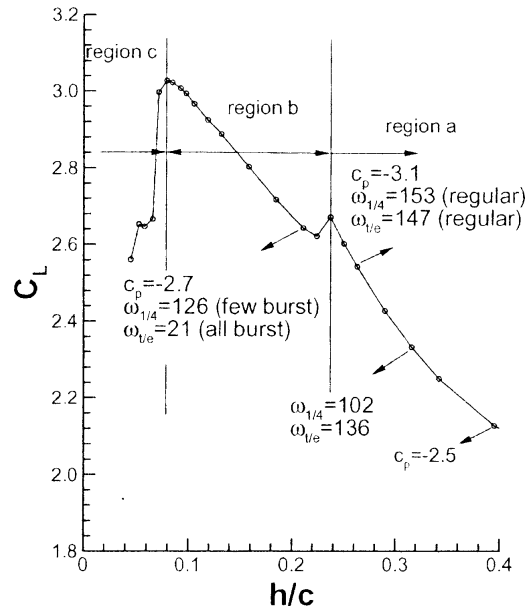


Figure 2.23: Graph of lift augmentation on a double-element wing due to the proximity of the ground taken from Zhang & Zerihaan (2004)

figure that as the ground is approached, the effect of the boundary is to increase the downforce that is produced by the wing. This lift augmentation reaches a maximum close to when $h/c = 0.08$ before dropping off close to the ground (Zhang & Zerihaan 2003).

In order to explain the flow physics associated with this trend, Zhang & Zerihaan (2004) performed surface flow visualisations, together with static pressure measurements and off-surface wake measurements in the form of Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV). They concluded that the graph could be split into three distinct regions, labelled a, b and c on Figure 2.23. In region a, the ground clearances are relatively large and as the floor is approached the wing and endplate acts as a diffuser and increases the suction underneath the wing, thereby increasing the lift. In this region they noticed that as the force was increased, the

peak vorticity in the edge vortex was augmented. In region b, they stated that the force enhancement continues to act. However, they suggested that this trend reaches a maximum as a consequence of vortex breakdown. The tip vortices strengthen as the gap to the ground is reduced whilst the adverse pressure gradient which exists over the rear of the aerofoil (in the pressure recovery region) also increases due to the elevated suction underneath the wing. Hence this makes the vortices prone to breakdown as the high swirl in a strong adverse pressure gradient cannot be sustained. Zhang & Zerihan (2003) reached these conclusions by examining the vorticity of the vortex during roll-up and in a cross-flow plane immediately downstream of the wing. Finally, as the ride height is reduced further separation occurs over the wing and there is a loss of downforce.

Moseley (1999) also visualised the flow downstream of a double element wing utilising total pressure surveys and PIV for off surface measurements. He noticed a similar behaviour to Zhang & Zerihan (2003), with vortex breakdown occurring as the ride height was reduced. The results from his total pressure surveys can be seen in Figure 2.24. The images contained in this figure show the time-averaged results of the wake surveys and breakdown can be identified by the enlarged core and larger region of total pressure loss at the two lowest ride heights of $h/c = 0.25$ and $h/c = 0.20$ (Figures 2.24(c) and 2.24(d) respectively). These findings were also confirmed by his PIV results. From the instantaneous vectors obtained by PIV in both the cross-flow and streamwise planes, Moseley (1999) deduced that the flow structure was that associated with the spiral-type breakdown as shown schematically in Figure 2.25.

During his research into the aerodynamic interaction mechanisms relevant to the underbodies of Formula 1 cars, Garrood (2004) performed laser-smoke flow visualisations behind a single element wing and endplate operating close to the ground ($h/c = 0.29$). He noticed a distinct difference in the behaviour of the vortex formed from the bottom of the endplate, when a moving ground plane was used in comparison to a stationary boundary. The resulting images from his flow visualisation are shown below in Figure 2.26. From the image with the stationary ground plane (Figure 2.26(a)), a distinct core can be identified where the smoke particles have

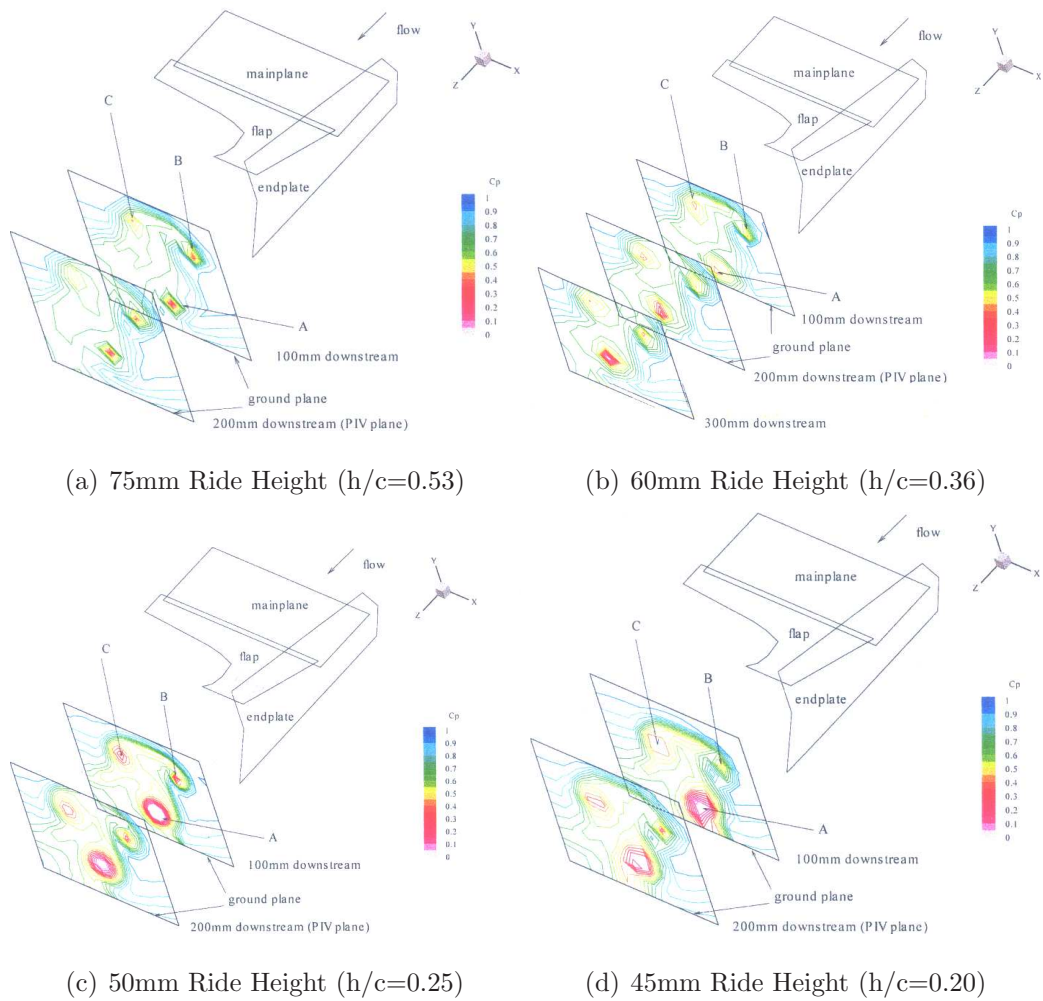


Figure 2.24: Results of a total pressure survey of the vortex system behind a Formula 1 Front Wing at different ride heights showing differences in flow structure performed by Moseley (1999)

been centrifuged out. The same core cannot be identified in Figure 2.26(b) when the rolling road is on. He also noticed a similar trend to Zhang & Zerihan (2004) and Moseley (1999) whereby breakdown was most likely for a reduced ride height. However, he concluded that there must be a different mechanism occurring, to explain the differences between the road on and road off cases.

From evaluating PIV images of the vortex and analysing the instantaneous values of the streamwise vorticity, Garrood (2004), noticed that with reduced ride height the endplate vortex has a growing interaction with the secondary vorticity which it lifts up from the ground plane (as discussed in Section 2.3.1.2). This introduces

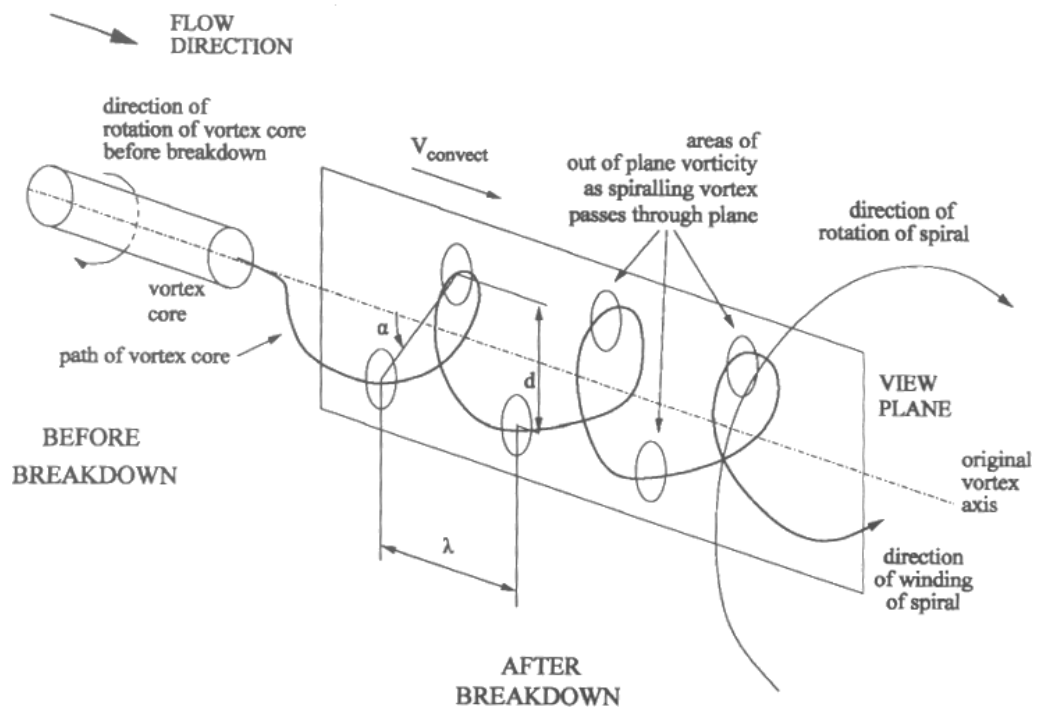


Figure 2.25: Schematic of vortex breakdown topology behind a Formula 1 front wing at a small ride height ($h/c=0.20$), as hypothesised by Moseley (1999)

a vertical motion on the primary vortex and hence it rises away from the ground plane and the secondary vorticity production stops. The vortex then descends again and moves laterally, whilst encouraging secondary vorticity to be produced again in a spatially cyclic manner (in a similar manner to that observed by Cutler & Bradshaw (1993a) and Cutler & Bradshaw (1993b) discussed in Section 2.3.1.2). This behaviour would generate a spiral trajectory of the primary vortex in similarity to the findings of Moseley (1999).

Although these previous researches have concluded that vortex breakdown can occur in a trailing vortex system from a race-car front wing at small ground clearances, they have not included the presence of the wheel which may affect the flow physics in this area. A discussion about the aerodynamics of an exposed racing wheel (such as that found on Formula 1 cars) will be the subject of the next section.

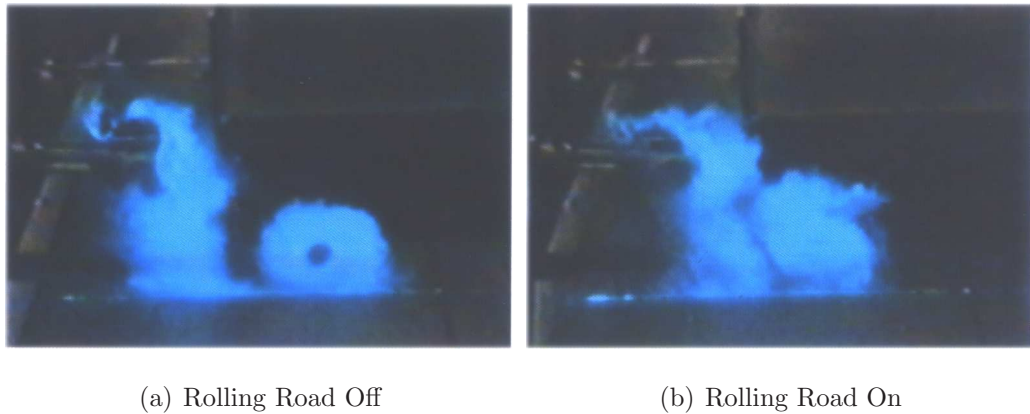


Figure 2.26: Laser-smoke flow visualisation of a lower endplate vortex ($h/c=0.29$), showing difference in structure for the case of rolling road off and on, performed by Garrood (2004)

2.4 Wheel Aerodynamics

According to Agathangelou & Gascoyne (1998), the drag originating from the exposed wheels on a race-car can account for approximately 40% of the overall drag. A wheel acts as a bluff body in the flow and generates a large wake. Hence, the aerodynamics associated with the front wheels have a large influence on the flow over the downstream components of the car. The influence of the wheel is also felt on the upstream components and is perhaps most apparent on the front wing and endplate, as their trailing edges are extremely close to the front wheels. Therefore, in investigating the flow originating from the front wing, it is prudent that the aerodynamics about exposed wheels are considered.

Discussions about the flow over exposed wheels have received relatively little attention in comparison to investigations into the mechanical performance of the wheel (Zhang, Toet, & Zerihan 2006). This is due to the complexity of analysing an isolated, rotating wheel both experimentally and by numerical analysis as well as to the secretive nature of the motorsport industry (Zhang, Toet, & Zerihan 2006).

Perhaps the most widely accepted research into this problem is that of Fackrell and Harvey (Fackrell & Harvey (1973), Fackrell (1974) and Fackrell & Harvey (1975)). Their experimental apparatus consisted of a wheel fitted with one pressure tapping connected to a pressure transducer. As the wheel rotated they were able to

record the pressure distribution for one rotation and then they averaged over many rotations. One of the resulting pressure distributions is shown in Figure 2.27. This

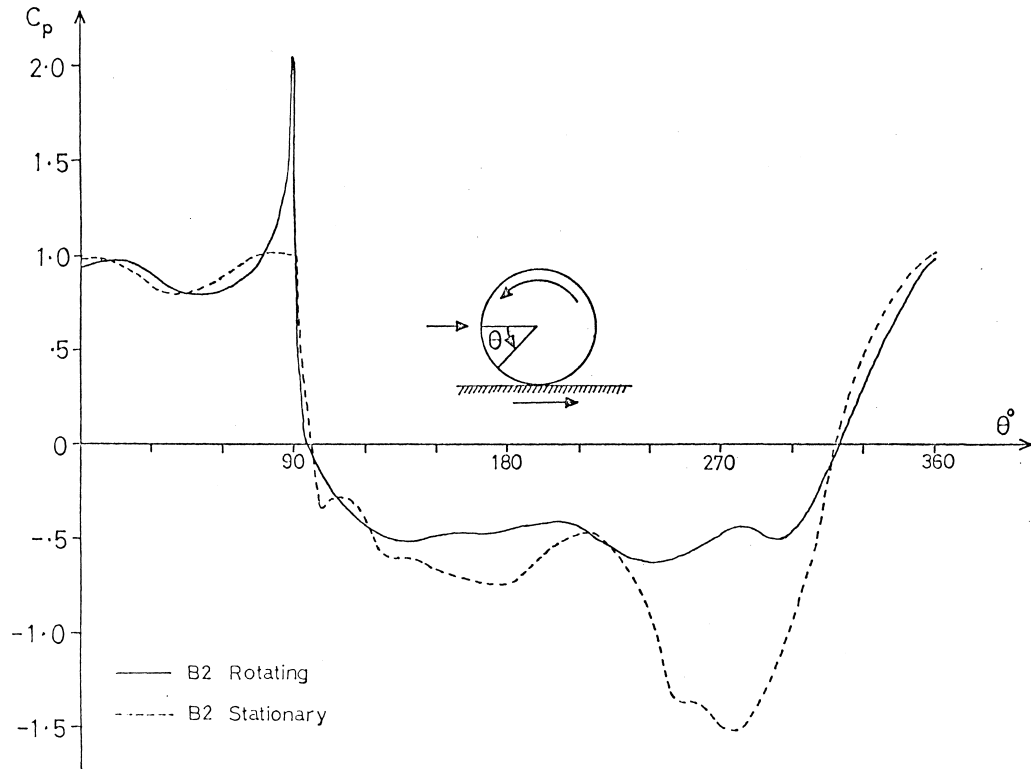


Figure 2.27: Static pressure distribution about both a stationary and rotating wheel as found experimentally by Fackrell (1974), (this wheel is referred to as B2 in his experiments)

figure contains the pressure distribution about the wheel for both the stationary and the rotating wheel, and the consequence of placing the wheel on the moving ground plane is apparent from this figure. The zero flow condition imposed near to the location of contact (contact patch) by the ground plane enhances the positive lift which acts on the wheel (Katz 1995). When the wheel is rotating there is large positive pressure peak directly upstream of the contact patch. This peak was attributed by Fackrell (1974) to be as a result of a phenomenon he termed ‘jetting,’ shown schematically in Figure 2.28. He postulated that the flow in this region occurs as a result of the coming together of the boundary layers on the wheel and the ground, which emerges sideways as a jet (McManus & Zhang 2006). Mears, Dominy, & Sims-Williams (2002) found a similar pressure distribution to that of Fackrell (1974) with

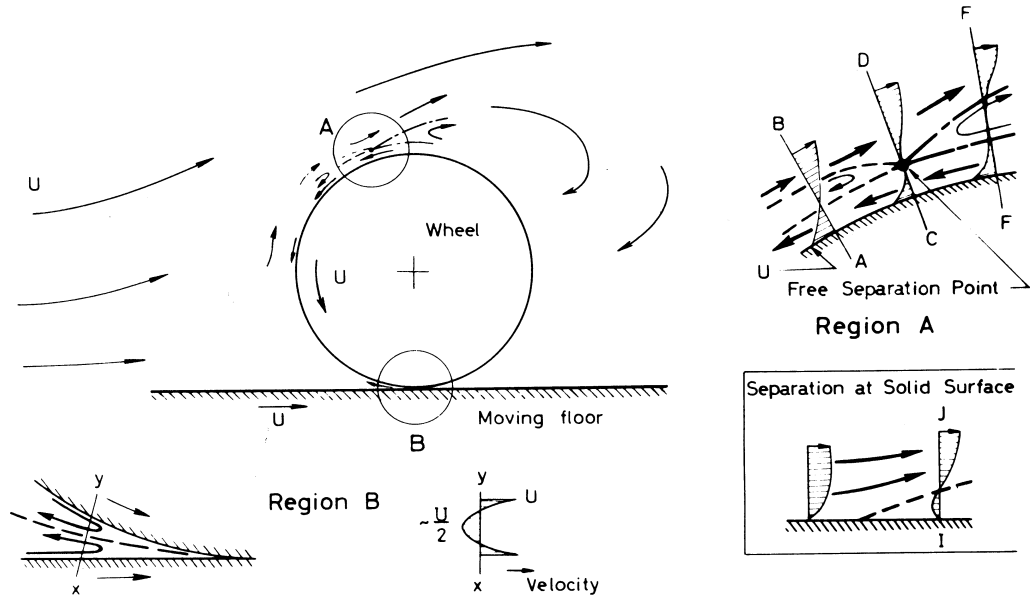


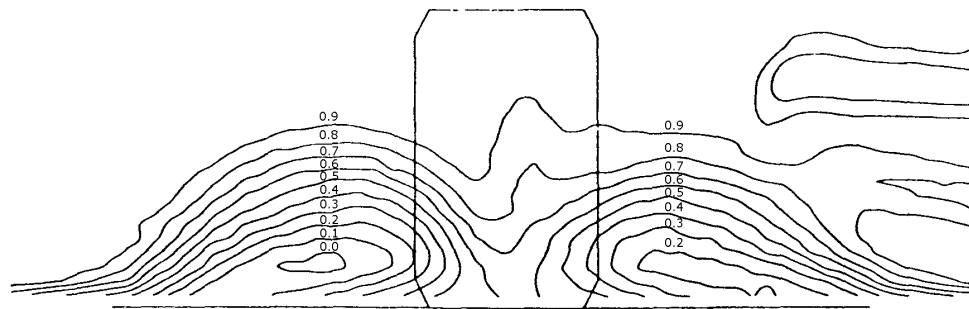
Figure 2.28: Schematic of the separation on a rotating wheel and details of the jetting flow as suggested by Fackrell & Harvey (1975)

a similar pressure peak which they noted reached a value above unity and hence must mean that work is being done on the fluid as it is being squeezed between the wheel and ground by viscous forces. They also found a negative pressure peak directly after the line of contact which is not always observed in either experiments or numerical calculations. Hence its physical presence is uncertain (Zhang, Toet, & Zerihan 2006).

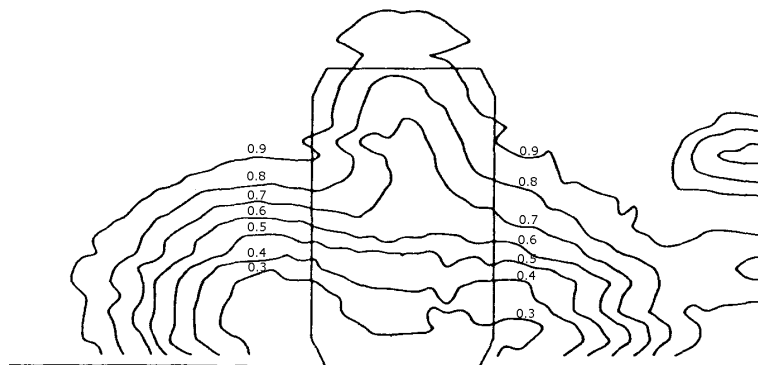
Using the pressure distributions and also laser-smoke flow visualisations, Fackrell (1974) estimated the separation point of the flow. He found that when the wheel is rotating, the flow separates at a position further upstream to that of a stationary wheel. This difference in the location of the separation point leads to less suction on the rotating wheel in comparison to the stationary wheel and therefore a lower lift value ($C_L = 0.56$ as opposed to $C_L = 0.77$).

The drag on the wheel is also affected by the rotation of the wheel. When the wheel is stationary the base pressure (downstream of the wheel near to $\theta \simeq 270^\circ$) is lower than when the wheel is rotating. This results in a higher drag for the stationary wheel when compared to the rotating wheel ($C_D = 0.76$ as opposed to $C_D = 0.48$ (Fackrell 1974)).

Another difference in the flow about the wheel when it is stationary or rotating is the wake. As shown in Figure 2.29 (produced by Bearman, de Beer, Hamidy, & Harvey (1988) on the same geometry as that of Fackrell (1974)), the stationary wheel generates a wide, short wake in comparison to the narrow, tall wake formed by the rotating wheel.



(a) Stationary Wheel



(b) Rotating Wheel

Figure 2.29: Total pressure contours (non-dimensional coefficients) in wake of wheel at 2.5 diameters downstream (Bearman, de Beer, Hamidy, & Harvey 1988)

The wake behind the wheel consists of vortical structures formed as a result of the flow over the wheel. In a paper on the aerodynamic characteristics of car wheels, Cogotti (1983) states that an isolated wheel can be considered as a cylinder with a short span, contacting the ground and turning about an axle perpendicular

to the direction of motion. As such Cogotti proposes that the complex flow field can be separated into three motion fields; that concerning the stationary isolated wheel away from the ground, one derived from the wheel rotation and the third as a consequence of the ground plane. By applying the theory of vortices associated with lifting bodies to these individual cases, Cogotti represented the wheel flowfield graphically as shown in Figure 2.30(c). This hypothesised wake structure is based on many assumptions and has been made without clear evidence from careful measurements. It is thought that assuming the wheel flow to be similar to that about a circular cylinder is an over simplification. As Fackrell & Harvey (1975) have shown complex flows such as the jetting phenomenon exist and may make these assumptions invalid.

This wake structure was amended by Merker & Berneburg (1992). In their work, the three pairs of vortices are still present. However, the lowest pair rotate in an opposite sense to that hypothesised by Cogotti (1983). In an attempt to evaluate the applicability of these vortical structures, Knowles, Saddington, & Knowles (2002) performed LDA on an isolated race-car wheel. They concluded by examining the vorticity in the near wake of the wheel (0.4 diameters downstream of the wheel), that there were distinct differences between the supposed vortices and the actual vortical structures present in the flow. Knowles, Saddington, & Knowles stated that the middle vortex pair and the inboard upper vortex, were suppressed by ‘real’ wheel geometry (such as the cavity of the wheel hub) and that the structure used to support the model in the tunnel influenced the flow. From their near-field, time-averaged data they noticed that the wake appears to be dominated by the upper vortices with the lowest pair exhibiting the lowest vorticity. Bearman, de Beer, Hamidy, & Harvey (1988) performed measurements with a nine-hole pressure probe in the far-field wake (2.5 diameters downstream), and noticed that the flow only consisted of two relatively weak vortices as shown in Figure 2.31(b). The peak vorticity in these structures is weaker than in the stationary case seen in Figure 2.31(a). It is thought that this could be a result of the differing upstream boundary layer profiles for the stationary and rotating case. In this set of experiments, a rolling road was utilised to rotate the wheel. Hence for the rotating wheel, there is no upstream boundary

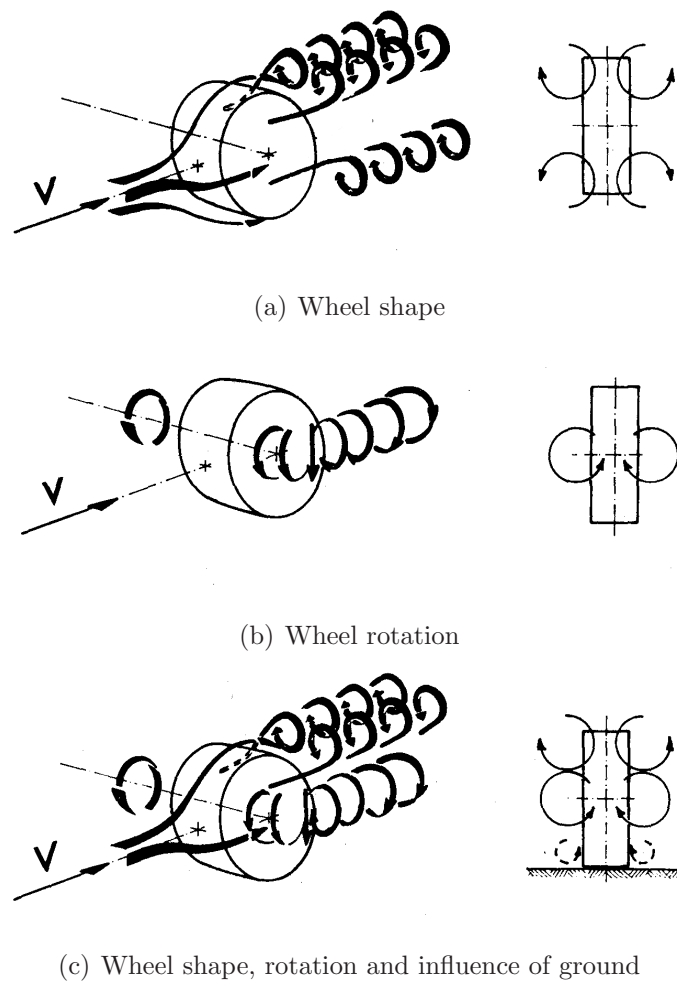
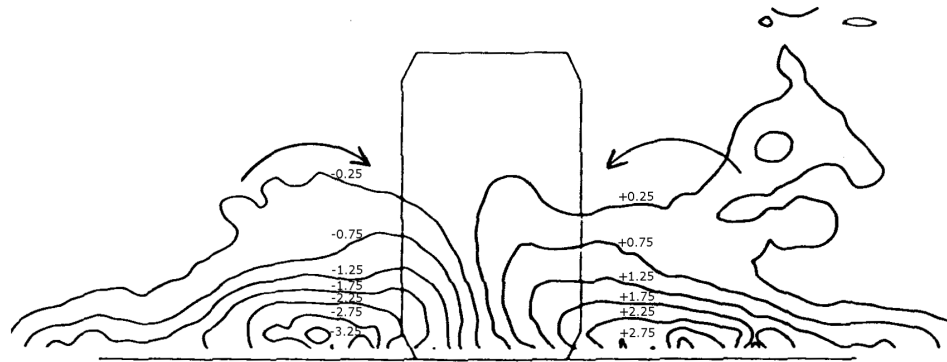


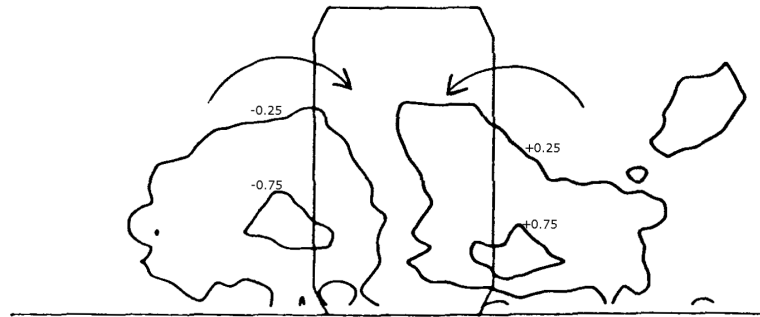
Figure 2.30: Complex wake pattern of isolated wheel, broken down into three simple flowfields and then superimposed (Cogotti 1983)

layer which over the stationary wheel forms a horseshoe vortex of the same rotation as that found by Bearman, de Beer, Hamidy, & Harvey (1988) and located close to the ground.

As suggested by Kellar, Pearse, & Savill (1999) during their numerical and experimental investigation about a Formula 1 type wheel, whilst the presence of the wheel is likely to affect the trailing vortex system from the front wing, the presence of the wing flow may also affect the wheel wake. The interaction between the wheel wake and the trailing vortex system will be examined during this research, the aims and objectives of which are stated next.



(a) Stationary Wheel



(b) Rotating Wheel

Figure 2.31: Streamwise vorticity contours (contours of $\omega D/U$) in wake of wheel at 2.5 diameters downstream (Bearman, de Beer, Hamidy, & Harvey 1988)

2.5 Research Aims and Objectives

From the literature reviewed in this chapter, it is apparent that the case of a vortex system travelling about a rotating wheel has not been investigated in detail. Several researchers have examined the flow over a simple race-car front wing operating close to the ground and have concluded that vortex breakdown can occur for small ride heights. However, a modern Formula 1 front wing produces a multiple trailing vortex system, and hence the vortices may behave differently from that of a single vortex as examined previously. It is also anticipated that the inclusion of the wheel will have a major effect on the behaviour of the vortex system and so this will need to

be investigated.

To summarise, the aims and objectives of this research are as follows:

- To investigate the vortex system shed from a modern Formula 1 front wing without the wheel and to determine whether the trends found previously at various ride heights are applicable.
- To investigate the effects of the presence of a rotating wheel on a single vortex as both initial position and strength of the vortex are varied.
- To examine the flow structure which is formed when the vortex system shed from a realistic front-wing geometry, travels about a rotating wheel.

The experimental set-up and analysis techniques which have been implemented to achieve these objectives will be discussed in the next chapter.

Chapter 3

Experimental Set-Up and Analysis Techniques

This chapter describes the experimental tools, techniques and models that were used to investigate the flow downstream of a race-car front wing.

3.1 Experimental Apparatus

All the experimental research that has been undertaken over the duration of this project has been completed in the Department of Aeronautics, Donald Campbell wind tunnel. This tunnel can be used for investigating the ground effect aerodynamics found on race-cars due to its rolling road and wake surveys can be conducted by using the three-axis traverse installed in the tunnel. The details of this facility will be discussed in this section.

3.1.1 Donald Campbell Wind Tunnel

The Donald Campbell wind tunnel is a closed return tunnel with a working section of $1.37m \times 1.22m$ in width and height and is $2.98m$ long ($4.5ft \times 4ft \times 9.78ft$). This low-speed facility produces a maximum flow velocity of approximately $45m/s$ and 93% of the flow over the cross-section of the working section is within $\pm 0.375\%$ of the centreline value (Bearman, Harvey, & Gardner 1976). The flow within the working

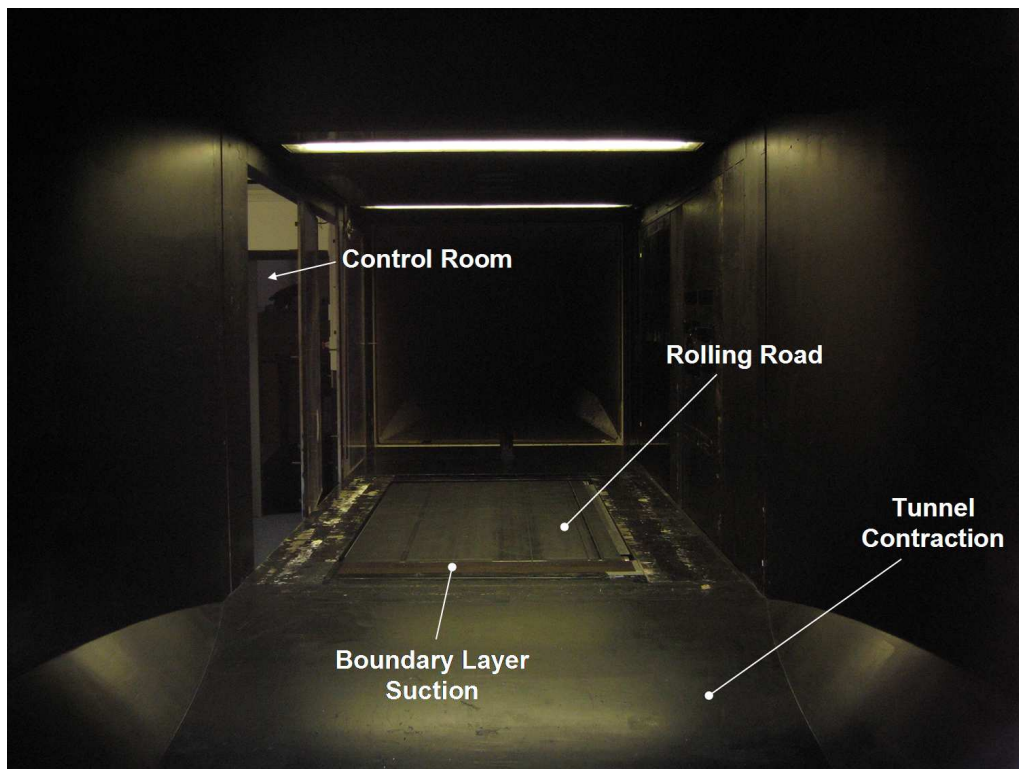


Figure 3.1: A photograph of the working section of the Donald Campbell Wind Tunnel as viewed from upstream

section is of good quality, with a maximum turbulence intensity of approximately 0.15% (Bearman, Harvey, & Gardner 1976).

3.1.2 Rolling Road

As Bearman *et al.* (1988) discuss in their paper on the effect of a moving floor on the wind tunnel simulation of road vehicles, the accurate representation of the moving ground plane is extremely important when investigating the flow about a race-car. A full-scale car on a race track on a windless day moves through still air. However in a wind tunnel this is very difficult to achieve and instead the car is made to be stationary with an air flow passing over it. Hence to replicate correctly the aerodynamics of a car on a track, the road is made to move at the same speed as the air. Wind tunnel testing is performed successfully on road-vehicles with a fixed road. However, Bearman *et al.* (1988) stated that the characteristics of a racing car: such as small ground clearances, downforce producing surfaces and exposed wheels;

ensure that for the correct simulation of the aerodynamics, it is imperative that a rolling road is used.

The moving floor in the Donald Campbell wind tunnel consists of a continuous belt stretched between two rollers and can be seen in Figure 3.1. The rolling road spans the majority of the working section and is 1.39m long and 0.81m wide (Bearman, de Beer, Hamidy, & Harvey 1988). This allows full car models of up to 25% to be tested in this facility.

The large negative pressures which are generated by inverted wings or other lifting bodies found on a race-car ensure that underfloor suction is required to prevent the moving belt from lifting. In the Donald Campbell tunnel, belt lift is minimised by the use of a suction box underneath the belt. The suction is provided by a fan and is applied to the belt through holes located over the platen. Although this design attempts to keep the friction between the platen and the belt to a minimum, the lack of a cooling system and an automatic tracking system limits the rolling road to a speed of 25m/s.

According to Bearman *et al.* (1988), another requirement for correctly modelling the flow over a race-car in a wind tunnel, is that of boundary layer suction. To replicate the correct conditions of a car moving through still-air, there should be no boundary layer over a rolling road. Hence the layer of slow moving air close to the tunnel floor which exists upstream of the rolling road, should be removed prior to passing over the moving floor. In the Donald Campbell wind tunnel this is achieved through a single suction plate located directly upstream of the moving floor, through which suction is applied by a fan. This system ensures that the boundary layer is removed to such an extent that there is only a small velocity deficit of approximately 0.2% of the freestream velocity close to the ground. The profile of this boundary layer is shown in Figure 3.2, which has been measured by the author along the centreline of the road and 375mm behind the suction plate.

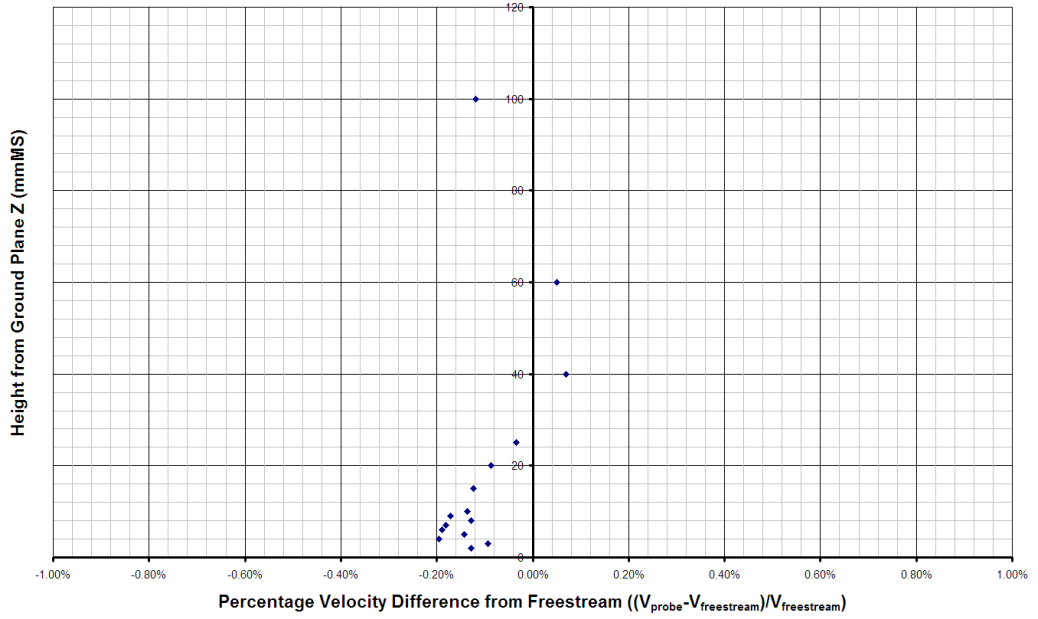


Figure 3.2: Experimental estimation of the boundary layer profile over the moving floor in the Donald Campbell wind tunnel at 375mm behind the suction plate and a freestream velocity of 25m/s (experiment performed by the author)

3.1.3 Three-Axis Traverse

As well as the rolling road, another important feature of the Donald Campbell wind tunnel is the three-axis traverse. This system which was extensively refurbished by Garrood (2004) prior to the commencement of this research project, consists of an arm on which a carriage is attached to traverse across the tunnel. Movement in the streamwise direction is achieved through a lead screw on either side of the tunnel and similarly a vertical axis is also present. The movement of the carriage on each of the three axes is achieved through stepper motors controlled by software which was written by Garrood (2004). This system facilitates the placement of a probe (attached to the carriage) within the working section of the tunnel and can be used to perform wake-surveys in cross-flow planes. Garrood (2004) states that the resolution of the traverse, without accounting for backlash and compliance due to wind loading, is $2.5\mu m$ in both the streamwise and horizontal axes, and $6.25\mu m$ in the vertical axis. More detailed information with regard to this system, can be found in Garrood (2004).

3.2 Wind Tunnel Models

In order to analyse the flow structure downstream of a realistic Formula 1 front wing geometry and to enable a direct comparison to be made with numerical simulations, a model was provided by McLaren Racing which mirrored that used in their computational simulations. This model was the focus for the majority of the project. However, as the research progressed it became apparent that the simplified case of a single vortex passing about a wheel would aid the understanding of this problem and hence two models were designed to achieve this. The specifics of these two models will be examined in Section 3.2.2.

3.2.1 McLaren Geometry

The 50% wind tunnel model provided by McLaren Racing replicated that used in their numerical simulations. These simulations made use of the longitudinal symmetry of the geometry and only examined the flow downstream of half the front wing together with a front wheel and bodywork representative of the actual car.

This design aided the installation of the McLaren model into the Donald Campbell wind tunnel as a complete 50% model would not have fitted adequately into the working section. A schematic of this installation is shown in Figure 3.3. From this figure it can be seen that a splitter plane is fixed into the tunnel so that in similarity to the numerical geometry, only the flow over half of the front wing is considered. Attached to this splitter plate is the nose-cone bodywork and the front wing (the entire 50% wing) is mounted through the splitter plate. Downstream of the front wing the front wheel is mounted via a wishbone and pillar support from outside of the rolling road. A photograph of the model installed in the tunnel can be seen in Figure 3.4.

The principle feature of the wind tunnel model is the front wing and endplate. This wing is a 50% scale version of a design which was current at the start of the research. It is a multi-element wing which comprises of three elements, termed the mainplane, turning vane and flap (see Figure 3.5). The aerofoil sections and planform of these elements vary along the span. Gurney flaps are attached to the

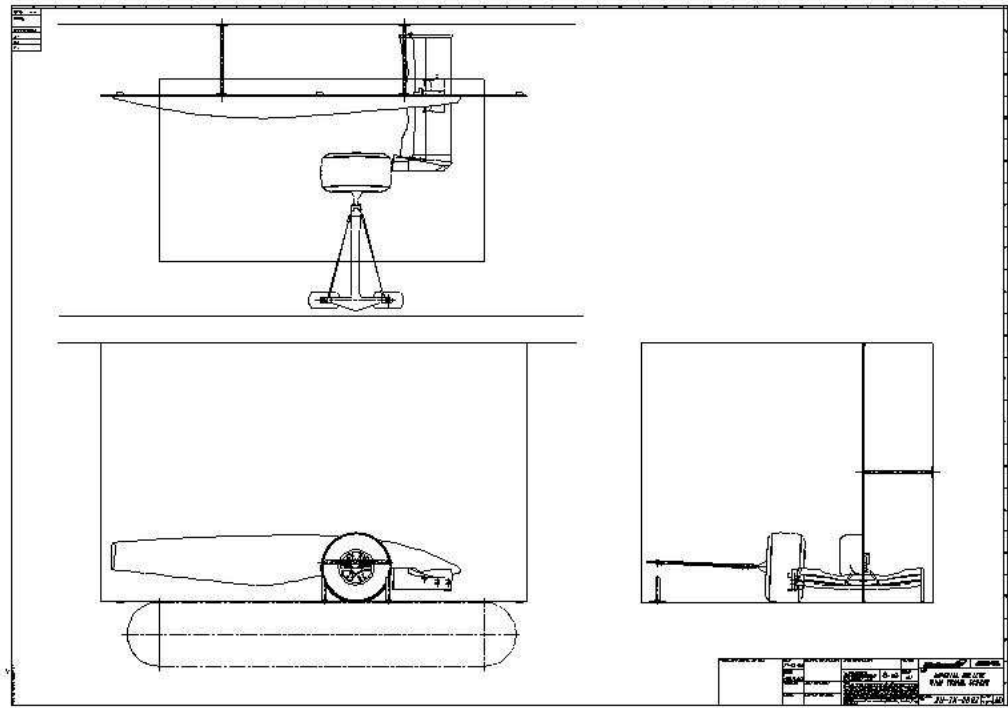


Figure 3.3: The technical drawing of the McLaren model as installed in the Donald Campbell Wind tunnel, drawn by A Henstridge (McLaren Racing)

flap at both an outboard and centre-span position (refer to Figure 3.5(a)). From Figure 3.5(c) it can be seen that the ground clearance of the wing is also not constant along the span, with the lowest point in a region under the centre of the wing and the clearance increasing with distance outboard towards the endplate. As discussed in Section 1.2 the endplates which are attached at the outboard ends of the wing have increased in complexity over the years. The endplate on this wing has an aerofoil cross-section and is yawed to the flow as seen in Figure 3.5(a). When viewed from the side (Figure 3.5(b)) and from downstream (Figure 3.5(b)) the scallop which exists near the bottom, trailing edge of the endplate can be seen. A lifting surface in the form of a half delta wing is attached to the outboard side of the endplate and this component is termed the canard. Along the lowest edge of the endplate a flat thin piece of geometry is attached. Termed the footplate this component overhangs the endplate on both the inboard and outboard sides. The footplate is the lowest point on the endplate and the gap between its trailing edge and the ground plane is used to define the ride height of the wing. It is this complex endplate design which

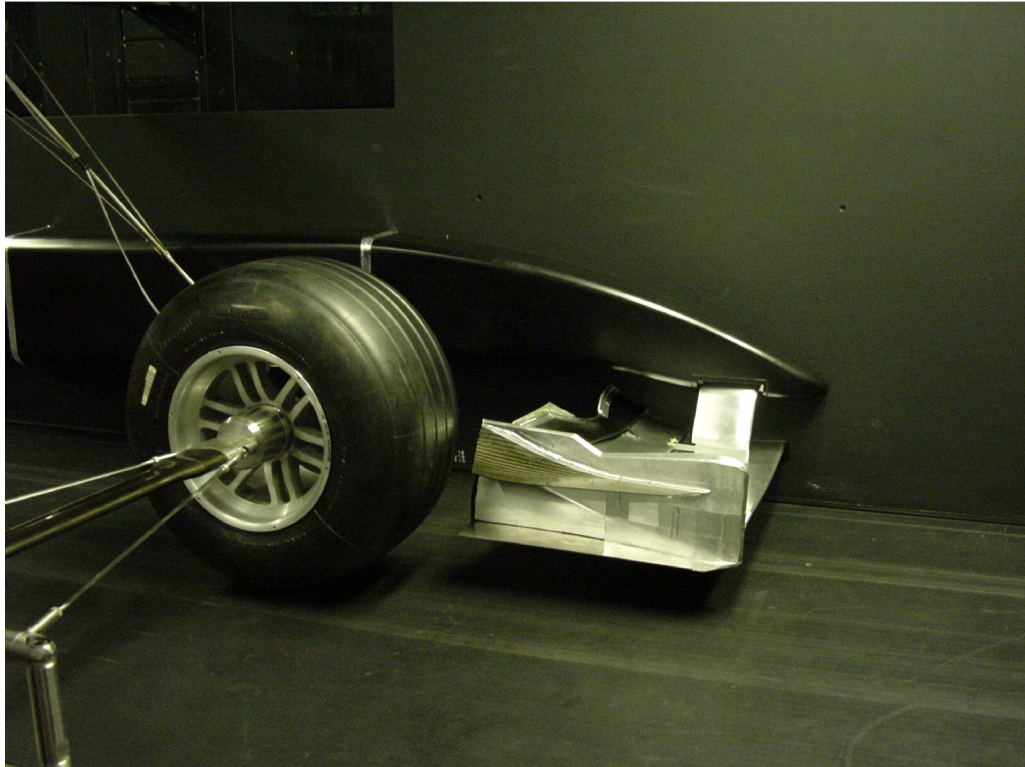
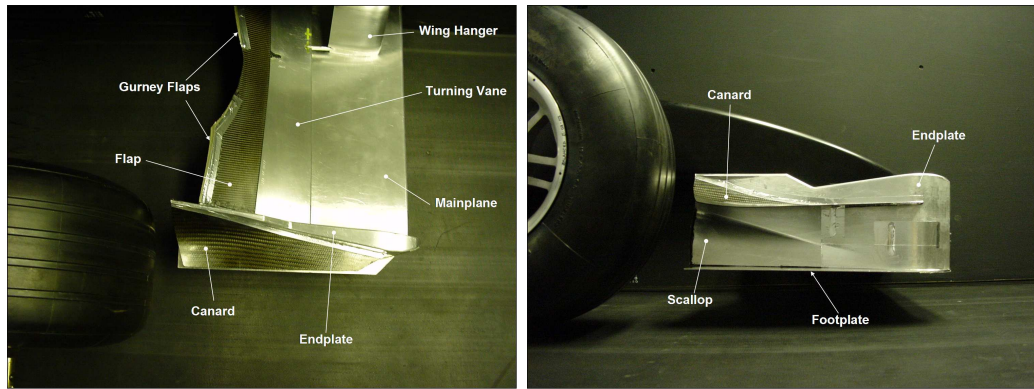


Figure 3.4: A photo of the McLaren model installed in the Donald Campbell wind tunnel

generates the multiple trailing vortex system which has been investigated in this research project. Once it is generated it immediately encounters the presence of the front wheel as can be seen in Figures 3.4 and 3.5.

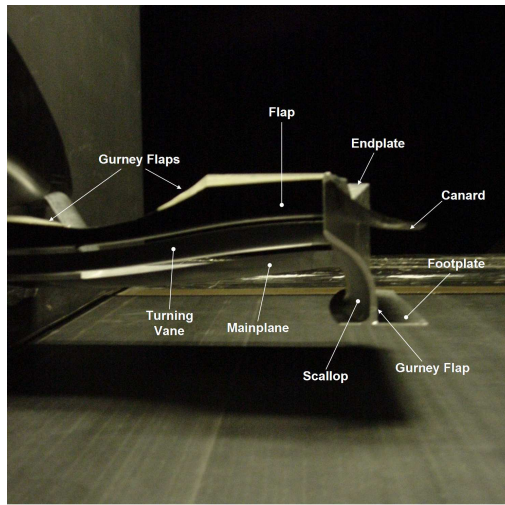
The front wheel is a 50% scale replica of the full-scale Michelin tyre. As such it is a pneumatic tyre with four grooves and has a diameter of $D = 330mm$. To simplify the complex geometry downstream of the wheel, at the commencement of the project it was decided that the brake duct and suspension members should not be included. Hence the model was supported from outboard of the wheel by a wishbone attached to a pillar, as can be seen in Figure 3.4. By varying the height of the pillar the camber of the wheel could be varied, but for the duration of the research this was maintained at an angle of 2.5° to the vertical. Another parameter that could be varied on the wheel is the tyre pressure. This was maintained at $7psi$ throughout the project.

The main parameter that can be modified to vary the vortex system shed from



(a) Viewed from above

(b) Viewed from the side



(c) Viewed from downstream

Figure 3.5: Photographs of the front wing of the McLaren model viewed from various perspectives

the front wing is its ride height. By placing spacers in between the wing hanger and wing, this could be modified. The ride height was defined by the lowest clearance between the wing and the ground plane. This occurred at the footplate and hence this is used to define the ride height. Due to the pitch of the model within the tunnel (approx 1.1° nose down, to replicate the situation in the McLaren numerical simulations), the smallest clearance occurs at the leading edge of the footplate. However, since the vortex system is shed from the trailing edge, the ride height is defined by a distance from the trailing edge of the footplate to the ground plane (h). Four different ride height configurations were evaluated and the absolute gaps

in terms of the model-scale (MS), the full-scale value (FS) and the normalised value (by the mainplane chord, h/c_{mp} , where $c_{mp} = 124.9mmMS$) are shown in Table 3.1. The lowest of these four ride heights coincided with that found on Formula 1 cars prior to the change in regulations which occurred in 2005 ($h/c_{mp} = 0.36$). The 2005 regulations raised the front wing by 50mmFS and therefore the ride height of $h/c_{mp} = 0.56$ reflects this change. The other two ride heights were chosen to help provide a better understanding of the effect of ground clearance on the behaviour of the trailing vortex system. Note that for the two highest ride heights, the bodywork was also raised by $\Delta Z = 50mmFS$ ($\Delta Z = 25mmMS$).

Ride Height (h)		
<i>Model-Scale (mmMS)</i>	<i>Full-Scale (mmFS)</i>	<i>Non-Dimensional (h/c_{mp})</i>
45	90	0.36
60	120	0.48
70	140	0.56
85	170	0.68

Table 3.1: Details of the four different ride height configurations

With the model installed in the tunnel the maximum blockage is approximately 8% of the tunnel cross-section. To account for this the tunnel with only the splitter plate and bodywork installed in the working section, was calibrated with a pitot-static tube. It is acknowledged that the velocity inside the tunnel will change when the wheel and wing are added. Although there are corrections which can be applied to such parameters as the overall forces acting on the body, the author is unaware of any corrections which can be applied to the entire velocity field to account for a blockage which varies with downstream distance.

The maximum Reynolds number that can be obtained with this model, based on the mainplane chord and an air speed of 25m/s is $Re_{c_{mp}} = 2.0 \times 10^5$. The numerical results undertaken by McLaren are obtained from solving the Reynolds Averaged Navier-Stokes (RANS) equations coupled with a k- ϵ turbulence model. This CFD is performed on the full-scale geometry, at a velocity of 36m/s and as such has a

$Re_{cmp} = 5.7 \times 10^5$. Due to the turbulence model the flow is turbulent everywhere and therefore to enable comparison between the numerical and experimental results, grit strips were included on the lifting surfaces of the wind tunnel model to promote transition.

3.2.2 Single Vortex Models

As the research progressed, it became apparent that the placement of a single vortex upstream of the rotating wheel in various positions and with differing strengths would aid the understanding of the problem. Hence two models were designed which would facilitate this. The details of these models will be discussed in this section.

3.2.2.1 Single Element Model

The purpose of the single element model was to generate a single vortex which could be placed in various positions upstream of the wheel and then its behaviour examined as it navigated about this rotating body. To achieve this objective, it was decided that the vortex should be generated by a rectangular planform wing with a NACA 0015 aerofoil cross-section (i.e. symmetrical with 15% maximum thickness). The wing of span 300mm and of chord 100mm (c), was cantilevered over the rolling road from a pillar support. The support located into a slot outboard of the rolling road which allowed the wing to be moved in a streamwise direction along the length of the road. The wing was connected to the pillar support through a collar which allowed both the lateral and vertical placement of the wing to be modified. Finally slots existed on an endplate which controlled the angle of incidence and hence the strength of the vortex could be adjusted. A photograph of this model in the wind tunnel can be seen in Figure 3.6. Note that in this figure, the wheel is located on the opposite side of the tunnel to that with the McLaren model. This orientation made the evaluation of the flow with certain experimental techniques easier and will be discussed further in Section 3.4.

This model generated a trailing vortex which rolled up from the tip of the wing

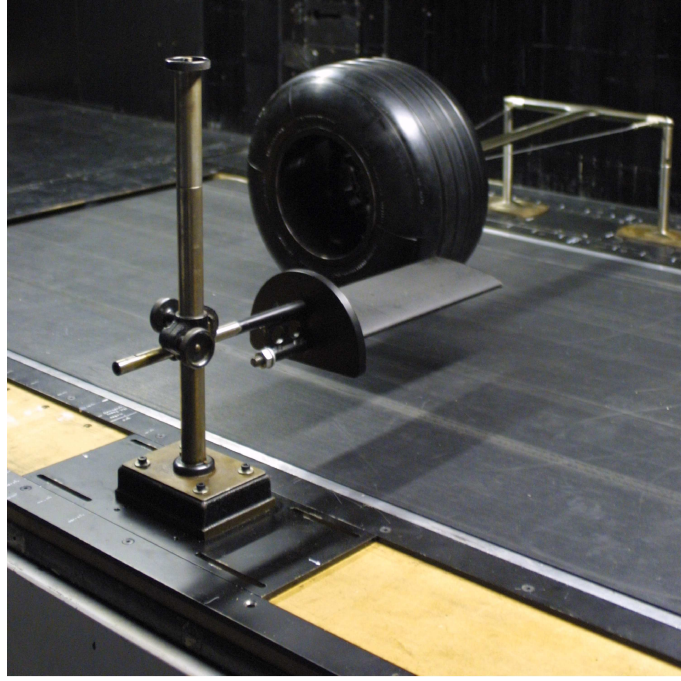


Figure 3.6: A photo of the single element model installed in the wind tunnel with the rotating wheel

and could be placed laterally, vertically and longitudinally about the upstream face of the wheel with varying strength ($0^\circ < \alpha < -15^\circ$, i.e. pitch down). However, due to the aerodynamics of the rotating wheel, the accurate, repeatable placement of the vortex upstream of the wheel in the desirable position became difficult. Hence a very small endplate was attached to the wing tip to aid the placement of the vortex as shown in Figure 3.7. The blockage of this model, at approximately 3.6% of the wind tunnel cross-section, was much less than that of the McLaren model. For the experiments using this model, the calibration of the tunnel when empty was used.

As with the McLaren model front wing, transition strips were fixed to the suction side of the aerofoil in accordance with the methods of Versmissen (1974) to promote transition. The Reynolds number of the model based on the chord is $Re_c = 1.6 \times 10^5$.

3.2.2.2 Double Element Model

The design and manufacture of a double element model was deemed necessary so that a vortex of a similar strength to the vortices shed from the McLaren front wing could be produced (this was not possible with the single element model).

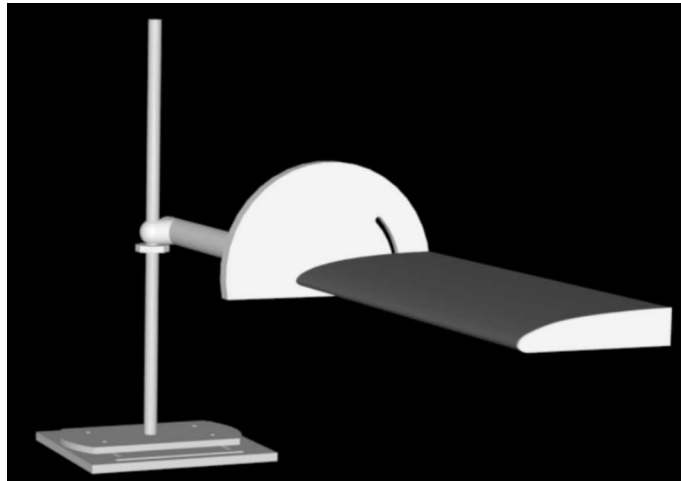


Figure 3.7: CAD representation of the single element model, with small endplate attached

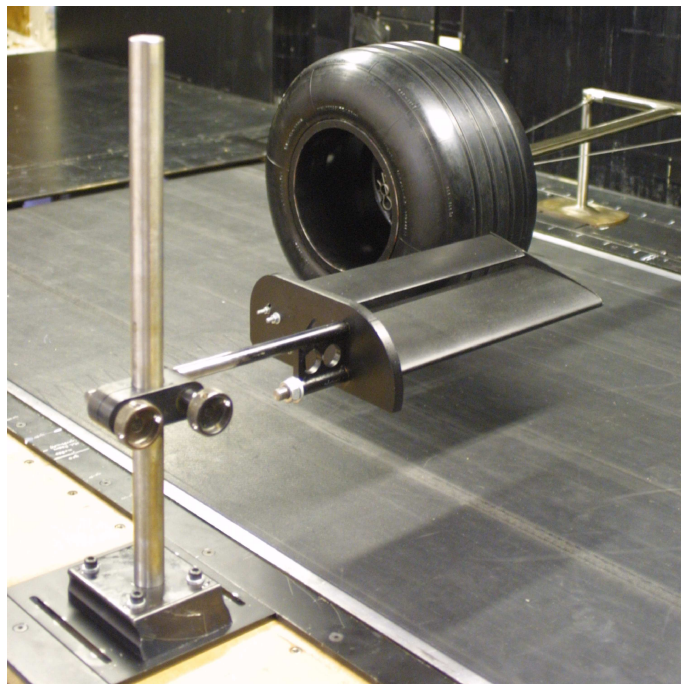


Figure 3.8: A photo of the double element model installed in the wind tunnel with the rotating wheel

The support structure, and hence placement of the wing within the wind tunnel, was almost identical to that used on the single element wing and can be seen from the photograph shown in Figure 3.8.

The wing consisted of two elements; a mainplane and a flap. The mainplane was

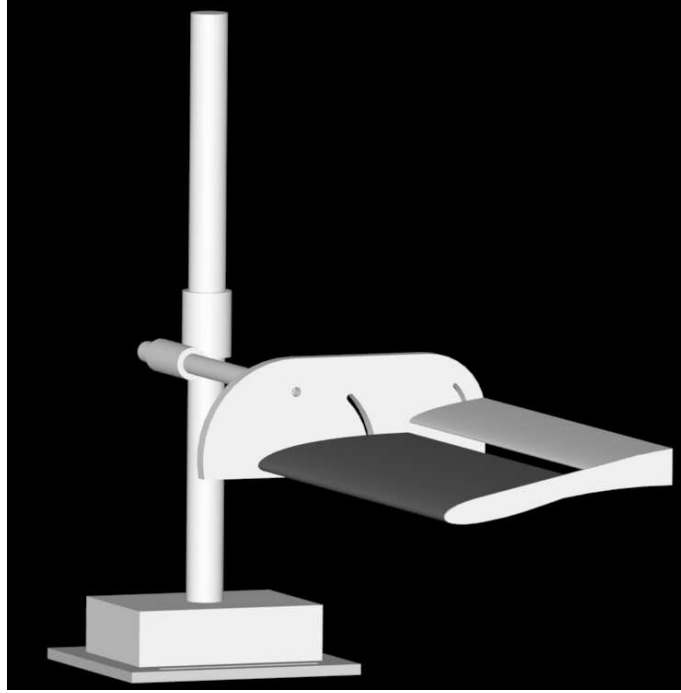


Figure 3.9: CAD representation of the double element model, with small endplate attached

identical to that of the single element model and the flap was positioned downstream and slightly above the trailing edge of the main element. This second element had an aerofoil section of NACA 0012, a chord of $c = 50mm$ and a span equal to the main element ($300mm$). The incidence of the mainplane could be varied from $0^\circ < \alpha_{mp} < -15^\circ$ and the flap from $0^\circ < \alpha_{fp} < -25^\circ$.

As with the single element model, a small endplate was designed to aid the repeatable placement of the vortex generated at the tip. This reduced the effect of the cross-flows present in front of the wheel so that the vortex would be shed as close to the desired location as possible. However, the design for this model was more complicated as a compromise had to be made between the accurate placement of the vortex and the distance taken for the vortex to roll-up. This resulted in the design shown schematically in Figure 3.9.

As with the single element model and the McLaren geometry, transition strips were placed on the suction surface of the mainplane and the Reynolds number (based on the mainplane) and blockage are identical to that of the single element model.

3.3 Axis Convention

The axis system adopted for this research project replicated that used by McLaren in their CFD, so that direct comparisons between the experimental and numerical results could be easily made.

The right-handed axis system is defined as shown in Figure 3.10. The Y-axis is orientated with the streamwise direction (in Figure 3.10(b) this is into the page), the X-axis is aligned laterally from the centreline to the left outboard side of the model and the Z direction goes with the vertical direction. All of the coordinates are referenced to a location on the car which is 25mmFS above the ground plane, with the Y datum begin associated with the front bulkhead of the car and the symmetry plane (splitter board) is the X=0 position.

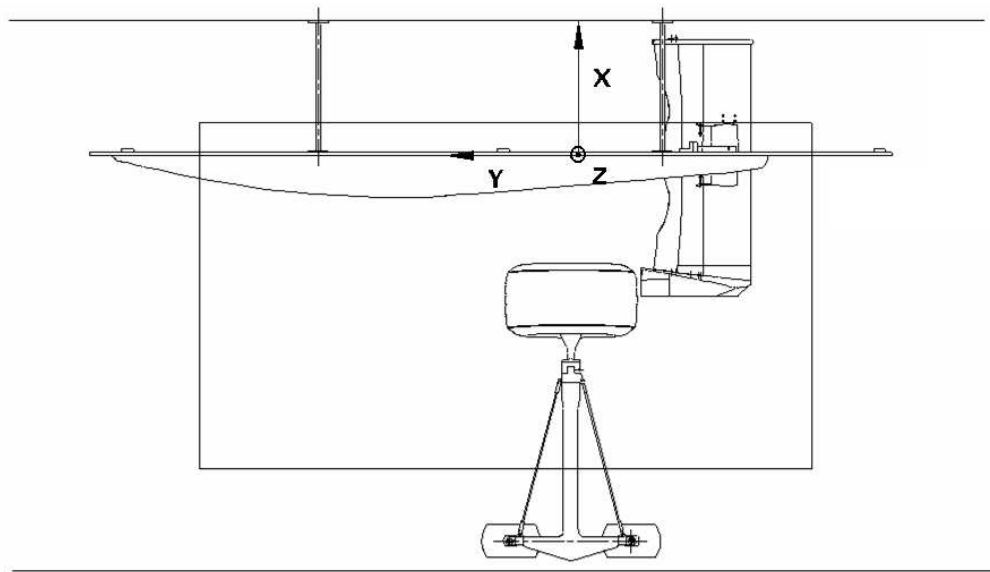
The numerical results from the CFD performed by McLaren are referenced to the full-scale car. Therefore to aid comparison, all of the results which are presented in this thesis will also be converted to full-scale coordinates (denoted as FS).

This definition of the coordinate system, ensures that the main features of the model have values as stated in Table 3.2.

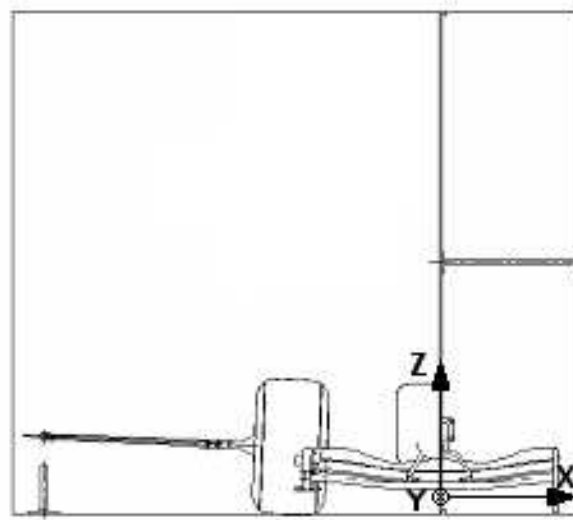
Description of Location	Value in Coordinate System
Trailing edge of endplate	$Y = -300mmFS$
Leading edge of wheel	$Y = -291mmFS$
Longitudinal point of contact of wheel	$Y = 39mmFS$
Trailing edge of wheel	$Y = 369mmFS$
Ground plane	$Z = -25mmFS$
Axis of wheel	$Z = 305mmFS$
Highest point of wheel	$Z = 635mmFS$
Outboard face of wheel	$X = -900mmFS$

Table 3.2: Table showing values of certain items of interest in the analysis region and their location in the adopted coordinate system

Figure 3.11 shows the extremities of the analysis region in which the flow has



(a) Viewed from above



(b) Viewed from upstream

Figure 3.10: A schematic of the McLaren model, showing the adopted axis convention)

been investigated. The most upstream point in the region is associated with the position of the trailing edge of the endplate on the front wing. The analysis region contains the flow inboard of the wheel and the flow downstream of the wheel is interrogated until a value of $Y = 600mmFS$ is reached. To enable comparison with

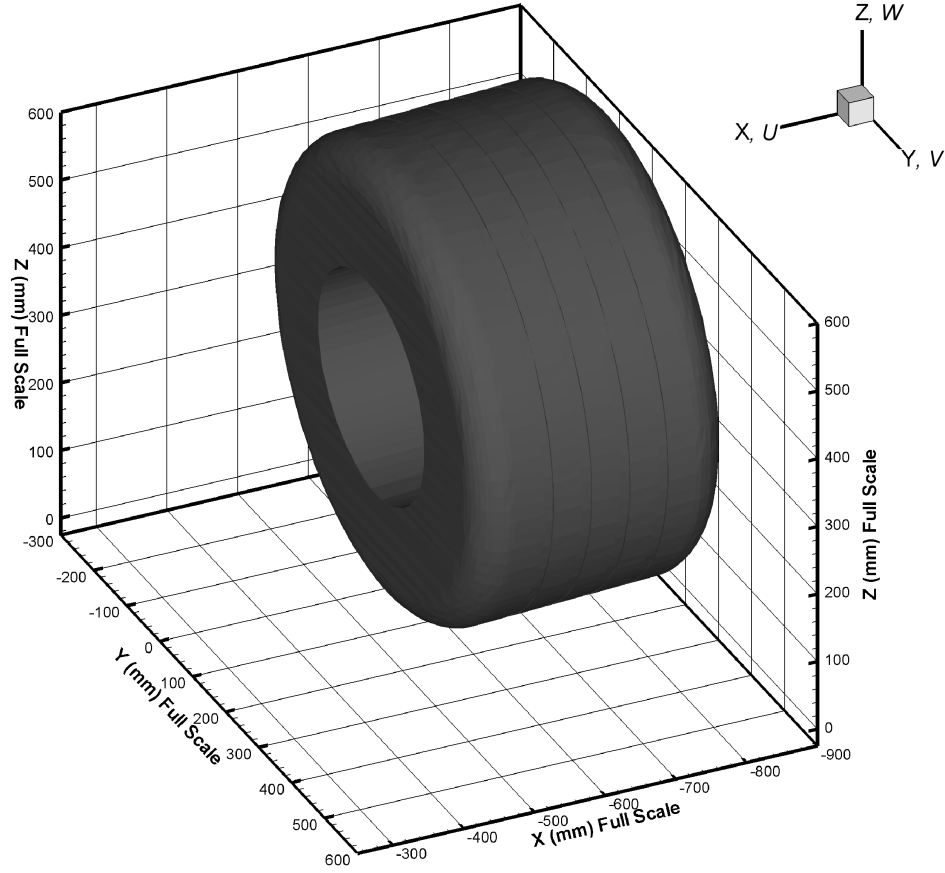


Figure 3.11: A diagram of the region of interest about the wheel, showing the axis system in full scale coordinates and definitions for the components of velocity (Note that the freestream velocity (V_∞) is aligned with the Y-axis)

work discussed in the literature review, it is useful to state what the bounds of the analysis region are when non-dimensionalised by the wheel diameter. If the location of the point of contact of the wheel on the ground plane is taken as a datum then the flow is evaluated from a distance of -0.51 diameters upstream of the contact patch to a value of 0.85 diameters downstream of this point.

3.4 Experimental Techniques

Four different techniques have been used to evaluate the flow about the models discussed in previous sections, the details of which will be commented on next.

3.4.1 Total Pressure Surveys

Total pressure can be used as a tool for investigating the behaviour of the wake from a wing because as discussed in Section 2.3.1.2, it decreases from the freestream value in regions of high shear. Hence this could be used to identify the slow moving wake and vortex cores shed from the endplate, as they can be identified as regions of energy loss.

To obtain total pressure distributions in the analysis region, the wind tunnel's three-axis traverse system was used to perform wake surveys in planes perpendicular to the freestream direction (i.e. X-Z planes in the adopted axis convention). The traverse together with its software, allowed a total pressure probe to be moved about a predefined grid and the resulting pressure value recorded.

The total pressure probe used for the wake surveys is similar to that described in Kiel (1935). According to this paper, the Kiel total pressure probe can be used to measure the total pressure in the flow and will remain accurate with the flow inclined by up to 40° to the probe. However, Garrood (2004) measured the range of yaw insensitivity with the same probe used in these experiments, to be closer to 35° .

To measure the pressure obtained from the Kiel total pressure probe, a pressure transducer was used to convert the pressure into a voltage. The voltage signal was then read by a data acquisition computer (using a National Instruments PCI-6229 card), and converted into the non-dimensional total pressure coefficient as defined in Equation 3.1, where $P_{t_{probe}}$ is the total pressure measured by the probe, $P_{s_{tunnel}}$ is the static pressure at the most upstream point of the working section and $P_{t_{tunnel}}$ is measured upstream of the contraction.

$$C_p = \frac{P_{t_{probe}} - P_{s_{tunnel}}}{P_{t_{tunnel}} - P_{s_{tunnel}}} \quad (3.1)$$

The maximum resolution of the data points in the wake surveys is governed by the diameter of the Kiel probe which was determined to be $2mm$. However, as a consequence of the large timescales involved in making a high resolution scan, this resolution was not used over an entire survey plane. A first survey was made with a coarse resolution of $10mm$ and the results from this preliminary scan were used as



Figure 3.12: A photo of the McLaren model in the Donald Campbell tunnel showing the total pressure probe attached to the probe support and traverse

a basis to look at any specific regions of interest at a higher resolution. Therefore the results of the total pressure surveys presented in this thesis may contain data both with a coarse and fine resolution.

To move the probe about the analysis region the probe was attached to the traverse by a large probe support as can be seen in Figure 3.12. The size of this support was dictated by the geometry of the model, with the dimensions limited by the presence of the splitter plane and the wheel. Although every effort was made to maintain the rigidity of the probe in the flow when connected to the traverse via this support, the probe was seen to visually buffet more with this set-up than when attached directly.

At each point in the wake survey the voltage signal from the pressure transducer

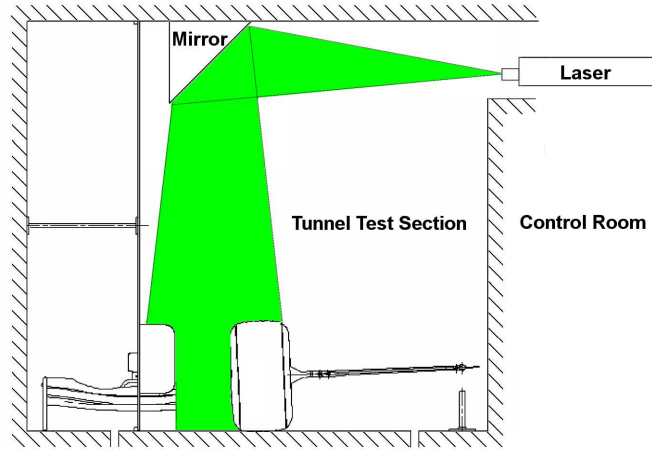
was sampled for a duration of 2 seconds at a frequency of 200Hz after having settled for a period of 1 second. The time-averaged pressure was then obtained from the mean of this signal and an indication of the error of this method can be found by observing the standard deviation. The standard deviation values were usually less than $C_p \approx 0.15$. Erroneous values which were obtained due to the flow exceeding the yaw insensitivity of the probe were removed from the plots.

This method produces a time-averaged observation of the flow by an intrusive method. Hence, by investigating the flowfield in this way, the behaviour of the flow may be affected. Therefore laser smoke flow visualisation was also performed.

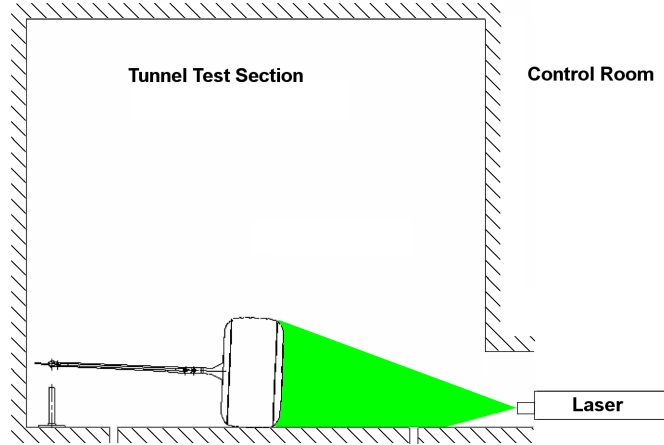
3.4.2 Laser-Smoke Flow Visualisation

Visualisation of the flow-field downstream of the wind tunnel models was performed by recording the behaviour of smoke particles travelling with the flow. This involves seeding the specific area of interest, illuminating the area with a laser sheet and recording the resulting images. This method is both non-intrusive and instantaneous.

To provide the seeding, non-persistent smoke particles were produced by a Concept Spirit 900 smoke generator and introduced into the settling chamber upstream of the working section of the wind tunnel. The smoke particles travelled with the flow and were illuminated in a plane perpendicular to the freestream by a laser sheet generated by a Class IV Spectra Physics, 5 Watt Argon-Ion Laser. This laser was located in the control room of the wind tunnel and entered the wind tunnel through a slot in the wall. To provide illumination of the flow inboard of the wheel with the McLaren model, a mirror was attached to the roof of the tunnel and orientated at 45° so that the laser sheet was reflected vertically to the floor. The set-up was different for the single wing models, as without the limitations of the splitter plane, the wheel was changed over to the other side of the tunnel. With this set-up the mirror was not required. These two-set-ups are shown schematically in Figure 3.13. Note that although the orientation of the wheel is different in the two cases, all of the results from the single wing models have been mirrored so that a direct comparison



(a) Laser set-up for McLaren model



(b) Laser set-up for single wing models

Figure 3.13: Schematic of laser set-ups for both models as viewed from downstream

can be made.

A JAI CV-M1 digital CCD camera was used to record the images of the illuminated smoke particles. This camera can record images of resolution 1300×1030 pixels at a frame rate of 12 frames per second. For all of the flow visualisation experiments performed during this research, the shutter was set at $1/400$ and the visualisation was recorded for a duration of 10 second. From the 120 frames recorded one individual frame was selected which was deemed to be representative of the flow for presentation in this thesis.

To prevent excessive smoke dispersion, during the laser-smoke visualisations the wind tunnel was operated at $12.5m/s$.

3.4.3 Hot-Film Anemometry

The two methods discussed so far have provided information that can be used to give a qualitative understanding of the behaviour of the velocity field. To obtain quantitative information on this flow field, hot-film anemometry and particle image velocimetry have been utilised.

Hot-film anemometry has been performed by using a tri-axial hot film probe attached to the traverse to gain information on all three components of the velocity vector.

The probe that was used was the Dantec Dynamics 55R91 triple sensor fibre-film probe. This probe can be seen in Figure 3.14 and consists of three mutually perpendicular sensors. From these three sensors the three-dimensional flow field can be obtained when the flow vector is within a 70.4° acceptance cone. A fibre film sensor has been used as they are more robust than standard wire probes which makes them more applicable for measuring the flow near a rolling road. One negative aspect of a hot-film probe is that the maximum frequency response of the sensor is lower (maximum of 90KHz) than a standard hot wire. However, for these experiments this was not a problem as the probe was largely used to obtain the mean velocity.

To produce the voltage signal from the hot-film probe, each sensor was connected to a DISA 55M10 constant temperature anemometer (CTA). These were operated with a bridge ratio of 5:1 and an overheat ratio of 1.5.

The output from the CTA's were connected to the data acquisition computer from which specifically written software could process the results. This software was written by the author and was largely based on the software used for the total pressure surveys and was used to perform the calibrations, set-up the analysis grids, sample the voltages and calculate the velocities. Velocity calibration was performed in-situ in the wind tunnel with a pitot-static probe over the full range of expected velocities. Together with a polynomial fit of the calibration data the expected ac-

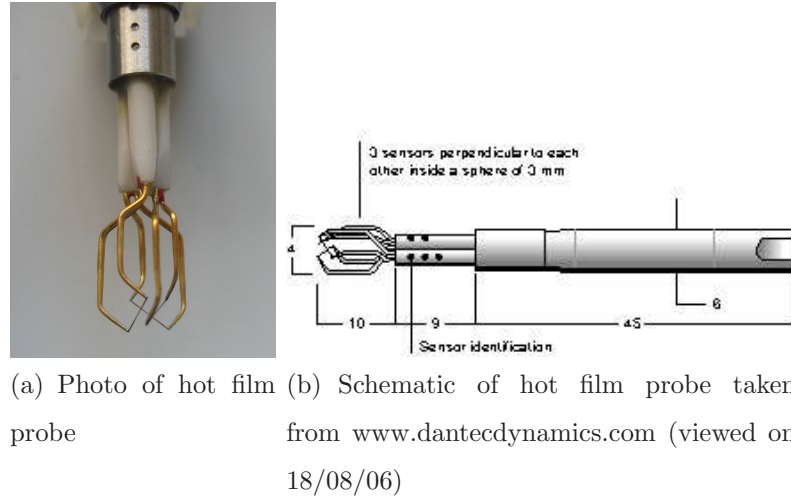


Figure 3.14: Details of the Dantec Dynamics tri-axial fiber-film probe (55R91)

curacy from such a calibration is typically $\pm 1\%$ above $5m/s$. Tri-axial probes also require a directional calibration as individual sensors only resolve the velocity which is perpendicular to it. This calibration is only dependant on the geometry of the probe and hence the manufacturers default calibration values were used.

In similarity with the total pressure surveys, performing a high resolution wake survey of the velocity field with the hot-film probe could be very time intensive. Hence for all of the results presented in this thesis, a coarse scan is first performed where one point every $7mm$ is examined and then in areas of interest a finer resolution of $3.5mm$ is used (the maximum spatial resolution of this probe is $1.3mm$). At every point in the scan, the voltage signals from the probe are sampled over a period of 2 seconds after having settled for 1 second, at a frequency of $50KHz$. From these signals and the calibration data, the velocity vector is calculated and then the mean and fluctuating part of the velocity are converted into a mean and root mean square velocity with the Reynolds shear stress tensor also calculated.

The uncertainties in this method mostly originate from the calibration of the sensors. However, there are sources of error from the actual probe itself, the positioning of the probe and temperature fluctuations. The effect of temperature drift was accounted for by correcting the voltage signal from each individual film by the relationship shown in Equation 3.2 obtained from Jørgensen (2002), where E_{corr} is

the corrected voltage, E_a is the acquired voltage, T_w is the temperature of sensor when operating, T_0 is the ambient reference temperature and T_a is the ambient temperature during acquisition.

$$E_{corr} = \left(\frac{T_w - T_0}{T_w - T_a} \right)^{0.5} \cdot E_a \quad (3.2)$$

The combination of all of these errors account for a total inaccuracy of approximately 1% (Jørgensen 2002). However when the uncertainty of the calibration procedure is included, this value rises to approximately 3% if the above procedure is followed. It must also be remembered that this method is intrusive.

3.4.4 Particle Image Velocimetry (PIV)

In order to obtain information on the velocity field in cross-flow planes by a non-intrusive method, a commercial two dimensional PIV system was used. This system (manufactured by Dantec Dynamics), consists of a seeding generator, a double pulsed laser, a CCD camera, and Dantec's FlowManager software.

A Litron 125mJ double pulsed Nd:YAG laser was set-up in a similar manner to that used for the laser-smoke visualisation, where a mirror was required for the McLaren model but not for the single wing models. The laser sheet illuminates the oil particles that are produced by the seeding generator. These tracer particles are of approximate size $3 - 6\mu m$ and were introduced to the flow downstream of the working section. The 1600×1196 pixel CCD camera was placed in the working section, approximately 1.8m downstream of the laser sheet. This distance was kept constant by moving the camera on an optical track, by the same amount as the laser which was mounted on a milling table base. This ensured that the dimensions of the field of view were identical for all planes.

Synchronisation and control of the timing of the laser and camera are achieved through the FlowManager software, which is also used to process the resulting images. The timing interval between laser pulses could be varied and was set so that the majority of the vectors in the illuminated plane, moved by approximately a quarter of the interrogation cell (of size 32×32 pixels, equating to $3.6mmMS \times 3.6mmMS$ or $0.03(c_{mp})^{-1} \times 0.03(c_{mp})^{-1}$), whilst staying within the laser sheet (2mm thickness).

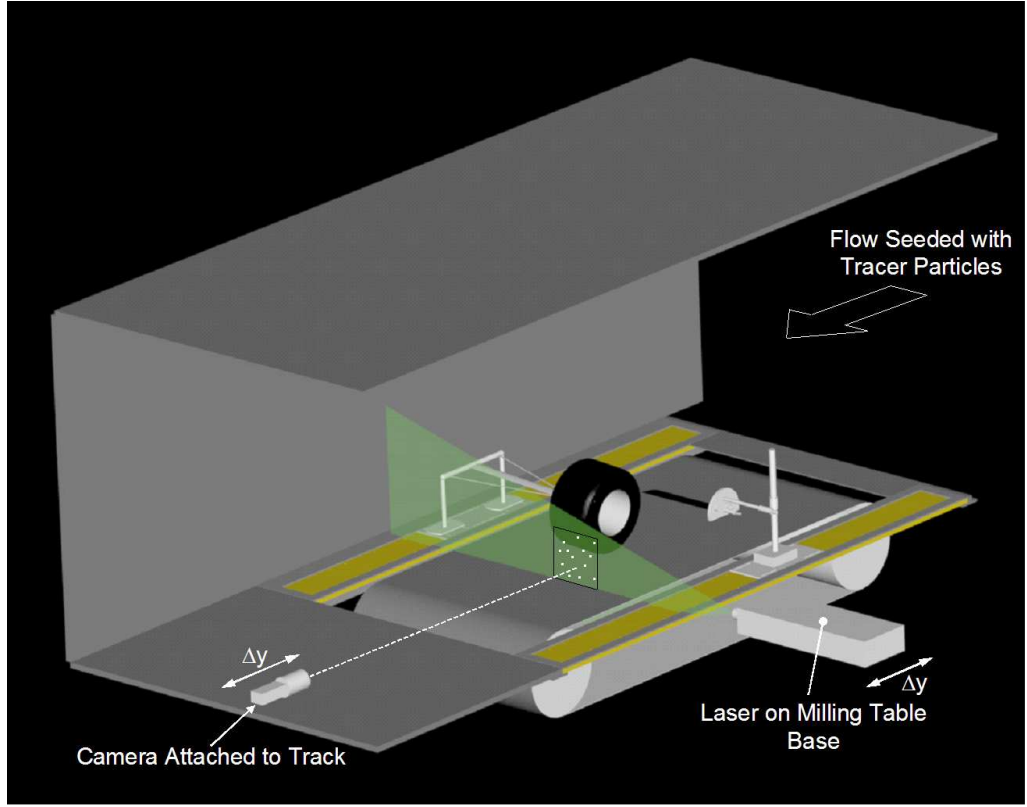


Figure 3.15: Schematic of the PIV set-up in the Donald Campbell wind tunnel

This led to values from $15 - 60\mu$ seconds. The software also performed the adaptive correlation which produced the velocity field from the particle images, and filtering and validation was also undertaken with this software. Hence the analysis field of dimensions $358.5mmMS \times 358.5mmMS$ contained 7227 vectors with a vector resolution in both axes of $3.6mmMS$. Therefore this resulted in approximately 3 vectors inside each vortex core. The experimental set-up of the PIV system for the single wing model is summarised by the schematic shown in Figure 3.15.

The main error associated with PIV measurements in three-dimensional flow fields is that of parallax. This error occurs when there is a component of velocity normal to the laser sheet, and increases with offset from the camera axis. It appears as an apparent velocity to the camera and is not physical (Bearman, Harvey, & Stewart 1999). This error can be seen diagrammatically in Figure 3.16. The magnitude of this error is affected by the velocity normal to the sheet and the distance the particles are away from the camera axis. This relationship can be described by

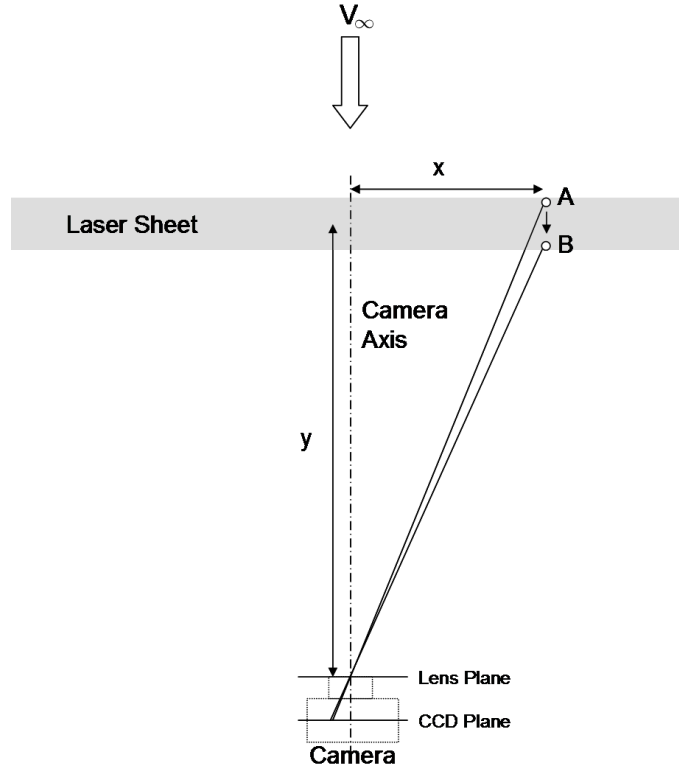


Figure 3.16: Illustration of the parallax error

Equation 3.3, where V_a is the apparent velocity from the parallax, V the velocity of the particle normal to the light sheet, X the distance of the particle from the optical axis and Y the distance from the camera to the light sheet.

$$V_a = \frac{Vx}{y} \quad (3.3)$$

From this equation it can be seen that the error can be reduced by increasing the distance between the camera and the laser sheet. In the experiments performed for this thesis, the distance was maintained at $1.8m$ and the maximum distance from the optical axis was $175mm$. Hence the theoretical parallax error that could be obtained with this set-up was 9.7% . This compares well with the parallax error found experimentally shown in Figure 3.17. To obtain this figure, the tunnel was operated at a freestream velocity of $25m/s$ and was empty. The PIV system was set-up as for the single wing models with the laser sheet entering from the control room, along the floor of the tunnel. The tunnel was seeded and the camera set at the distance away from the laser sheet used in all of the experiments ($1.8m$). Then

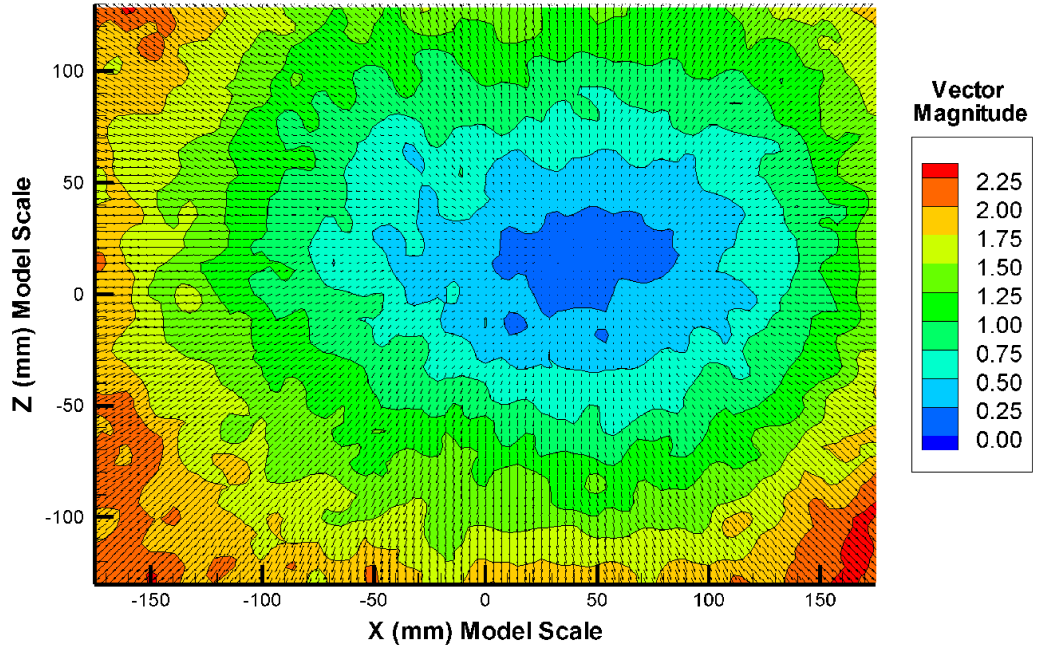


Figure 3.17: PIV of cross-flow in an empty tunnel showing time-averaged U and W vectors in the X-Z plane, used to estimate the parallax error with a freestream velocity of 25m/s. The contours are coloured with velocity magnitude

the PIV system was used to obtain the movement of the particles through the laser sheet. 75 images were obtained and post-processed with the same method as for all of the other PIV experiments and the vector maps time-averaged. The resulting time-averaged plot of the cross-flow velocity shows that the error is smallest in the centre of the field of view and the maximum apparent velocity occurs at the edges and was found to be 2.25m/s (9%).

3.5 Post-Processing Procedure

Once the velocity field had been found experimentally the results were post-processed to obtain the vorticity field and to identify and characterise the vortices within the flow-field. This was achieved by a piece of software which was written by the author.

As discussed in Section 2.2.2, vorticity is defined as the curl of the velocity vector. As such, in a three dimensional velocity field, there are three components of vorticity. The component which can be obtained from the PIV data is the streamwise

component and is defined below in Equation 3.4.

$$\omega_y = \frac{\partial w}{\partial x} - \frac{\partial u}{\partial z} \quad (3.4)$$

To find a value for this differential quantity four different algorithms were evaluated. The details of three of which can be seen in Table 3.3.

Algorithm	Implementation	Accuracy	Uncertainty
Center Difference Scheme	$\left(\frac{df}{dx}\right)_i \approx \frac{f_{i+1}-f_{i-1}}{2\Delta X}$	$O(\Delta X^2)$	$\approx 0.7 \frac{\epsilon_u}{\Delta X}$
Least Squares Approach	$\left(\frac{df}{dx}\right)_i \approx \frac{2f_{i+2}+f_{i+1}-f_{i-1}-2f_{i-2}}{10\Delta X}$	$O(\Delta X^2)$	$\approx 1.0 \frac{\epsilon_u}{\Delta X}$
Richardson Extrapolation	$\left(\frac{df}{dx}\right)_i \approx \frac{f_{i-2}-8f_{i-1}+8f_{i+1}-f_{i+2}}{12\Delta X}$	$O(\Delta X^3)$	$\approx 0.95 \frac{\epsilon_u}{\Delta X}$

Table 3.3: Table showing the algorithms used for three of the four vorticity estimation schemes (Raffel, Willert, & Kompenhans 1998)

This table shows the algorithm for a single differential quantity as implemented by each of the three schemes, together with the accuracy due to the truncation error. The table also contains an estimate of the error in the differential estimate due to an uncertainty in the velocity estimate (ϵ_u), which will be very important for calculations resulting from experimental PIV.

The Richardson extrapolation is a scheme that was formulated to minimise the truncation error and the least squares algorithm was constructed to reduce the effect of the random errors (Raffel, Willert, & Kompenhans 1998). Therefore it would seem reasonable to utilise the least squares approach for PIV data. However this scheme tends to smooth out the vorticity due to the weighting of terms further away from the data point.

In their book on the utilisation of PIV as an experimental tool, Raffel *et al.* (1998) discuss these differing schemes for the estimation of the vorticity field and state that the use of one-dimensional schemes for the calculation of a two-dimensional field is inadequate. Hence the circulation scheme is suggested as a more appropriate approach. This scheme is shown below in Equation 3.5.

$$(\omega_y)_{i,j} = \frac{\Gamma_{i,j}}{4\Delta X\Delta Z} \quad (3.5)$$

where

$$\begin{aligned}
 \Gamma_{i,j} = & \frac{1}{2}\Delta X(U_{i-1,j-1} + 2U_{i,j-1} + U_{i+1,j-1}) \\
 & + \frac{1}{2}\Delta Z(W_{i+1,j-1} + 2W_{i+1,j} + W_{i+1,j+1}) \\
 & - \frac{1}{2}\Delta X(U_{i+1,j+1} + 2U_{i,j+1} + U_{i-1,j+1}) \\
 & - \frac{1}{2}\Delta Z(W_{i-1,j+1} + 2W_{i-1,j} + W_{i-1,j-1})
 \end{aligned}$$

Raffel *et al.* (1998) explain that this scheme performs better than the three previous schemes primarily due to the larger amount of velocity data which is incorporated into the calculation.

The estimation of the streamwise vorticity by each of these four different algorithms on an experimental vortex whose velocity was obtained from PIV is shown in Figure 3.18. The characteristics of the different algorithms can be seen from this figure, with the least squares approach smoothing out the data, and the Richardson extrapolation estimated a lower peak vorticity than the others. For all of the velocity fields discussed in the remainder of this thesis, the circulation scheme will be used to estimate the streamwise vorticity.

Once the vorticity has been calculated the post-processing software attempts to find the centre of any vortices within the field of view. Discussed in Section 2.2.1 were three different definitions for locating a vortex; that associated with a patch of vorticity, the definition of closed or spiralling streamlines and a mathematical condition which reduces to an eigenvalue problem. Each of these three definitions can be implemented into methods for finding the centre of a vortex. The definition which states that a vortex is a concentrated patch of vorticity can be used to find the centre of a vortex by locating the centroid of that patch of vorticity. The closed or spiralling streamlines definition implementation is slightly more complicated. This definition has been implemented by selecting a point and calculating the tangential velocity distribution about that point. The center of the vortex is determined as the point which has the greatest tangential velocity acting about it, i.e. the centre of rotation. This is implemented by estimating a vortex center and calculating the tangential velocity distribution acting about it. Then the tangential velocity is also

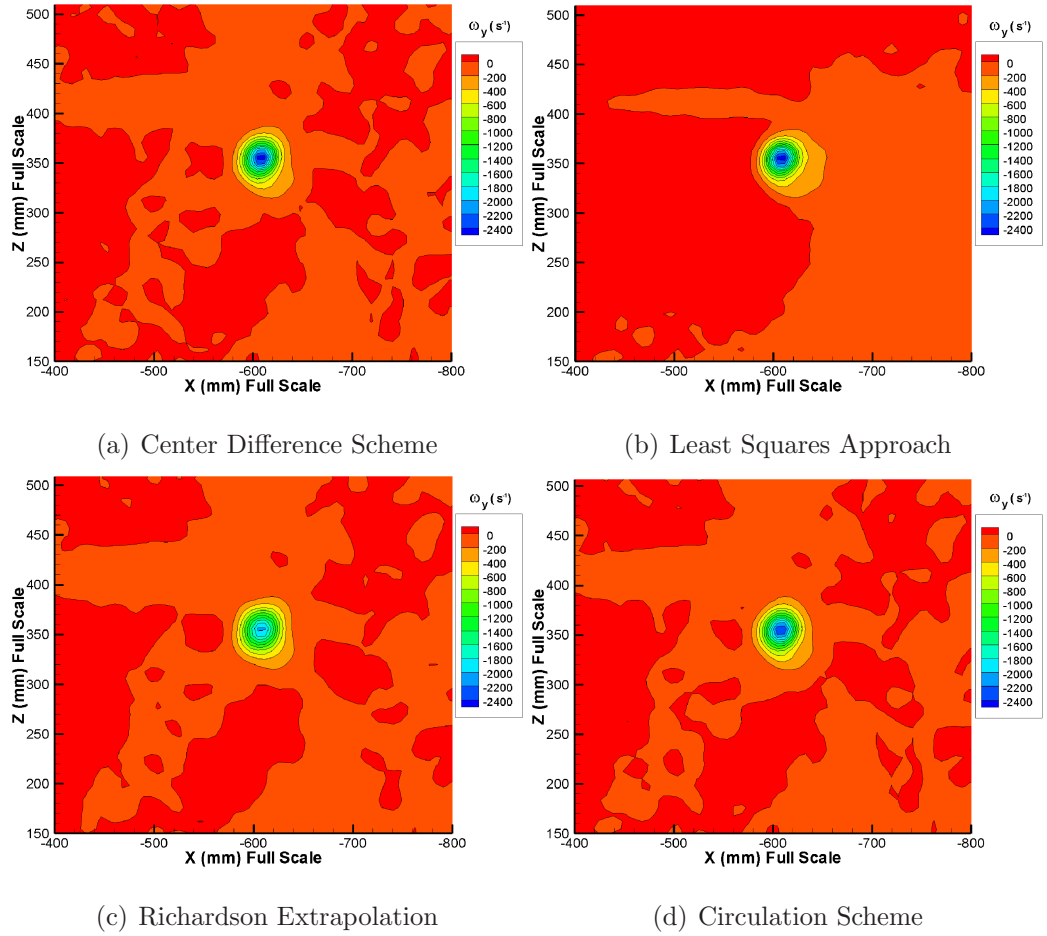


Figure 3.18: Comparison of the different algorithms used for estimating the streamwise vorticity from the velocity field of an isolated vortex obtained experimentally by PIV

estimated at points near to this estimated center. If any of these has a greater peak tangential velocity than the estimated center, the routine is repeated with the point with the highest peak tangential velocity as the new estimated center. The vortex center is found when the estimated center has the greatest tangential velocity (Lear 2003). The mathematical condition has also been implemented. This was achieved by finding the symmetric and asymmetric components of the gradient of the velocity, squaring these values and then adding them together and finding the eigenvalues of this new matrix. The vortex core is then defined as the region where the second smallest eigenvalue λ_2 is negative. The centroid of this region is calculated and the centre of the vortex found.

These methods have been utilised to find the centre of a theoretical Lamb-Oseen vortex and the experimental vortex shown in Figure 3.18. The results of the three methods are shown below in Table 3.4.

Analysis Method	Lamb-Oseen Vortex		Experimental Vortex	
	$X(mmFS)$	$Z(mmFS)$	$X(mmFS)$	$Z(mmFS)$
Theoretical Centre	-610	-110	Unknown	Unknown
Vorticity Centroid	-603	-103	-610	356
Max U_θ	-610	-110	-608	354
λ_2 Centroid	-610	-110	-609	354

Table 3.4: Table showing the results from the three different methods for locating the centre of the vortex for both a theoretical and experimental vortex

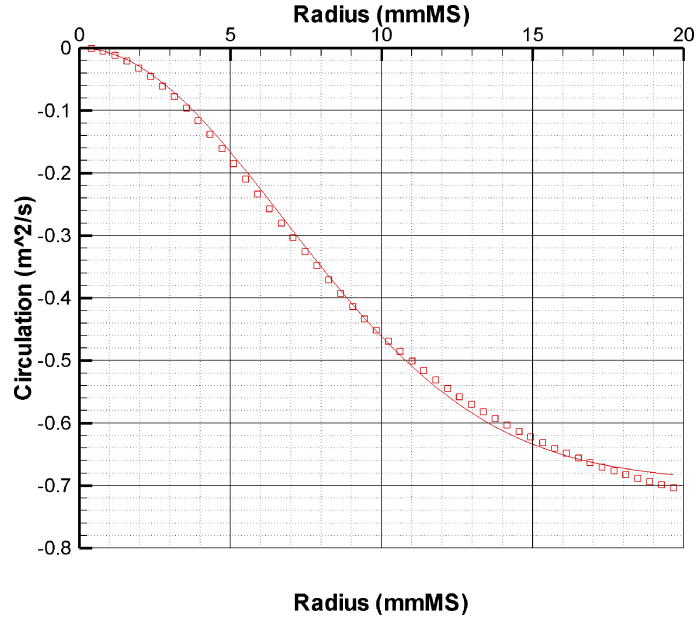
As can be seen from the results contained in this table, the Lamb-Oseen vortex was located at a nominal position of $X = -610mmFS$ and $Z = -100mmFS$. Both the maximum tangential velocity and the λ_2 method located this point accurately. However, the vorticity centroid method was not as successful. This is a consequence of the sensitivity of this method to the resolution of the mesh of data points. For the experimental vortex, the actual centre is unknown. The Z location of the vortex centre predicted by the vorticity threshold method is different from the other two methods. With the experimental vortex the velocity vectors may be noisy due to experimental errors and hence this differential method will be prone to noise as well as the resolution of the velocity vectors. Therefore it appeared appropriate to select the method for locating the centre of a vortex from either of the other two methods. As discussed in Section 2.2.1 the main benefit of the λ_2 method is that it is more successful at finding vortices whilst other methods may erroneously predict vortical structures where they are known not to exist. This additional benefit of the λ_2 method is not required when examining the wake shed from the front wing, as the vortices in the analysis field are strong and well-defined. Therefore this would suggest that either of the maximum tangential velocity method or the λ_2

method would be appropriate. Lear (2003) utilised the maximum tangential velocity approach and hence this was selected at the beginning of this research project and was used throughout.

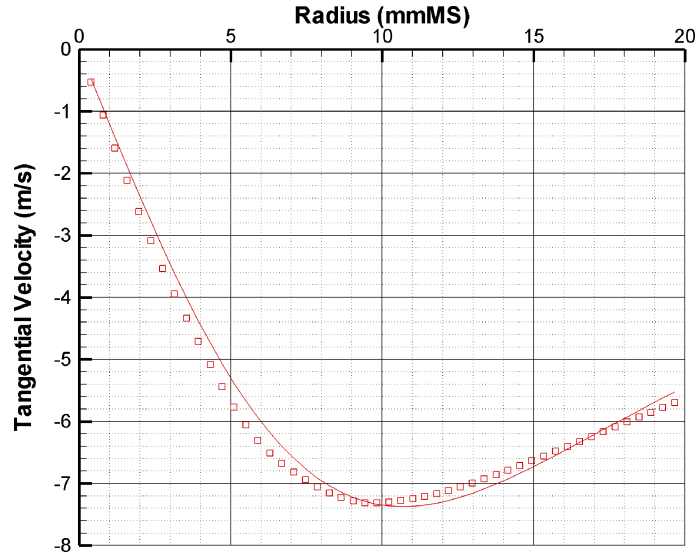
Once the centre had been estimated it was possible to determine the characteristics of the vortex. This was achieved by performing a theoretical fit of the Lamb-Oseen vortex model to the data. To undertake this the circulation about the vortex centre is estimated by calculating the line integral of the velocity about ever increasing circular paths. Then a non-linear fit of the Lamb-Oseen model is performed on the experimentally deduced circulation and the parameters total circulation (Γ_0) and core radius ($r_c = \sqrt{4\nu t}$) are obtained. To validate this method the velocity field of a Lamb-Oseen vortex has been parameterised and the errors in the returned values of Γ_0 and r_c were found to be 0.03% and 5% respectively. It is thought that these errors were a result of combination of the discretization of the velocity onto the mesh, the curve-fitting algorithm and computational error. An example of this fit on an experimental vortex (the same one as discussed above), can be seen in Figure 3.19. From the fit approximate values for the strength of the vortex (Γ_0) and the core radius (r_c) were given as $\Gamma_0 = -0.7m^2/s$ and $r_c = 10.7mmMS$.

It is noted that the accuracy of these results is based on both the quality of the Lamb-Oseen fit to the data and the estimation of the centre of the vortex. The theoretical fit of the Lamb-Oseen model can only be undertaken on an isolated, axis-symmetric vortex. Hence when two or more vortices are close to merging this method cannot be utilised. Therefore this method was only used when the vortices were considered to be isolated. The resulting R^2 errors (where $R^2 = \sum[y_i - f(x_i, a_1, a_2, \dots, a_n)]^2$) which gives a indication on the quality of the curve fitting with this method, were found to be $R^2 > 0.99$. This value is very high and shows a good fit to the data. However, it must be noted that the curve fitting algorithm is based on a minimalisation of this error.

Another error which may be present in the parameterisation of these vortices is associated with the PIV set-up used to obtain the velocity vectors. The PIV system used in these experiments is a two-dimensional system and hence can only be used to obtain two velocity components. For the majority of the experiments performed



(a) Circulation distribution



(b) Tangential velocity distribution

Figure 3.19: The results from the fitting of the Lamb-Oseen vortex model to the experimental results

and presented in this thesis, the PIV is used to obtain details on the velocity in the X-Z plane (U and W vectors i.e. crossflow). However, the flow downstream of the wing and about the wheel is three-dimensional. Therefore if any of the vortices pass through the laser sheet at any angle which is not perpendicular to the laser sheet, then an otherwise axisymmetric vortex may appear to be skewed. This would

result in the vorticity being shared between the three components of vorticity and would lead to a reduction in the calculated streamwise vorticity (ω_y). The estimated circulation of the vortex will also be reduced. For example if the axis of a vortex were to be at an angle of 45° to the laser sheet then the vortex would appear to have $1/\sqrt{2}$ times its real circulation. To minimise the effect of this error the parameterisation of the vortices has only been implemented in regions where the axis of the vortices is believed to be passing through the sheet at an angle close to 90° (i.e. in the near-field).

It has been stated that for all of the laser-smoke flow visualisation results which are presented in this thesis, the freestream velocity of the tunnel was set to 12.5m/s ($Re_{cmp} = 2.0 \times 10^5$), whereas all of the other experimental results were obtained when the tunnel was operating at 25m/s ($Re_{cmp} = 2.0 \times 10^5$). Also the results from these experiments will be compared with the computational results provided by McLaren which were undertaken at a Reynolds number of $Re_{cmp} = 5.7 \times 10^5$. To compensate for these differences in Reynolds number, transition strips were attached to the models to enforce transition to a turbulent boundary layer and hence the assumption could be made that the flow predicted from these different freestream velocities would be the same.

The validity of this assumption can be examined by making use of the post-processing program discussed above. PIV results were taken on the McLaren geometry in identical configurations with the freestream velocity at both 12.5m/s and 25m/s . The resulting velocity vectors of a single vortex behind the McLaren model is shown below at these two air speeds in Figures 3.20(a) and 3.20(a). Using the post-processing code the vorticity was calculated and non-dimensionalised by the freestream velocity and the diameter of the wheel. This resulted in the two vorticity fields shown in Figures 3.20(c) and 3.20(d). Note the full velocity field from which these figures are taken is shown in Figure 4.8.

As can be seen from these figures, in spite of the fact that the velocity vectors at the lower freestream velocity are approximately half that of the 25m/s case, the size and shape of the vortex is extremely similar. The resemblance between the two vorticity fields is very high with the absolute values of the non-dimensional vorticity

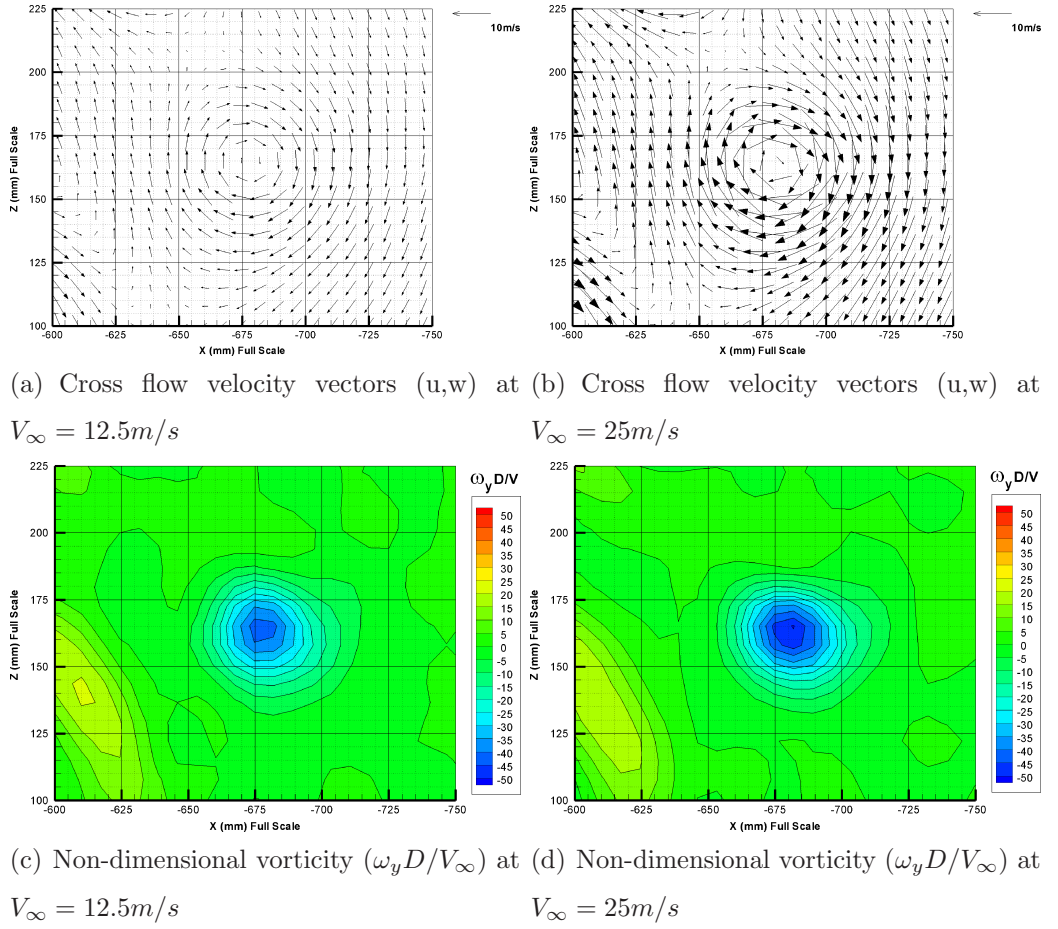


Figure 3.20: Comparison of the vortex generated by the canard on the McLaren model at two different freestream velocities

being almost identical. This is also the case with the results from the Lamb-Oseen vortex fit to this velocity data. Again the non-dimensionality of the circulation is achieved through the freestream velocity value and the diameter of the wheel. The resulting values for the circulation of the vortex at the freestream velocity speed of 12.5 m/s was $\Gamma / (DV_\infty) = -0.125$ and at the higher speed of 25 m/s this value was $\Gamma / (DV_\infty) = -0.127$.

Therefore it can be assumed that the results from both the laser-smoke flow visualisations performed at the lower velocity can be compared with the results from the other methods to examine the flow downstream of the models.

Chapter 4

Flow Structure Downstream of McLaren Geometry Without Wheel

This chapter discusses the results associated with research conducted on the McLaren geometry without the inclusion of the wheel. One limitation of the McLaren model is that it is very difficult to obtain information on the initial configuration of the vortex system directly downstream of the wing due to the presence of the wheel. Therefore without the practical limitations of the wheel, the results obtained during this set of experiments allows the velocity field directly downstream of the wing to be analysed and discussions on the topology and characteristics of the front wing vortex system can be made. Also of interest is the behaviour of the vortex system as it travels downstream unimpeded by the wheel and how the ride height and the ground plane affect the flow structure.

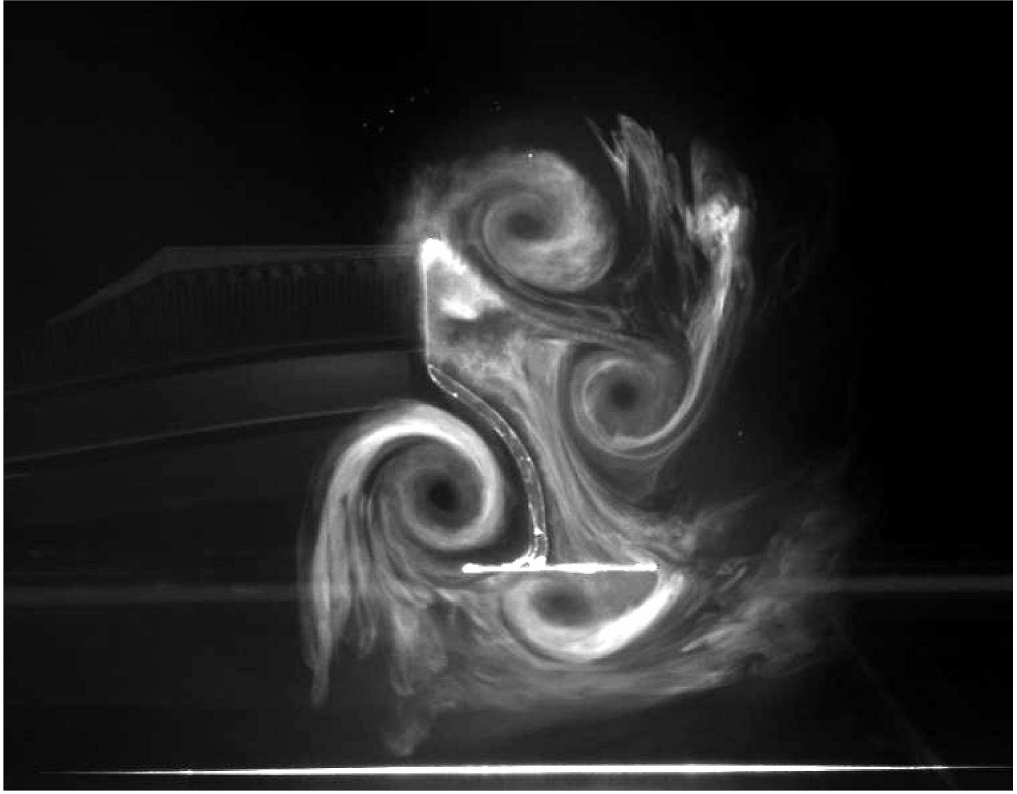


Figure 4.1: Laser-smoke visualisation (looking upstream) of the flow in a plane directly downstream of McLaren model ($Y = -300mmFS$), without wheel at a ride height of $h/c_{mp} = 0.48$ and with a moving ground plane ($V_{\infty} = 12.5ms^{-1}$)

4.1 Near-Field: Initial Topology of Vortex System

4.1.1 Front Wing Wake Topology

The vortex system in the near-field of the wing set at a moderate ride height ($h/c_{mp} = 0.48$), as visualised by the laser and smoke technique can be seen in Figure 4.1. This technique can be used to identify the behaviour of a vortex system as vortex cores can be identified by regions in which smoke particles have been centrifuged out.

From this image it can be seen that there are four vortical structures contained within the wake. Perhaps the most distinct vortex is that located inboard of the

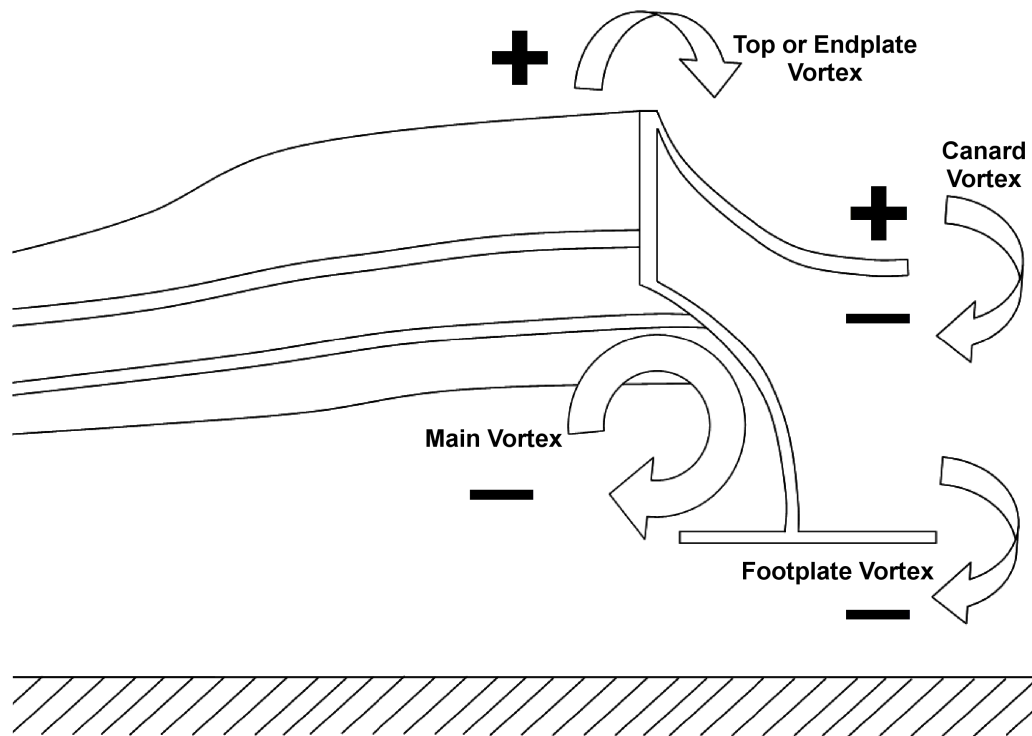


Figure 4.2: A schematic of the topology of the vortex system downstream of the McLaren front wing and endplate

endplate, on the lower left of this figure. This vortex is termed the *main trailing vortex* and is the wing-tip vortex which would be located at the tip of the wing if the endplate were not present. It is formed from the circulation generated over the front wing and rolls up along the lower edge of the endplate where the pressure difference formed by the large negative pressures beneath the wing acts. The sense of rotation of the flow about this structure is consistent with that of a tip vortex generated by an inverted wing and is clockwise when viewed looking upstream, as can be seen from the schematic of the vortex system shown in Figure 4.2. Hence the main vortex produces an upwash in the wake of the wing.

At the top of the endplate another vortex can be visualised. Termed the *top or endplate vortex*, this structure is generated by the pressure difference which is present across the endplate in this location due to the high pressure which acts over the upper surfaces of the wing elements. Shown schematically in Figure 4.2, this vortex's strength is also probably enhanced as a consequence of the the aerofoil shaped endplate (aerofoil cross-section in the horizontal plane, refer to Figure 3.5(a)). The

endplate is yawed to the flow and hence its curvature would generate a pressure difference across it which would enhance that felt near the top thereby increasing the circulation of the vortex shed from the upper tip of the endplate.

The third vortex visible in Figure 4.1 is generated by the presence of the canard attached to the outboard side of the endplate. Located slightly beneath the trailing edge of this delta wing, the *canard vortex* is formed by the shear layer which is generated along the leading edge of the canard (discussed in Section 2.2.2). Due to the orientation of the canard, this lifting surface produces downforce and consequently the pressure difference which acts across this delta wing is as shown schematically in Figure 4.2, generating a vortex with a clockwise sense of rotation.

The fourth and final vortex which makes up the trailing vortex system behind the McLaren front wing can be seen in Figure 4.1 located directly underneath the footplate. This vortex is termed the *footplate vortex* and is formed as a consequence of the pressure difference across the footplate. The presence of the footplate enhances the efficiency of the front wing and endplate by reducing the leakage of the low pressure flow underneath the wing. It also creates a negative pressure on its underside as a consequence of the small ground clearance which causes air to be accelerated beneath it. The pressure difference acting across the footplate causes a shear layer to be shed which rolls-up to form a vortex with a clockwise sense of rotation as shown schematically in Figure 4.2.

Further analysis of this system of four co-rotating vortices which is shed from the McLaren front wing and endplate can be made from examining the results of the hot-film anemometry survey which is shown in Figure 4.3. Presented in this figure are all three components of velocity with the cross-flow being represented by the vectors and the streamwise velocity by the coloured contours. One problem associated with this time-averaged, intrusive method is that only velocity within a 70° acceptance cone to the probe axis can be resolved. Hence information about the velocity field where there are regions of large cross-flows such as near the main or top vortex (see Figure 4.3), cannot be obtained.

Clearly distinguishable from the results contained in this figure is the slow moving wake which is formed downstream of the wing elements and the endplate. These

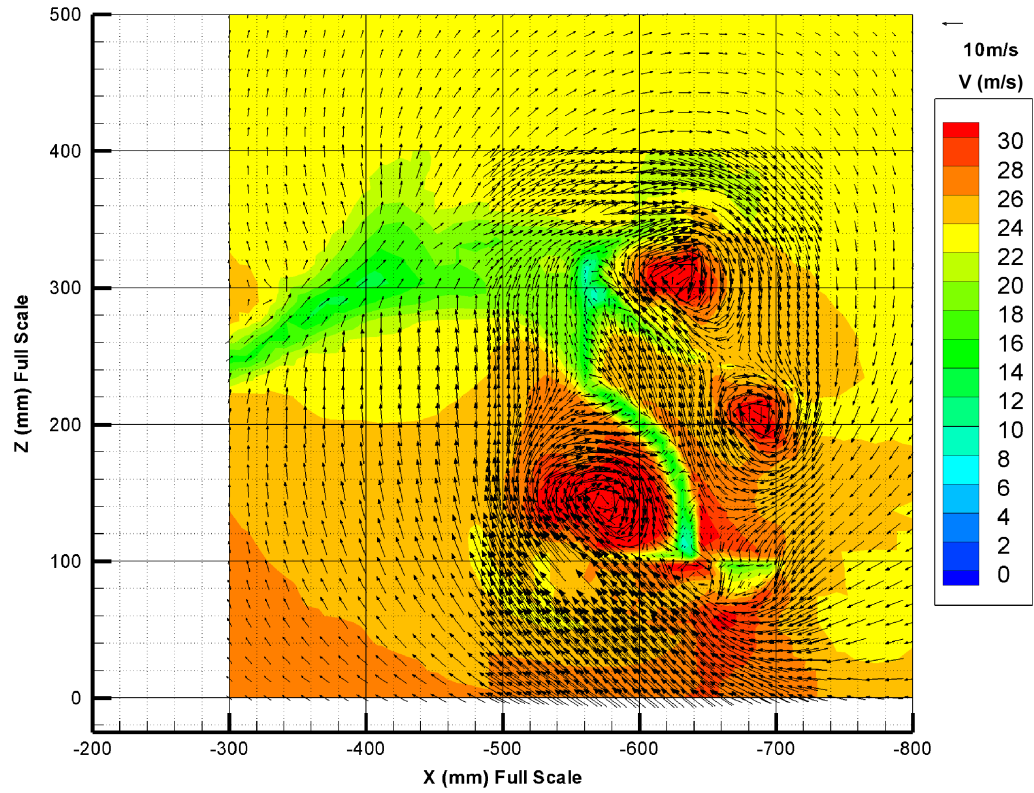


Figure 4.3: Time-averaged velocity field as obtained by hot-film anemometry directly downstream of McLaren model ($Y = -300mmFS$) at a ride height of $h/c_{mp} = 0.48$ and with a moving ground plane ($V_{\infty} = 25ms^{-1}$)

regions can be used to identify the approximate position of the endplate and wing geometry. Also visible is the faster streamwise velocities beneath the wing and footplate which are a consequence of the negative pressures which were discussed above. The vortex system is also identifiable from this figure with the three rotational structures attributed to the main, top (or endplate) and canard vortices. The footplate vortex is also visible. However these results highlight a more complex flow than can be concluded from the qualitative observations made from the flow visualisation. On close inspection, Figure 4.3 shows that the flow in the vicinity of the footplate consists of a small rotational structure located near to a region of reduced streamwise velocity. By examining the surrounding vectors and those within this area of reduced velocity, it can be seen that this slow moving region appears to be a consequence of the large cross-flow which is present beneath the endplate. This flow encounters the upper surface of the footplate at an oblique angle and appears

to separate off its most outboard edge, resulting in a slower velocity.

From this time-averaged velocity field the axial velocities inside the vortices can also be determined. It can be seen from this data that each of the vortices contains a region of streamwise velocity which is faster than that of the freestream (denoted by the red contours). Values as high as 30m/s have been obtained when the freestream velocity was 25m/s . Therefore the vortices in the front wing wake can be defined as jet-like vortices.

In the introduction to this thesis, the trend of loading up the outboard parts of a Formula 1 front wing and endplate in order to minimise the flow losses over the centre of the wing were discussed. A measure of the energy losses in the flow can be obtained by examining the total pressure distribution. Therefore a total pressure wake survey has been performed behind the McLaren wing at the position and same ride height as the laser-smoke and hot-film anemometry results presented above so that the losses associated with the front wing wake can be discussed. This is shown in Figure 4.4.

From this figure it can be seen that the largest energy losses originate from the slow-moving wake and the centres of the vortices. Three of the four vortices in the trailing vortex system can be easily identified with the separated region near the footplate vortex also exhibiting a region of total pressure loss. The top or endplate vortex is not so easily distinguishable. There is a region of total pressure loss near its location. However the total pressure distribution in this area does not show the near axis-symmetric properties of the other vortices. The values presented in this plot are the mean total pressure coefficients sampled over the duration of 2 seconds and so it maybe that this feature is not as steady as the other vortices and hence the region of energy loss is smeared. It may also be that the top vortex has not fully rolled up at this point in the flow.

Whilst performing this wake survey, mean values of the coefficient of total pressure as high as $C_p = 6.0$ were obtained with corresponding high values for the standard deviation. These values were measured close to the back of the scallop on the trailing edge of the endplate which has small Gurney flap attached to it. These results are not physical and are thought to be a consequence of the flow exceeding

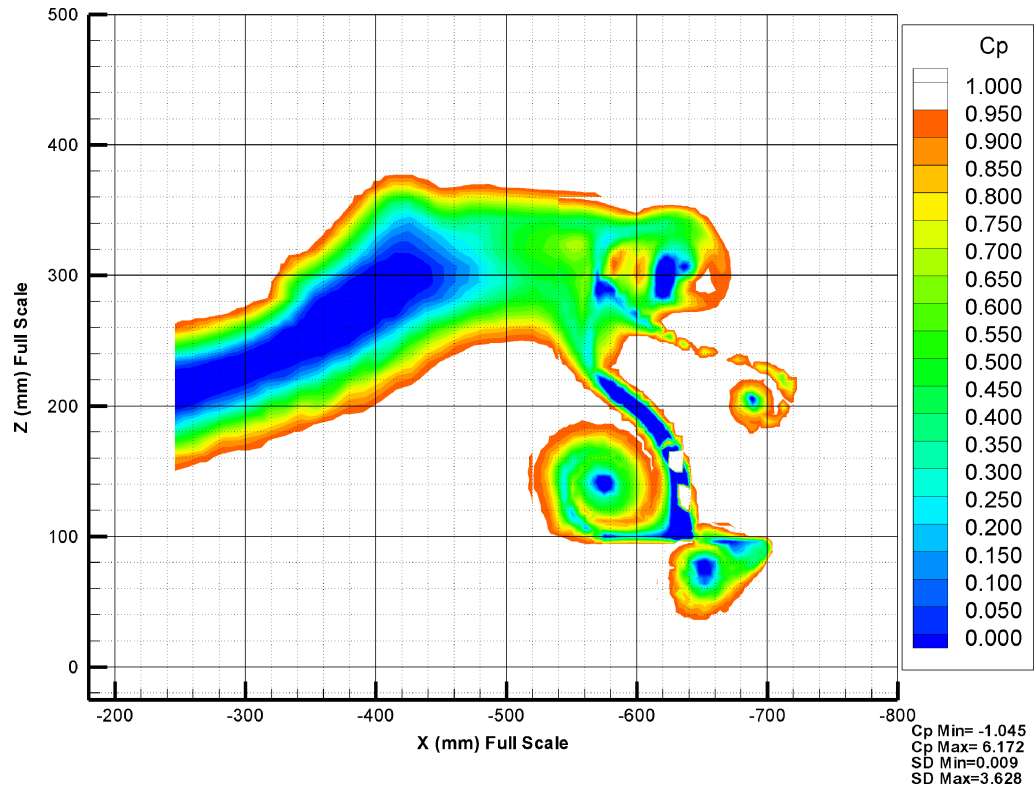


Figure 4.4: Total pressure distribution directly downstream of the front wing of the McLaren model ($Y = -300mmFS$) without the wheel, at a ride height of $h/c_{mp} = 0.48$ and with a moving ground plane ($V_\infty = 25ms^{-1}$)

the yaw insensitivity of the probe and hence have been removed from the figure.

Each of the experimental techniques used to examine the flow in the near-field of the McLaren model without the wheel, has shown that the wake consists of a vortex system containing four co-rotating vortices. These vortices are formed due to the pressure differences which act across various parts of the complex geometry of the endplate. In general the techniques are in good agreement with one another. This is in spite of the fact that the laser-smoke visualisation has been undertaken at a lower freestream velocity than the other two methods. By performing experiments of the flow structure at different ride heights these experimental methods can also be compared to the numerical analysis performed by McLaren. This will be undertaken in the next section.

4.1.2 Effect of Ride Height

All of the discussion in the previous section was made on the results from the vortex system generated by the McLaren front wing at a moderate ride height of $h/c_{mp} = 0.48$. In this section the flow structure of the wake shed from the wing when operated at ride heights both lower and higher than this value will be analysed.

Figure 4.5 shows the time-averaged results from the PIV experiments performed on the McLaren model at all four ride heights. This data is obtained from averaging the instantaneous velocity fields sampled over a period of five seconds at a sample rate of 15Hz (75 images). Plotted in this figure are contours of the non-dimensional streamwise vorticity field (normalised by the freestream velocity and the wheel diameter), and the cross-flow velocity vectors. Note that for clarity, in this figure only half of the vectors are plotted with a vector begin skipped between each one that is presented.

Figure 4.5(b) shows the time-averaged flow structure as determined by PIV downstream of the McLaren model at the same ride height as was discussed at length in the previous section ($h/c_{mp} = 0.48$). From this figure the vorticity generated by the four vortices contained within the trailing vortex system can be seen. The patch of vorticity which is located close to where the footplate vortex is positioned can be seen to be less axis-symmetric than the other three vortices. It is thought that this asymmetry is generated by the separation off the outboard edge of the footplate. This separation helps to generate a large region of negative vorticity as the slow moving flow in this area is very close to the large cross-flows which exist beneath the endplate. Hence there is a large velocity gradient which produces a region of negative streamwise vorticity.

Also visible in this figure is a region of weak positive vorticity located in between the canard and main trailing vortex. This can be partly attributed to the Gurney flap on the arc of the endplate scallop, where the slow moving wake downstream of this geometry is located close to the rotational structures of the main and canard vortex. However this region of positive vorticity may also be a consequence of experimental inaccuracy. One problem associated with the PIV method when

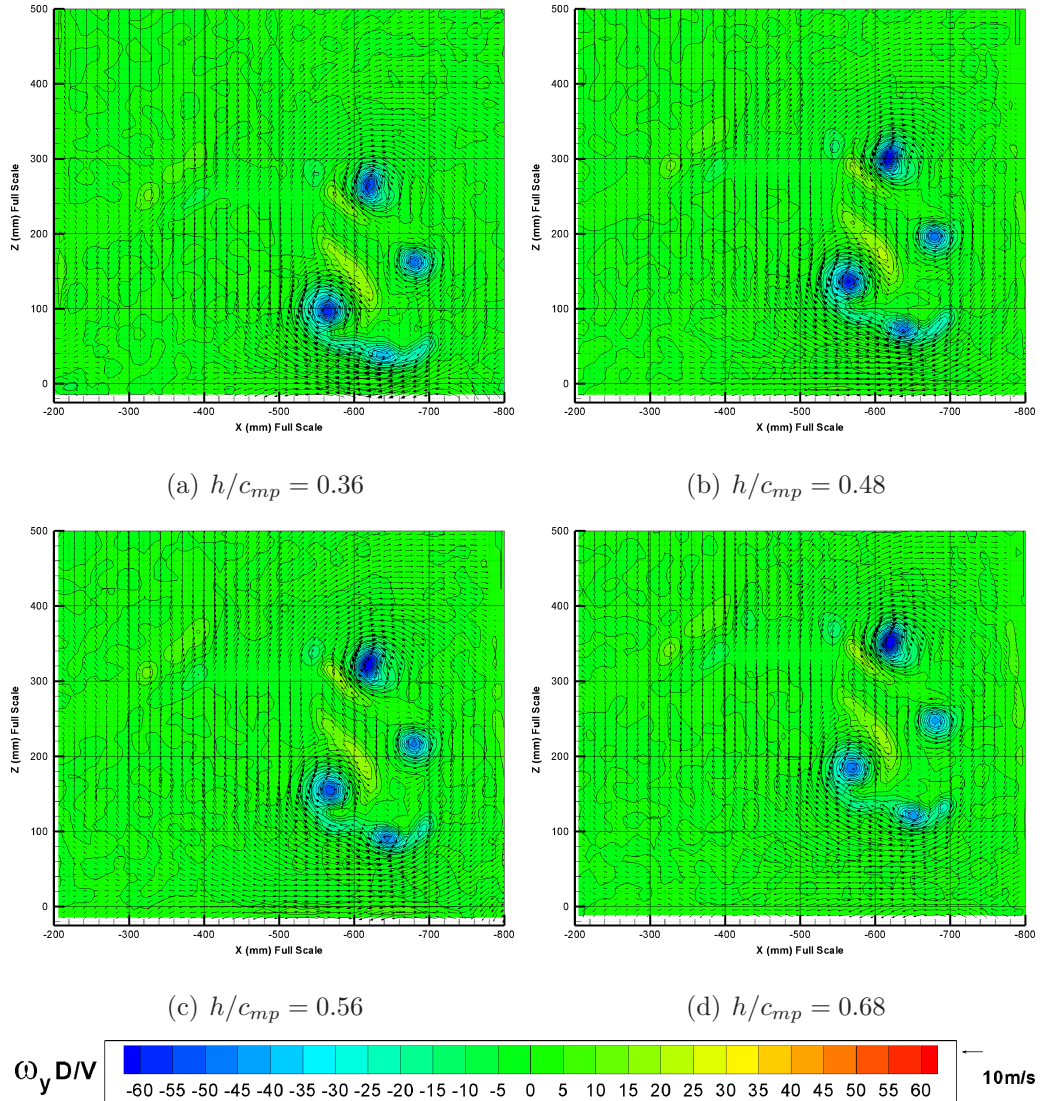


Figure 4.5: Velocity and non-dimensional vorticity field directly downstream of McLaren model ($Y = -300mmFS$) as determined by PIV without wheel at varying ride heights with a moving ground plane ($V_\infty = 25ms^{-1}$)

examining the flow close to the model is that of reflections. Although the model has been painted to minimise reflections from the laser sheet, the outline of the endplate and wing elements are still clearly visible in the PIV images. During the post-processing of the particle images in FlowManager (to produce velocity vectors) a method was devised to reduce this adverse effect. This method involved taking the average of all 75 particle images (so that no individual particles could be identified,

only the objects which were common to all of the images, i.e. the model geometry), and then subtracting this average away from each of the 75 particle images. This prevented the geometry from being visible in the processed images (only the seeding particles were visible) and hence minimised the possibility of the geometry correlating and producing erroneous vectors. Unfortunately this method did not completely eradicate the problem as the reflections from the geometry effectively swamped the region with light and any particles which were close to this reflection were lost. Hence after post-processing the images often did not contain sufficient particles close to the geometry. Therefore as can be seen from the plots in Figure 4.5(b), the outline of the flap and endplate can be seen as the locations where the magnitude of the cross-flow velocity vectors are close to zero which is not entirely physical.

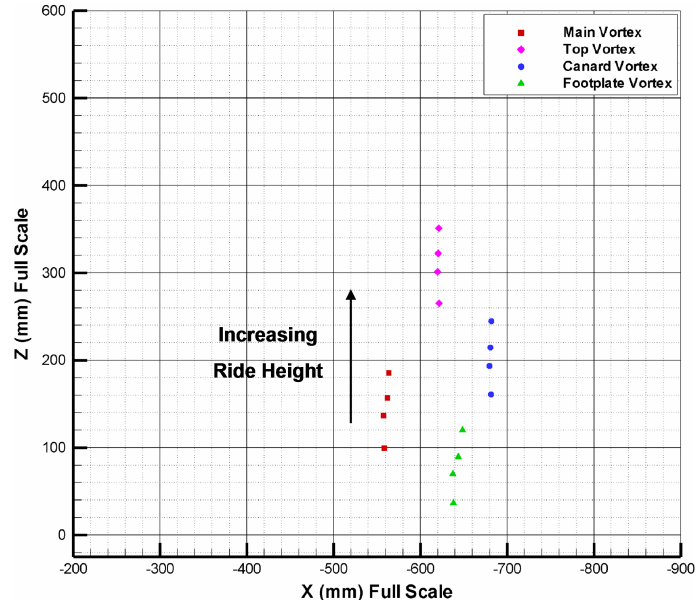
From comparisons between the experimentally determined flow structures in the near-field of the McLaren model at the differing ride heights contained within Figure 4.5, it can be seen that as the ride height is increased the vortices within the front wing wake are displaced vertically. This change in the vertical location of the vortex centres is a direct consequence of the geometry from which the vortices are formed being raised. Another difference between the vortex system at different ride heights is the relative magnitude of the streamwise vorticity which is associated with the presence of each of the four vortices.

At the lowest ride height (Figure 4.5(a)), it can be seen that the main trailing vortex appears to be the strongest vortical structure, with its streamwise vorticity close to its centre greater in magnitude than any of the other three vortices. As the ride height of the wing is increased (Figures 4.5(b), 4.5(c) and 4.5(d)) it can be seen that the peak vorticities within the cores of the main trailing and canard vortices decrease whilst that of the footplate vortex remains approximately constant. Conversely the endplate vortex's strength increases (shown by the darker blue near the centre of the vortex as the ride height is increased). It is thought that these changes can be attributed to the ground effect (refer to Section 2.3.4), with the main trailing vortex diminishing in strength as the lift augmentation associated with small ride heights is reduced with distance away from the ground plane.

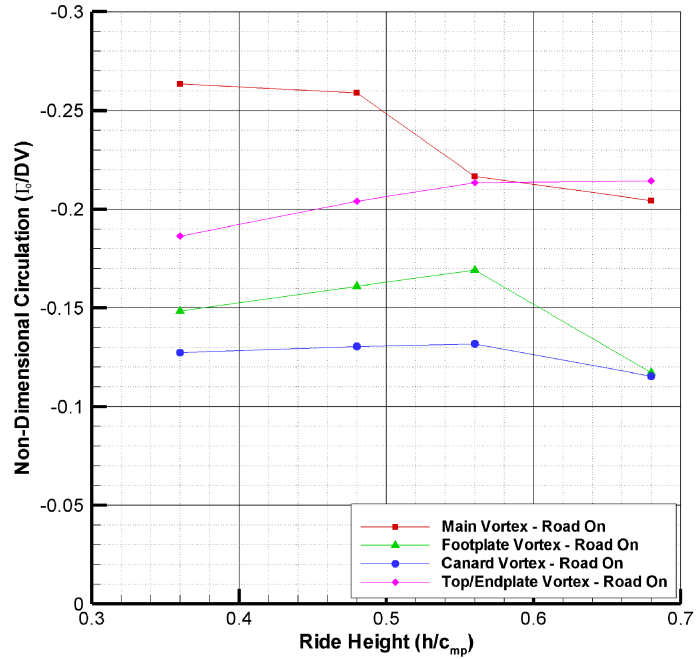
These observations are strengthened by examining the results of the vortex parameterisation performed by the post-processing code discussed in Section 3.5. During this process the cross-flow velocity vectors obtained from the PIV experiments were examined to find the centres of the four vortices and then a fit of the Lamb-Oseen vortex model applied. This was undertaken for all of the 75 instantaneous images and the mean positions of the centres and circulation were obtained together with their standard deviations. The results of this parameterisation can be seen in Figures 4.6(a) and 4.6(b), which show the mean position of each of the vortices at the four different ride heights and the strength of the vortices with changing ride height. Please note that the lines between the data points in Figure 4.6(b) are for visual aid only and do not necessarily represent a fit of the data

The results from these two figures show that as the ride height is increased that the vertical position of the vortices increases correspondingly. All of the vortices maintain a reasonably constant lateral position with only the footplate vortex moving slightly outboard with increased ride height. This change may be a consequence of the fact that as the vortex is moved away from the ground the velocity induced between it and its image will be reduced. It has also been already stated that the footplate vortex is not entirely axisymmetric and since the post-processing routines are based on this assumption the centre of the footplate vortex may also be less accurately determined than the other vortices.

The slight asymmetry in the footplate vortex may also affect the result from the Lamb-Oseen vortex model fit and hence the estimated circulation of the vortex. The strengths of the vortices are plotted with ride height in Figure 4.6(b). As can be seen from this figure, the discussion that was made with regard to the peak vorticity within the individual vortices is reinforced by these results. At the lowest ride height the strongest vortex in the system is the main vortex. As ride height is increased this feature weakens and the endplate vortex strengthens. The circulation about the canard vortex appears unaffected by the change in height away from the ground plane, inferring that the canard is unaffected by the ground effect. The reasons behind the trend of the circulation of the footplate vortex to peak at a moderate ride height is less clear. This could be due to the inaccuracy in the assumption of



(a) Position of the centres of the vortices at different ride heights



(b) Graph of the non-dimensional circulation of the vortices with varying ride height

Figure 4.6: The results of the vortex parameterisation of the four vortices at each of the ride heights, in the near-field of the McLaren model ($Y = -300mmFS$) without the wheel and with a moving ground plane

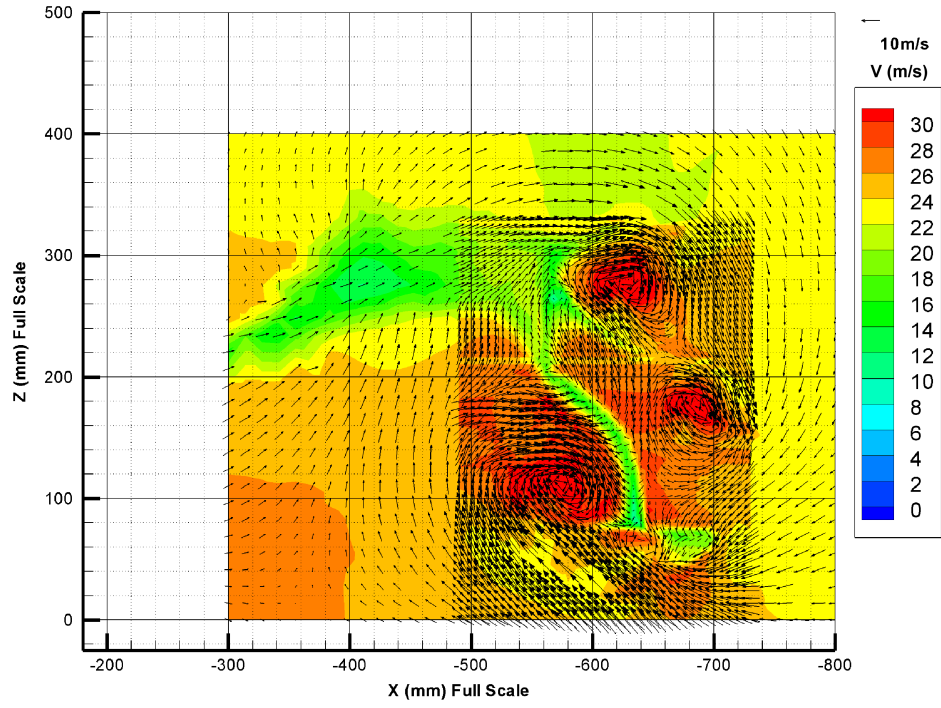
axisymmetry or it could be due to the complex aerodynamics associated with this feature. To help with the understanding of these aerodynamics the results from the wake survey with the hot-film probe at the minimum and maximum ground clearances are shown in Figures 4.7(a) and 4.7(b) respectively.

As at the moderate ride height of $h/c_{mp} = 0.48$ discussed in the previous section, the small rotational feature and the separation region associated with the footplate are clearly apparent in both of these results. At the lowest ride height of $h/c_{mp} = 0.36$ the cross-flow underneath the footplate is very strong due to the reduced clearance between this geometry and the ground plane. Consequently the footplate vortex appears to be smaller. As the clearance between the endplate and the ground is increased the cross-flow is of a lower intensity and the rotational structure of the footplate vortex is larger. However, at this larger ride height the pressure difference acting across the footplate will be reduced resulting in a weaker vortex. It may be that there is a peak in the strength of this vortex due to the play-off between the increased pressure difference and the size of the vortex.

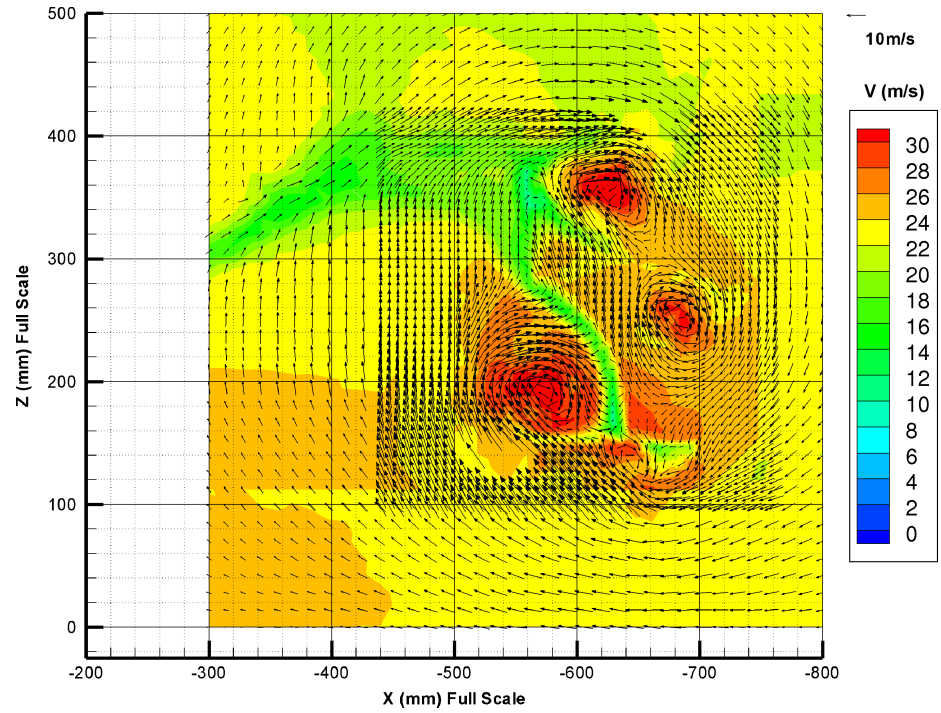
The motivation for this research partly originated from the results of CFD performed by McLaren (McLaren (2003b) and McLaren (2003a)). The configuration about which the McLaren CFD has been undertaken is a full-scale version of the wind tunnel model used in this research, with the wing set at a ride height of $h/c_{mp} = 0.36$ and with a freestream velocity of $V_\infty = 36m/s$. Numerical computations have been undertaken both with and without the wheel. Hence it is prudent to compare the results from these numerical investigations together with those from the experiments.

A total pressure plot taken from the McLaren CFD (McLaren 2003a) in the near-field ($Y = -300mmFS$) is presented in Figure 4.8(d) together with the experimental laser-smoke visualisation of the flow in the same configuration (Figure 4.8(a)). Also included in this Figure is the vorticity field evaluated from the PIV results at the reduced velocity ($V_\infty = 12.5m/s$) used for the flow visualisation and also the vorticity for the maximum experimental velocity of $V_\infty = 25m/s$ used for all of the other experimental techniques.

As can be seen from the results contained within this figure, all of the different



(a) $h/c_{mp} = 0.36$



(b) $h/c_{mp} = 0.68$

Figure 4.7: Velocity field as determined by hot-film anemometry directly downstream of McLaren model ($Y = -300mmFS$) at the lowest and highest ride height with a moving ground plane ($V_{\infty} = 25ms^{-1}$)

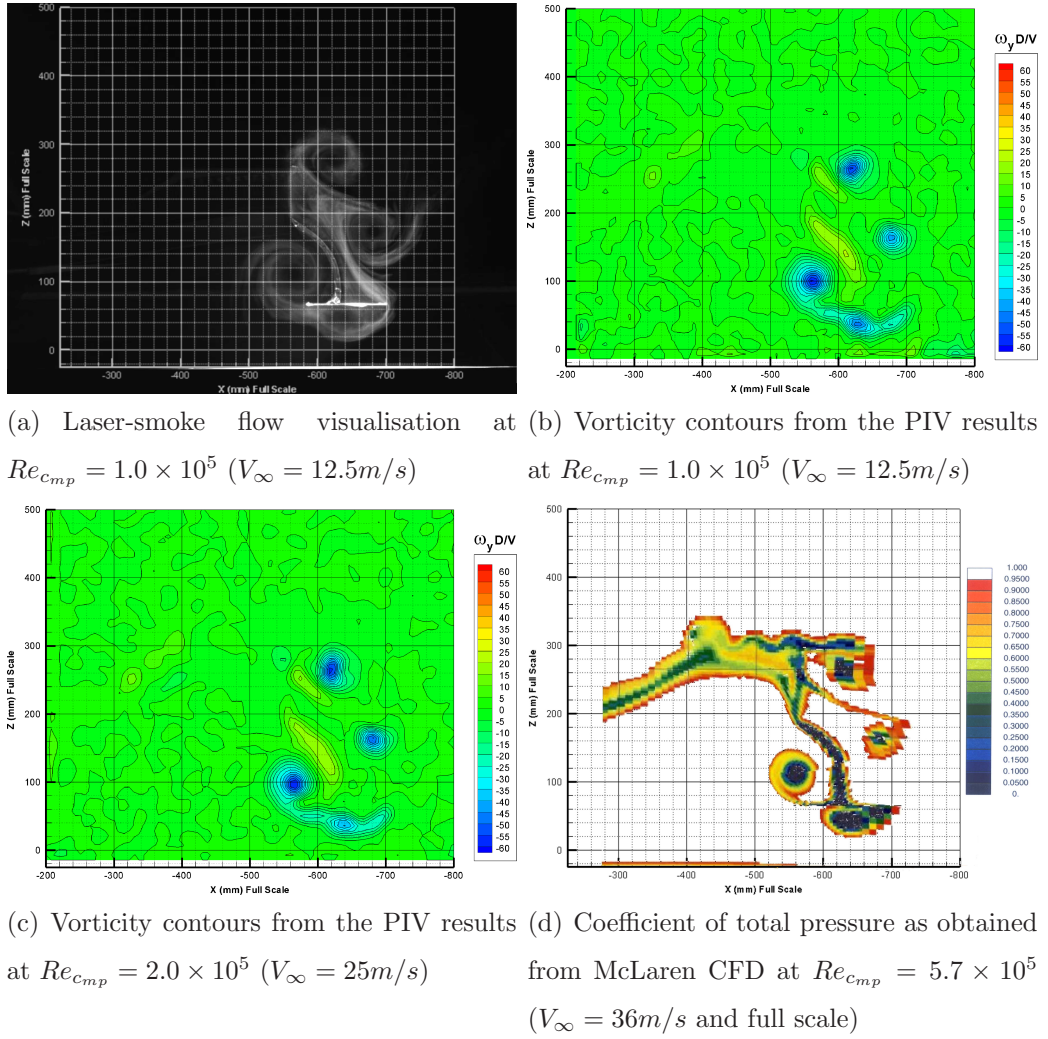


Figure 4.8: Flow in the near-field ($Y = -300mmFS$) of McLaren front wing at a ride height of $h/c_{mp} = 0.36$ with moving ground plane as predicted by various techniques at varying Reynolds number

techniques predict the same flow topology. Even with varying freestream velocities and varying scale (experimental model is 50% scale whereas CFD is based on full-scale model), all of the vortices are of a similar size and are located in a similar position.

It is noted, from the work reviewed in Section 2.3.4, that several researchers (Zhang & Zerihan, Moseley and Garrood) have found that trailing vortices from inverted wings close to a ground plane are prone to vortex breakdown. From results presented in this section, there is no evidence of this phenomenon occurring in

the near-field of the McLaren front wing. This is probably a consequence of the smallest ground clearance between the wing and the floor being $h/c_{mp} = 0.36$, whereas Zhang & Zerihan, found that breakdown occurred at ride heights smaller than approximately $h/c = 0.24$ (Figure 2.23), and Moseley found that breakdown occurred at $h/c_{mp} = 0.25$ and $h/c_{mp} = 0.20$. As discussed in section 2.3.3 Hall (1972) states that vortex breakdown is more likely to occur when the swirl angle ($\phi = \tan^{-1}(U_\theta/U_x)$), exceeds 40° . Hence this value can be used to provide an indicator as to the probability of vortex breakdown. By making an estimate of the axial velocity inside each vortex from the hot-film results the angle of swirl for each vortex at all the ride heights was found to be less than this value, with the greatest values occurring for the main vortex at the lowest ride height. These values are shown below in Table 4.1. Therefore it is unlikely that any of the the vortices in the McLaren will breakdown when the wing is at each of these different ride heights. This compares well with the other experimental results.

Vortex	$\phi(^{\circ})$ for different ride heights (h/c_{mp})			
	<i>0.36</i>	<i>0.48</i>	<i>0.56</i>	<i>0.68</i>
Main	30.1	29.9	29.3	25.5
Footplate	21.8	24.9	23.9	21.9
Canard	21.7	21.7	21.4	19.5
Top	25.9	28.4	27.3	29.6

Table 4.1: Table of the estimated swirl angle for all of the vortices at different ride heights

Garrood found that breakdown occurred at a ride height $h/c_{mp} = 0.29$ with a moving ground plane. However this phenomenon was not present when the ground plane was forced to be stationary. The effect of the state of the ground plane (moving or stationary), on the flow downstream of the McLaren geometry will be examined in the next section.

4.1.3 Effect of Rolling Road

In Section 2.3.4 the work of Garrood (2004) was discussed. He noticed that the behaviour of a trailing vortex operating in close proximity to the ground ($h/c_{mp} = 0.29$) was different when the ground plane was stationary to when it was moving (he noticed that a well-structure coherent vortex with a stationary ground plane, would collapse when the rolling road was activated). So far all of the results that have been discussed in this chapter were obtained with a moving ground plane and no evidence of vortex breakdown has been observed. However, it may be that there are differences in the flow structure of the wake in these two cases. Figure 4.9 presents the near-field results of the flow downstream of the McLaren geometry at the lowest ride height ($h/c_{mp} = 0.36$), with both a stationary and moving ground plane.

As can be seen from this figure both the time-averaged results from the PIV and the instantaneous results of the flow visualisation exhibit no sign of a breakdown in the structure of any of the vortices in either of these cases. Also the structure of the wake is very similar between the stationary and moving ground plane, with the vortices appearing to be located in almost identical positions. This statement is backed-up by the results from the vortex parametrisation performed by the post-processing code of all of the vortices at varying heights, the results of which are shown in Figure 4.10.

From the plot of the vortex positions in Figure 4.10(a) it can be seen that the centres of the vortices are largely unaffected by the rolling road being on or off. The only vortex which shows a slight difference in its location is the footplate vortex at the lowest ride heights. This is a consequence of the fact that in the case of the stationary ground plane there is a conventional boundary layer whereas with the moving ground plane the flow is moving at the freestream velocity. The footplate vortex is the closest structure to the ground plane and hence is the most affected. This is also the case for the circulation of the vortices as can be seen in Figure 4.10(b) where the strength of the individual vortices is plotted with varying ride height for both the stationary and moving ground plane conditions. The results presented in this figure show that for main, top and canard vortices the strengths of the vortex

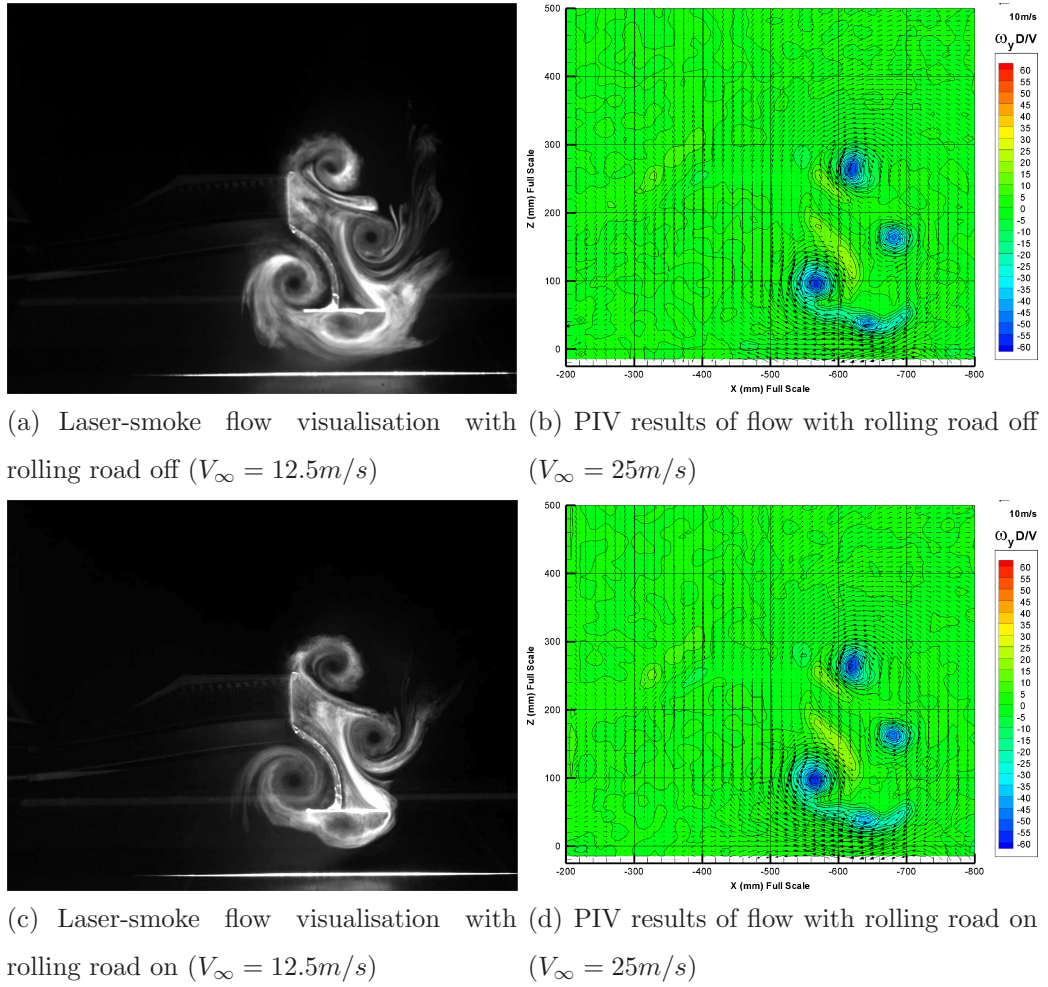
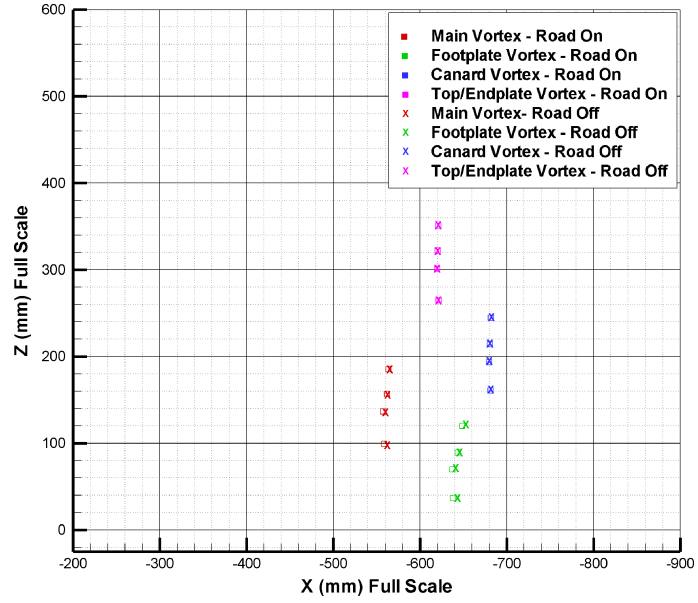
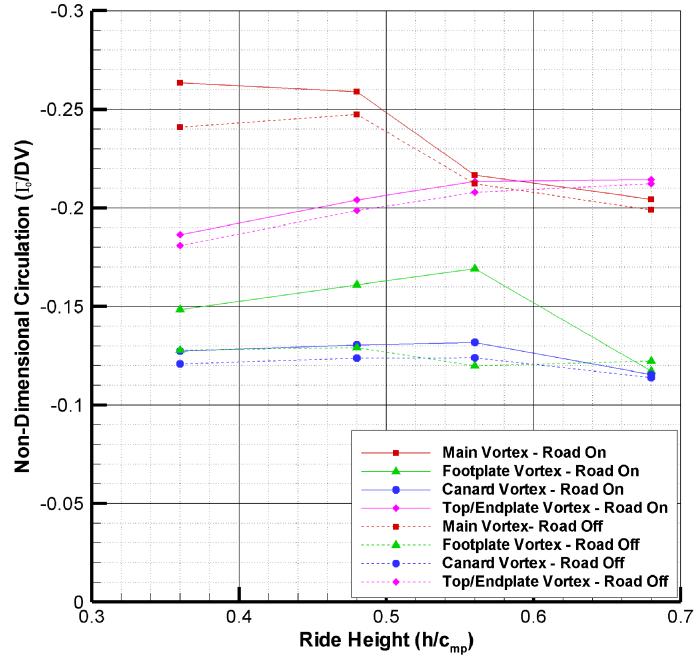


Figure 4.9: Comparison of flow immediately downstream of McLaren front wing ($Y = -300mmFS$) for flow with and without a moving ground plane at a ride height of $h/c_{mp} = 0.36$

are slightly less when the road is off to when there is a moving ground plane. It is thought that this is a result of the presence of the boundary layer over the stationary ground plane which can be seen in Figure 4.11. This boundary layer can thicken beneath an inverted aerofoil close to the ground as a result of the large negative pressures which act along the lower surface of such an aerofoil. The thickening of the boundary layer is greatest near the leading edge of the aerofoil where the suction is the highest and can affect the flow which approaches the aerofoil thereby reducing the effective incidence of the approaching air ($\alpha_2 < \alpha_1$). Therefore, when the floor is stationary a wing may produce less lift due to the presence of the boundary layer



(a) Position of the centres of the vortices at different ride heights



(b) Graph of the non-dimensional circulation of the vortices with varying ride height

Figure 4.10: The results of the vortex parameterisation of the four vortices at each of the ride heights, in the near-field of the McLaren model ($Y = -300mmFS$) without the wheel for both the road on and road off cases

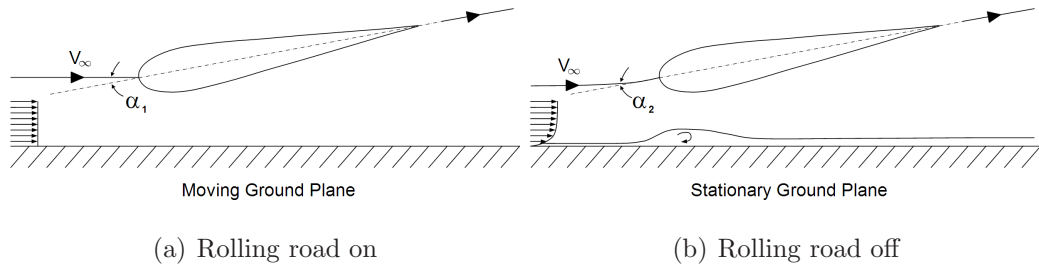


Figure 4.11: Schematic of the effect of the differing ground plane conditions on the aerodynamics of a wing operating close to the ground

over the stationary ground plane when compared to a moving ground plane. This reduction in lift would result in less circulation of the trailing vortices which can be seen in Figure 4.10(b). This effect is felt most at the footplate where the ground clearance is the least and this can be seen by the large decrease in strength of this feature when the road is off. It must also be remembered that the footplate vortex is the least axisymmetric of the vortices and therefore may contradict the assumption of an isolated, axisymmetric vortex required to apply the Lamb-Oseen vortex model to the data and hence the results from this feature may be erroneous.

4.2 Far-Field: Behaviour of Vortex System With Distance Downstream

So far in this chapter only the results from the near-field flow structure have been discussed and analysed, with observations on how the ride height of the wing and the state of the ground plane (moving or stationary) affects the trailing vortex structure.

In the next section, the behaviour of the vortex system as it travels downstream will be examined, again considering the effect of the ride height of the wing as well as discussing the effect of the stationary and moving ground plane.

4.2.1 Behaviour of Vortex System

The main experimental techniques which have been used to analyse the downstream development of the front wing trailing vortex structure are the laser-smoke flow visu-

alisation, PIV and total pressure surveys. Hot film anemometry has not been utilised due to the length of time required to perform a wake survey with this technique. Figures 4.12 and 4.13 show the results of the total pressure survey performed in planes downstream of the McLaren model at a moderate ride height of $h/c_{mp} = 0.48$.

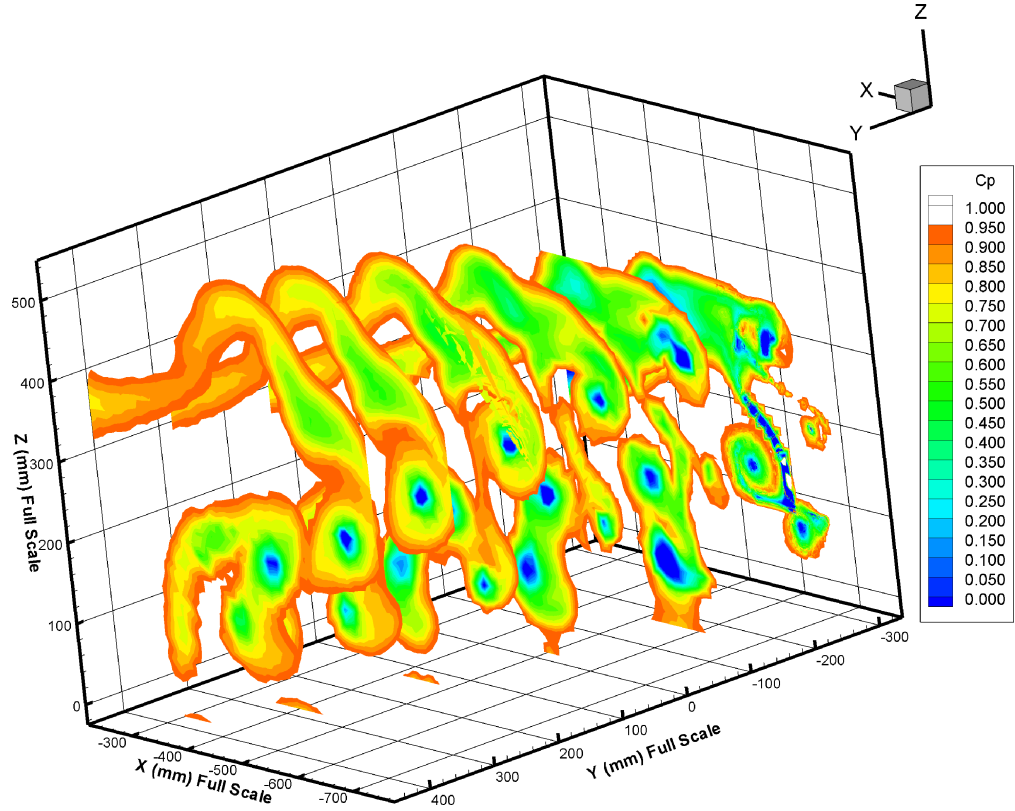


Figure 4.12: Results of total pressure surveys in cross-flow planes downstream of McLaren model at a ride height of $h/c_{mp} = 0.48$, without the wheel and with a moving ground plane ($V_\infty = 25m/s$)

From the data contained within these figures it can be seen that as the trailing vortex system travels downstream the vortices interact with one another. The results from examining the near-field data of the vortices in this configuration showed that the main and top vortices were stronger than the footplate and canard vortices. Consequently as the trailing vortex system passes downstream, the relative intensity and proximity of the footplate and canard vortex ensure that these two vortices are substantially displaced in both the X and Z axes due to the induced velocity of the main vortex. The trajectories of these two features appear to be consistent with

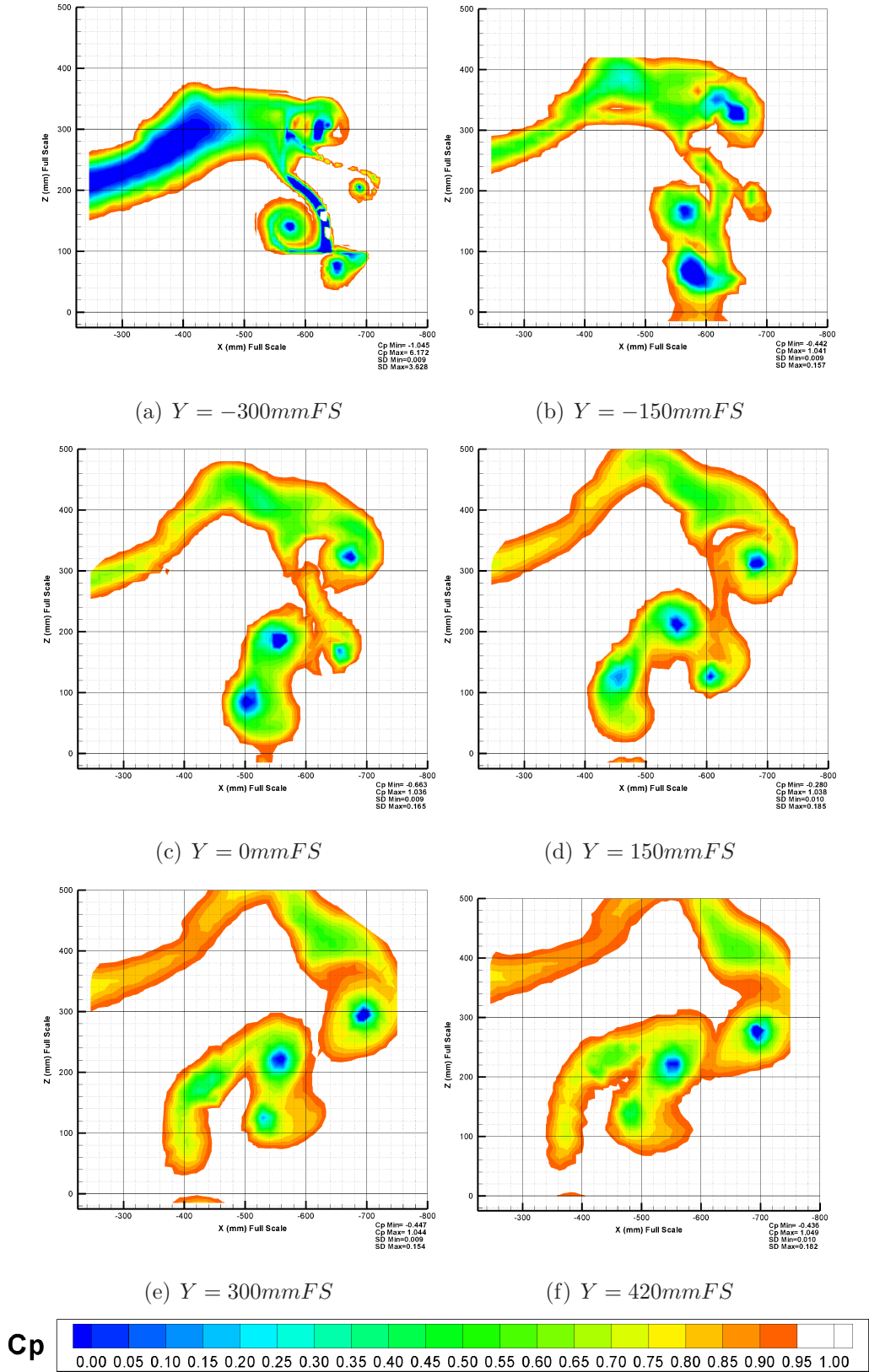


Figure 4.13: Total pressure distribution in planes downstream of McLaren model at a ride height of $h/c_{mp} = 0.48$, without the wheel and with a moving ground plane ($V_{\infty} = 25m/s$)

the commencement of orbiting around the main vortex which occurs prior to the merging of two or more unequal co-rotating vortices (discussed in Section 2.3.1.1). The movement of the footplate vortex inboard by the induced velocity from the other vortices is also enhanced by the induced velocity of the image vortex resulting from the modelling of the effect of the ground plane (refer to Section 2.3.1.2). In spite of the fact that the canard and footplate vortices are weaker than the main vortex, the induced velocity from these two features are felt by the main vortex. As the system travels downstream the main vortex is displaced upwards. This behaviour reduces the separation distance between itself and the top vortex which is of a more comparable strength to the main vortex at this ride height (although it is still weaker). Therefore as the vortex system travels downstream the trajectories of these two vortices resembles that of two slightly unequal co-rotating vortices undergoing the early stages of merging (refer to the images of unequal merging in Figure 2.17).

These observations about the behaviour of the vortex system without the wheel are confirmed by the plots of the time-averaged iso-surface of vorticity obtained from the PIV experiments and presented in Figures 4.14 and 4.15. These plots are generated from 55 planes of time-averaged velocity vectors and hence are not based on three-dimensional data in spite of their appearance.

By containing more planes of data and by selecting a vorticity level which shows only the vortex cores, it can be seen that the observations made from the total pressure results are reinforced by the results in these figures. The canard and footplate vortex can be seen to commence orbiting the main vortex whilst main and top vortex also influence each others trajectories.

The resulting velocity fields from the PIV system in this configuration can also be used as an input to the vortex parameterisation code, the results of which can be seen in Figures 4.16 and 4.17

Figure 4.16(a) shows the resulting trajectories predicted by the post-processing routines. This plot replicates the behaviour seen in the iso-vorticity data. However, note that the trajectories of the footplate and canard vortex do not exist throughout the entire domain as they interact with other vortices and hence cannot be assumed to be isolated which is necessary to parameterise the vortices. The locations of the

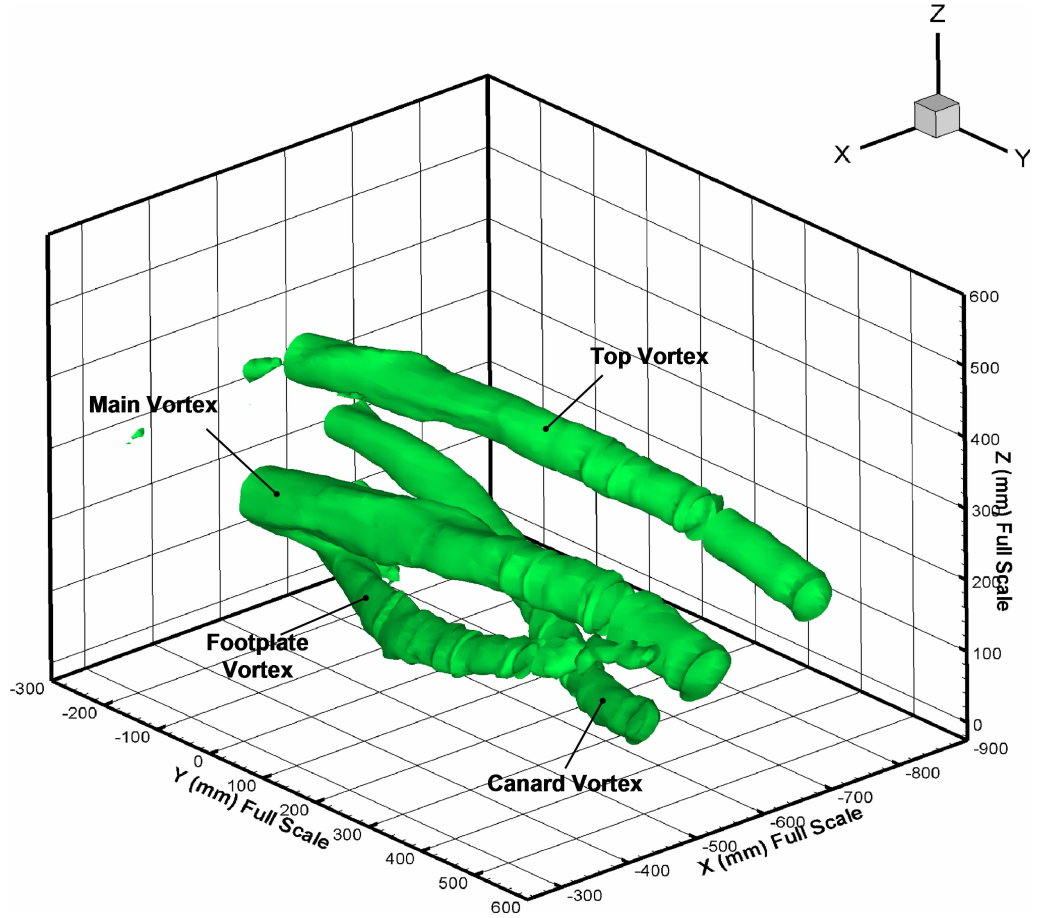


Figure 4.14: Isosurface of non-dimensional vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at a ride height of $h/c_{mp} = 0.48$, without the wheel and with a moving ground plane ($V_\infty = 25m/s$)

centres of the vortices are estimated from the instantaneous velocity fields obtained at each plane with a mean centre and standard deviation being returned. The values of the standard deviation can be used to provide an insight into the steadiness of the vortices within the flow. Figures 4.17(a) and 4.17(b) present the results of the standard deviations in the X and Z axes respectively. As can be seen from these figures, the vortices are at their steadiest when they are shed from the endplate with values of approximately $\pm 2mmFS$. The highest values are associated with the footplate vortex due to the uncertainty of the assumption of axisymmetry of this feature as discussed previously. This magnitude of the standard deviation in the near field is largely a result of the method that was used for finding the centre of the vortex. As discussed in Section 3.5, the centre was found by finding the centre

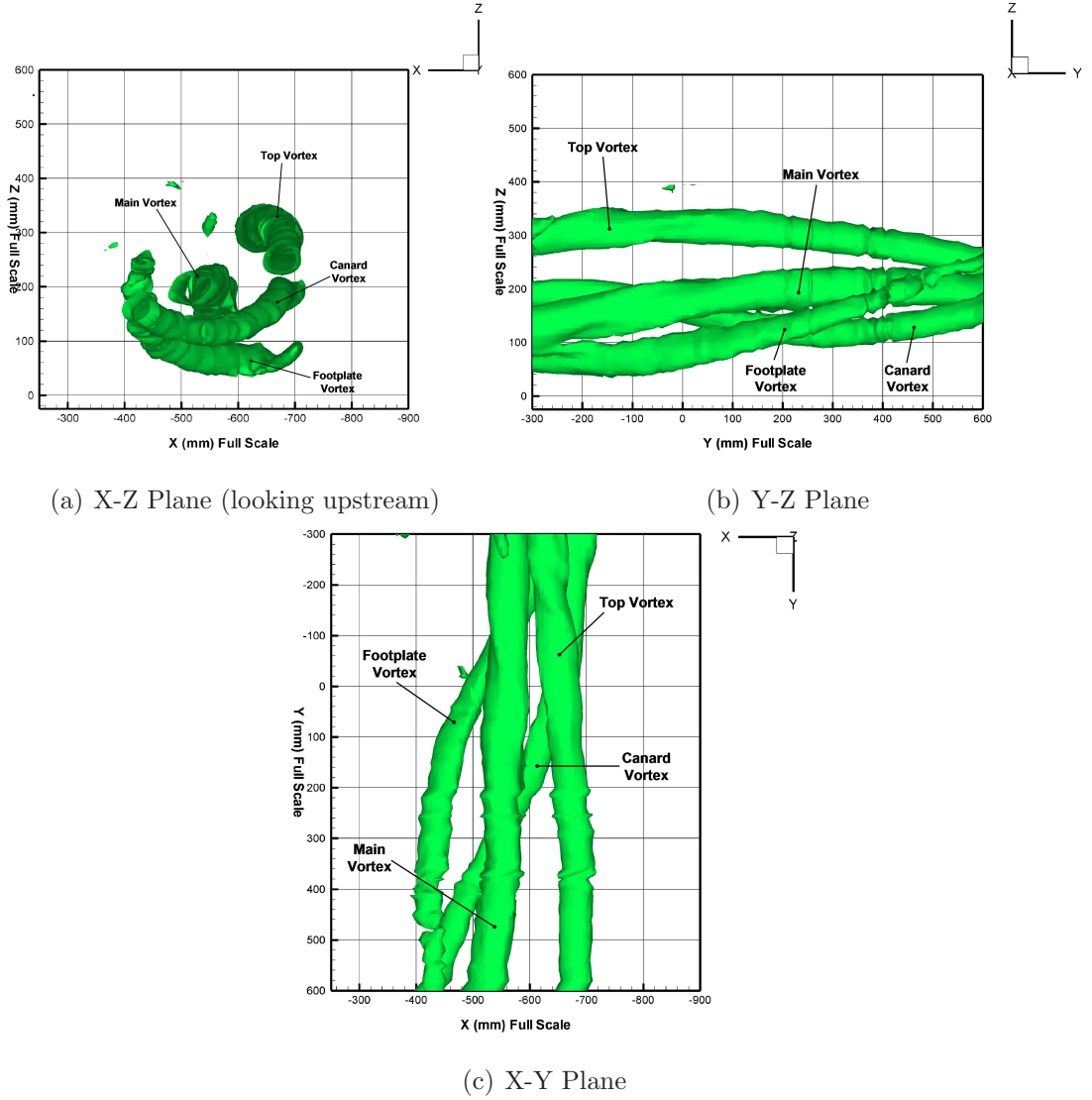
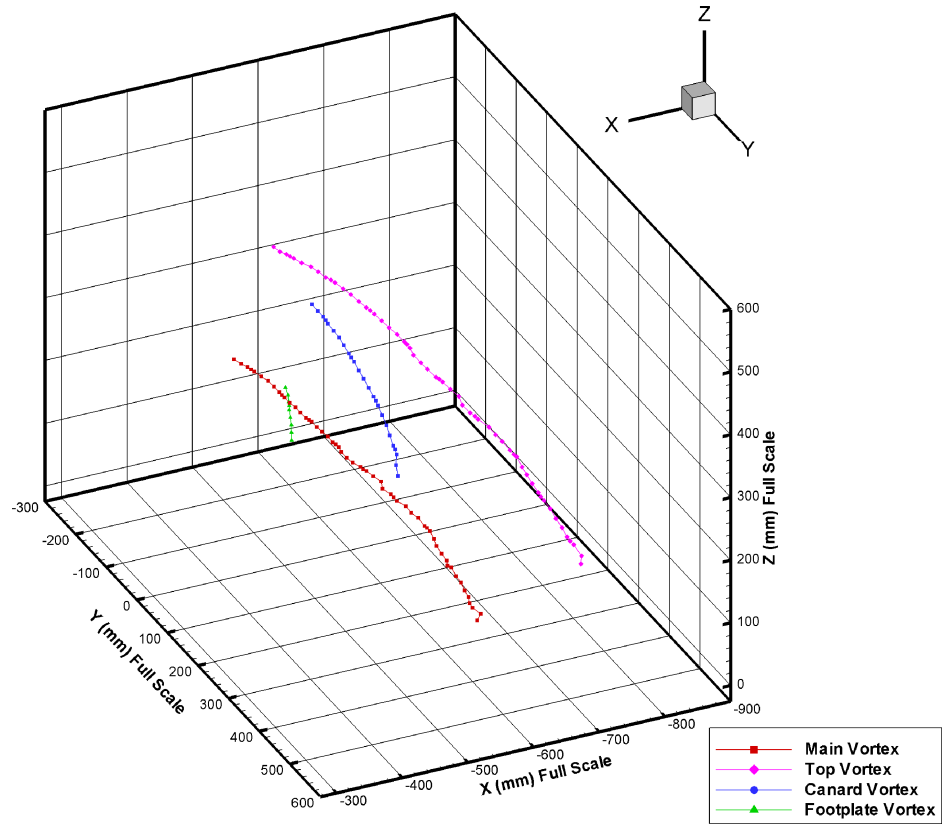


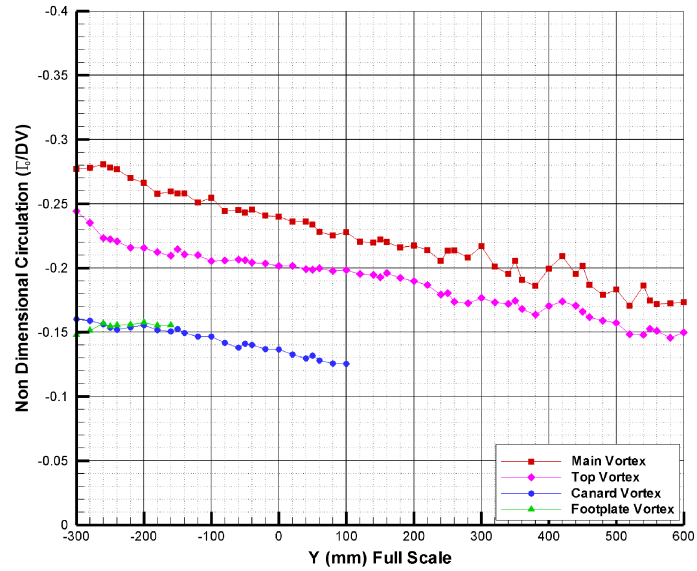
Figure 4.15: Different viewpoints of isosurface of non-dimensional vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at a ride height of $h/c_{mp} = 0.48$, without the wheel and with a moving ground plane ($V_\infty = 25m/s$)

of rotation by comparing the maximum value of the tangential velocities at varying points around the estimated centre of the vortex. The sensitivity factor of this method was set so that the accuracy of the method was $\pm 1mmFS$. The remaining $1mmFS$ of the standard deviation of the vortex centre may be attributed to the unsteadiness of the vortex as well as experimental error (discussed in Section 3.4.4).

It can be seen from Figures 4.17(a) and 4.17(b) that as the vortex system travels downstream the values of the standard deviation increase. This is coupled with a

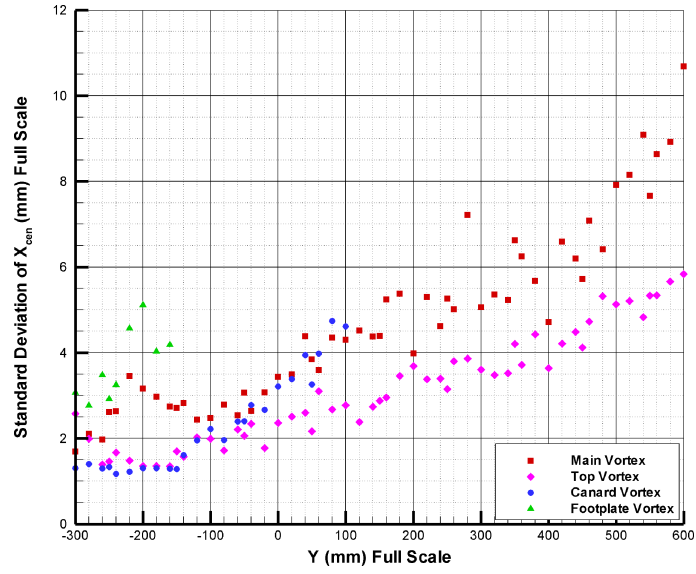


(a) Plot of vortex trajectories

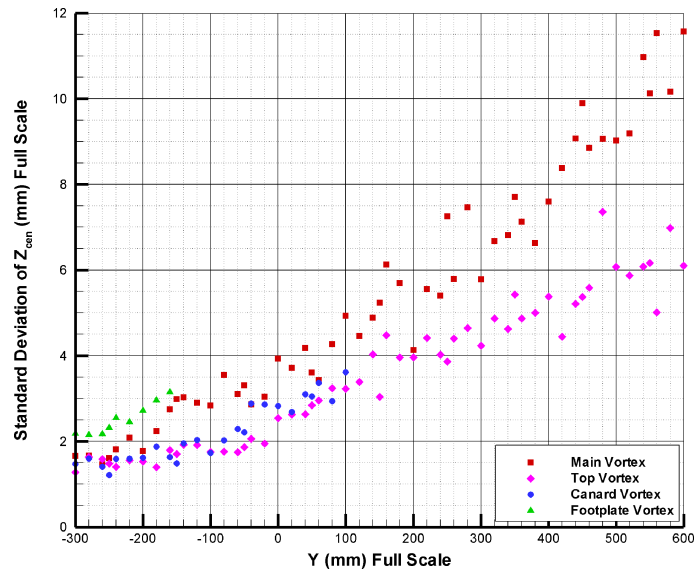


(b) Non-dimensional circulation with downstream distance

Figure 4.16: Results of vortex parameterisation code of McLaren model at a ride height of $h/c_{mp} = 0.48$ without wheel and with a moving ground plane



(a) Standard deviation of X coordinate of vortex center with downstream distance



(b) Standard deviation of Z coordinate of vortex center with downstream distance

Figure 4.17: Standard deviations of vortex centers as obtained from vortex parameterisation code of McLaren model at a ride height of $h/c_{mp} = 0.48$ without wheel and with a moving ground plane

reasonably large reduction in the circulation of the vortices throughout the analysis region. It may be that these two features are a consequence of the increased interaction of the vortices with downstream distance, vortex wandering, a result of the post-processing technique or a combination of these effects. In Section 2.2.3 the con-

cept of vortex wandering or meandering was introduced. Devenport *et al.* (1996) stated that wandering amplitudes increase roughly linearly with downstream distance and also would decrease for a weaker vortex. The trend in Figures 4.17(a) and 4.17(b) would appear to be roughly linear and indeed the strongest vortex (main vortex) is also subject to the greatest fluctuations indicating that this unsteadiness may well be a consequence of vortex wandering. An increase in interaction between the vortices as the separation distances between the cores decrease may result in increased fluctuations of the vortices seen in Figures 4.17(a) and 4.17(b) but this would not necessarily explain the decrease in the circulations viewed in Figure 4.16(b). This may be a result of the assumption of an isolated axis-symmetric vortex used to parameterise the vortices. As the vortices interact and move closer to one another this assumption becomes increasingly invalid. To estimate the circulation of the vortices a cut-off radius was used which effectively ignored the vorticity outside of a circle equal to this radius. The size of this radius was the average of the location where the vorticity dropped below 5% of the peak vorticity in the core. Hence when the distance between the vortices diminishes the vortices will become less axis-symmetric and hence some of the vorticity may have been ignored and therefore the estimated circulation will decrease.

4.2.2 Effect of Ride Height

The results discussed previously on the effect of the ride height of the McLaren wing on the vortex system in the near-field, have shown that as the ride height of the wing is increased that the relative positions of the vortices in the trailing vortex system are maintained, with only a small variance in the position of the footplate vortex. However there was less similarity in the way that the circulations of the individual vortices changed when the clearance between the wing and ground plane was increased. As the ride height was increased the circulation of the top and footplate vortex was strengthened, whilst that of the canard vortex maintained relatively constant. During the same experiments the circulation of the main trailing vortex decreased as the lift augmentation resulting from the small clearances with

the ground plane diminished.

Whilst comparing the downstream flow structure of the vortex system shed from the McLaren front wing at different ride heights, these observations aid the explanation on its behaviour. Instantaneous images from the laser-smoke flow visualisation of the vortex system at select planes for the wing at the lowest and highest ride heights ($h/c_{mp} = 0.36$ and $h/c_{mp} = 0.68$ respectively), are shown in Figure 4.18.

From the images in this figure the effect that raising the wing has on the behaviour of the vortex system can be seen. At the moderate ride height discussed above, it was discussed how the bottom three vortices start to interact very quickly due to the induced velocity field which mostly originates from the strong main trailing vortex. At the lowest ride height, the same interaction of these three vortices occurs with the footplate and canard vortices orbiting and merging with the main vortex. At the lowest ride height the separation distance between these vortices and the top vortex is maintained. At the highest ride height, these weaker vortices still interact with the main vortex. However the reduced circulation of the main vortex together with the increased intensity of the top vortex ensures that whilst the footplate and canard vortices still orbit the main vortex, the main and top vortex begin to interact and the separation distance between these structures is reduced.

This behaviour explains the difference in flow structure seen at the furthest point downstream of the analysis region for the different ride heights shown in Figure 4.19. At the lowest ground clearance $h/c_{mp} = 0.36$ shown in Figure 4.19(a) the vortex system has formed a ‘figure of eight’ like structure. The strength of the main vortex ensures that it is in the process of merging with the footplate and canard vortex and forms one side of this structure whilst the other side is formed by the relatively weaker top vortex. At the highest ride height of $h/c_{mp} = 0.68$ (Figure 4.19(d)), an ‘arch-like’ structure is formed due to the stronger top vortex reducing its separation distance with the other vortices.

As with the behaviour of the vortex system at $h/c_{mp} = 0.48$, from the results obtained during this research there is no evidence of a change in structure which would be indicative of vortex breakdown at any of the ride heights. It appears that the system forms different downstream structures due to the varying circulation of

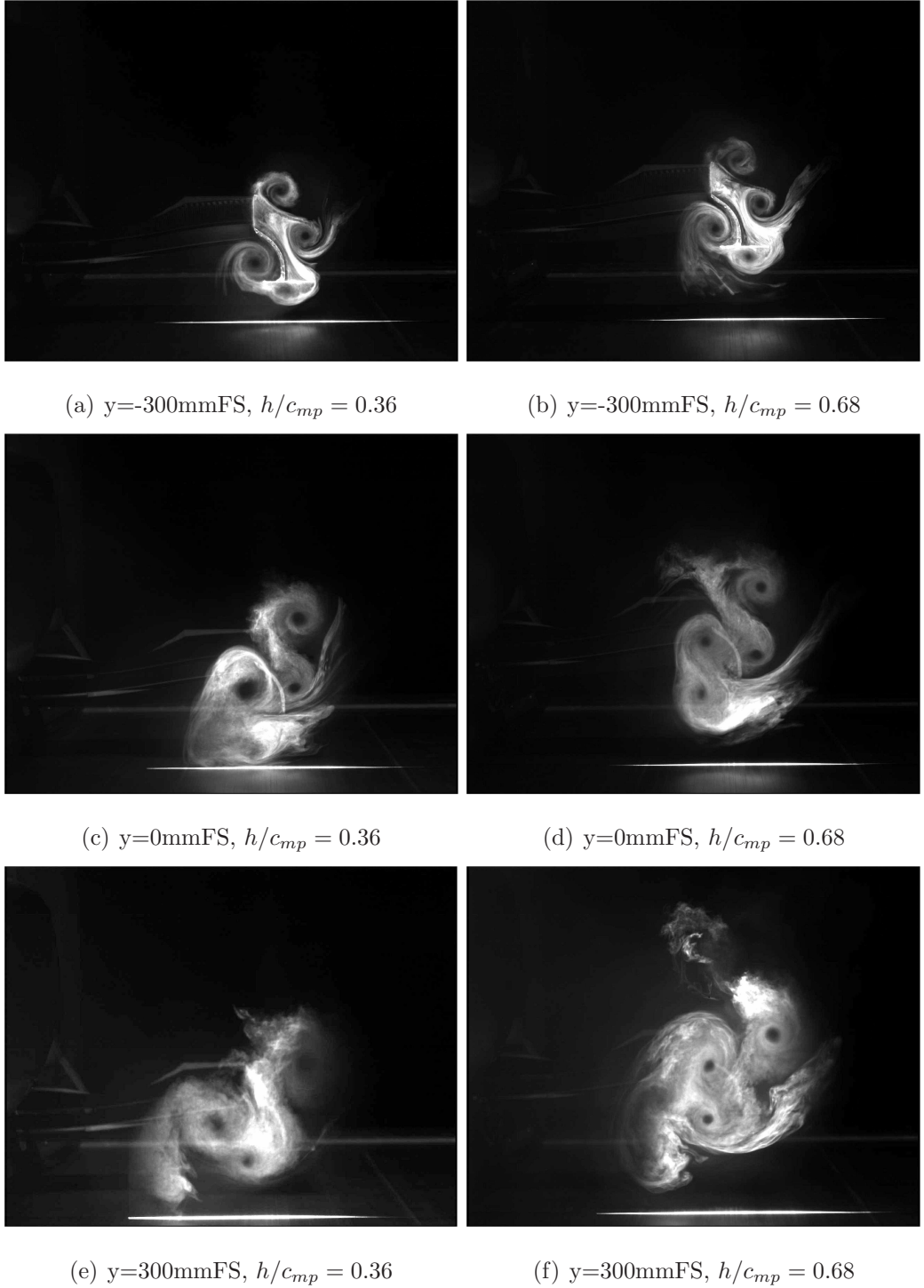


Figure 4.18: Images from laser-smoke flow visualisation of vortex system downstream of McLaren model at the lowest and highest ride heights, without the wheel and with a moving ground plane ($V_\infty = 12.5\text{m/s}$)

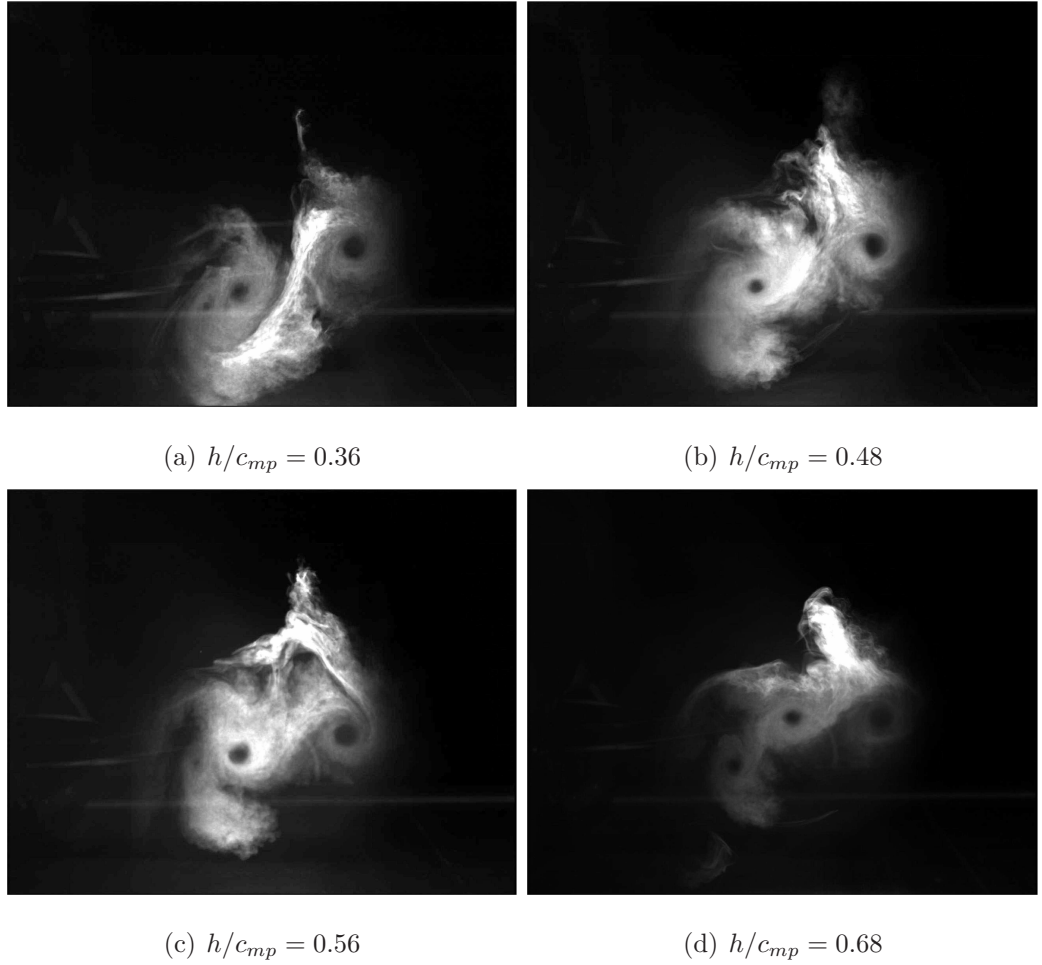


Figure 4.19: Images from laser-smoke flow visualisation in the far-field downstream of McLaren geometry ($Y = 600mmFS$) at all ride heights, without wheel and with a moving ground plane ($V_\infty = 12.5m/s$)

the two dominant vortices (main and top) in the different configurations. The next section examines the effect of the rolling road on the vortex system.

4.2.3 Effect of Rolling Road

Two plots of iso-surfaces of vorticity are shown in Figure 4.20, one where the ground plane is moving and the other when this boundary is stationary.

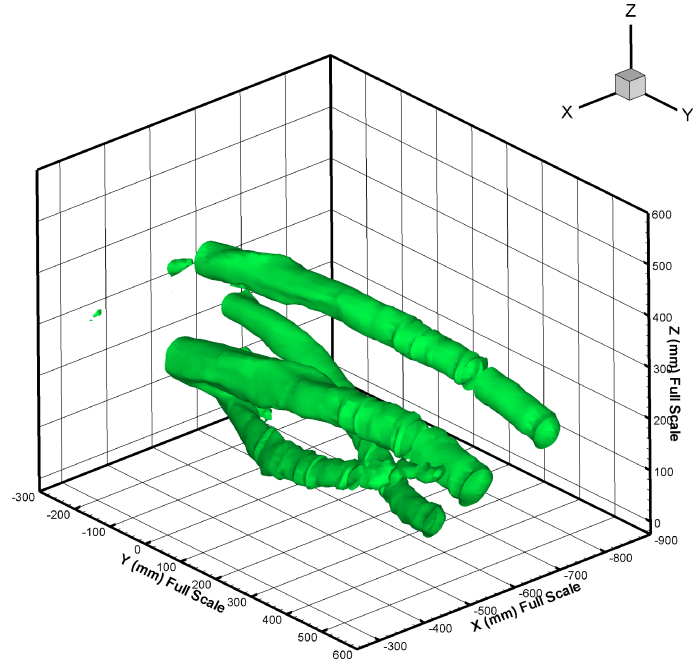
The behaviour of the vortex system in these two configurations is almost identical and there are very little differences to be observed between them. The only distinguishable difference is the placement of the canard and footplate vortex in the

very far-field. When the road is on these features are closer to the main vortex due to the increased circulation of this vortex compared to the case of the stationary ground plane. Therefore the induced velocity field has a greater effect on these vortices with the moving ground plane and are consequently displaced closer to the main vortex.

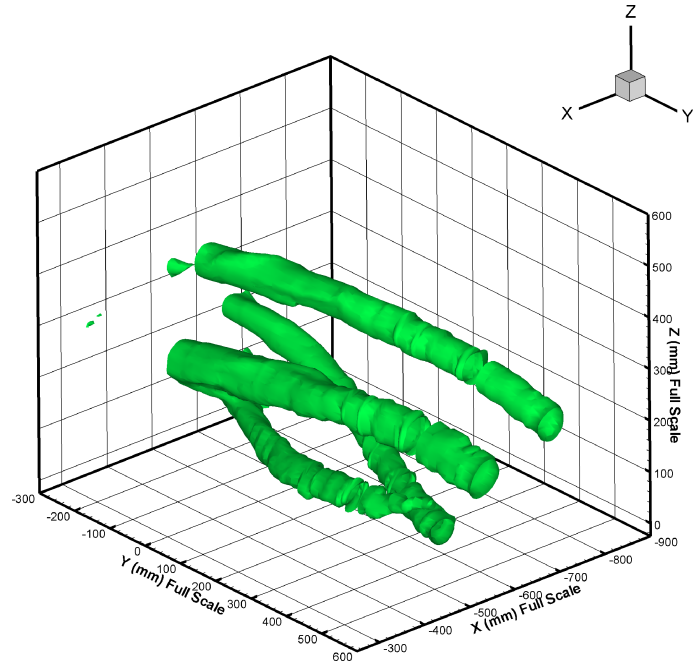
4.3 Concluding Remarks

This chapter has shown that the vortex system downstream of the McLaren front wing consists of four co-rotating vortices whose relative positions in the near field vary very little with changes in ride height. The dominant vortices in this system are the main trailing vortex and the vortex which is shed from the top of the endplate. At the lowest ride height the main vortex is the strongest with its circulation decreasing with an increased ground clearance. Conversely the circulation of the top vortex increases with ride height and with the wing in its highest configuration is the strongest feature in the flow. As the vortex system travels downstream the behaviour of the vortices is largely governed by the relative strengths of the main and top vortex. At all ride heights the weaker footplate and canard vortex interact with the main vortex which maintains a separation from the top vortex at the lowest ride height to form a ‘figure of eight’ structure. At the highest ride height the strength of the top vortex ensures that this separation distance is reduced and all four vortices appear to interact with one another.

It is also apparent from the results contained within this chapter that there are no abrupt changes in flow structure or disorder which would be indicative of vortex breakdown. The vortex system appears to be well-ordered and the individual velocity fields of the vortices, induce the system to merge together. Therefore it is thought that without the wheel the configuration of the system is not prone to breakdown. Whilst other researchers have made remarks to the contrary it is noticed that these have been made for wings operating at lower ride heights than have been examined during this research. In this study it was decided not to investigate the behaviour of the system below the minimum ride height permissible by the Formula



(a) Moving ground plane



(b) Stationary ground plane

Figure 4.20: Comparison of iso-surface of non-dimensional vorticity ($\omega_y D/V_\infty = -8$), generated by McLaren model without the wheel, at a ride height of $h/c_{mp} = 0.48$, with and without a moving ground plane ($V_\infty = 25m/s$)

1 regulations. Hence it may be that vortices within this system would breakdown at lower ride heights.

The information gained from this chapter has provided an insight into the flow downstream of the McLaren geometry. However the omission of the rotating wheel is an over simplification of the application of the aerodynamics about a race-car front wing. As discussed in Section 2.4, the flow about a rotating wheel is complex and its proximity to the trailing edge of the front wing makes it likely that the vortex system will be greatly affected by its presence. To examine this effect the next chapter analyses the results obtained from passing a single isolated about a rotating wheel in varying locations and strengths relevant to this trailing vortex system.

Chapter 5

Observations on the Behaviour of a Vortex Passing About a Wheel

From the previous chapter it has been shown that the wake from the McLaren front wing consists of a complex trailing vortex system of four co-rotating vortices. When the wheel is included then this complexity is compounded by the aerodynamics surrounding the rotating wheel. Through considering the more simplified case of a single vortex passing about the wheel, this chapter acts as an intermediate step between the analysis of the McLaren trailing vortex system with and without the wheel.

The key component of this investigation was a single vortex with a strength that could be varied, placed ahead of the wheel in many different positions. To ensure that the results from this analysis provided the greatest insight into the trailing vortex shed from the McLaren front wing, the starting locations of the vortex were chosen to coincide with the positions of the individual vortices in the McLaren system. From the previous chapter it is known that the experiments on the McLaren front wing were performed in four different ride height configurations and the resulting vortex system consisted of four distinct vortices. Hence there are sixteen initial positions in which the single vortex has been placed and its behaviour evaluated. These positions can be seen in Figure 5.1 where the locations of the single vortex ahead of the wheel are plotted at each of the three different strengths. In this figure a

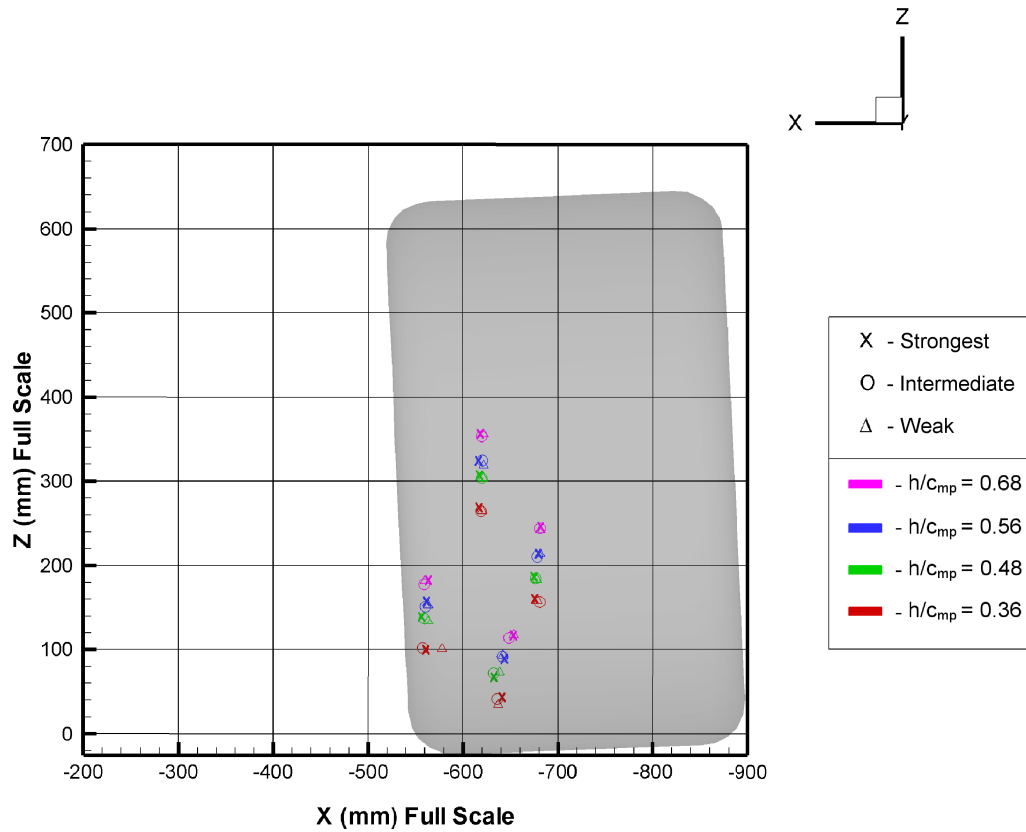


Figure 5.1: Plot showing initial positioning of vortices for single vortex investigation at a plane of $Y = -200mmFS$ without wheel (wheel silhouette included to show its position relative to vortex)

silhouette of the wheel is included for information only but was not actually present when the centres of these vortices were evaluated due to the practical limitations restricting the field of view when the wheel is in place. Also note that the Y-plane in which the positions have been estimated is $Y = -200mmFS$. In similarity to the McLaren geometry the trailing edge of the models used to generate the single vortex was placed at $Y = -300mmFS$. However as will be discussed in the next section, $Y = -200mmFS$ was chosen to be a location where the more accurate positioning of the vortex could be obtained as the vortex was nearly, if not entirely rolled up in this position.

Before the behaviour of the single vortex about the wheel is examined, both the aerodynamics about the isolated wheel and the characteristics of the single vortices are analysed.

5.1 Isolated Vortices

The two single wing models were designed to generate vortices which provided a range of circulations whilst also producing a vortical structure similar to those in the McLaren vortex system. As was demonstrated in the previous chapter, the vortices shed from the McLaren front wing have circulations which are estimated to fall within the range $-0.115 \leq \Gamma_0/DV_\infty \leq -0.264$ (see Figure 4.6(b)). To generate a vortex which would have a strength of the largest magnitude (termed the strongest vortex), the double-element single wing model was designed and manufactured (See Section 3.2.2.2). Two weaker vortices were generated by the single element wing model (termed the intermediate and weakest strength vortices), which provided the desired range of circulation.

Figure 5.2 shows the non-dimensional, time averaged vorticity field of the strongest vortex in planes downstream of the model, without the wheel. As can be seen from this data, the vortex rolls-up to form an axisymmetric vortex which passes through the analysis domain. However the roll-up process is not immediate and occurs over a small streamwise distance. This distance is a consequence of the small endplate which was deemed necessary to aid the repeatable placement of the vortex and to maintain the centre of the vortex in the desired position, even with the large cross-flows present in front of the wheel (see Section 3.2.2). Without an endplate, vorticity generated at the wing-tip quickly rolls-up to form an axisymmetric wing tip vortex. When an endplate is present, the vorticity is formed along its upper and lower edges. With distance downstream these interact and merge together to form a single vortex. The time taken for this interaction and merging process to occur is increased as the distance between the two regions of vorticity is made bigger. Hence the vortex formed from a wing with a large endplate will take longer to roll-up than that of a wing with a smaller or no endplate. Hence as can be seen from this vorticity data, the strongest vortex takes a couple of planes to roll-up (the distance between planes is $\Delta Y = 100mmFS$).

The characteristics of the roll-up process can also be seen in the results from the parameterisation of this vortex shown in Figure 5.3. The calculation of the properties

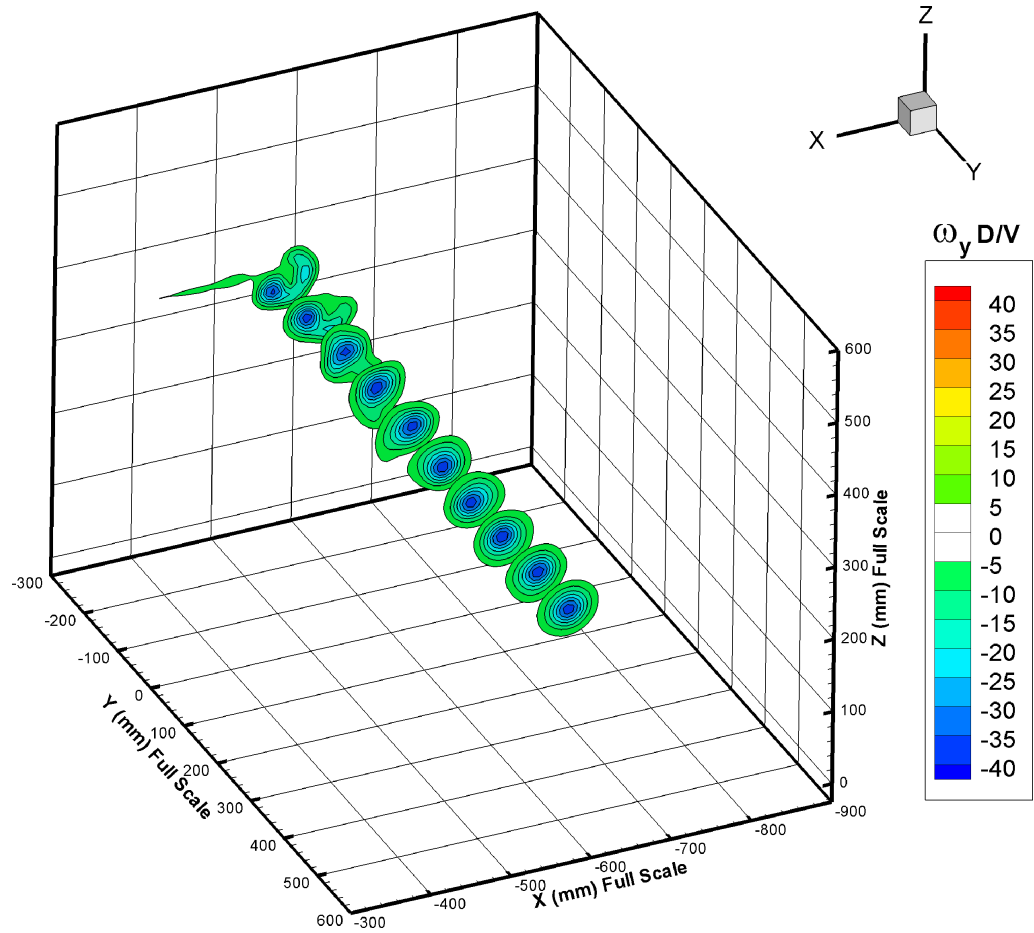
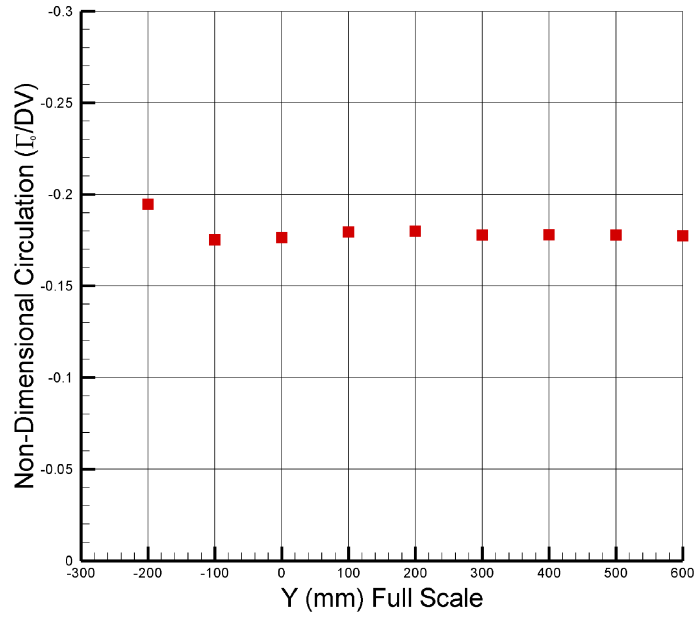


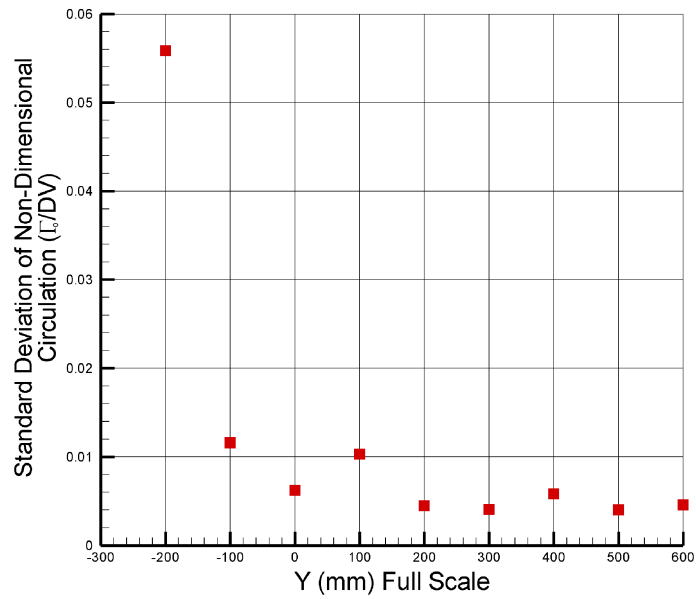
Figure 5.2: Time-averaged non-dimensional vorticity ($\omega_y D/V_\infty$) of strongest vortex plotted in planes downstream of double-element single wing model without wheel

of the vortex was undertaken on all 75 instantaneous PIV vector images at each location downstream of the wing. This provided the mean location of the centre and the mean strength as well as the standard deviations of these properties. From these results it can be seen that the mean circulation settles to an almost constant value of $\Gamma_0/DV_\infty = -0.175$ downstream of $Y = -100mmFS$. From this result it can be seen that the circulation is of the desired order and is stronger than the canard vortex and footplate vortex of the McLaren system and of a similar magnitude to the top vortex at the lowest ride height. Unfortunately the circulation of this vortex is less than that of the main vortex in all of the ride height configurations.

The plot of the standard deviation of the circulation is presented in Figure 5.3(b). From this figure the characteristics of the roll-up process can be inferred. Just



(a) Mean of non-dimensional circulation



(b) Standard deviation of non-dimensional circulation

Figure 5.3: Plot of non-dimensional circulation (Γ_0/DV_∞) of strongest vortex as it passes through the analysis region unimpeded by the wheel

downstream of the model ($Y = -200mmFS$) the value of the standard deviation is very high at 0.056, this value drops dramatically past $Y = -100mmFS$ settling to a value (albeit with some scatter) below 0.005. This trend is a consequence of the vortex model requiring the assumption of axisymmetry which is only satisfied

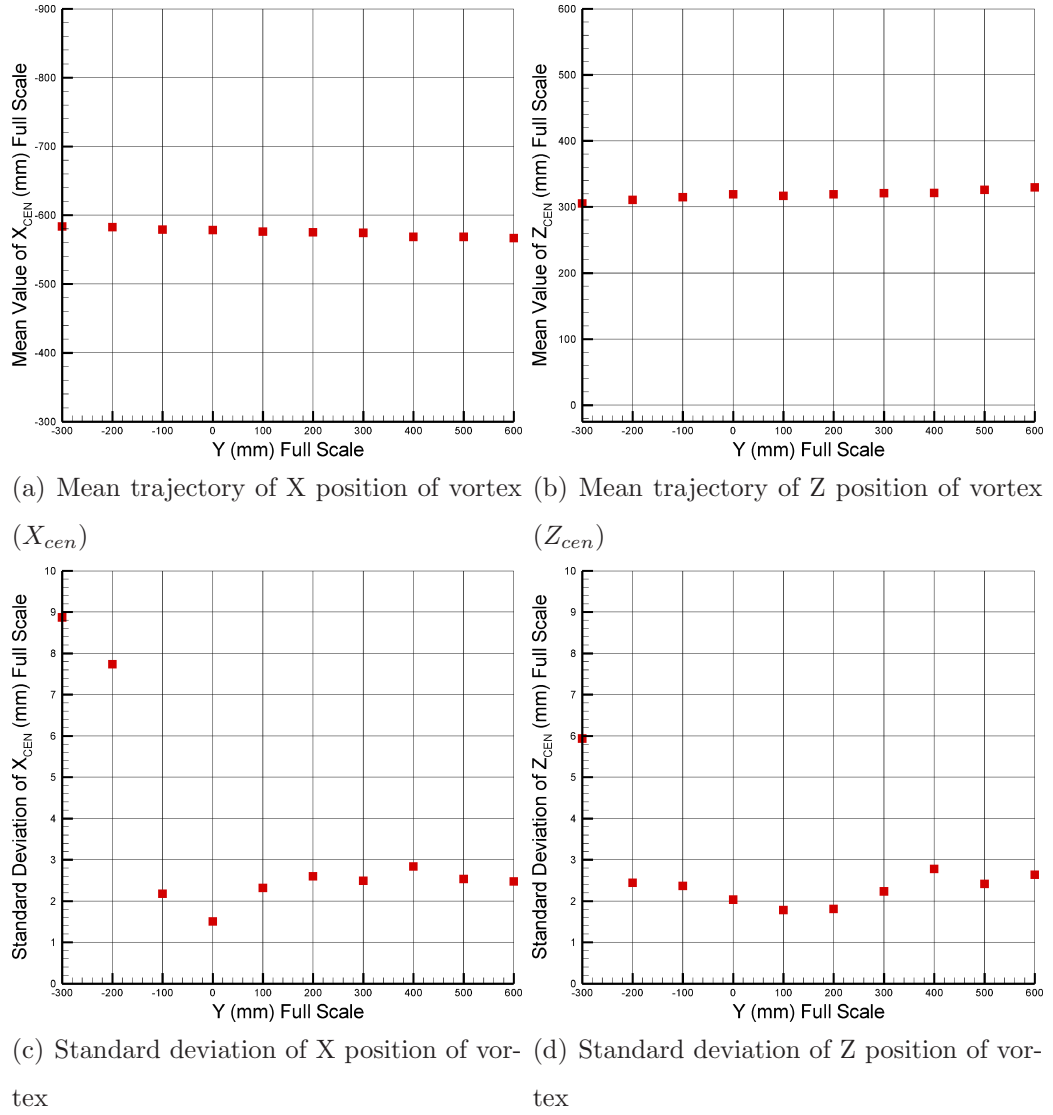


Figure 5.4: Mean and standard deviation of centre of strongest vortex with downstream distance

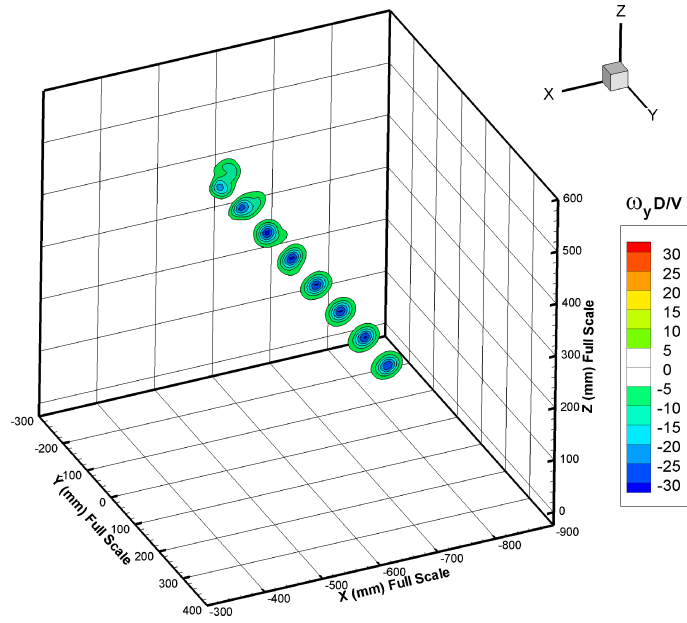
once roll-up has been completed. Hence it can be concluded from this data together with the plot of the vorticity field (Figure 5.2), that this vortex is not fully rolled up until $Y = -100mmFS$.

The contradiction of the asymmetry assumption during roll-up is also responsible for the high values of the standard deviation of the position of the vortex centre shown in Figure 5.4. These higher values settle down to a reasonably constant value once roll-up has been completed. The absolute values of these standard deviations are consistent with values obtained in the near-field of the McLaren trailing vortex

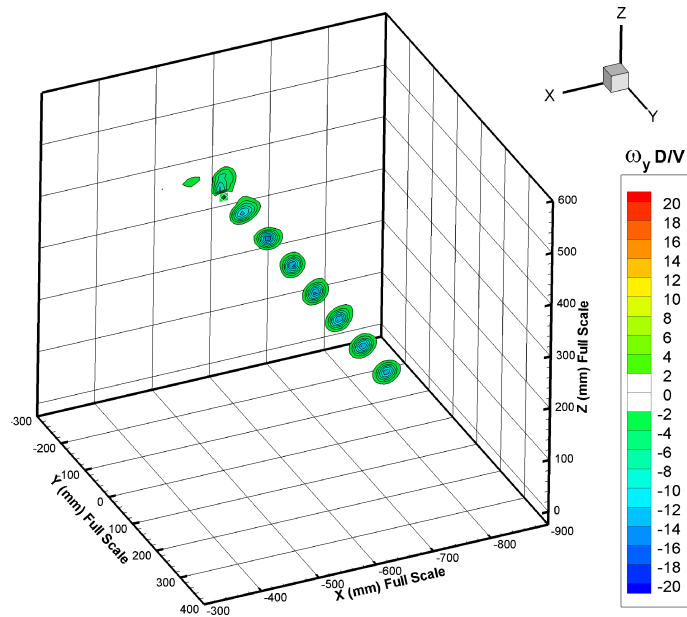
system (refer to Section 4.2.1). However the larger fluctuations seen downstream on the vortices in the McLaren system thought to be due to the vortices interacting or wandering have not been replicated by this single vortex. It is also noted that for this case the assumption of an isolated axis-symmetric vortex is met through the entire analysis region and the estimated circulation is also constant.

Also contained within Figure 5.4 are plots of the mean vortex trajectory in both the lateral (Y-X) and vertical (Y-Z) perspective. Note that for the discussion in this chapter the convention for calling a movement in the positive X-direction as inboard and the negative X-direction as outboard will be maintained. As can be seen from Figures 5.4(a) and 5.4(b), the mean trajectory of the vortex through the domain is reasonably constant with only a small displacement inboard (positive X) with downstream distance (approximately $20mmFS$) and a small vertical movement (approximately $35mmFS$ in the positive Z direction). It is thought that the lateral displacement is due to the induced velocity from its image vortex in the ground plane. As such this movement would be more pronounced if the vortex were stronger or closer to the ground plane. The vertical displacement is due to the upwash from the tip vortex which is shed from the other end of the wing on the double element model. Ideally this movement should be zero. However, this was not possible due to practical limitations prohibiting a very large span wing. Hence the effect was minimised by making the span as large as practically possible.

The behaviour of the two weaker vortices (termed the intermediate and weakest vortex) shed from the single element model are very similar to the strongest vortex as can be seen from the vorticity fields shown in Figure 5.5. It can be seen that due to the smaller endplate on this model, that the roll-up of the vortex occurs in a shorter distance than the strongest vortex. This observation is also backed-up by the trends in the mean and standard deviation of the circulation of these two structures shown in Figure 5.6. Once roll-up has been completed the intermediate strength vortex has a constant circulation of approximately $\Gamma_0/DV_\infty = -0.085$ and the weaker vortex a strength of approximately $\Gamma_0/DV_\infty = -0.030$. Although weaker than any of the vortices in the McLaren geometry these values allow examination of the behaviour of a vortex over a range of circulations to be undertaken.



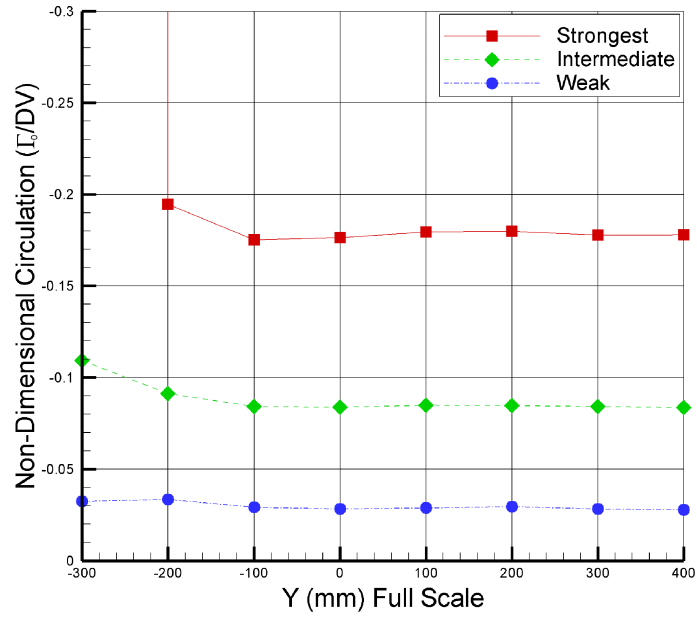
(a) Intermediate strength vortex



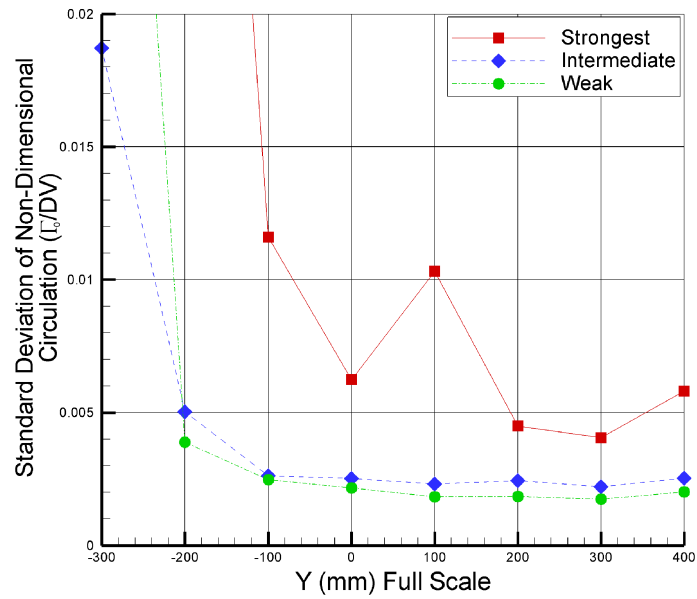
(b) Weakest strength vortex

Figure 5.5: Time-averaged non-dimensional vorticity ($\omega_y D/V_\infty$) of vortices generated by single element model, plotted in planes downstream of model without wheel

Although not plotted, the trajectories of the intermediate and weakest vortices are very similar to the strongest vortex with smaller displacements in both the lateral and vertical directions. There is only a hint of inboard movement as the interme-



(a) Mean of non-dimensional circulation



(b) Standard deviation of non-dimensional circulation

Figure 5.6: Plot of non-dimensional circulation (Γ_0/DV_∞) of vortices generated by single element model as they pass through the analysis region unimpeded by the wheel

intermediate strength vortex passes through the domain whilst the vertical displacement is approximately $10mmFS$. The lateral and vertical movement for the weakest vortex is approximately $5mmFS$ inboard and $4mmFS$ upwards. The reduction in these

displacements in comparison to the strongest vortex is deemed to be a consequence of the reduced circulation of these vortices.

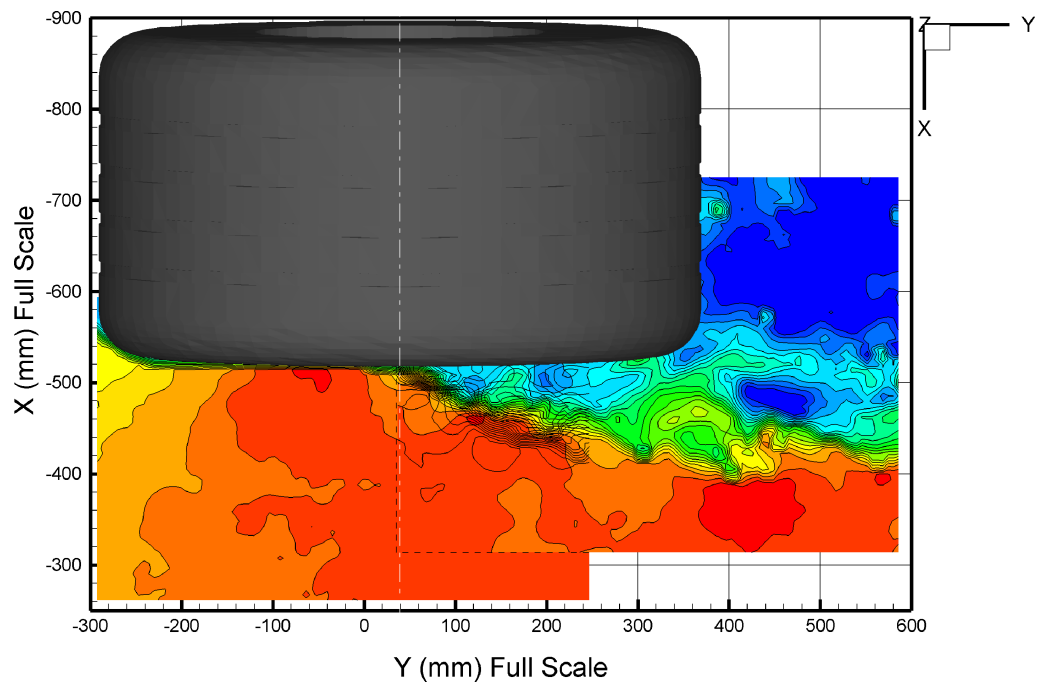
From this section it can be concluded that the three vortices generated by the two single wing models maintain a reasonably constant trajectory throughout the analysis domain with very small fluctuations. The strengths of the vortices cover a range of circulations with the strongest vortex comparable to those shed from the McLaren geometry.

5.2 Flow about the Isolated Wheel

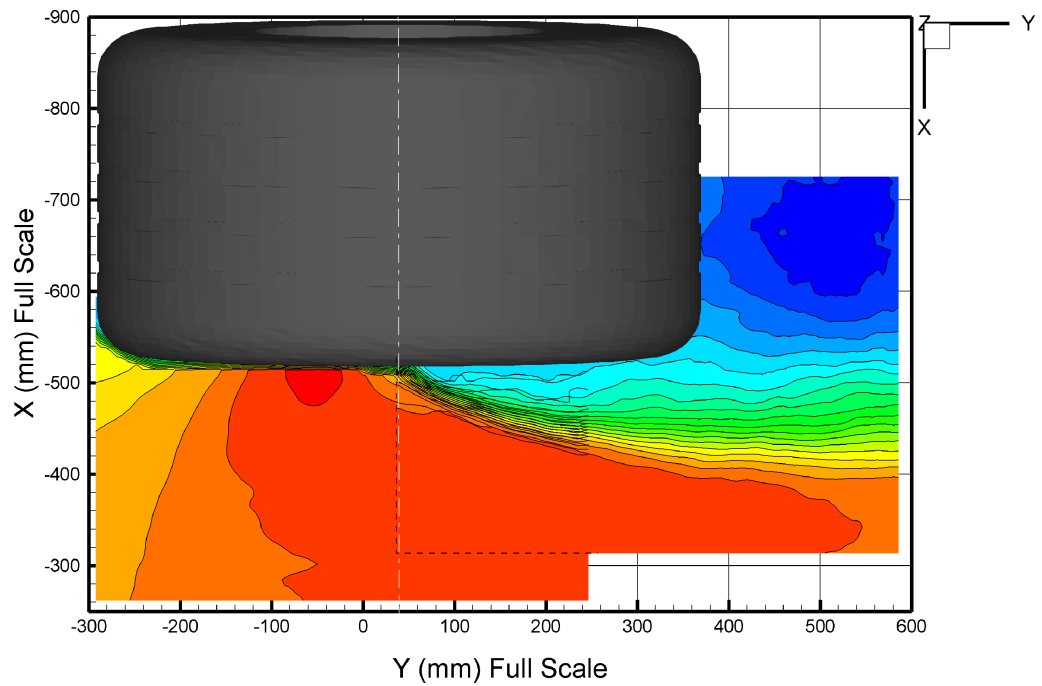
As was reviewed in Section 2.4, the published literature regarding the aerodynamics of an isolated rotating wheel is limited. Hence in order to fully evaluate the behaviour of a vortex passing close to a rotating wheel, a small examination of the flow about the rotating wheel was carried out.

To investigate the flow about the wheel, PIV was performed in planes parallel to the ground plane thereby producing V and U velocity vectors in the Y-X plane. As with other bluff-bodies, the flow about and downstream of the wheel is thought to be unsteady. However as a full examination of the time dependant flow structure is beyond the scope of this investigation, primarily time-averaged results will be presented. This is still thought to provide valuable information as can be seen from Figure 5.7 where the instantaneous and time-averaged (75 sets of velocity vectors over a period of 5 seconds) results are shown at the lowest evaluated height above the ground ($Z = -10mmFS$, $0.02D$ above the ground plane). Note that in this figure, the results are obtained from placing the camera in two separate positions and then the results are combined to give a more extensive view. The overlap is marked by the black dotted line in the plots and the centreline of the wheel is included as a white dash-dot line. Hence the flow field upstream of the contact patch has been obtained at a different time from the downstream flow structure.

From this figure it can be seen that although small scale vortical structures are lost in the time-averaged velocity field, it is a good general representation of the flow. The flow is moving from left to right and the slow moving wheel wake is easily



(a) Instantaneous velocity field



(b) Time-averaged velocity field

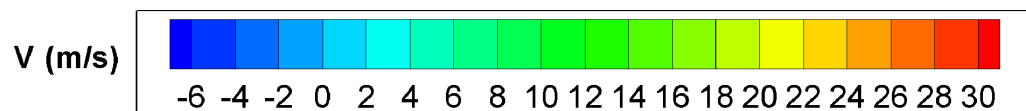


Figure 5.7: Comparison of instantaneous and time-averaged streamwise velocity field in horizontal plane of $Z = -10\text{mmFS}$ (0.02D above ground plane) about isolated rotating wheel

identifiable by the blue contours downstream of the wheel. Also visible is the ‘jetting flow’ hypothesised by Fackrell (1974) which can be seen emanating from underneath the wheel, just ahead of the contact patch. In the instantaneous data this shear-flow appears to have a periodicity which is lost in the time-averaged data.

As height from the ground plane is increased the jetting flow disappears and the wheel wake becomes narrower as can be seen from the streamwise velocity contours shown in Figure 5.8. This behaviour is also replicated in the figures of the total pressure distribution in the near wake of the wheel shown in Figure 5.9. This data is in good general agreement with that found by Fackrell (1974) and the shape of the wake is similar to the total pressure distribution examined further downstream by Bearman *et al.* (1988) shown in Figure 2.29(b).

As was discussed in Section 2.4, several researchers have proposed topologies for the vortex structure in the wake of a rotating wheel. Merker & Berneburg (1992) amended that suggested by Cogotti (1983) to suggest the structure which is shown in Figure 5.10. The theory used to hypothesise this structure is based on many assumptions and not on actual experimental measurements. Knowles *et al.* (2002) performed experiments in the near-field of a 40% Champ car wheel, in an attempt to ascertain the applicability of this theoretical suggestion to that of a realistic geometry. They obtained time-averaged results (over a duration of 15 seconds), in planes downstream of the model with Laser Doppler Anemometry (LDA) and produced the vorticity plots contained within Figures 5.11 for both a parallel and cambered wheel (4° to the vertical).

From their results they concluded that the lower or jetting vortices which were largely a result of the strong viscous interactions near the contact patch were present as suggested by Merker & Berneburg (1992). The upper vortices which Knowles *et al.* (2002) stated were conventional trailing vortices associated with lifting bodies, can also be identified. However they found that the peak vorticity associated with the inboard upper vortex is weaker and spread over a larger region than that the equivalent vortex on the outboard side. After inspection of the velocity vectors Knowles *et al.* (2002) concluded that this vortex is affected by the hub flow, which acts to suppress it. They also stated that the flow through the hub together with

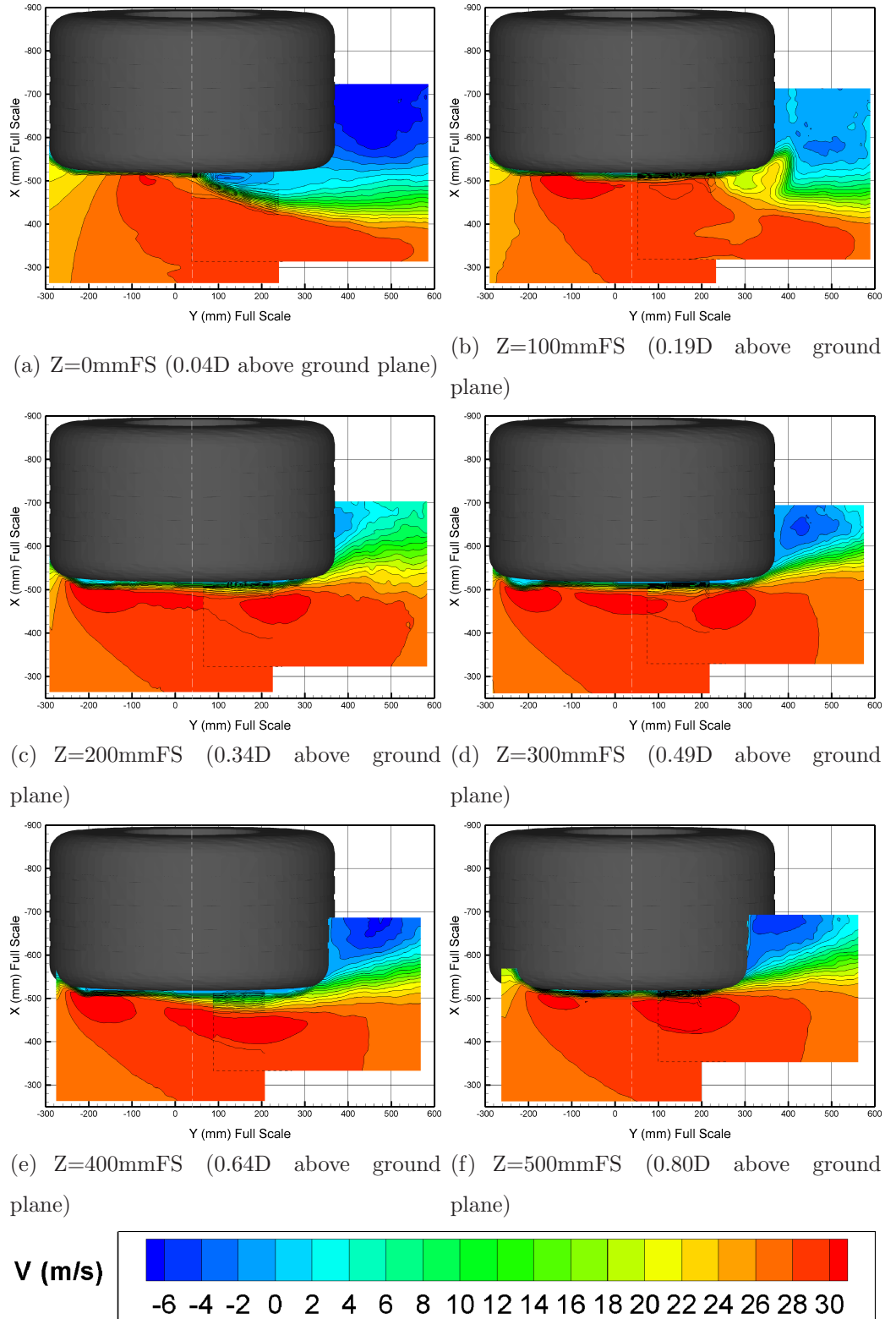


Figure 5.8: Velocity field in horizontal planes (X-Y planes) about the isolated rotating wheel at different heights above the ground plane (Z values)

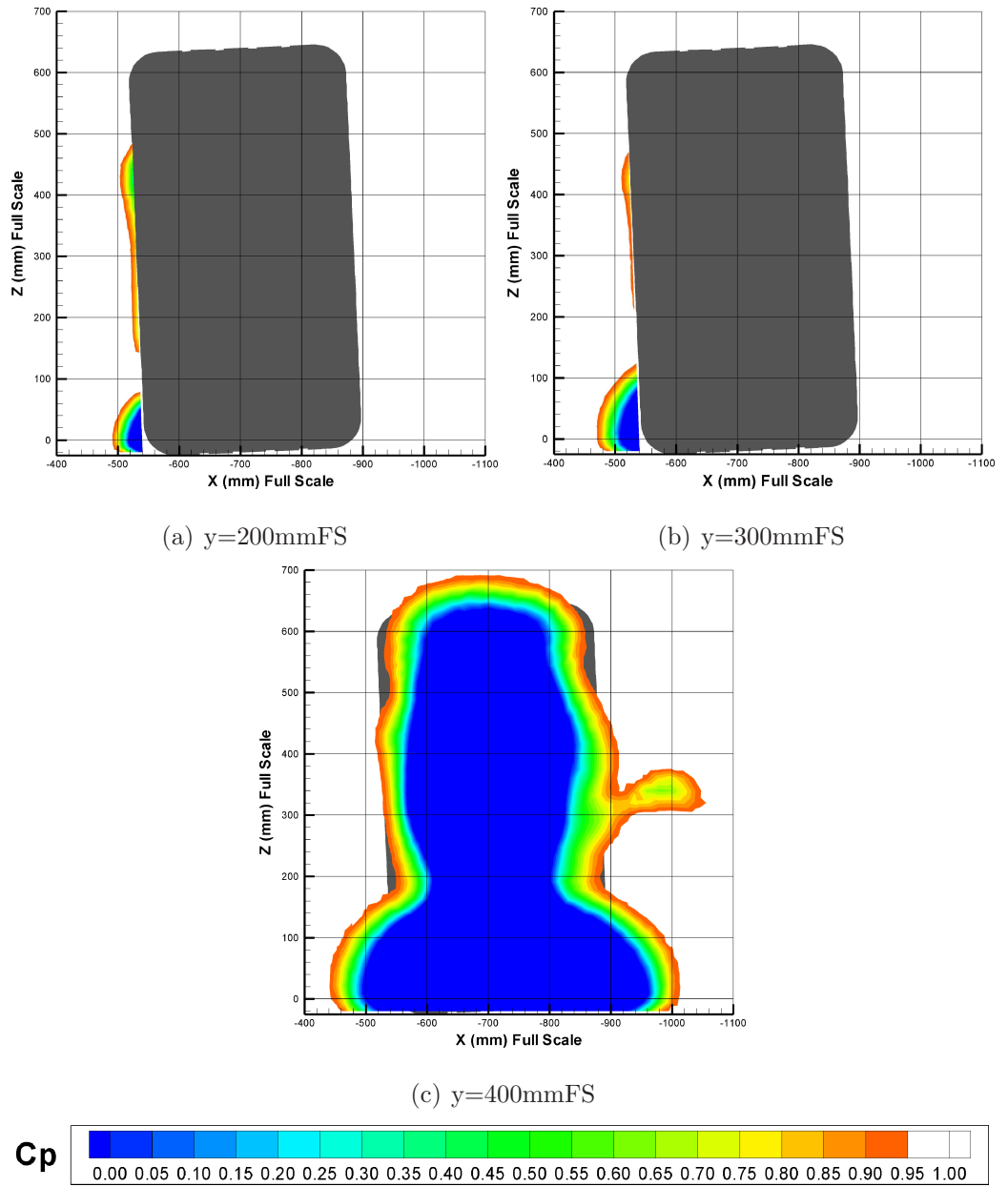


Figure 5.9: Time-averaged total pressure distribution in planes about the isolated rotating wheel ($V_\infty = 25\text{m/s}$)

the presence of the wheel support on the outboard side (the right of the figures) that restricts the formation of the hub vortices predicted by Cogotti (1983) and Merker & Berneburg (1992).

With the wheel cambered the wake has the same topology as that of the parallel wheel. However, the upper vortices have a greater peak vorticity than the lower vortices and are more intense than those in the wake of the parallel wheel and the

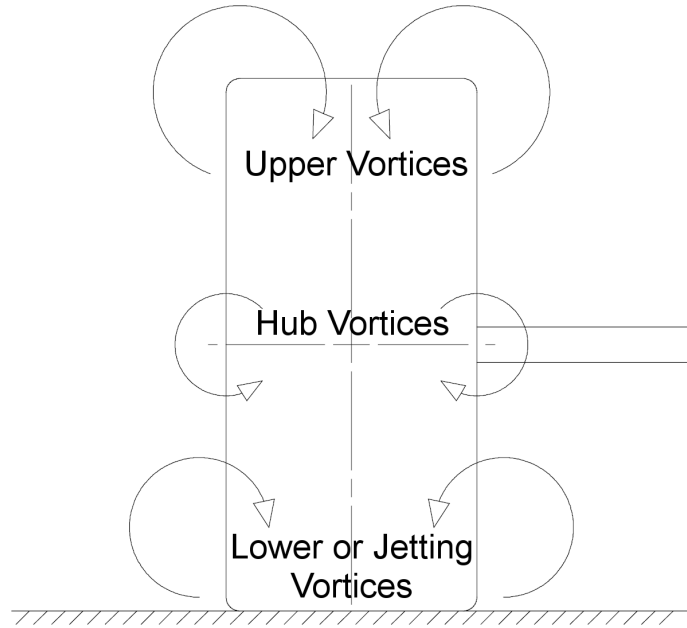


Figure 5.10: Schematic of the theoretical vortex structure in the near-field wake of a rotating wheel as proposed by Merker & Berneburg (1992)

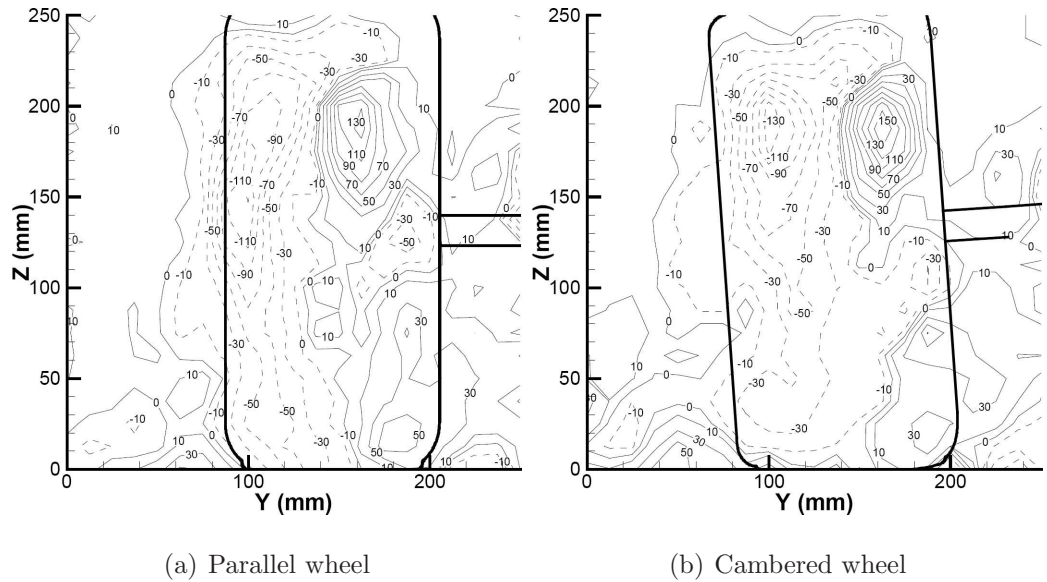


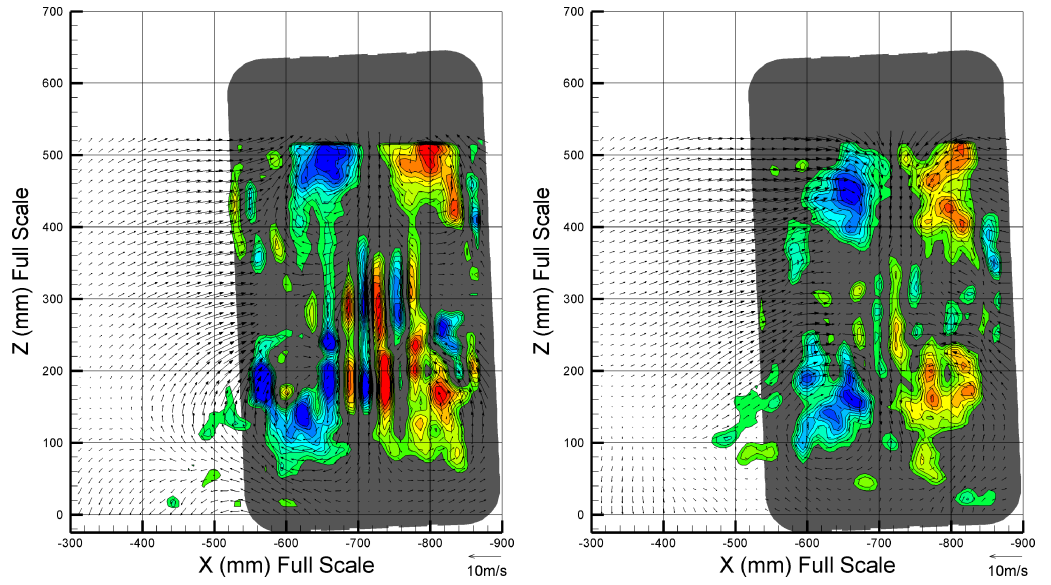
Figure 5.11: Time-averaged vorticity contours (s^{-1}) at a plane equivalent to $Y = 394mmFS$ ($0.04D$) downstream of both a parallel and cambered 40% rotating wheel at a freestream velocity of $V_{\infty} = 20m/s$, as performed by Knowles *et al.* (2002) (negative values are indicated by dashed lines)

inner upper vortex is not spread over such a large area.

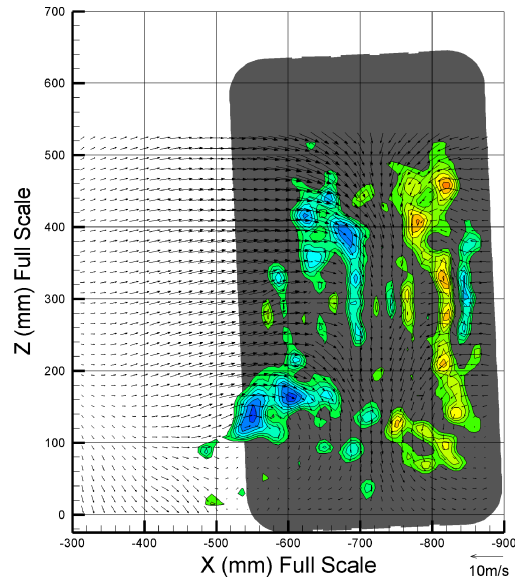
The wheel used for the research presented in this thesis is a 50% representation of a Formula 1 wheel and hence in similarity to that used by Knowles *et al.* (2002) has a hub and is supported from the outboard side by a wishbone support. The resulting time-averaged vorticity contours plotted in planes downstream of the wheel as obtained through PIV experiments can be seen in Figure 5.12. The effect of one of the experimental errors that can occur in PIV measurements can be seen in these vorticity images of the wheel wake. Close to the middle of the wheel small vertical regions of high intensity vorticity can be seen. These are thought to be a result of reflections of the laser sheet in the grooves of the pneumatic wheel. Particles in these regions would be lost in the reflections and hence the calculated velocity in this area would be zero, resulting in large velocity gradients and hence vorticity. Although effort was made to reduce this error, it has not been completely eradicated and is at its worst closest to the wheel.

These time-averaged vorticity contours were calculated from 75 instantaneous images obtained over a 5 second period (at a sampling frequency of 15Hz). One instantaneous plane of vorticity is shown in Figure 5.13 at $Y = 500mmFS$ as an example of the instantaneous flow from which the time-averaged plots are calculated. By comparing the instantaneous data with the equivalent time-averaged vorticity field presented in Figure 5.12(b), it can be seen that whilst the streamwise vorticity is generally much stronger in the instantaneous data, it is difficult to visualise a clear topology. Nevertheless there is intense vorticity of the same sign in this instantaneous data close to the vortical structures visible in the time-averaged vorticity field. The wheel wake is known to be unsteady and hence the vortical structures in the time-averaged wake will have a lower peak vorticity as instantaneously the position of the structures will vary.

From the time-averaged representation of the wheel wake shown in Figure 5.12 several of the observations made by Knowles *et al.* (2002) can be confirmed. In agreement with their results the topology of the wake consists of two pairs of counter-rotating vortices; the upper vortices and the lower or jetting vortices and there is little evidence of the middle pair. However there are differences between the two



(a) $Y = 400\text{mm}FS$ (0.05D downstream of the wheel) (b) $Y = 500\text{mm}FS$ (0.20D downstream of the wheel)



(c) $Y = 600\text{mm}FS$ (0.35D downstream of the wheel)

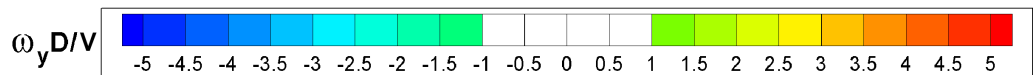


Figure 5.12: Individual planes of time-averaged non-dimensional vorticity downstream of isolated rotating wheel ($V_\infty = 25\text{m/s}$)

sets of experimental results. The peak vorticities associated with the upper vortices although greater than that of the lower vortices, are substantially different. Taking

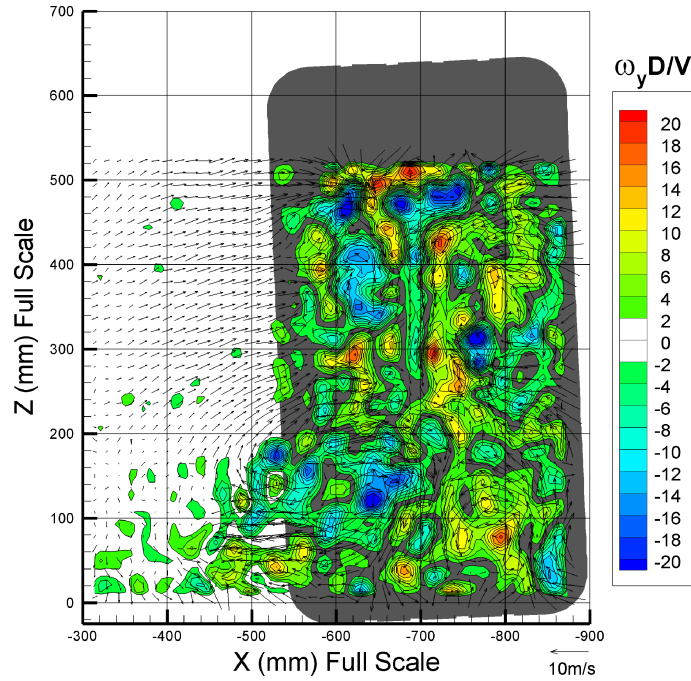


Figure 5.13: An instantaneous plane of non-dimensional vorticity obtained downstream of the isolated rotating wheel at $Y = 500mmFS$ ($V_\infty = 25m/s$)

the vorticity field associated with the cambered wheel shown in Figure 5.11(b) the peak vorticity of the upper vortices is approximately $\omega_y/DV_\infty = \pm 1.7$ compared to $\omega_y/DV_\infty = \pm 5.0$ found by this research. Although the camber of the two wheels are different (Knowles *et al.* (2002) used 4° whilst this research has been conducted on a wheel with 2.5° camber), this would not have generated the difference as the results from the parallel and cambered wheel of Knowles *et al.* (2002) are of a similar order. It is more likely that the differences originate from the experimental technique used to obtain these values. Knowles *et al.* (2002) used LDA to produce 441 time-averaged velocity vectors for which the sample time was 15 seconds. In this research the PIV technique produced 7227 time-averaged velocity vectors over a duration 5 seconds over approximately the same region. Therefore the longer time duration and the lower vector resolution used to produce the results of Knowles *et al.* (2002) could explain the difference between these two sets of experimental results.

In an attempt to quantify the approximate circulation of the vortices in the wake of the wheel, a Lamb-Oseen vortex model has been applied to the time-averaged

velocity field downstream of the wheel. The quality of the fit of this model to the data at $Y = 400mmFS$ was poor due to the errors caused by the reflections and the fact that the upper vortices were close to the boundary of the data and hence Table 5.1 shows the circulations of both of the inner vortices at $Y = 500mmFS$ and $Y = 600mmFS$. The proximity of the outer vortices to the boundary of the data also caused inaccuracies in the application of the vortex model and hence their results are not presented here. It is noted that these values are only approximate as, due to the unsteady wake, the time-averaging of the velocity field may affect the predicted circulations.

Vortex	Non-Dimensional Circulation (Γ_0/DV_∞)	
	$Y = 500mmFS$	$Y = 600mmFS$
Inboard Lower	-0.143	-0.118
Inboard Upper	-0.119	-0.135

Table 5.1: Approximate circulation values of the inboard vortices in two planes downstream of the isolated wheel wake as obtained from the time-averaged PIV velocity field ($V_\infty = 25m/s$)

From these results it can be seen that in the plane closest to the wheel, the lower or jetting vortex is the strongest feature. Further downstream this trend is reversed and it is the upper vortex whose circulation is greater. It is uncertain whether this trend is physical or a result of experimental error. At $Y = 500mmFS$ there are still inaccuracies associated with the reflections from the wheel which may affect the results of this application of the vortex model. Nevertheless, these results show that the circulations of these wheel vortices are comparable to the weaker vortices that are generated by the McLaren front wing (whose circulations are $-0.115 \leq \Gamma_0/DV_\infty \leq -0.264$), in spite of their peak vorticity being substantially weaker.

As the wake structure flows downstream there is a tendency for the upper vortex pair to descend towards the lower pair. This can be seen in the vorticity data shown in Figure 5.12 and is also confirmed by the images from the laser-smoke flow

visualisation shown in Figure 5.14. These figures show the inboard half of the wake in which the inboard upper and lower vortices can be identified. If this behaviour continues downstream then the vortices would interact and merge together to leave a far-field wake structure with a single pair of vortices at the lower part of the wake. This was the structure obtained experimentally by Bearman *et al.* (1988) at a position of 2.5 diameters downstream of the wheel (shown in Figure 2.31(b)). They found a pair of counter-rotating vortices with a peak vorticity of $\omega_y D/V_\infty = \pm 0.75$ at their centres which is of a similar value to those found at a position of $y=600\text{mmFS}$ ($0.35D$ downstream of the wheel) shown in Figure 5.12(c).

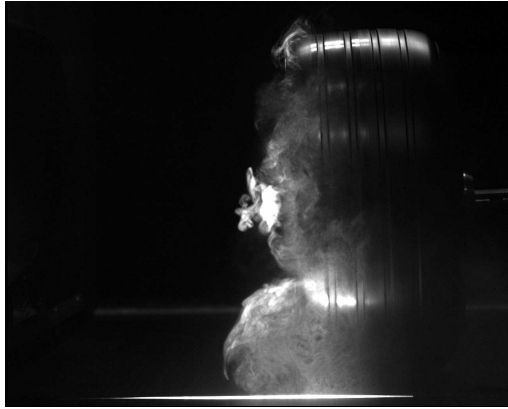
It has been shown that the aerodynamics of a rotating wheel are complicated and the flow is strongly affected by the presence of the ground plane and the rotation of the wheel. The aerodynamics near the ground are affected by the jetting flow resulting from the viscous interactions which take place near the contact patch and downstream of the wheel, the wake consists of two counter-rotating vortex pairs which are of a similar strength to the weaker vortices in the McLaren trailing vortex system.

In the next part of this chapter the single trailing vortices discussed in Section 5.1 will be placed in positions about the rotating wheel. The resulting behaviour of the vortex will be analysed together with the effect that the vortex has on the structure of the wheel wake.

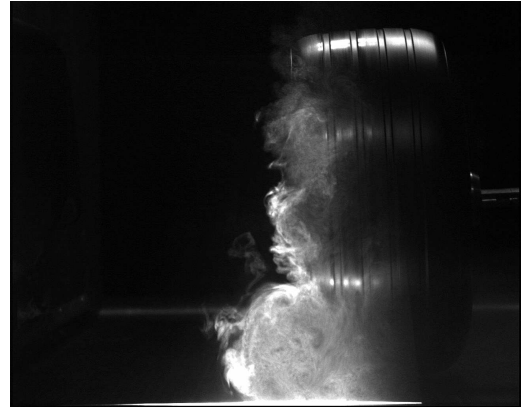
5.3 Single Vortex in Position of Main Vortex from McLaren System

The influence of the rotating wheel on the behaviour of a single vortex located in the position of the main vortex from the McLaren system for the four ride heights, has been investigated by positioning the three differing strength vortices in positions similar to that of the McLaren system. This is summarised by Figure 5.15 which shows the initial positioning of each of the vortices at the different ride heights.

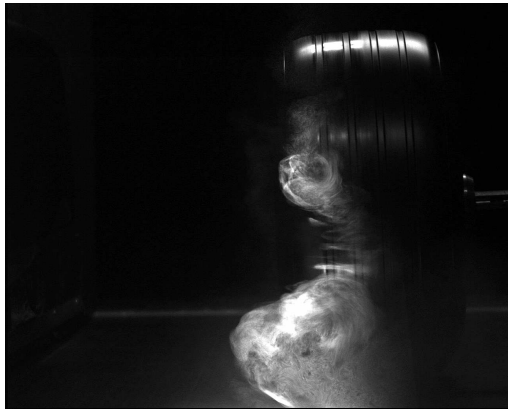
The resulting time-averaged vorticity field from placing the strongest vortex in



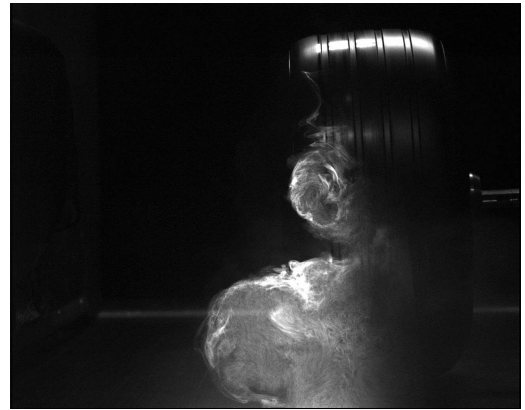
(a) $Y = 400mmFS$ (0.05D downstream of the wheel)



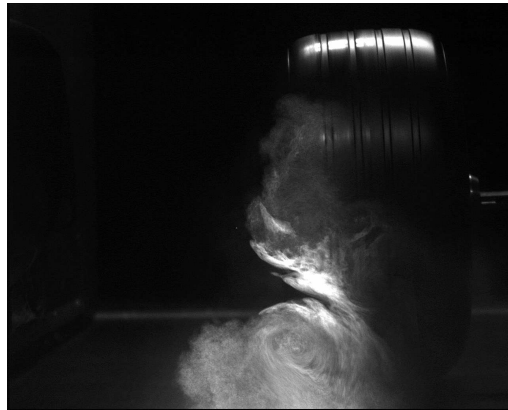
(b) $Y = 500mmFS$ (0.20D downstream of the wheel)



(c) $Y = 600mmFS$ (0.35D downstream of the wheel)



(d) $Y = 700mmFS$ (0.50D downstream of the wheel)



(e) $Y = 800mmFS$ (0.65D downstream of the wheel)

Figure 5.14: Instantaneous laser smoke flow-visualisation images of flow downstream of isolated rotating wheel ($V_\infty = 12.5m/s$)

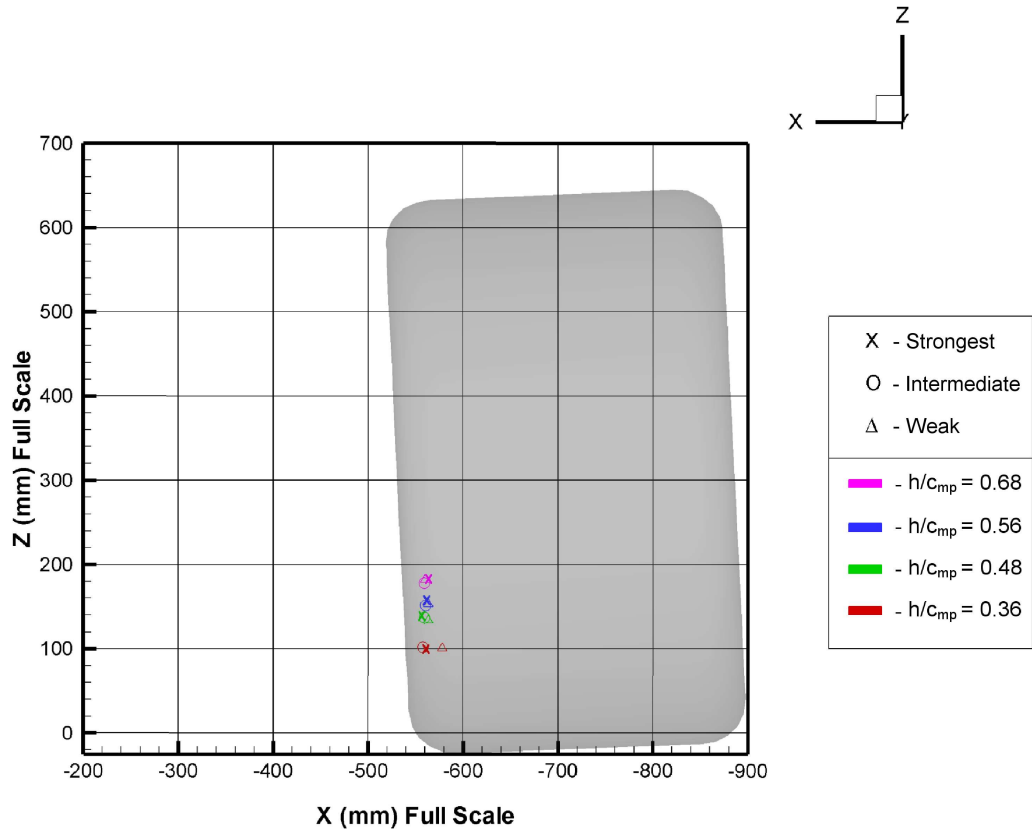


Figure 5.15: Plot showing initial positioning of vortices for single vortex placed in the main vortex position, at a plane of $Y = -200mmFS$ without wheel (wheel silhouette included to show its position relative to vortex)

each of the four different ride height configurations can be seen in Figure 5.16. To improve the clarity of these figures, vorticity values between $-5 \leq \omega_y D/V_\infty \leq 5$ have been removed. As was presented on the discussion on the aerodynamics of an isolated wheel, the levels of vorticity in the wake of the wheel are of the same order as these removed levels. Hence, in these figures it appears that there is no wheel wake which is incorrect. The effect of the single trailing vortex on the structure of the wheel wake will be examined later with modified vorticity contours.

From this vorticity data, the presence of the single vortex can be clearly identified passing inboard of the wheel. From the information contained within Figure 5.16 and the perspective from which the plots are presented, it is difficult to observe any distinct differences between the four ride height configurations. However this can be obtained by examining the trajectory of the vortex as determined by post-

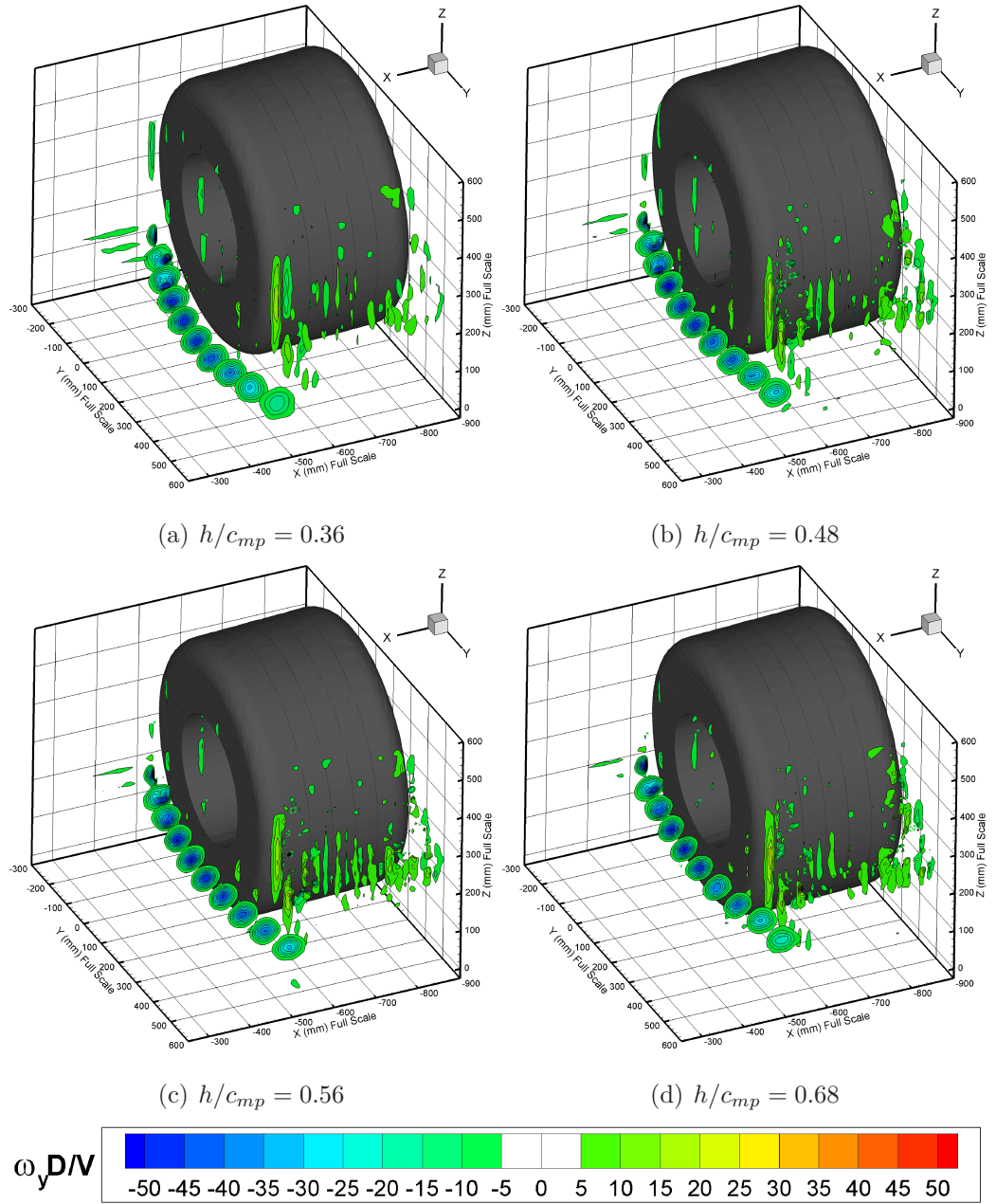
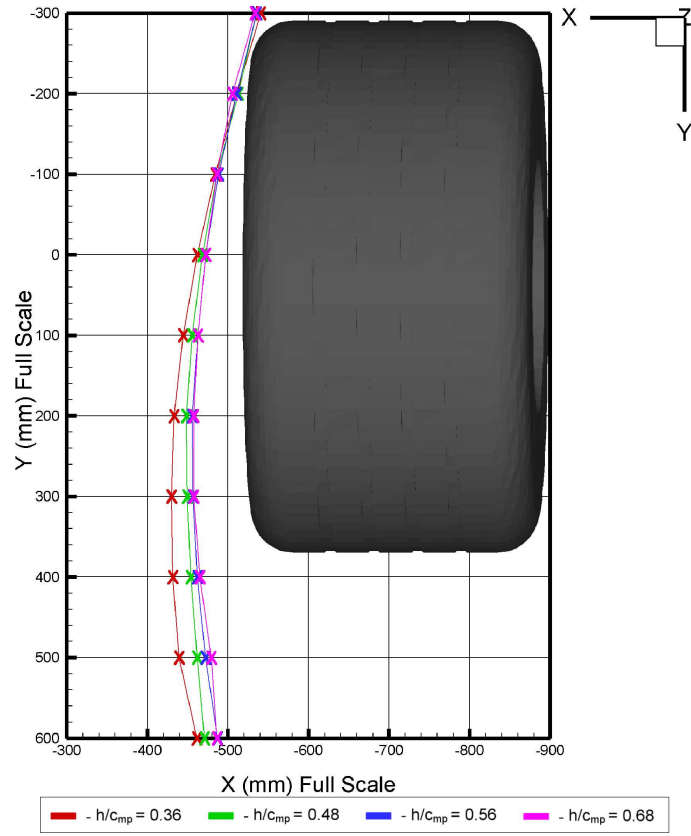


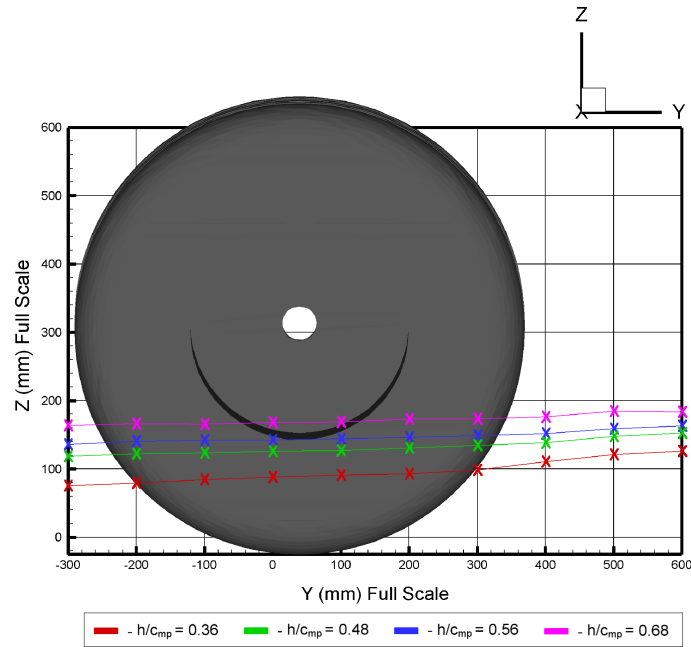
Figure 5.16: Non-dimensional time-averaged vorticity generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the main vortex position, as it passes about the rotating wheel at varying ride heights

processing the time-averaged velocity field to find the vortex centre. The results of this process is shown in Figure 5.17 where the trajectory of the vortex is plotted for the different ride heights as viewed in the X-Y and Y-Z planes.

As can be seen from Figure 5.17(a), the lateral trajectory shows the inboard movement (positive X direction) of the strongest vortex as it travels downstream



(a) X-Y plane



(b) Y-Z plane

Figure 5.17: Time-averaged trajectory of the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) about the wheel when located in the main vortex position at varying heights

about the wheel. Once the wheel has been passed the vortex curves back outboard towards the wheel wake. This lateral trajectory is mostly a result of the vortex travelling with the local flow, which would adopt this path. However, there are other influences which can explain the trend for the vortex in the lowest configuration to pass further outboard than when released in higher positions. As was shown in Section 5.2, the feature referred to as the ‘jetting’ flow, emanates from near the contact patch at an oblique angle to the rest of the flow. If the vortex passes close to this feature then it will be affected and may be pushed further inboard. The increase in inboard lateral movement with ride height may also be a direct result of the influence of the ground plane on the trailing vortex. The image vortex in the ground plane induces an inboard velocity on the wing vortex. As the distance away from the ground is increased the lateral movement caused by the induced velocity will be less. Due to the observed trend it is thought that this is the most likely explanation for the differing lateral trajectories.

As the vortex passes downstream of the trailing edge of the wheel it begins to interact with the wake from the wheel. From the time-averaged vorticity fields plotted in Figure 5.16, it can be seen that downstream of the wheel the peak vorticity associated with the strongest vortex decreases. This is a consequence of the interaction with large scale fluctuations from the wheel wake. Figure 5.18 contains plots of the instantaneous vorticity at two different points in the flow and at two different time instances (separated by $\Delta t = 0.46$ seconds), as well as the equivalent time-averaged vorticity. Note that the vorticity contour levels are the same for all of the plots contained within this figure and are the same as Figure 5.16 without the values between $-5 \leq \omega_y D/V_\infty \leq 5$ being blanked out. Inboard of the wheel at $Y = 0mmFS$, it can be seen that by comparing the instantaneous results shown in Figures 5.18(a) and 5.18(c) with the time-averaged equivalent in Figure 5.18(e), that the position of the vortex is steady and that the peak vorticity is of a similar value in each of the three plots. Downstream of the wheel at $Y = 600mmFS$, from the time-averaged vorticity field shown in Figure 5.18(f) it appears that the vortex has weakened as the peak vorticity is lower than other planes further upstream. However, upon inspection of the instantaneous vorticity plots in Figures 5.18(b)

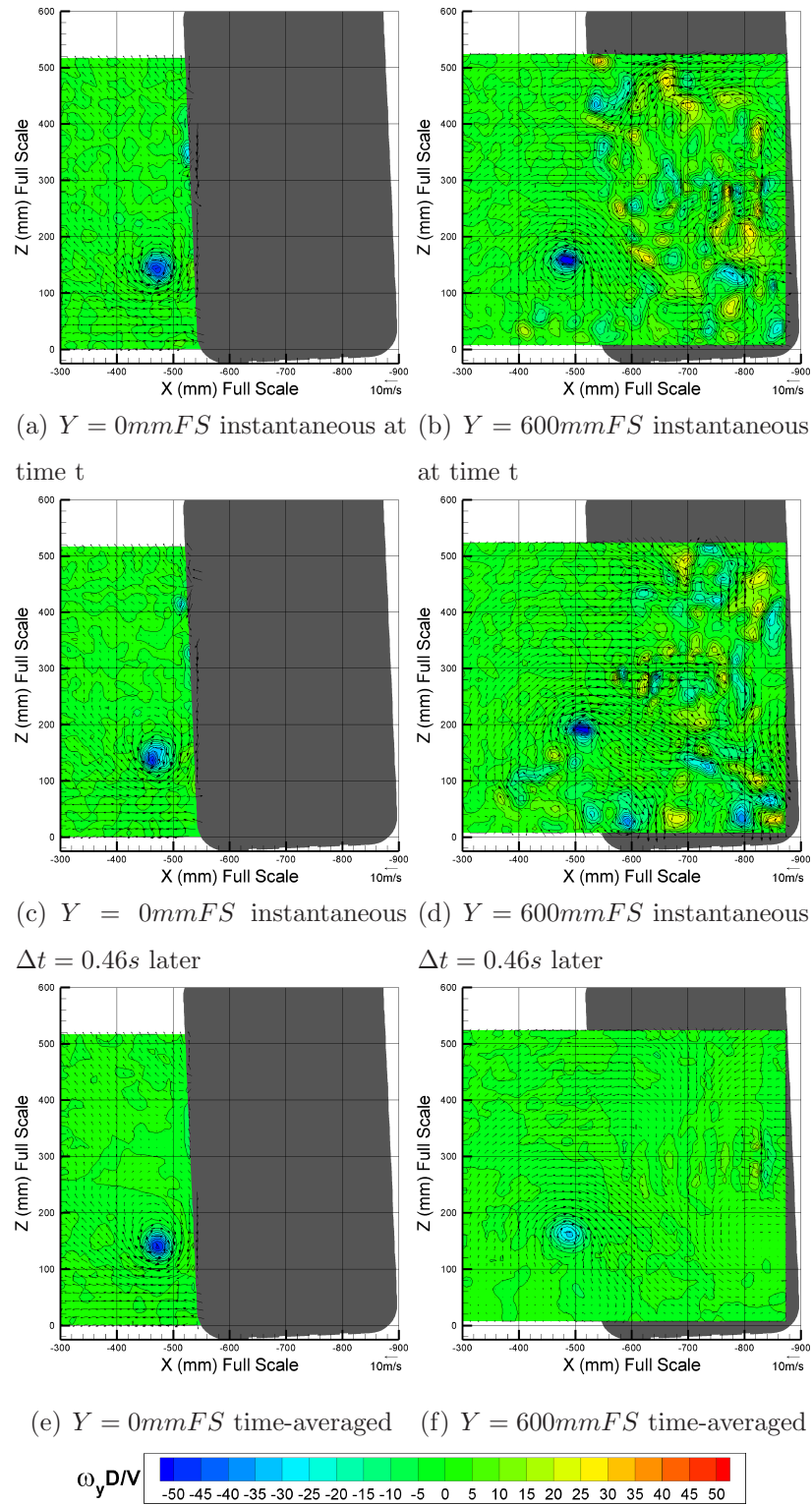


Figure 5.18: Comparison of instantaneous and time-averaged non-dimensional vorticity fields at two different points in the flow for the strongest vortex in the position of the main vortex at a ride height of $h/c_{mp} = 0.56$ as it passes about the rotating wheel

and 5.18(d), it can be seen that the peak vorticity of the vortex is of a similar value to that calculated further upstream. However, the position of the vortex centre in these two instantaneous plots is substantially different. The large scales from the wheel wake cause the vortex centre to vary instantaneously which diminishes the absolute value of the time-averaged vorticity.

Further observations on the interaction of the single vortex with the wheel wake can be made by examining the time-averaged vorticity field downstream of the wheel with reduced contour levels which allow the wake to be included. This is presented in Figure 5.19.

As can be seen from this figure, the positioning of the single vortex at a location similar to that of the main vortex in the McLaren system, causes it to interact with the like-signed inboard lower wheel wake vortex. This interaction is greater at the lowest ride height as the patches of vorticity associated with these two flow structures are in the closest proximity to one another. As the vortex is shed from higher ride heights, the separation between these two regions of negative vorticity increases and the interaction diminishes. The interaction of these two co-rotating vortical structures causes the vortices to orbit or merge together as a co-rotating vortex pair (see Section 2.3.1.1). This interaction leads to a clockwise motion of the wing vortex about the wheel vortex and is the reason for the change in the vertical trajectory of the vortex downstream of the wheel shown in Figure 5.17(b).

As was discussed in the introduction to this chapter, the effect of modifying the strength of the vortex has also been investigated. Figures 5.20 and 5.21 show the vorticity data and the trajectories of the vortex about the wheel when the strength of the vortex is varied whilst the initial position is maintained. The results contained within these figures are for the three different strength vortices (strongest, intermediate and weakest) in a position similar to the main vortex when the McLaren front wing was set at a ride height of $h/c_{mp} = 0.56$.

From this data, it can be seen that for each of the different strengths, the single vortex moves inboard and is still present as a coherent structure downstream of the wheel. In similarity with the strongest vortex at different heights, the peak vorticity of the vortex decreases as it becomes affected by the wake of the wheel. This

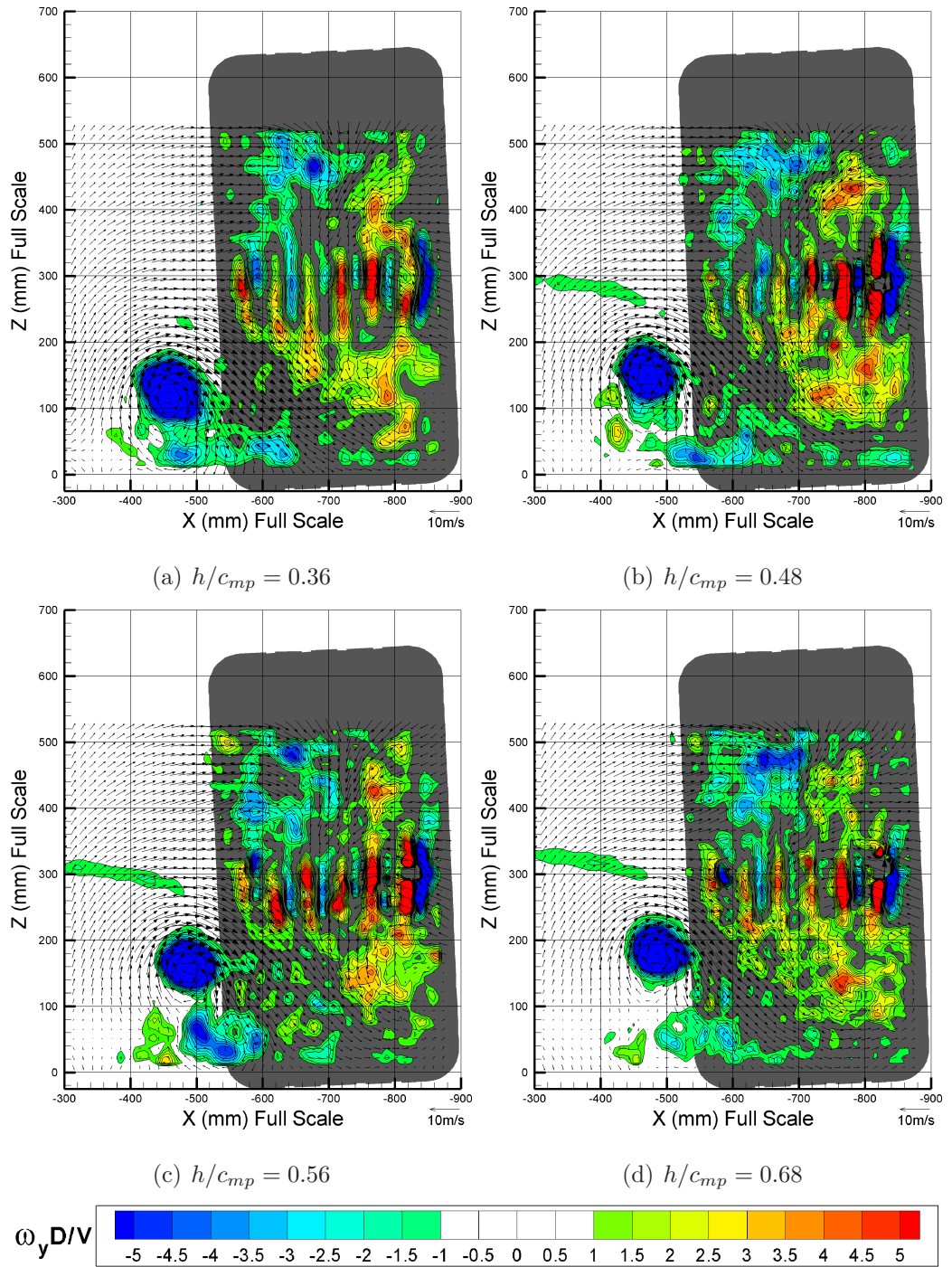


Figure 5.19: Non-dimensional time-averaged vorticity in the wake of the wheel ($Y = 600mmFS$) as generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the main vortex position at varying ride heights

appears more dramatic with these weaker vortices as the associated levels of vorticity diminishes below the $\omega_y D/V_\infty = -5$ cutoff at the furthest plane downstream.

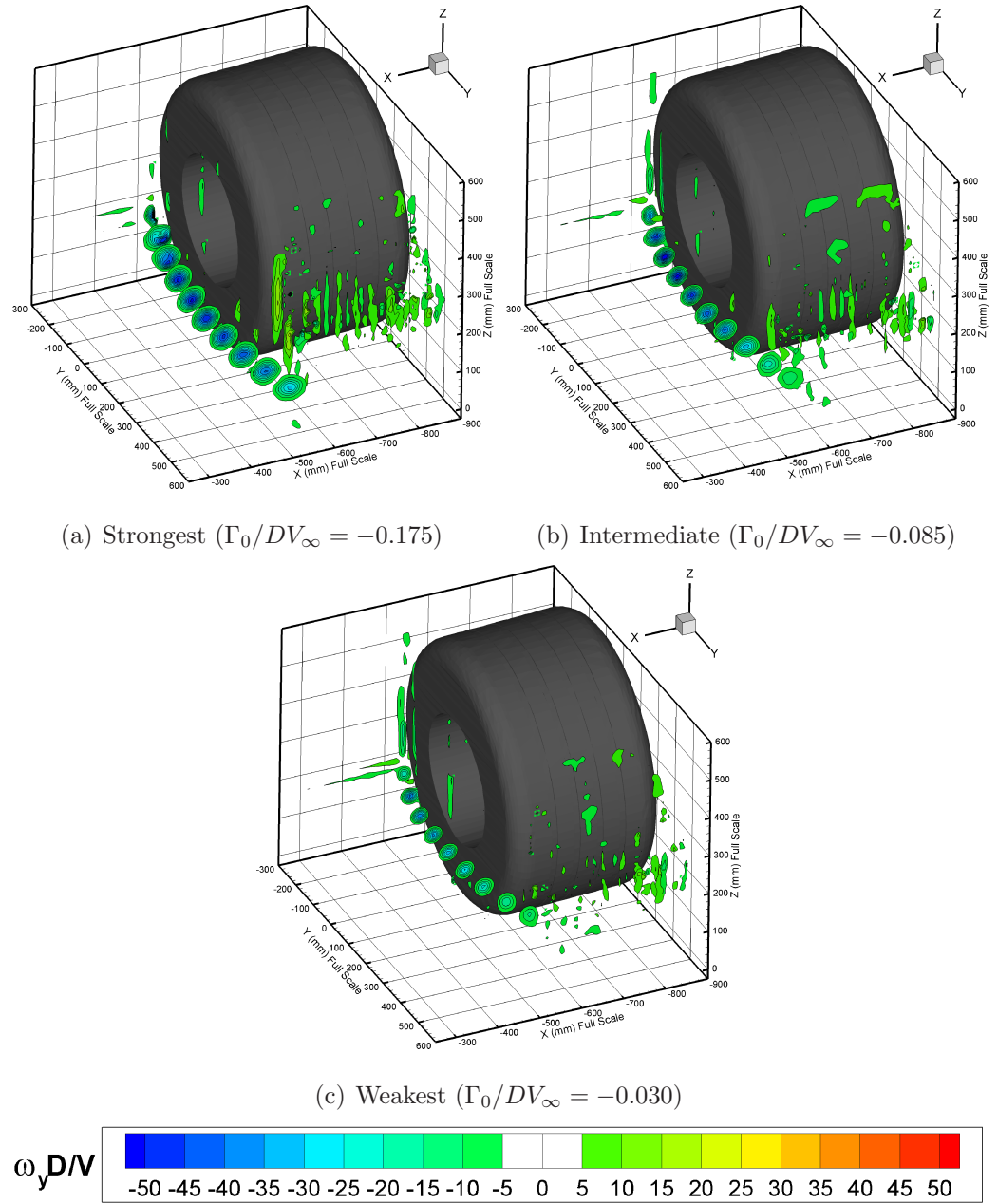
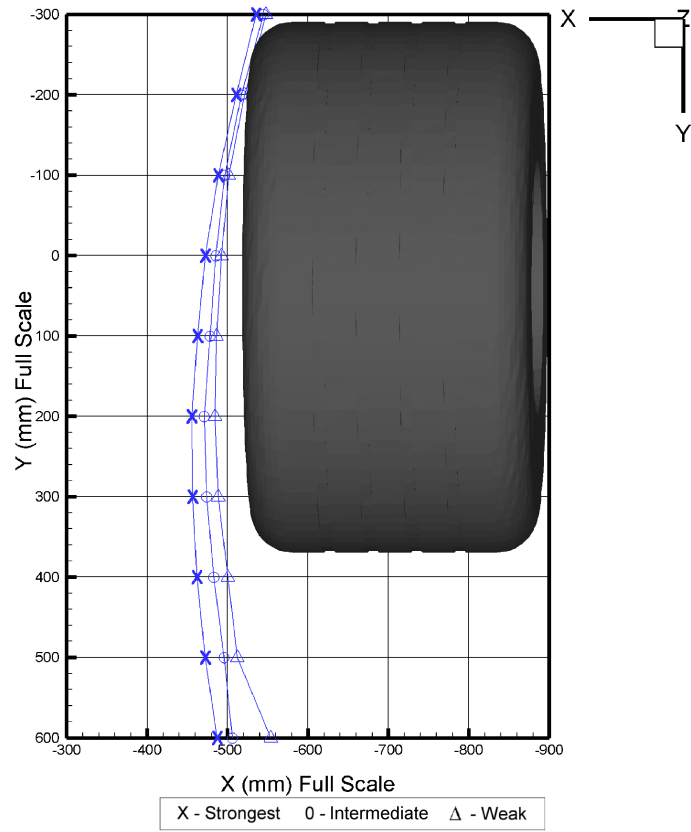
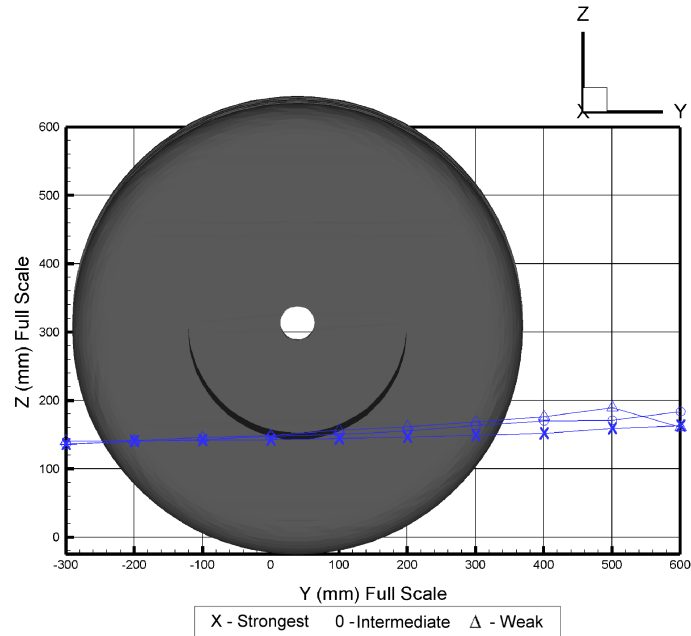


Figure 5.20: Non-dimensional time-averaged vorticity generated by the single vortex at varying strengths located in the main vortex position as a ride height of $h/c_{mp} = 0.56$ with the rotating wheel

From Figure 5.21(a), it can be seen that there appears to be a trend in the lateral displacement of the vortex trajectory as the circulation of the vortex is reduced. The strongest vortex has the most inboard trajectory with the lateral distance to the wheel decreasing as the circulation is reduced. Due to the constant height of the vortex in this investigation it is thought that the lateral movement is a consequence



(a) X-Y plane



(b) Y-Z plane

Figure 5.21: Trajectory of the single vortex at varying strengths located in the main vortex position at a ride height of $h/c_{mp} = 0.56$ as it navigates about the rotating wheel

of the interaction of the single vortex with the ground plane. The induced velocity from the image vortex in the ground plane would decrease as the circulation of the wing vortex is reduced. This would lead to the observed trend in the lateral trajectory of the vortex. As with the strongest vortex, the interaction with the wheel wake occurs downstream of the wheel and there is a corresponding vertical displacement in the trajectories of the vortices.

5.4 Single Vortex in Position of Top Vortex from McLaren System

In the previous chapter it was shown that the dominant feature in the McLaren trailing vortex system at low ride heights was the main vortex. However, as the ride height increases the circulation of the main vortex decreases and the strength of the top vortex increases. In this section the effect of placing a single vortex in a position similar to the top vortex will be examined.

The position of the single vortex placed at each of the different strengths and ride heights is shown in Figure 5.22. In comparison to the main vortex, this vortex is located at a higher distance above the ground plane and further outboard towards the longitudinal centreline of the wheel.

The vorticity field generated by the strongest vortex placed in the four different ride heights can be seen in Figure 5.23 and the trajectories, obtained after the post-processing, are presented in Figure 5.24.

From the plots of the time-averaged vorticity, it can be seen that when introduced at the position of the top vortex, the wing vortex passes closer to the wheel at a greater height above the ground plane than when placed in the main vortex position. The lateral trajectory of the strongest vortex presented in Figure 5.24(a), is similar to that of the same structure in the main vortex position, as it forms a lateral arc about the wheel with distance downstream. However due to its initial position further above the ground, it is less affected by the induced velocity from the image vortex in the ground plane. The height of the vortex also means that the flow about

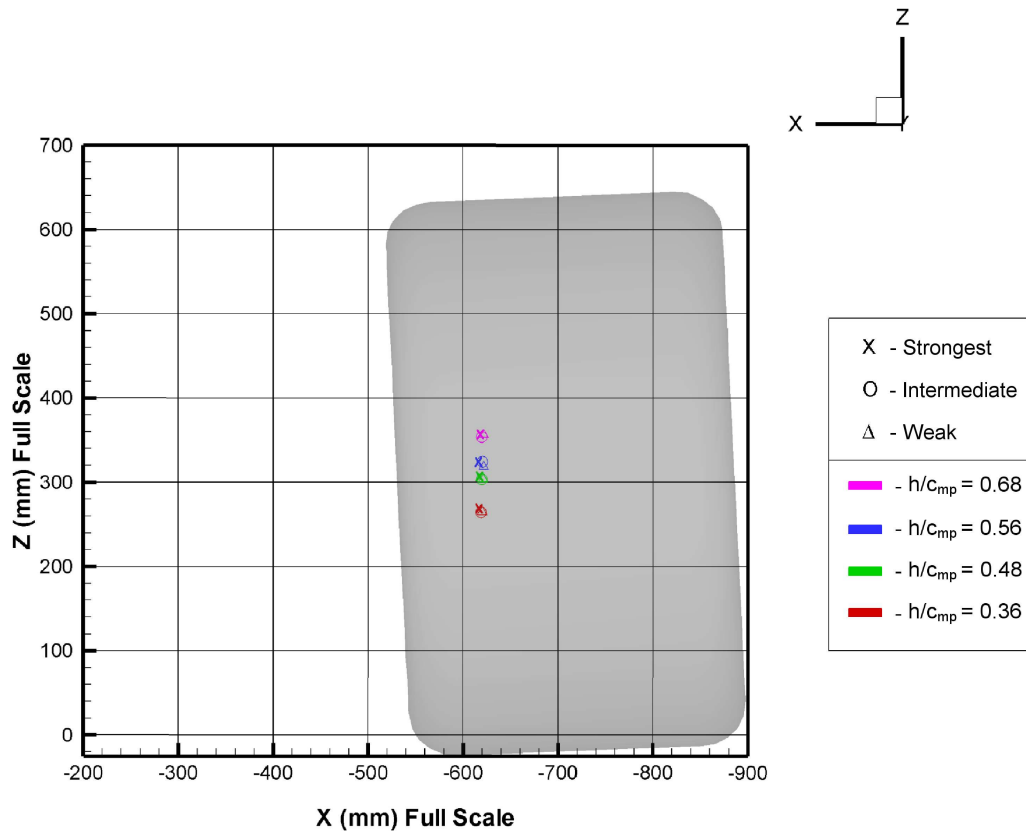


Figure 5.22: Plot showing initial positioning of vortices for single vortex placed in the top vortex position, at a plane of $Y = -200mmFS$ without wheel (wheel silhouette included to show its position relative to vortex)

the contact patch will not affect the path of the vortex and the curvature of the trajectory is a consequence of the local velocity about the wheel. This observation is reinforced by the fact that there is very little difference in the paths of the vortices about the wheel at the various ride heights.

When the vortex travels past the wheel, in agreement with the results from the main vortex position, the time-averaged peak vorticity decreases. This reduction in peak vorticity appears to occur earlier than was seen for the main vortex position. This is confirmed by the instantaneous vorticity fields shown in Figure 5.25. Inboard of the wheel at $Y = 0mmFS$ the centre of the vortex appears to be reasonably steady and the time-averaged peak vorticity is very similar to the instantaneous vorticity values. However just downstream of the wheel at $Y = 400mmFS$ the peak vorticity associated with the wing vortex in the time-averaged data is diminished from that

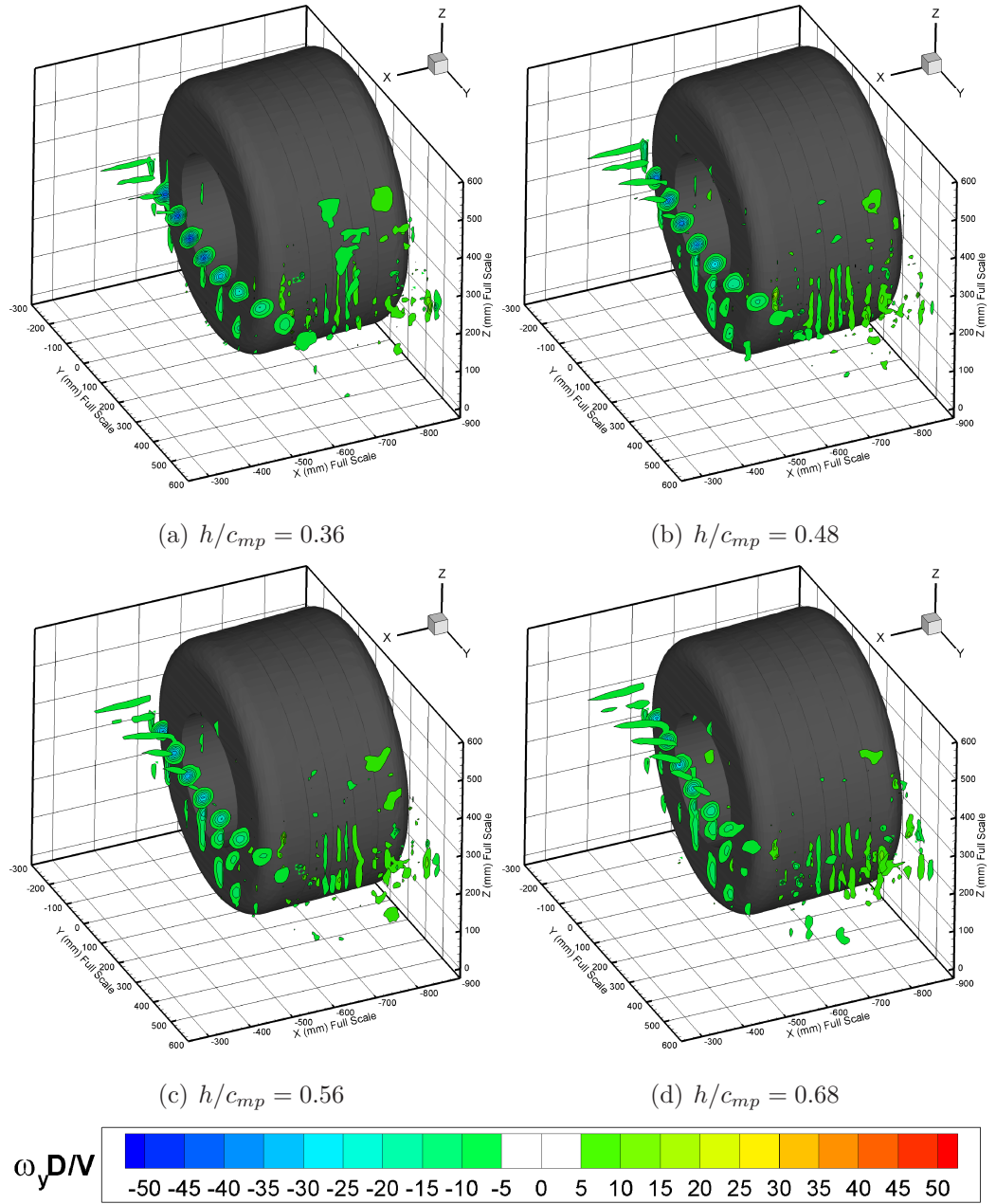
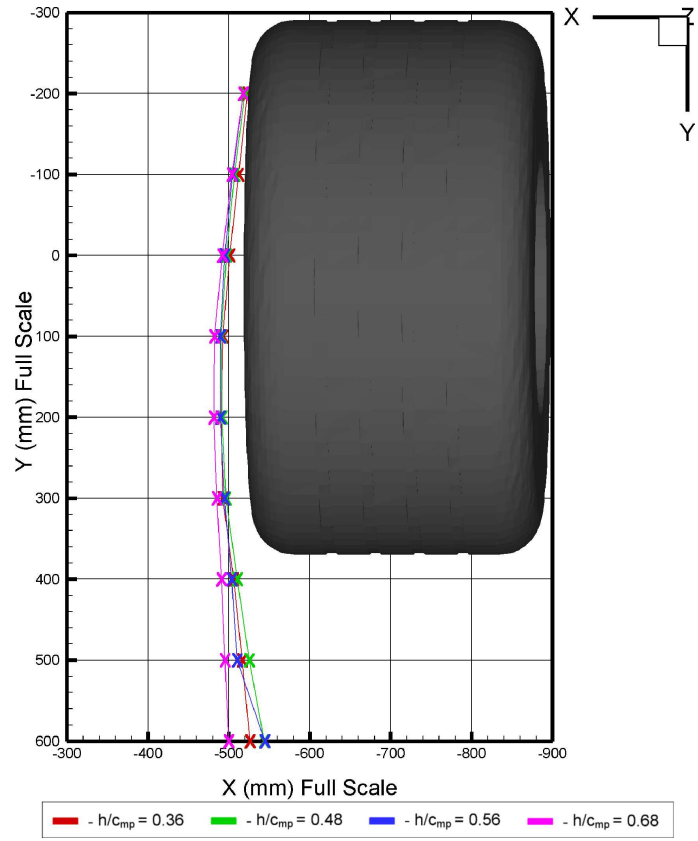
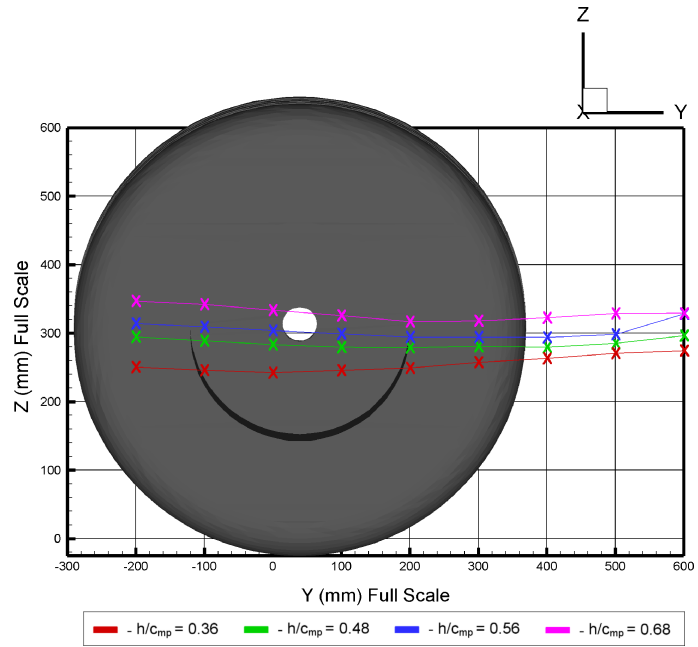


Figure 5.23: Non-dimensional time-averaged vorticity generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the top vortex position, as it passes about the rotating wheel at varying ride heights

upstream. By inspecting the instantaneous vorticity fields shown in Figures 5.25(b) and 5.25(d), it can be seen the vortex centre is in a different location from one instant to another, thereby causing the time-averaged peak vorticity to be less. In this configuration the unsteadiness in the vortex centre occurs at a location closer to the trailing edge of the wheel than when the wing vortex is in the main vortex

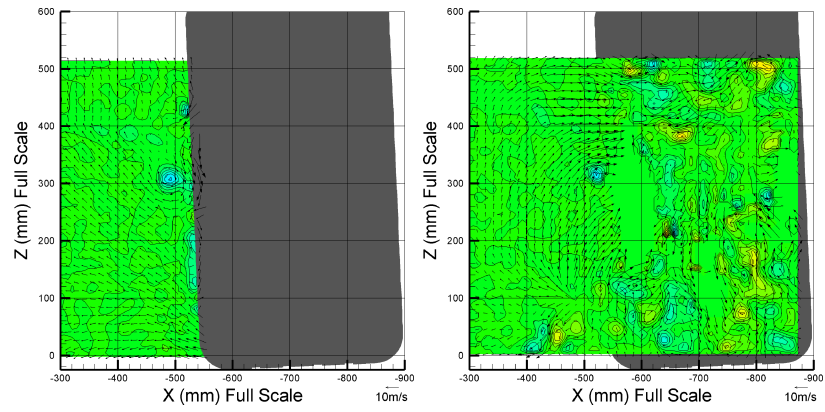


(a) X-Y plane

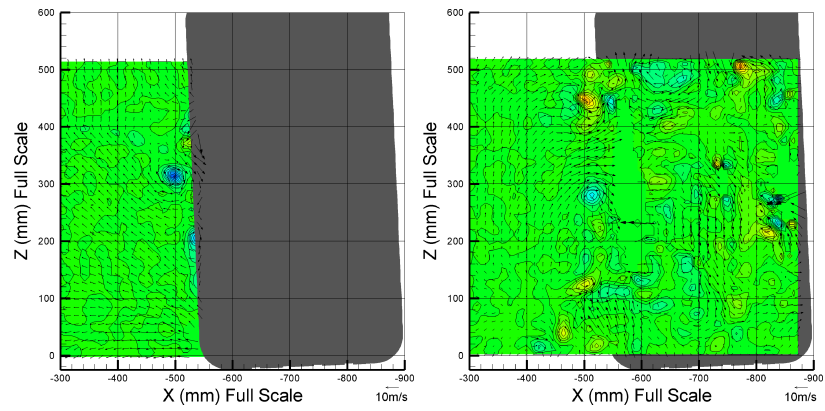


(b) Y-Z plane

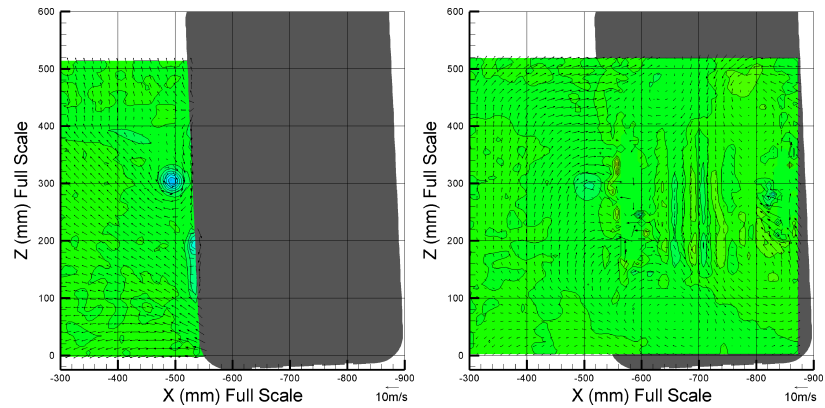
Figure 5.24: Trajectory of the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) about the wheel when located in the top vortex position at varying heights



(a) $Y = 0mmFS$ instantaneous at time t (b) $Y = 400mmFS$ instantaneous at time t



(c) $Y = 0mmFS$ instantaneous $\Delta t = 0.46s$ later (d) $Y = 400mmFS$ instantaneous $\Delta t = 0.46s$ later



(e) $Y = 0mmFS$ time-averaged (f) $Y = 400mmFS$ time-averaged

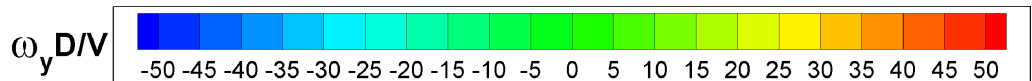


Figure 5.25: Comparison of instantaneous and time-averaged non-dimensional vorticity fields at two different points in the flow for the strongest vortex in the position of the top vortex at a ride height of $h/c_{mp} = 0.56$ as it passes about the rotating wheel

position. It is thought that that is a consequence of vortex being closer to the wheel when introduced in this position.

The interaction of the strongest vortex with the wheel wake when in the position of the top vortex, can be seen from the vorticity plots in Figure 5.26. It is apparent from these vorticity fields that the wing vortex interacts with the inboard upper vortex of the wheel wake. These two vortices are of the same rotation and hence begin to orbit and merge about one another. The interaction between these two vortices is more pronounced when the wing vortex is at the highest ride height (Figure 5.26(d)). In this configuration the vorticity associated with the wheel vortex is displaced by a greater amount than the other ride heights due to the influence of the wing vortex. The interaction between these two vortices appears to reduce as the ride height of the wing is decreased.

As with the single vortex located in the main vortex position, the effect of strength on the behaviour of a vortex introduced in a position similar to that of the McLaren top vortex has been examined. The resulting vorticity fields and trajectories for a vortex at the three different strengths at a ride height of $h/c_{mp} = 0.56$ are plotted in Figures 5.27 and 5.28 respectively.

In comparison to the time-averaged vorticity field generated by the single vortex in the main vortex position, the reduction in the peak vorticity of this structure about the wheel is much more pronounced. In Figure 5.27(c) the vorticity generated by the weakest vortex is almost indistinguishable even with reduced contour levels. However after post-processing the data, the presence of this vortex has been found and its path about the wheel determined. This is shown in Figure 5.28 where the outline of the wheel has been made transparent as the path of the intermediate and weakest vortex pass extremely close to the wheel and would otherwise not be visible due to the camber on the wheel.

By being closer to the wheel the vortex may be more affected by the aerodynamics caused by its rotation. The no-slip condition at the surface of the wheel causes the flow close by to rotate with it. Hence upstream of the wheel's centreline the air close to the wheel is descending whilst downstream of the contact patch the flow is being carried vertically upwards (see Figure 5.29). Therefore if a vortex is travelling close

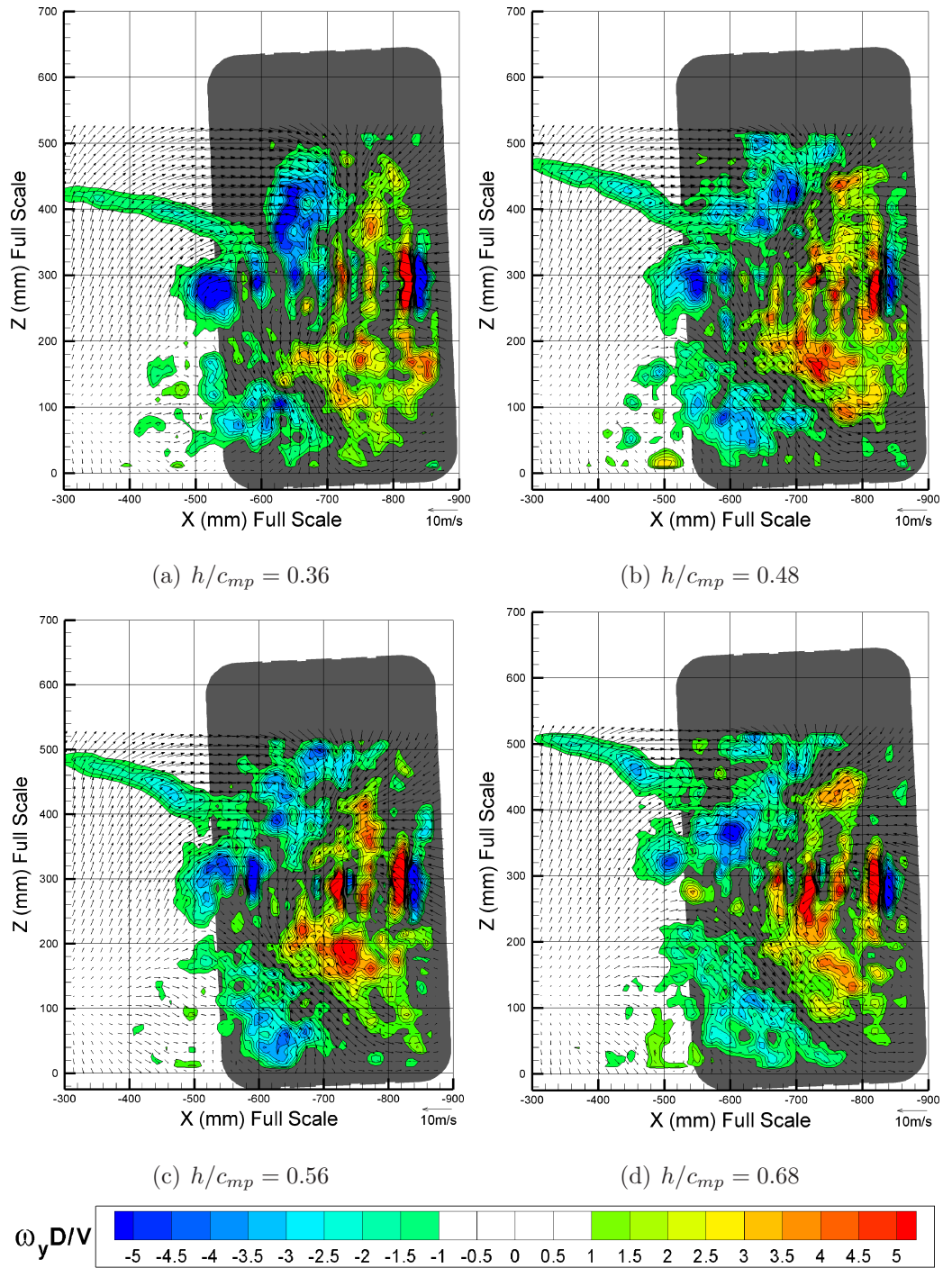


Figure 5.26: Non-dimensional time-averaged vorticity in the wake of the wheel ($Y = 600mmFS$) as generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the top vortex position at varying ride heights

to the wheel, the differences in the vertical velocity caused by the wheel rotation will tend to ‘shear’ the vortex. It is uncertain whether this is the reason why the

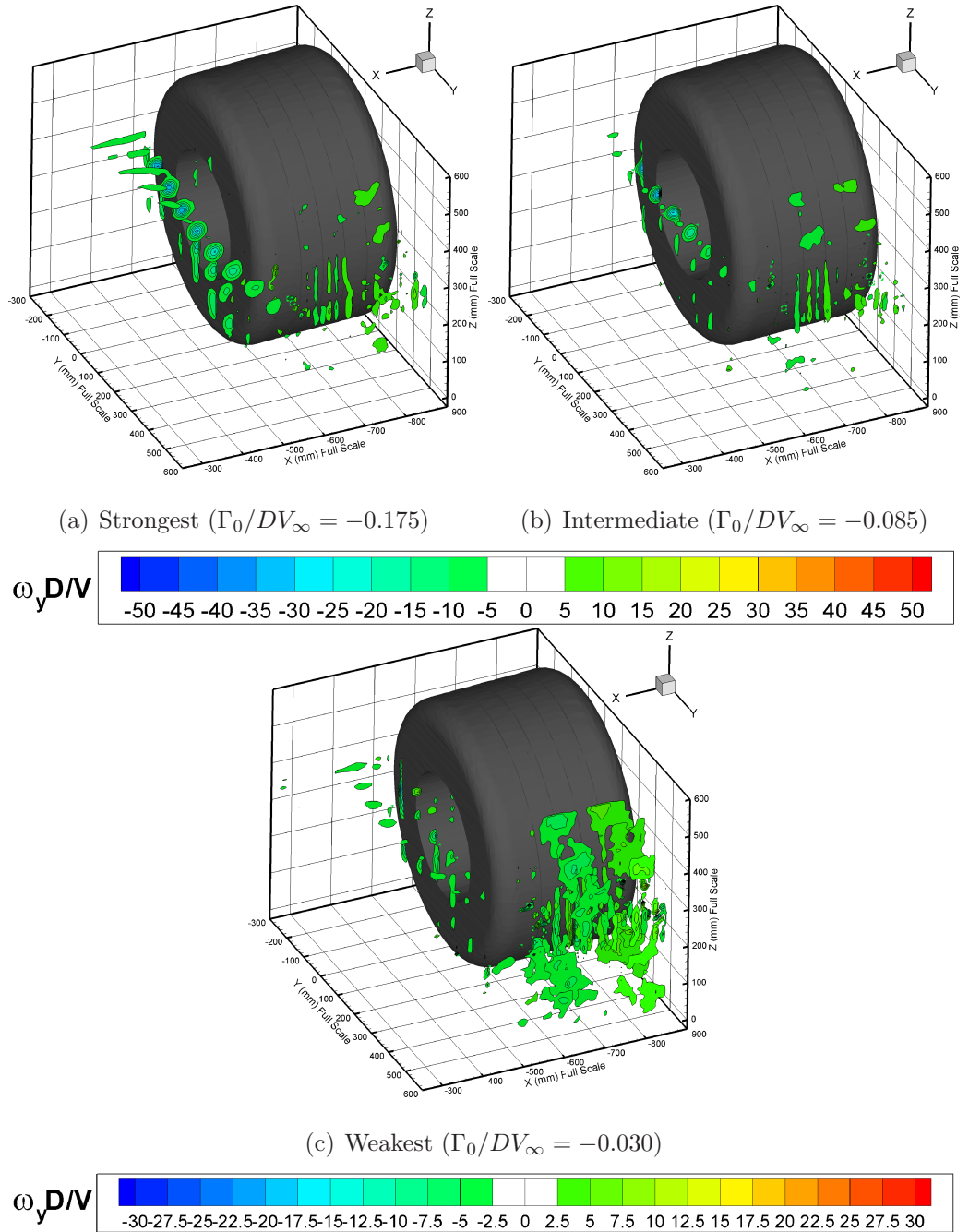
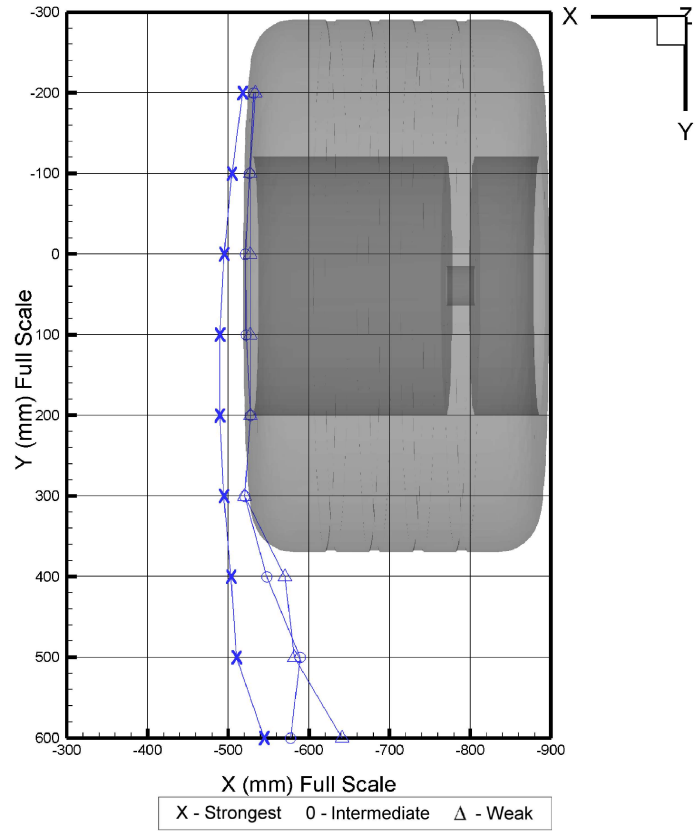
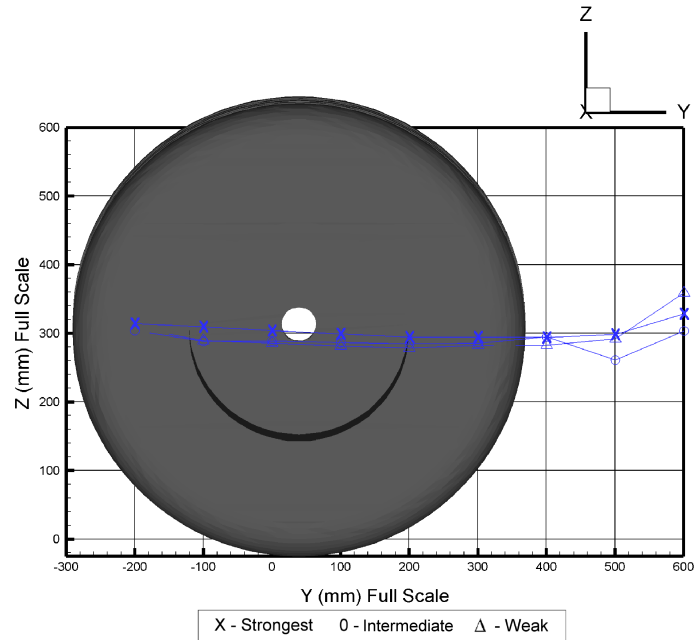


Figure 5.27: Non-dimensional time-averaged vorticity generated by the single vortex at varying strengths located in the top vortex position as a ride height of $h/c_{mp} = 0.56$ with the rotating wheel

time-averaged vorticity associated with the intermediate and weakest vortex is less than seen previously. The instantaneous vorticity fields (not presented here) show the vortex position to vary significantly with time and in some instances it is difficult



(a) X-Y plane



(b) Y-Z plane

Figure 5.28: Trajectory of the single vortex at varying strengths located in the top vortex position at a ride height of $h/c_{mp} = 0.56$ as it navigates about the rotating wheel

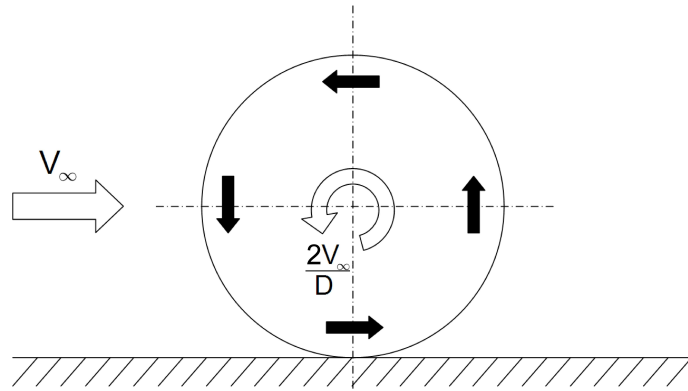


Figure 5.29: A schematic of the wheel showing the different velocities either side of the wheel centreline due to its rotation

to determine whether the vortex is present. If the rotation of the wheel was a cause of this unsteadiness then it would be expected that this would be reflected in the vertical path of the vortices which were obtained from the time-averaged velocity field (shown in Figure 5.28(b)). This is not the case and hence no clear conclusion can be drawn except that it is unlikely that a weak vortex travelling near to a rotating wheel will maintain a coherent structure as it travels downstream.

5.5 Single Vortex in Position of Footplate Vortex from McLaren System

The footplate vortex is the structure closest to the ground in the McLaren trailing vortex system. Hence a single vortex placed in a position similar to this feature is expected to undergo a strong interaction with the ground and may also interact with the wheel jetting flow which is present near the contact patch of the wheel.

The single vortex has been placed in positions equivalent to that of the footplate vortex and its behaviour investigated by obtaining vorticity plots of the flow associated with this vortex. The positioning of the vortex ahead of the wheel is summarised by Figure 5.30, and the vorticity associated with the strongest vortex at each of the different ride heights is shown in Figure 5.31.

As can be seen from the vorticity data of Figure 5.31 the behaviour of the vortex

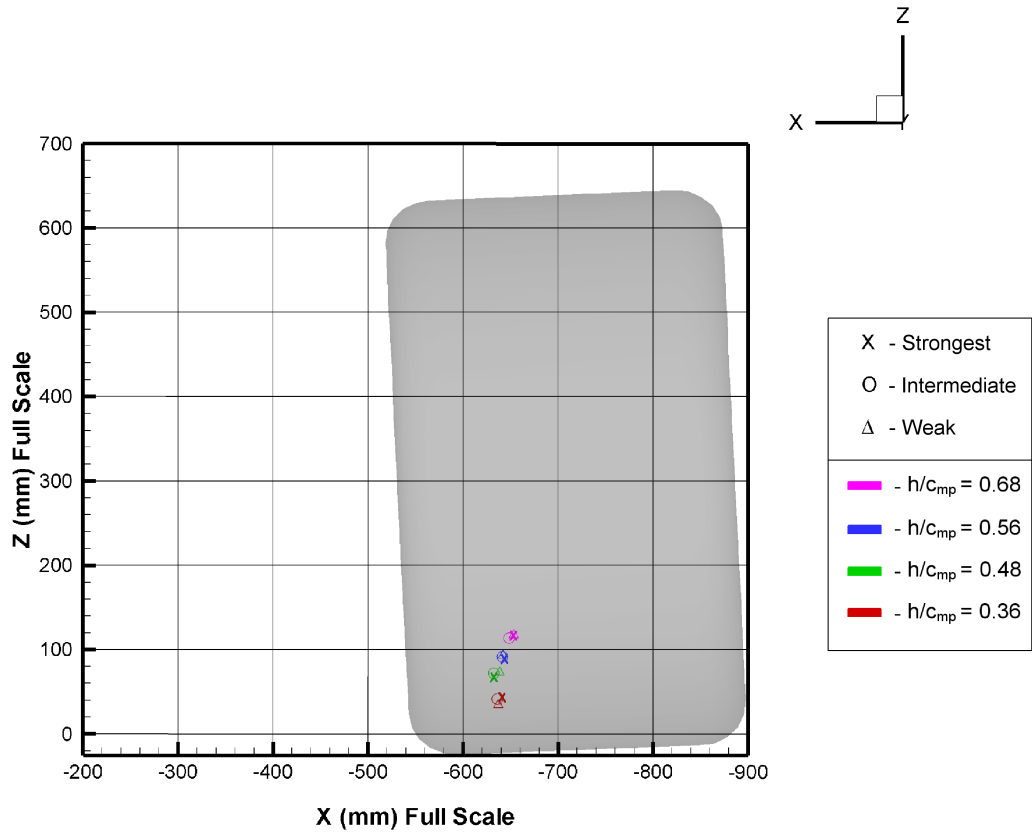


Figure 5.30: Plot showing initial positioning of vortices for single vortex placed in the footplate vortex position, at a plane of $Y = -200mmFS$ without wheel (wheel silhouette included to show its position relative to vortex)

varies substantially when placed in each of the different positions upstream of the wheel. This contrasting behaviour can be seen more clearly from the plots of the trajectories of the vortices shown in Figure 5.32. From this figure it can be seen that when a vortex is released at the lowest height above the ground ($h/c_{mp} = 0.36$), the vortex follows an arc-like path travelling inboard about the wheel before curving back towards the wheel once it has been passed. This curvature is similar to the trajectory of the wing vortex when it was released in the position of the main vortex (Section 5.3). The amount of inboard movement is greater when released in the lowest position of the footplate vortex with a minimum value of $X = -411mmFS$ compared to $X = -430mmFS$ when the vortex was in the main vortex configuration. This is in spite of the vortex being released in a more inboard initial position

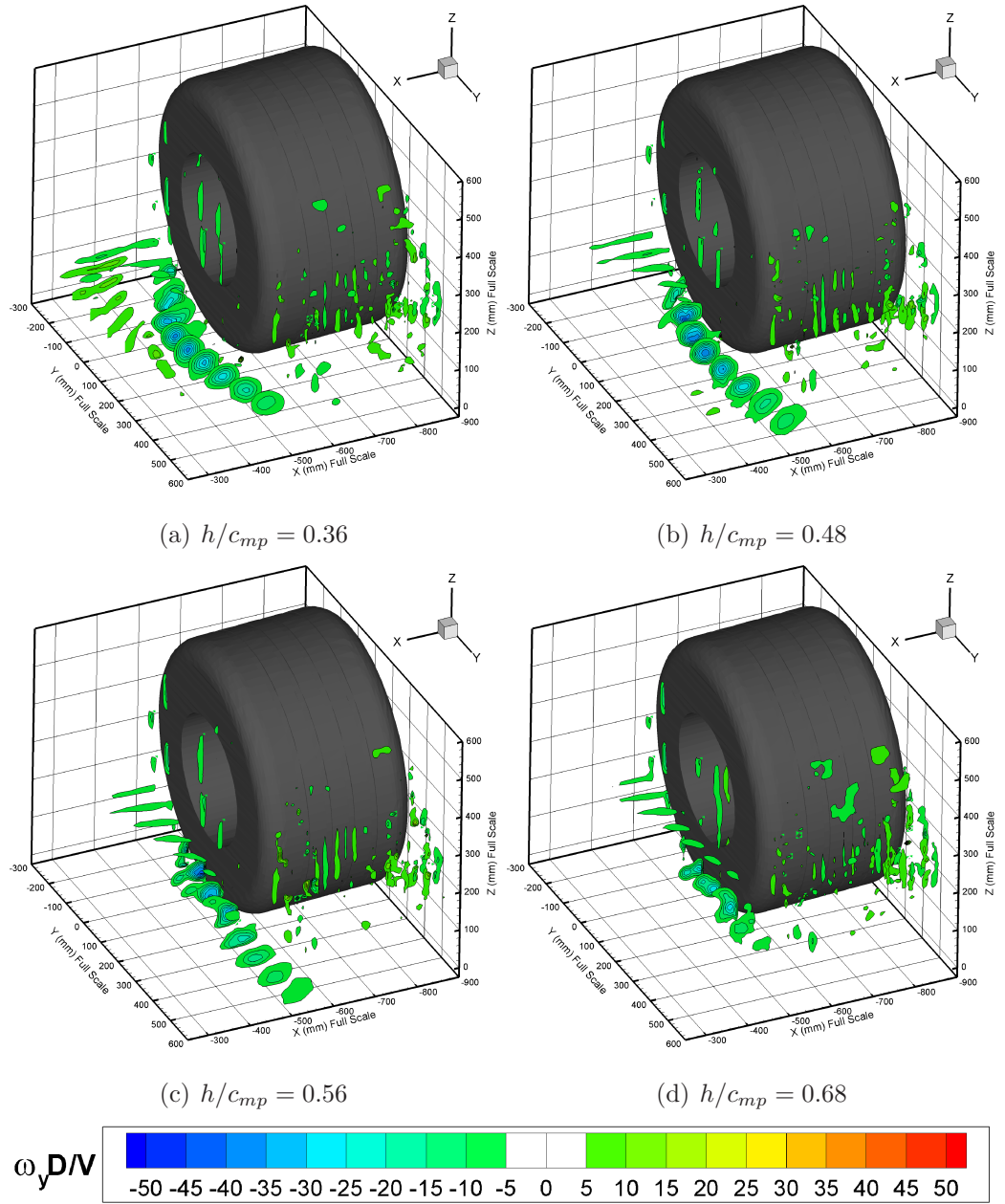
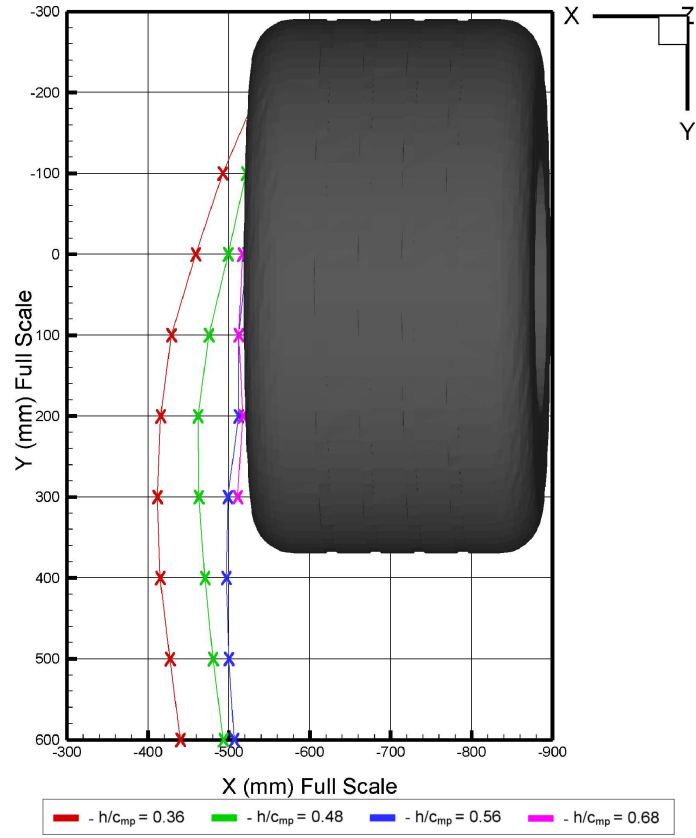
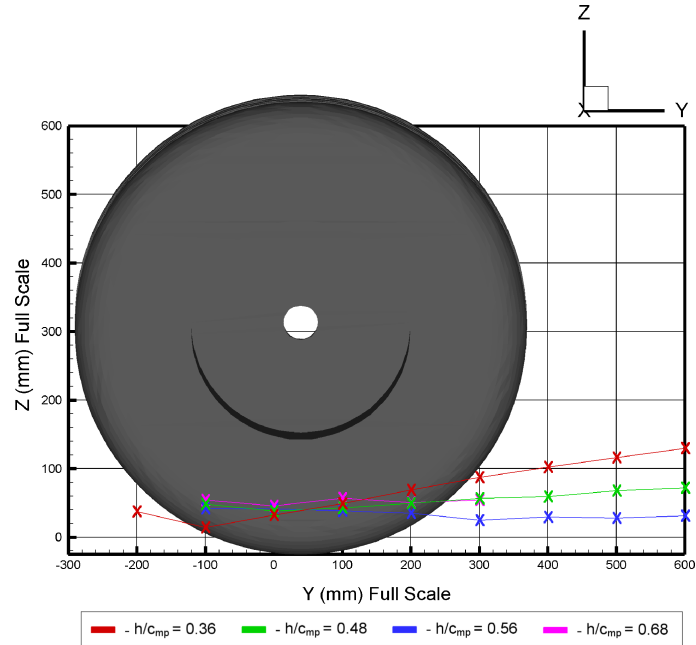


Figure 5.31: Non-dimensional time-averaged vorticity generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the footplate vortex position, as it passes about the rotating wheel at varying ride heights

than the main vortex. This greater lateral movement may be a result of the vortex travelling with the local flow velocity and hence the ‘jetting’ flow pushing the vortex further inboard. However a more likely explanation is that of the result of the image vortex due to the interaction with the ground. This observation is strengthened by examination of the trajectories of this vortex at higher ride heights. As the distance



(a) X-Y plane



(b) Y-Z plane

Figure 5.32: Trajectory of the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) about the wheel when located in the footplate vortex position at varying heights

between the ground plane and the vortex is increased it can be seen from Figure 5.32(a) that the lateral movement of the vortex trajectory is less.

The vertical path of the vortex is also affected by the ride height from which it is released. The trajectories of the vortices in the four different ride height configurations are presented in Figure 5.32(b). Initially the vortices all appear to descend about the front of the wheel which would be consistent with the vortex being affected by the flow rotating with the wheel. Slightly further downstream the path of the vortex in the two lowest configurations are deflected upwards. If the vortex in these two positions were the closest to the wheel then this behaviour could be explained by the flow rotating with the wheel. However, the paths of these two vortices are the furthest away from the wheel and hence if this were to be the reason for the deflection then it would be expected that there would also be an upward movement of the vortex in the two highest configurations. The presence of the vortex in the highest position can not be determined downstream of $Y = 200mmFS$, but the path of vortex at $h/c_{mp} = 0.56$ does not deflect upwards, it continues to descend. So far in this discussion the influence of the image vortex due to the interaction of the ground has been examined, but the effect of the image due to the solid boundary of the wheel has not been introduced. As with the interaction with the ground plane, the effect of the solid boundary of the wheel can be modelled by placing a reflection of the wing vortex in the boundary. This can be seen in Figure 5.33 where the image vortex system from the two boundaries is drawn schematically. As discussed previously the presence of the image in the ground plane (image vortex 1), would cause the vortex to move inboard due to the induced velocity (ΔU_1). The image vortex due to the wheel boundary would act to drive the vortex down by inducing ΔW_2 onto the wing vortex. It may be the result of this interaction that causes the vortex at $h/c_{mp} = 0.56$ to maintain a downward path in spite of the local flow rotating with the wheel.

The most likely explanation for the rebound in the vertical trajectory at the the lowest two ride heights is the viscous interaction with the ground plane. As was discussed in Section 2.3.1.2 when a vortex travels close to a solid boundary then vorticity of the opposite sign (secondary vorticity) may be generated. The

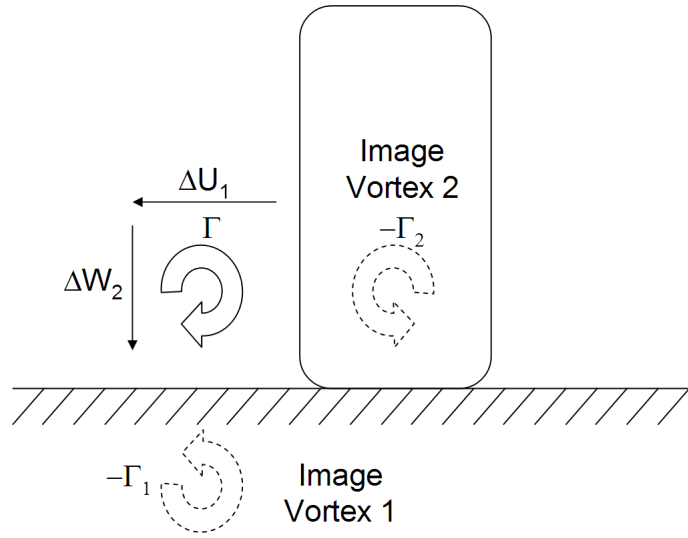


Figure 5.33: A schematic of the image vortices used to represent the interaction of the solid boundaries with the single trailing vortex as viewed looking upstream (ΔU_1 is the induced velocity due to image vortex 1 and ΔW_2 is from image vortex 2)

presence of this vorticity then causes the vortex to rebound away from the boundary. Secondary vorticity is present at the two lowest ride height configurations. One example of this is presented in Figure 5.34 which contains a plot of the vorticity field of the lowest vortex at $Y = 0mmFs$. The reduced vorticity contour levels allows the the secondary vorticity to be clearly visible inboard of the trailing vortex. As a result of the contrasting behaviour of the vortex as it passes about the wheel in each of the ride height configurations, the interaction with the wheel wake and hence flow structure formed downstream of the wheel is different in each case. This can be seen from the vorticity fields presented in Figure 5.35. At the highest ride height the presence of the vortex is not visible. However in this configuration the lower inboard wheel vortex has been displaced further inboard than was observed from the isolated wheel case. The presence of the single vortex in each of the other three ride configurations is easily distinguishable interacting with the inner lower wheel vortex. As the ride height of the wing vortex is reduced, the vertical position of this vortex centre is higher due to the reasons mentioned above (note that at $h/c_{mp} = 0.36$ and $h/c_{mp} = 0.48$ shown in Figures 5.35(a) and 5.35(b) respectively the remnants of the

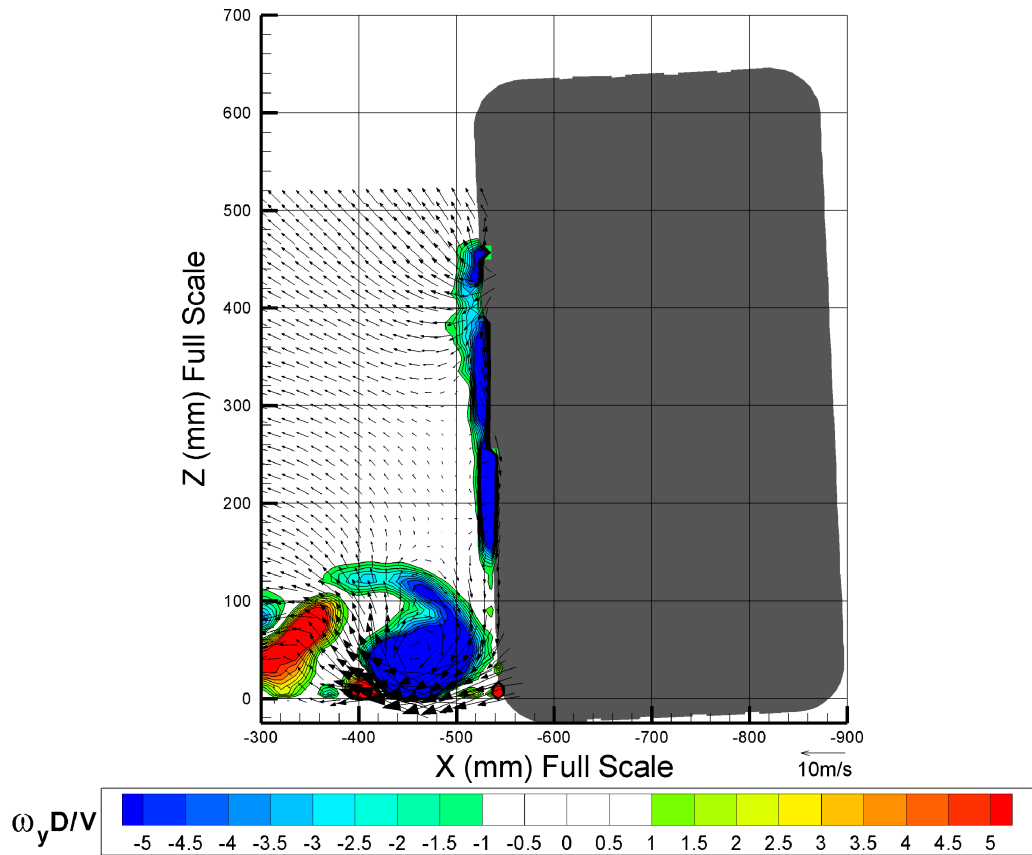


Figure 5.34: Non-dimensional time-averaged vorticity field as generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the lowest footplate vortex position ($h/c_{mp} = 0.36$) at $Y = 0mmFS$

secondary vorticity are visible). When the wing vortex is higher at $h/c_{mp} = 0.36$, the interaction with the wheel vortex is less and the two co-rotating vortices are at an early stage of merging than the two higher ride heights of $h/c_{mp} = 0.48$ and $h/c_{mp} = 0.56$. In these two plots it appears that two patches of vorticity have completely merged.

The sensitivity of the flow structure to the strength of the vortex when placed at a moderate ride height ($h/c_{mp} = 0.56$) can be evaluated from examining the vorticity and trajectory results shown in Figures 5.36 and 5.37 respectively.

From the data contained within these figures, it can be seen that when the vortex is reduced in strength that the lateral trajectories of the vortices are extremely similar passing close to the wheel. However the vertical trajectories of these vortices do differ with a reduction in strength causing the vortex path to be higher above the

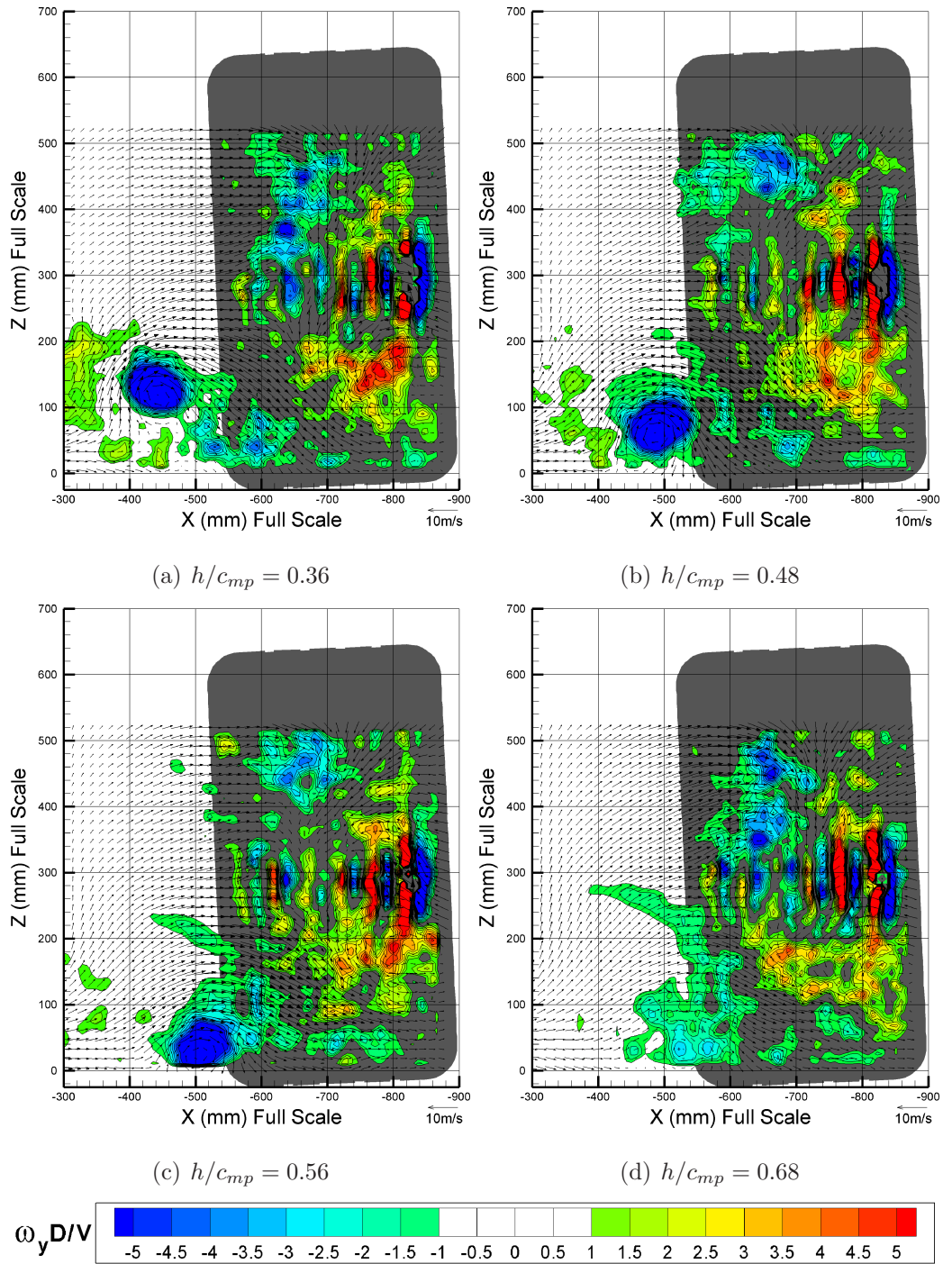


Figure 5.35: Non-dimensional time-averaged vorticity in the wake of the wheel ($Y = 600mmFS$) as generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the footplate vortex position at varying ride heights

ground with distance downstream. This could be a result of the effect of the image vortex as a result of the boundary of the wheel, weakening due to the reduction in

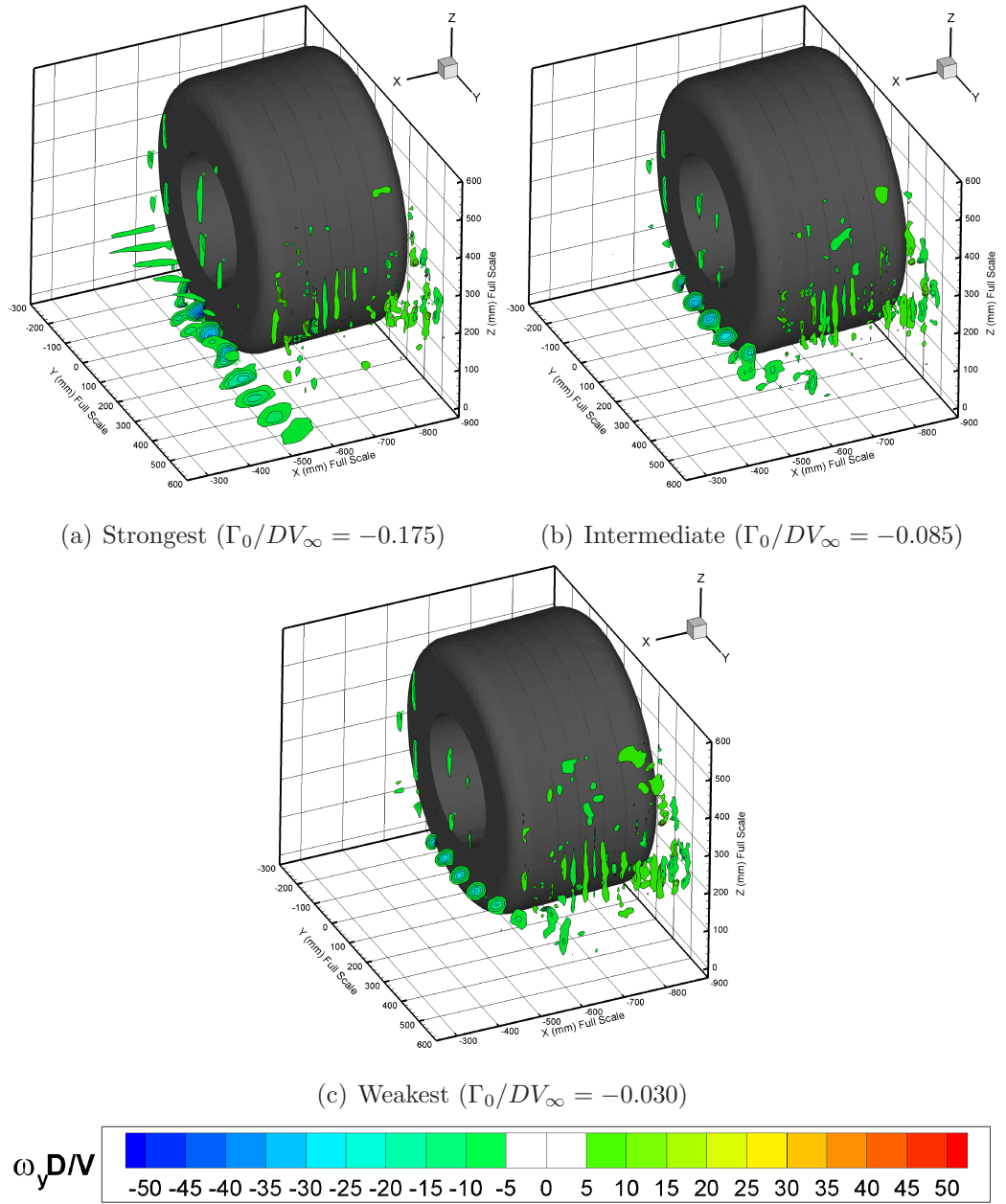
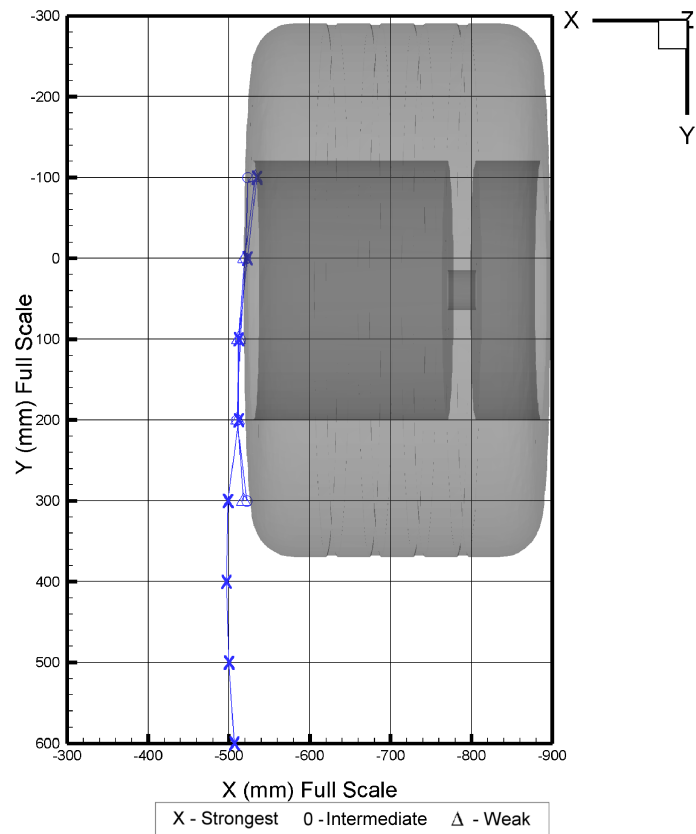
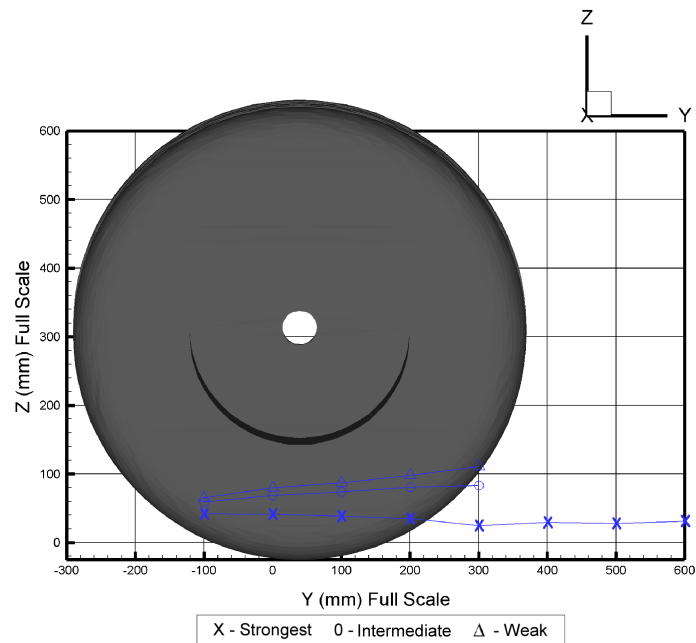


Figure 5.36: Non-dimensional time-averaged vorticity generated by the single vortex at varying strengths located in the footplate vortex position as a ride height of $h/c_{mp} = 0.56$ with the rotating wheel

circulation and the flow rotating upwards downstream of the contact patch having a greater influence on the path of the single vortex. This effect places the two weaker vortices close to the lower, inboard wheel vortex and their presence is lost within the wake of the wheel.



(a) X-Y plane



(b) Y-Z plane

Figure 5.37: Trajectory of the single vortex at varying strengths located in the footplate vortex position at a ride height of $h/c_{mp} = 0.56$ as it navigates about the rotating wheel

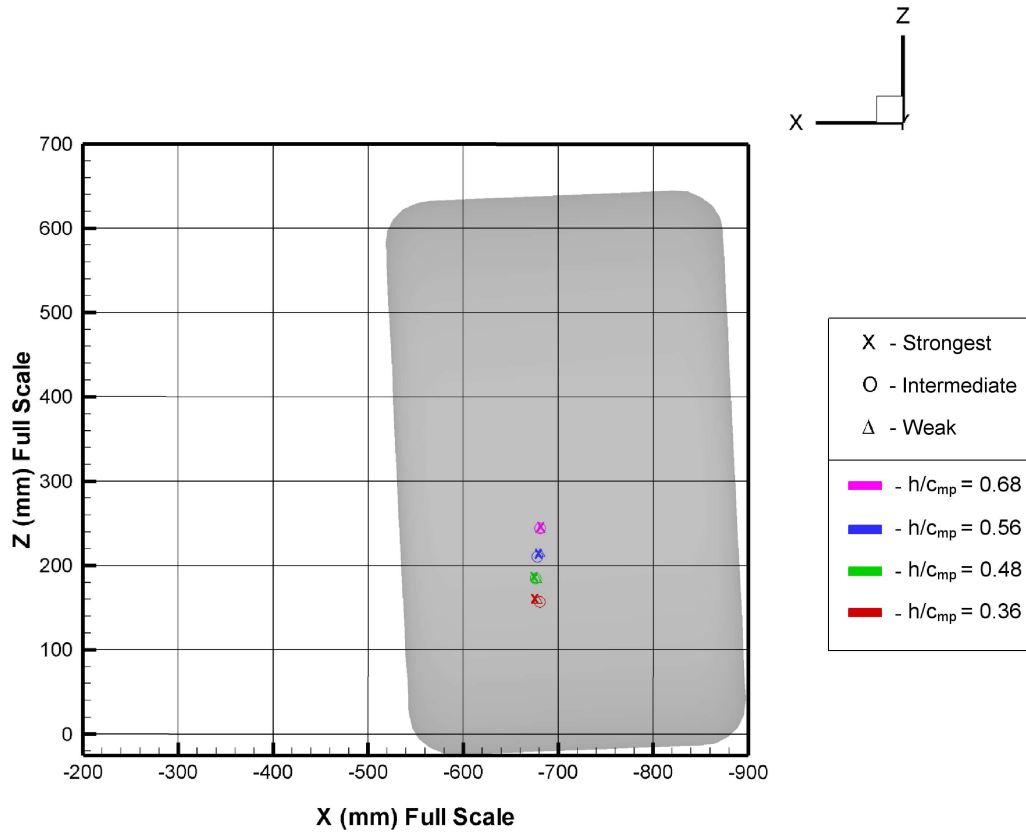


Figure 5.38: Plot showing initial positioning of vortices for single vortex placed in the canard vortex position, at a plane of $y=-200\text{mmFS}$ without wheel (wheel silhouette included to show its position relative to vortex)

5.6 Single Vortex in Position of Canard Vortex from McLaren System

The final position in which the single vortex has been placed is that of the canard vortex in the McLaren trailing vortex system. This vortex is the most outboard vortex, close to the longitudinal centreline of the wheel at a height which is in between the main and top vortex. The initial positions of the single vortex in this configuration are shown in Figure 5.38 and the resulting vorticity data for the strongest vortex in each of these positions is shown in Figure 5.39.

From the time-averaged vorticity shown in Figure 5.39 it is difficult to distinguish the presence and behaviour of the trailing vortex. At the lowest ride height of $h/c_{mp} = 0.36$ inboard of the wheel, it appears that the vortex is positioned ex-

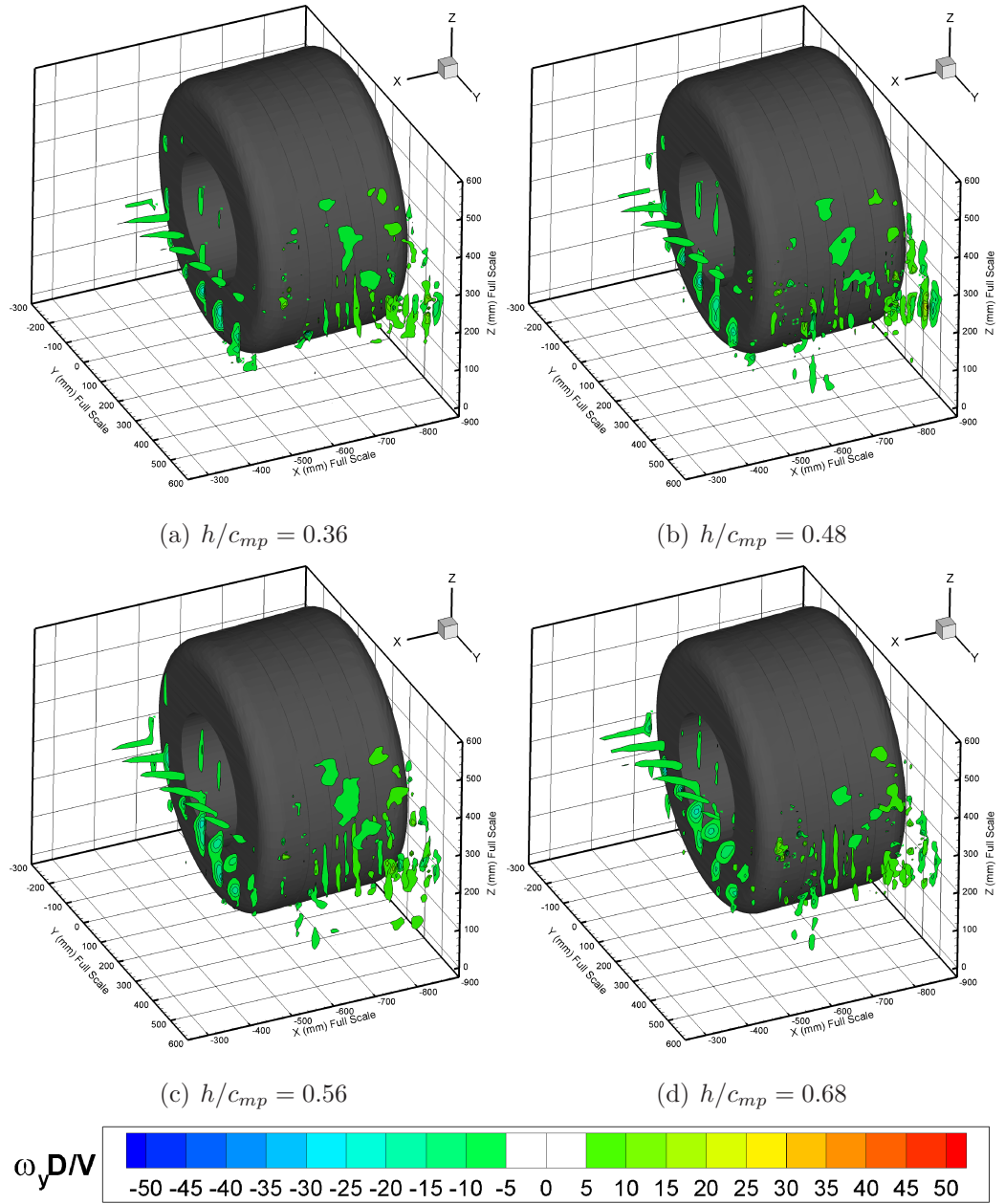


Figure 5.39: Non-dimensional time-averaged vorticity generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the canard vortex position, as it passes about the rotating wheel at varying ride heights

tremely close to the sidewall of the tyre slightly beneath the hub. Downstream of the wheel the vortex is not visible. As the ride height is increased, the time-averaged vorticity associated with this vortex also increases in height whilst it remains in close proximity to the wheel.

The low values of the peak time-averaged vorticity associated with the vortex

in this position do not appear to be as a result of the time-averaging. As can be seen from the instantaneous vorticity data inboard of the wheel at $Y = 0mmFS$ presented in Figure 5.40, the vorticity associated with the wing vortex is in a similar position in both time instances. However in one instance shown in Figure 5.40(b) the vortex appears to be spread out over a larger area next to the sidewall of the wheel. It may be that these flowfields are a result of the vortex undergoing or having undergone breakdown. However it is not possible to accurately determine whether this has occurred from the results obtained during this research.

Downstream of the wheel, the single vortex is unidentifiable in the wake of the wheel at all ride heights. This is shown in Figure 5.41 where although the vorticity of the wing vortex can not be seen in comparison to the wake of the isolated wheel, the upper, inboard wheel vortex has a greater peak vorticity whilst the vorticity associated with the lower, inboard vortex appears to be enlarged as a result of the wing vortex.

The effect of reducing the strength of the vortex, whilst placed in a position similar to that of the canard vortex at a ride height of $h/c_{mp} = 0.56$, is shown in Figure 5.42. With the reduced contour levels the strongest vortex is more distinguishable, as is the wake from the double element wing. However, as the strength is reduced it becomes extremely difficult to determine the behaviour of the vortex and it can only be concluded that a coherent vortex structure is not possible in these configurations.

It is thought that the weakness of the single vortex when placed in positions similar to the canard vortex is a consequence of the vortex being initially placed further outboard than any of the other vortices. This places this vortex extremely close to the sidewall of the tyre which could draw the vortex into the boundary layer which is rotating with the tyre thereby losing a coherent structure.

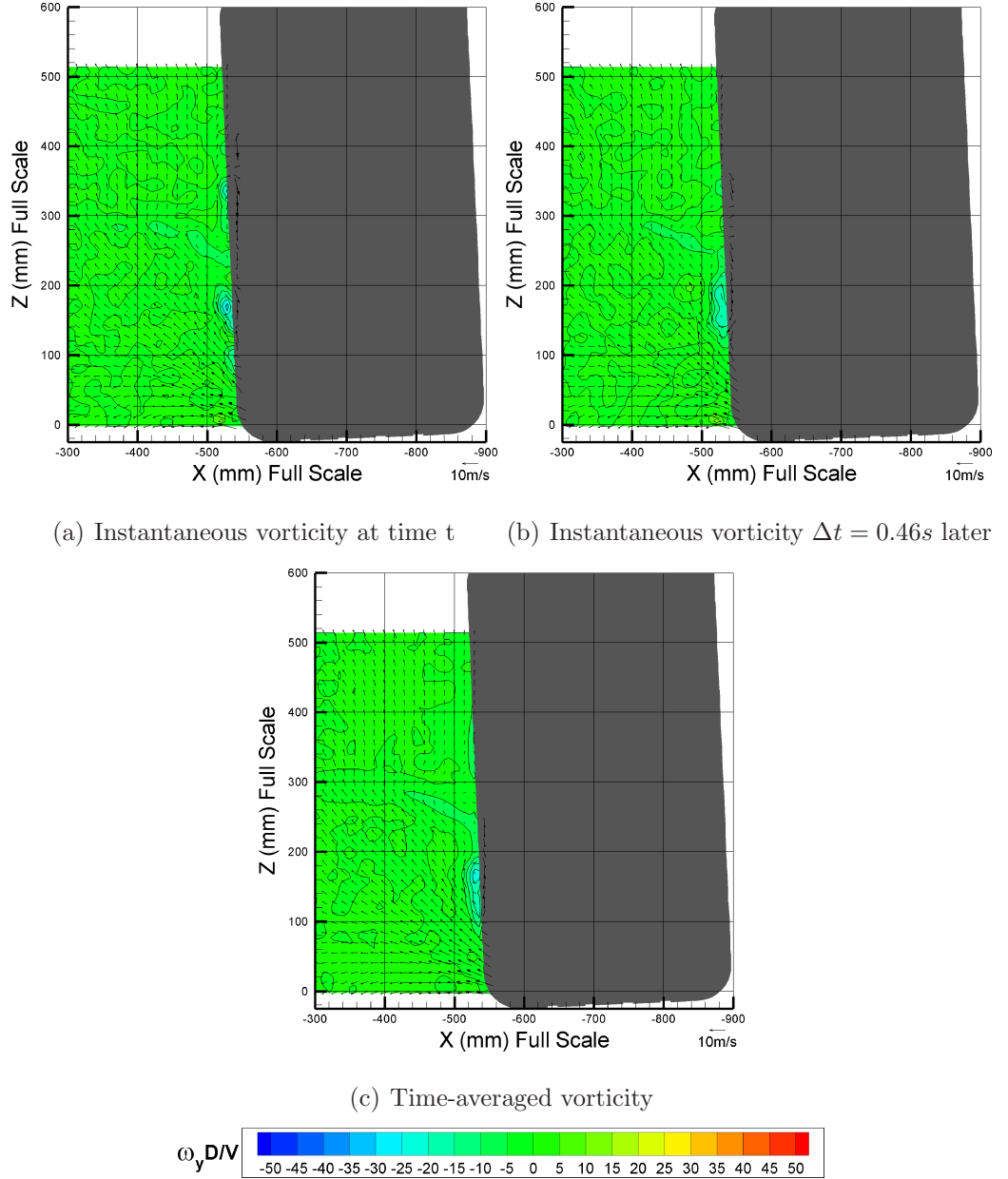


Figure 5.40: Comparison of instantaneous (from two different instances in time) and time-averaged non-dimensional vorticity fields inboard of the wheel at $Y = 0mmFS$ for the strongest vortex in the position of the canard vortex at a ride height of $h/c_{mp} = 0.56$

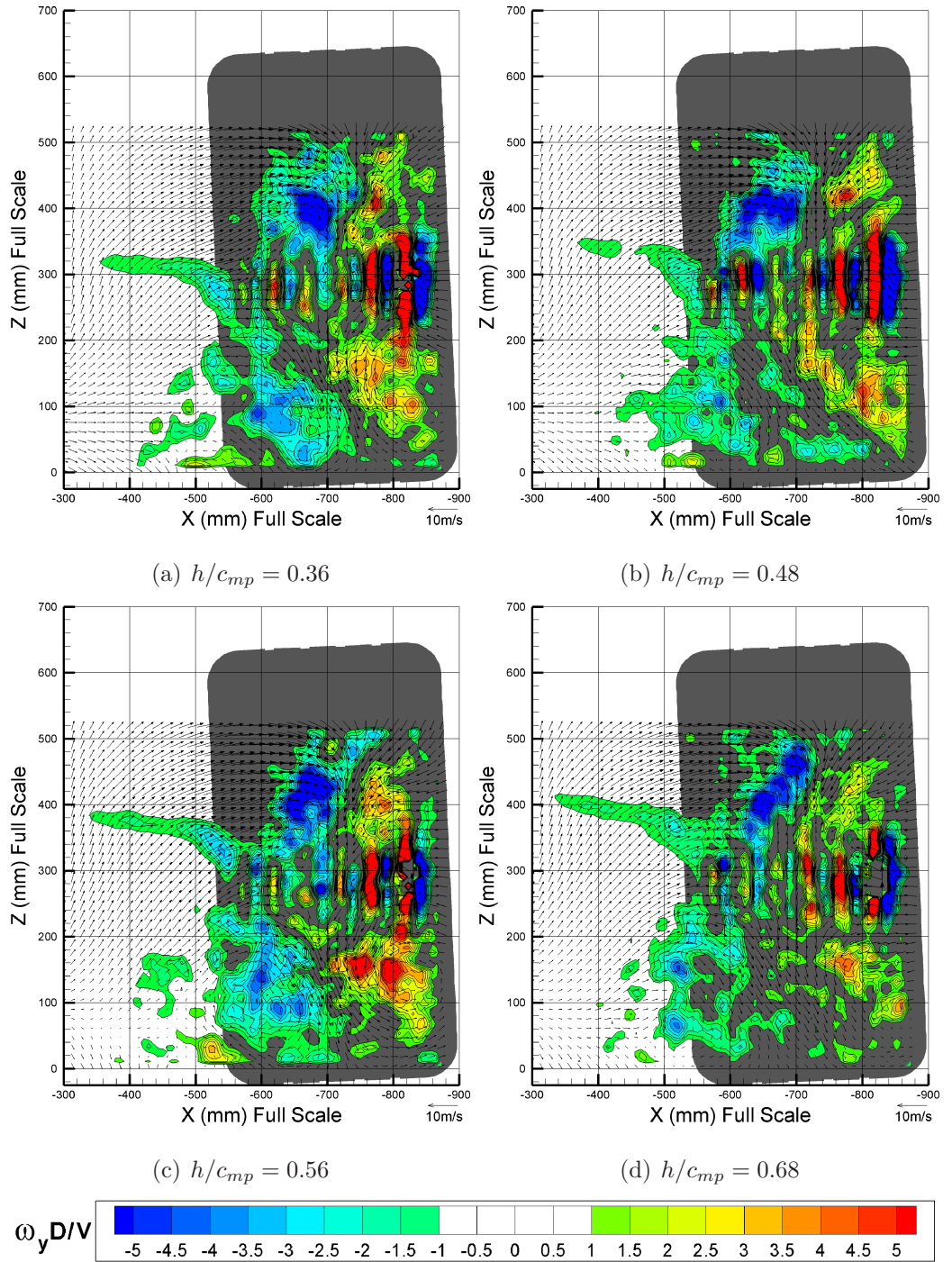


Figure 5.41: Non-dimensional time-averaged vorticity in the wake of the wheel as generated by the strongest vortex ($\Gamma_0/DV_\infty = -0.175$) located in the canard vortex position at varying ride heights

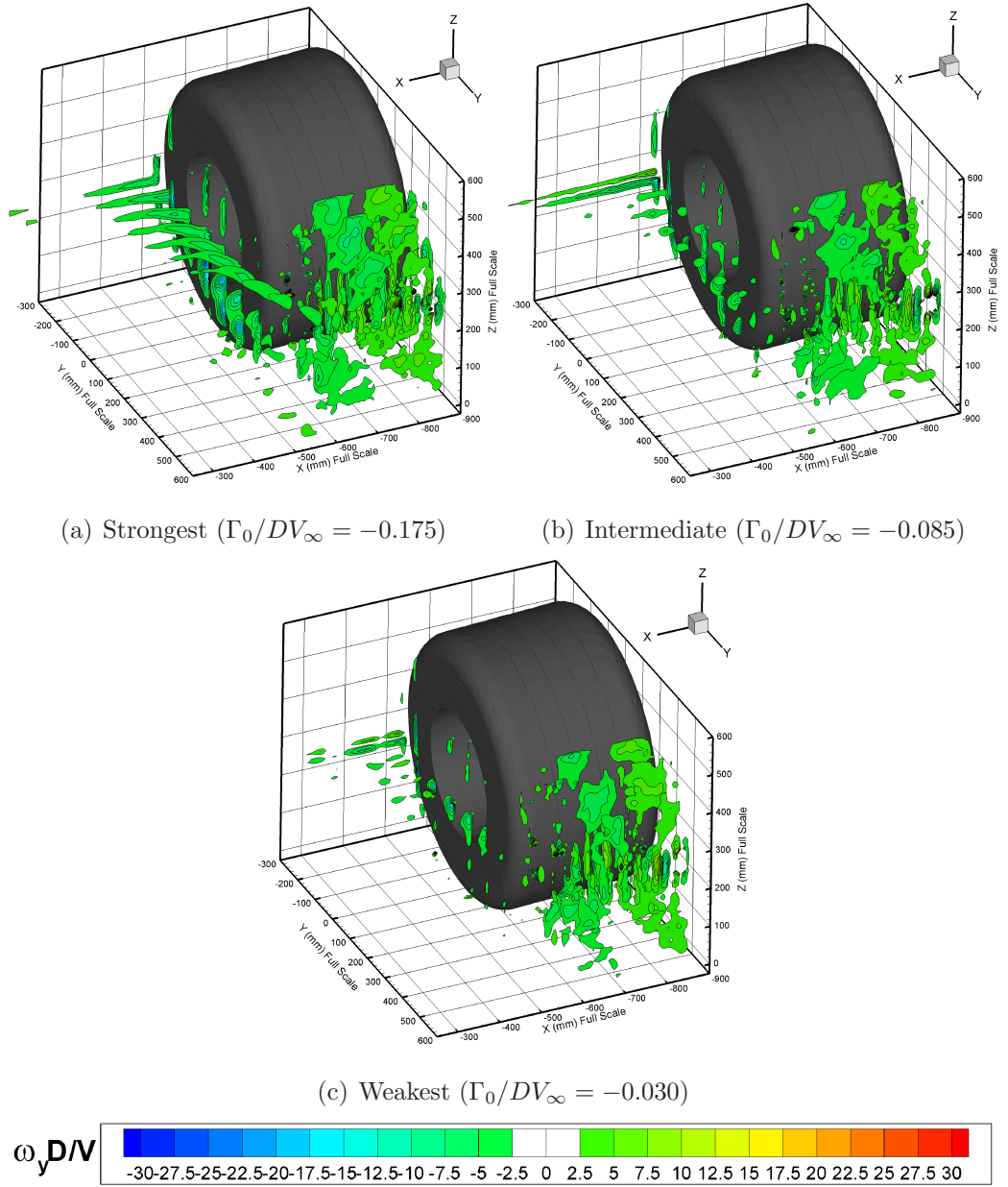


Figure 5.42: Non-dimensional time-averaged vorticity generated by the single vortex at varying strengths located in the canard vortex position as a ride height of $h/c_{mp} = 0.56$ with the rotating wheel

5.7 Concluding Remarks

The results contained in this chapter have shown that a single trailing vortex behaves quite differently when placed in various positions and strengths about a rotating wheel.

With a single vortex placed in a position similar to that of the main vortex in the McLaren trailing vortex system (in line with the inboard face of the wheel and at a moderate ride height), the vortex follows the local flow velocity and traces an arc-like path inboard of the wheel. The lateral movement of the vortex is increased when either the vortex is brought closer to the ground or its circulation increased, due to the induced velocity from the image vortex as a result of the ground plane interaction.

If the initial position of the vortex is lowered even further then a viscous interaction with the ground plane may take place. As was seen with the wing vortex in the position of the footplate vortex, an upward deflection in the vertical trajectory of the vortex may occur as the result of secondary vorticity being generated.

If a single vortex is released in a position which brings it close to the sidewall of the wheel (as with the vortex in the location of the top vortex), then the vortex may be affected by the flow which rotates with it. This is a difficult environment for a vortex to endure as the direction of the vertical velocity changes either side of the contact patch. The vertical trajectory of a vortex travelling close to the wheel may also be affected by the image vortex which is present as a result of the wheel acting as a solid boundary.

If the vortex is released still further outboard (as with the vortex in the position of the canard vortex) then the vortex may interact with the boundary layer which is attached to the rotating wheel thereby making the possibility of a coherent trailing vortex travelling downstream unlikely.

Downstream of the rotating wheel the vortices are affected by the differing scales which are present in the unsteady wake. This causes the positioning of the vortex to vary instantaneously and the effect is greater with a reduced distance between the vortex centre and the wake.

The wake of an isolated rotating wheel consists of two pairs of counter-rotating vortices; the upper and lower vortex pairs. If the trajectory of the single vortex causes it to be located near to one of the inner structures of either of these two pairs, then the two co-rotating structures will interact. The level of interaction depends on the separation distance between the wing and wheel vortex, with both the initial stages of merging (orbiting) and fully merged structures having been observed. As a result of this interaction the structure of the wheel wake can be modified substantially by the upstream placement of the single trailing vortex.

This chapter has provided an insight into how a vortex may be affected by the presence of the wheel and has briefly examined the effect of modifying its position or strength. The knowledge gained from this study will be used in the next chapter to help analyse the behaviour of the McLaren trailing vortex system as it passes about the wheel in the four different ride height configurations.

Chapter 6

Flow Structure Downstream of McLaren Geometry With Wheel

This chapter examines the behaviour of the trailing vortex system generated by the McLaren front wing and endplate as it travels downstream about the rotating wheel. From the research presented in Chapter 4 it is known that the front wing wake consists of four co-rotating vortices. When unimpeded by the wheel, the vortices within the system begin to interact and merge with one another as they travel with the flow. The aerodynamics about an isolated rotating wheel were examined in Chapter 5 together with the investigation of the behaviour of a single vortex released in positions and strengths comparable to that of the McLaren trailing vortex system. The observations from this chapter highlighted the complexity of the flow about a rotating wheel and the variations in the flow structure formed inboard and downstream of the wheel as a result of the initial position and strength of the vortex.

The results contained within this chapter use the observations and knowledge gained from the research contained within the previous two chapters to evaluate the flow structure formed by the McLaren vortex system about the wheel. This will be carried out by using results from experimental measurements of total pressure, laser-smoke flow visualisations and PIV.

The chapter will split into two main sections. First the behaviour of the vortex

system shed from the McLaren front wing and endplate at a moderate ride height will be examined then the effect of modifying the ground clearance of the wing will be considered. Finally the experimental results will be compared to the equivalent McLaren CFD which was the source of motivation for this project.

6.1 Behaviour of Vortex System at a Moderate Ride Height ($h/c_{mp} = 0.48$)

At the moderate ride height of $h/c_{mp} = 0.48$ the results from Chapter 5 have shown that without the wheel the main and top vortices are the strongest features in the McLaren trailing vortex system (Section 4.1.2 and Figure 4.6). Therefore, as the vortex system travels downstream these two features dominate the flow and begin to rotate about one another. At the same time the weaker structures of the footplate and canard vortices, interact and merge with the main vortex. These process result in a downstream flow consisting of a ‘figure of eight’ structure.

From the observations of Chapter 5 it is thought that this behaviour of the trailing vortex system will be dramatically affected by the inclusion of the rotating wheel. To evaluate the influence of the wheel, the flow structure will be examined at varying locations with the wing set at this moderate ride height.

6.1.1 Near-Field

In attempting to obtain information on the near-field flow structure of the McLaren trailing vortex system, the presence of the wheel introduces a practical difficulty. The span of the McLaren front wing places the endplate in a position in front of the wheel (see Figure 3.5) and together with the location of the camera downstream of the model, the visibility of the flow in the near-field by either the flow visualisation or PIV methods is limited (see Figure 6.1). The estimation of the total pressure distribution is also not possible due to the physical dimensions of the probe. Consequently the initial configuration of the vortex system shed from the front wing and endplate of the McLaren geometry is unknown. This practical limitation is high-



Figure 6.1: Field of view from flow visualisation camera located downstream of the model, highlighting the physical limitations on the visibility of flow in the near-field of the McLaren front wing and endplate

lighted by the data shown in Figure 6.2, where the streamwise vorticity contours at a plane of $Y = -300mmFS$ are presented. Note that due to reflections from the geometry of the front wing there is a region of erroneous vectors which have been removed. The limited information on the near-field flow structure can be observed in this figure. A region of negative vorticity can be identified just ahead of the wheel which is attributed to the main vortex. As this vortex is passing around the front of the wheel it is likely that its axis will be tilted to the laser sheet. Therefore the PIV results may suffer from the associated errors discussed in Section 3.5. Hence the vorticity associated with this vortex may not be accurately represented by the streamwise component shown in Figure 6.2. As a consequence of this error as well as the lack of visibility of the entire vortical structure, the characteristics of this vortex cannot be accurately estimated.

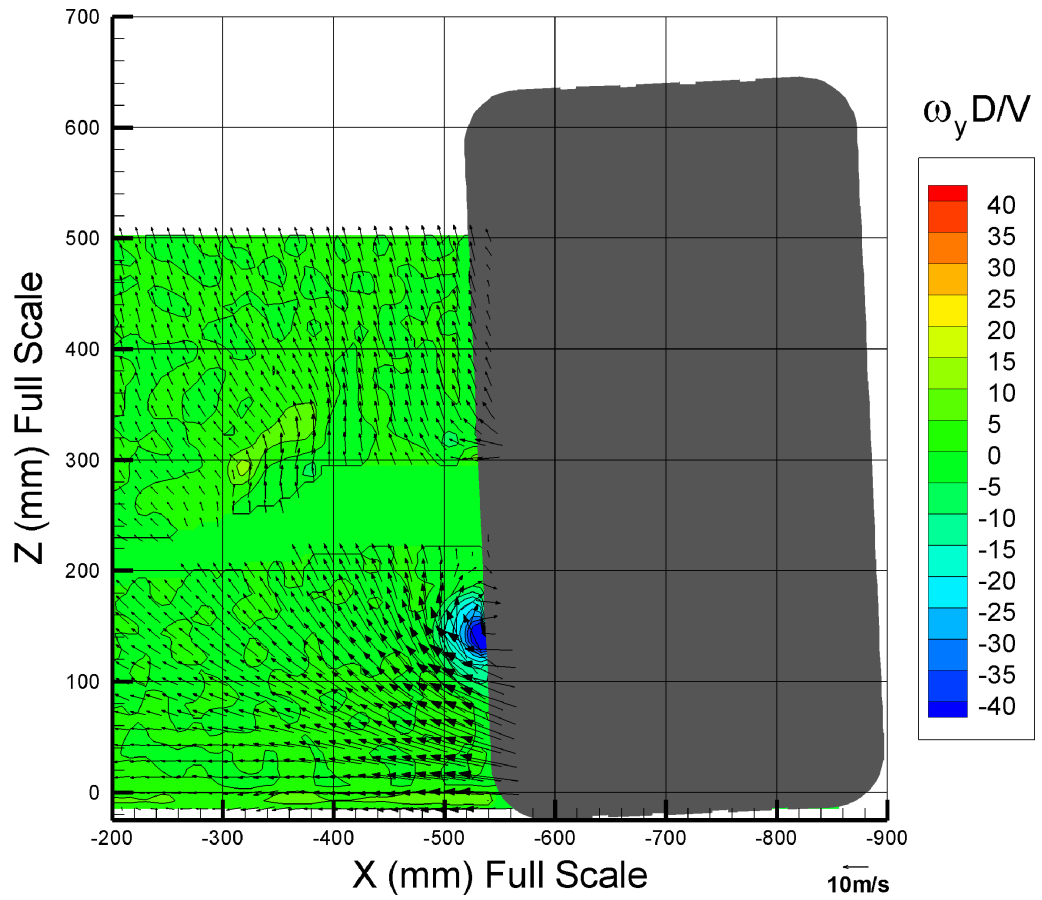


Figure 6.2: Non-dimensional time-averaged vorticity contours downstream of the McLaren model at a ride height of $h/c_{mp} = 0.48$ with the rotating wheel ($V_\infty = 25m/s$)

Slightly further downstream at $Y = -250mmFS$ the flow about the upstream part of the rotating wheel causes some of the vortices to travel inboard and their presence can be inferred from the laser-smoke flow visualisation image presented in Figure 6.3. The core of the main vortex can clearly be seen inboard of the wheel in this figure as are indications of the presence of both the footplate and top vortex ahead of the wheel.

As a result of the limited information on the near-field flow structure, the characteristics of the vortex system obtained in Chapter 4 will be used as a indication of the likely configuration of the system. This assumes that the wheel has minimal effect on the structure of the vortex system which will not necessarily be the case.



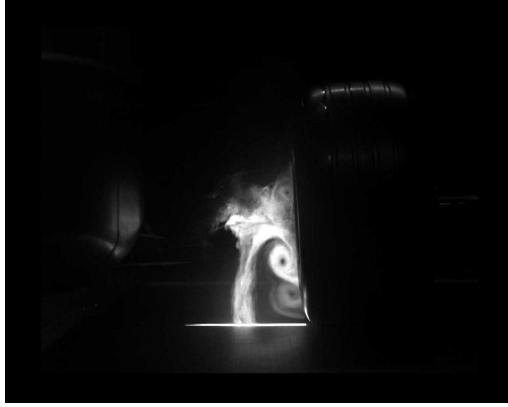
Figure 6.3: Laser smoke flow visualisation of flow in the near-field of the McLaren model ($Y = -250mmFS$) at a ride height of $h/c_{mp} = 0.48$ with rotating wheel ($V_{\infty} = 12.5m/s$)

6.1.2 Inboard of the wheel

As the system travels inboard about the front of the wheel, the visibility of the top and footplate vortices improves. The cores of these two vortices can be seen with that of the main vortex in the images of the flow inboard of the wheel shown in Figure 6.4.

From these results it can be seen that as the vortices travel downstream inboard of the wheel, the flow structure is dominated by the behaviour of the main and footplate trailing vortices whilst the visibility of the top vortex decreases. Once about the leading edge of the wheel the main and footplate vortices begin to orbit about one another due to the induced velocity created by each of the structures.

The characteristics of this orbiting process can be used to examine the influences on the vortex system as a result of the presence of the wheel. From the results of



(a) $Y = -200mmFS$



(b) $Y = -100mmFS$



(c) $Y = 0mmFS$



(d) $Y = 100mmFS$



(e) $Y = 200mmFS$



(f) $Y = 300mmFS$

Figure 6.4: Laser smoke flow visualisation of flow inboard of wheel of McLaren model at a ride height of $h/c_{mp} = 0.48$ with rotating wheel ($V_{\infty} = 12.5m/s$)

Chapter 4 it is known that without the wheel the main vortex has a circulation which is approximately 60% stronger than that of the footplate vortex ($\Gamma_0/DV_\infty = -0.259$ and $\Gamma_0/DV_\infty = -0.161$ respectively). If two vortices of these strengths were orbiting away from the influences of the wheel and the ground, then they would orbit about a point close to the strongest vortex (refer to Section 2.3.1.1). It can be seen from the images in Figure 6.4 that this does not appear to be the case as the vortices rotate about a location which is approximately in the middle of the two structures. This effect may be a result of the interaction with the solid boundaries formed by the inboard edge of the wheel and the ground plane or a consequence of the aerodynamics about the wheel modifying the relative strengths of the two vortices.

As has been discussed in both Section 2.3.1.2 and Chapter 5, the interaction of a vortex system with the solid boundaries of the wheel and the ground plane can be modelled by the method of images. The resulting induced velocity field generated by the image vortices will affect the motion of these two vortices and may be a reason for the difference in the orbiting process when the wheel is included.

Another possible explanation for the behaviour of these two vortices could be due to a change in their relative strengths. The tendency of the vortices to rotate about a point which is close to the middle of the two structures suggests that they may have circulations which are closer to each other than was previously found in Chapter 4. A change in the strengths of the vortices may result from the aerodynamics in front of the wheel. As was seen in Section 2.4 (Figure 2.27), the rotating wheel generates a region of high pressure upstream of its contact patch. The footplate is located near to this region and the pressure difference which acts across the footplate and causes the formation of the vortex, may be enhanced.

A change in strength of the orbiting vortices may also be a result of the canard vortex. From Chapter 4 it is known that the trailing vortex system from the McLaren front wing and endplate consists of four vortices. However, from the results presented so far only three vortices have been identified. Unfortunately due to the lack of information of the flow ahead of the wheel the behaviour of the canard vortex is unknown. In Chapter 5 when the single vortex was placed in the position of

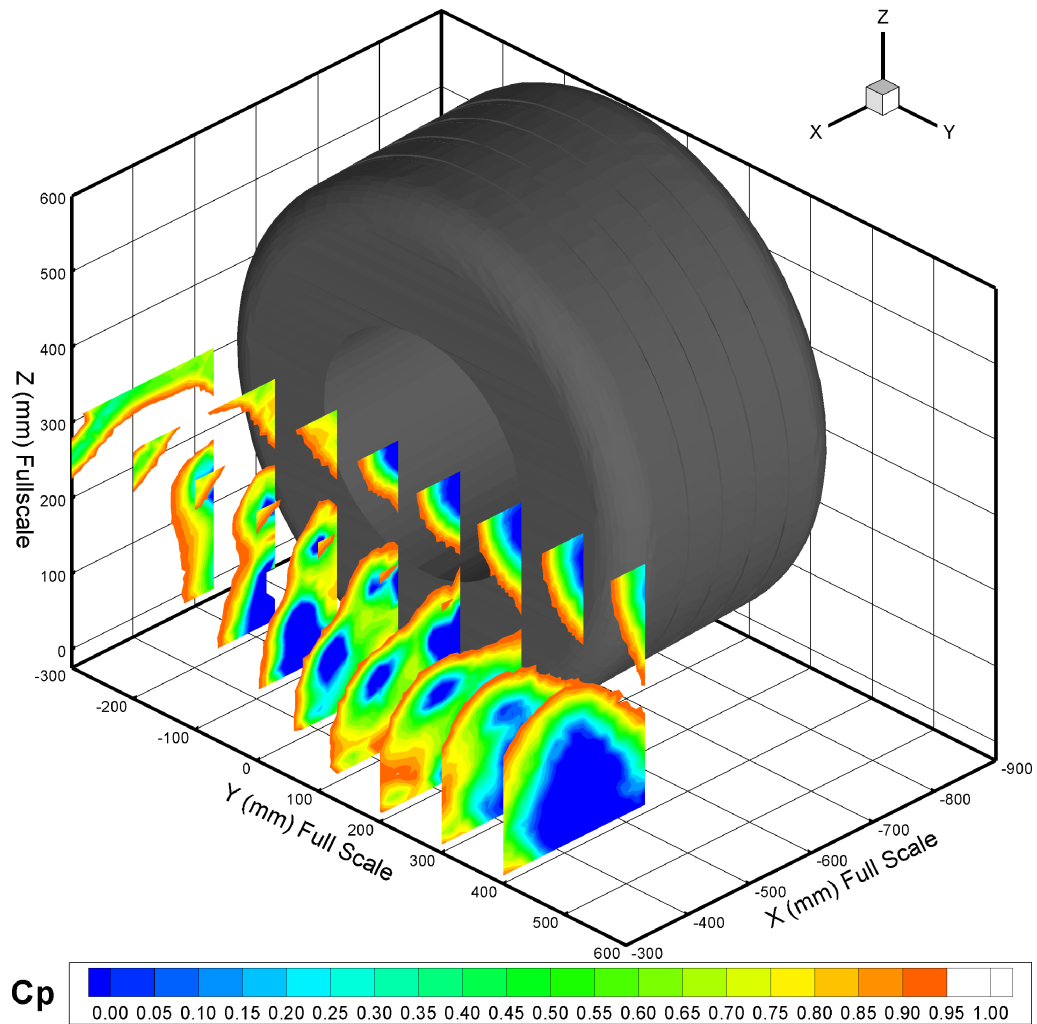


Figure 6.5: Total pressure distribution of flow generated by McLaren front wing at a ride height of $h/c_{mp} = 0.48$ with rotating wheel ($V_\infty = 25m/s$)

the canard vortex streamwise vorticity was observed inboard of the wheel, beneath its hub (lower than the position from where the vortex was released). Therefore it may be that due to the aerodynamics in front of the wheel the canard vortex has interacted with the other vortices. However due to the limited information with regard to this vortex, this cannot be confirmed.

The results of the total pressure survey in planes inboard of the wheel have also identified the tendency for the main and footplate vortices to orbit about one another. Shown in Figure 6.5 the vortices can be observed as regions of low total pressure.

As can be seen from this figure, the interaction of the two vortices generates

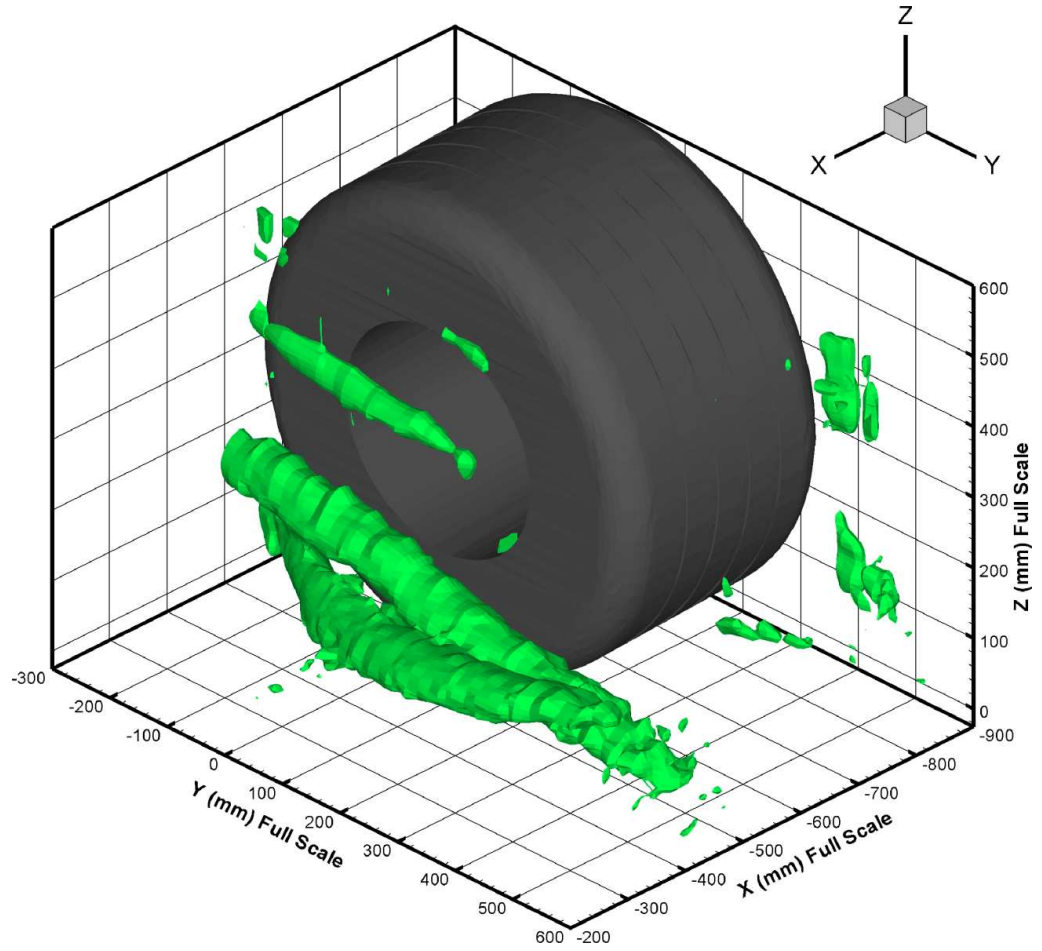


Figure 6.6: Iso-surface of non-dimensional time-averaged vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at a ride height of $h/c_{mp} = 0.48$ with the rotating wheel ($V_\infty = 25m/s$)

a large region of energy loss. The exact flow physics which are involved in the formation of this structure can not be extracted from these results as the cores of the vortices soon become lost in a larger region of low total pressure.

More information on the flow inboard of the wheel and the formation of the large region of energy loss can be gathered by examining the vorticity results obtained from PIV. As was undertaken on the trailing vortex system without the wheel, 55 X-Z planes of time-averaged cross-flow velocity vectors have been used to generate a time-averaged vorticity field. The results of this technique are presented in Figures 6.6 and 6.7 where iso-surfaces of non-dimensional time-averaged vorticity are plotted downstream of the McLaren model with the rotating wheel.

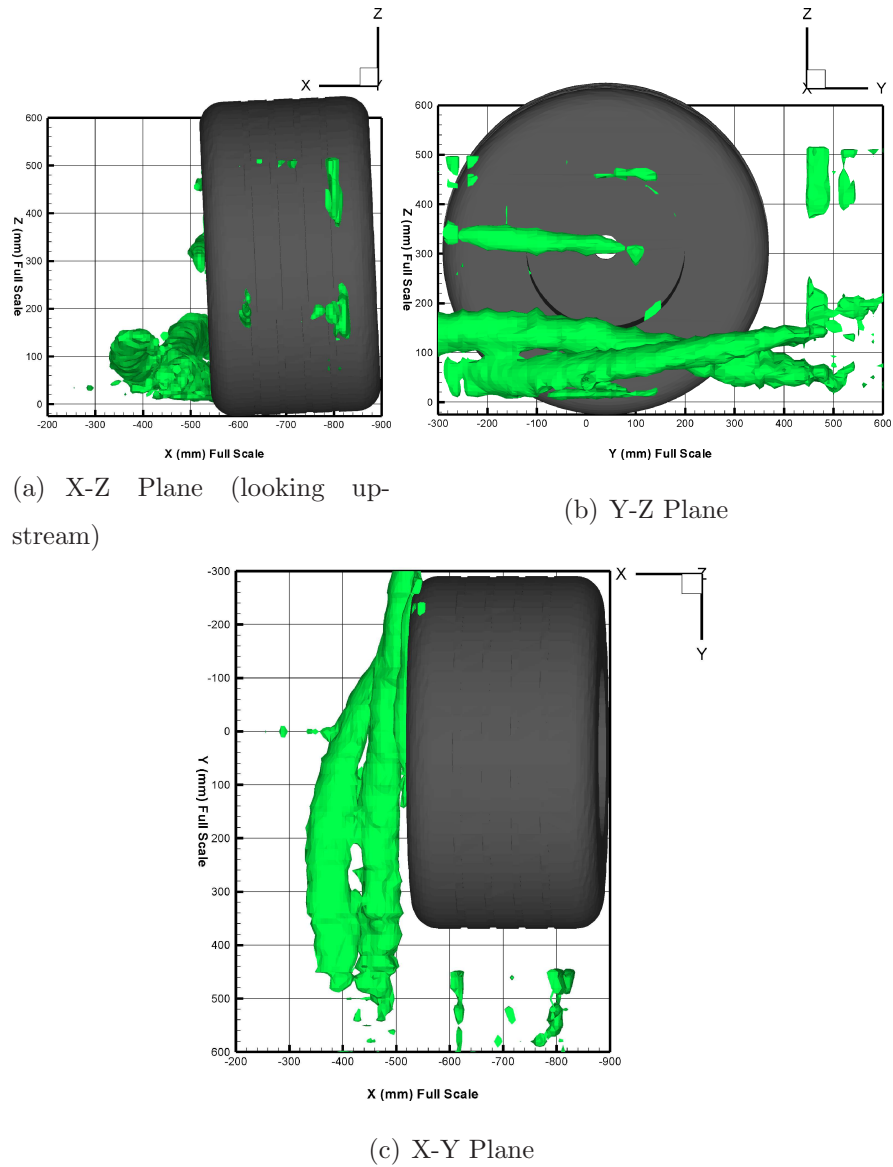


Figure 6.7: Different viewpoints of iso-surface of non-dimensional time-averaged vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at a ride height of $h/c_{mp} = 0.48$, with the rotating wheel ($V_\infty = 25m/s$)

As can be seen from this data, the interaction of the main and footplate vortices inboard of the wheel is very similar to that concluded from the other two techniques.

The formation of the region of low total pressure is a direct result of the continued interaction of the main and footplate vortices. At $Y = 300mmFS$ and $Y = 400mmFS$ where this structure has been observed, Figures 6.6 and 6.7 demonstrate that the vorticity from the two vortices is still present as independent struc-

tures. Past this point they continue to orbit about one another until downstream of the wheel the time-averaged vorticity begins to decrease. This diffusion of vorticity may be a consequence of the peak vorticity of the merging vortices decreasing but also may result from the large scale fluctuations of the wheel wake.

The presence of the top vortex can also be confirmed from the PIV results. As was observed from the flow visualisation, this structure appears to weaken as it travels downstream close to the rotating wheel. The consequences of a single vortex travelling close to the wheel was discussed in Chapter 5. The conclusions from this study were that the time-averaging of vorticity data can sometimes be misleading, with unsteadiness causing vortical structures to diffuse in the time-averaged plots whilst being observed in the instantaneous data. Therefore it is necessary to examine the instantaneous results to fully evaluate the behaviour of this structure. This is illustrated in Figure 6.8 where the instantaneous vorticity results at two different instances in time and two different streamwise planes are plotted with their time-averaged equivalents.

From the data contained within this figure it can be seen that at the more upstream plane of $Y = 0mmFS$, the top vortex has a reasonably steady, coherent structure. This is deduced from the similarity of the position of the vortex and its peak vorticity in both the time-averaged and instantaneous results. (compare Figure 6.8(e) with Figures 6.8(a) and 6.8(c)). Further downstream at $Y = 200mmFS$ the agreement is not as good and the top vortex appears to be absent in the time-averaged vorticity data (Figure 6.8(f)). Instantaneously the presence of this structure is also questionable. As can be seen from Figures 6.8(b) and 6.8(d), there are patches of vorticity close to the side wall of the wheel. However, none of these patches would indicate a coherent vortex structure and due to their irregularity in each of the two time instances, it is thought that the top vortex has been adversely affected by both the flow rotating close to the wheel and that associated with the wheel hub.

From the instantaneous data contained within this figure it can also be seen that at $Y = 0mmFS$ both the instantaneous and time-averaged structures of the main and the footplate vortex are very similar. However, further downstream at $Y =$

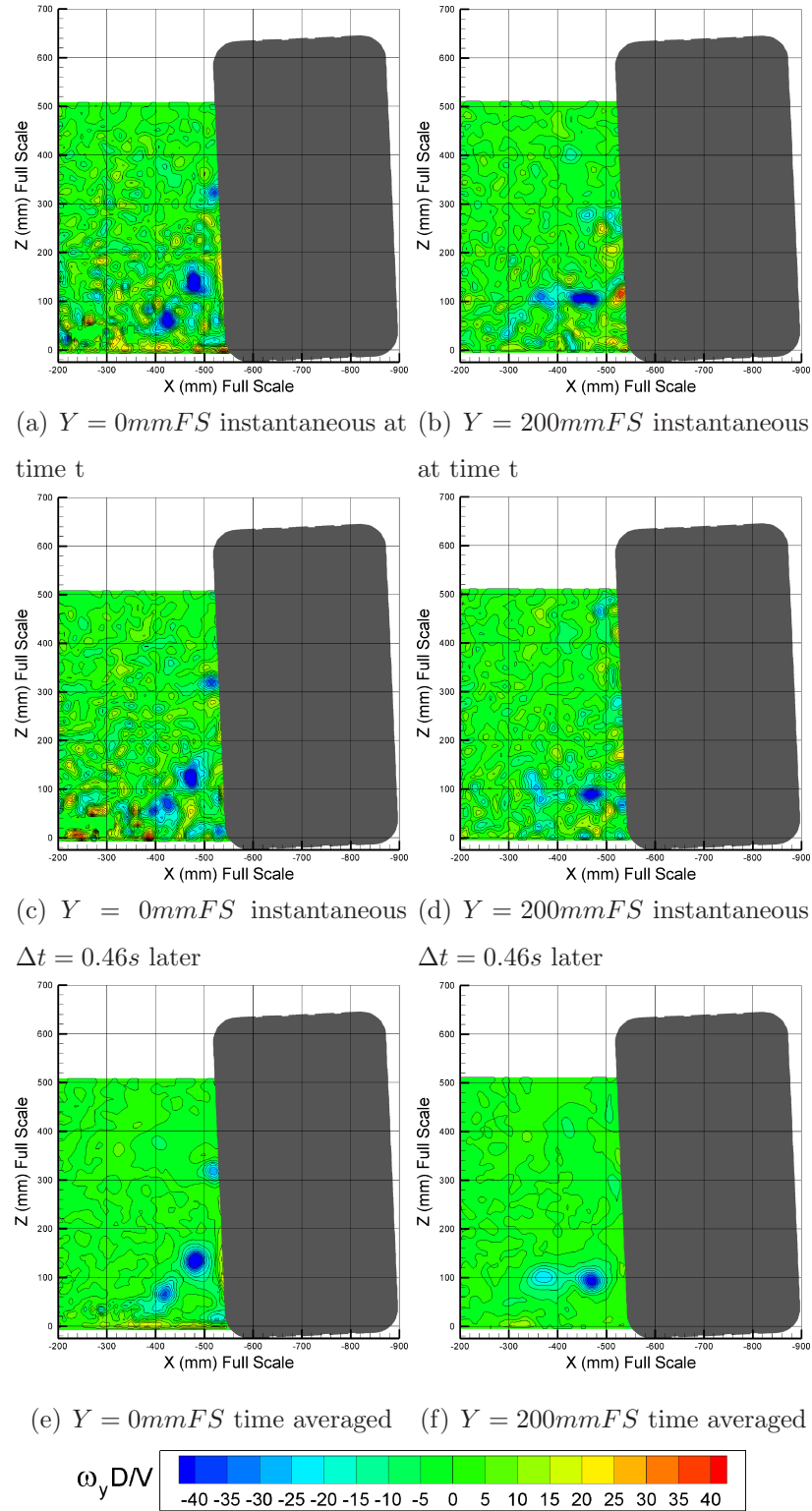


Figure 6.8: Comparison of instantaneous and time-averaged non-dimensional vorticity fields at two different points in the flow downstream of the McLaren model at a ride height of $h/c_{mp} = 0.48$ with the rotating wheel ($V_\infty = 25m/s$)

200mmFS the time-averaged vorticity of the footplate vortex is slightly weaker than its instantaneous values. This may arise due to slight irregularities in the structure of this feature at the two different time instances which may be a consequence of the strong interactions taking place between the footplate and the main vortex, as these two vortices merge together.

In comparison with the vorticity results presented previously in Chapters 4 and 5, it can be seen from the instantaneous results shown in Figure 6.8 that there appears to be a greater amount of fluctuations in the calculated vorticity across the field of view. It is thought that these fluctuations are more likely to be due to experimental inaccuracies than actual physical characteristics of the flow. In contrast to the single wing and wheel model used to produce the results of Chapter 5, illumination of the flow inboard of the wheel on the McLaren model was achieved by the reflection of the laser-sheet in a mirror (refer to Section 3.4). The reflection in the mirror may cause a drop in the intensity of the laser sheet due to the quality of the mirror.

Another contribution to this error may be a direct result of the strength of the vortical structures downstream of the McLaren model. To accurately capture the large cross-flow velocities generated by the McLaren trailing vortex system, it was necessary to reduce the timing interval between the particle images. Unfortunately this reduced the displacement of the particles in slower moving parts of the flow to the order of one or two pixels. Hence the uncertainty in these regions may be higher as a result of the shortened time-interval.

6.1.3 Downstream of the wheel

Downstream of the wheel the large region of energy loss observed in the total pressure distribution is associated with a large region of swirling air. This can be seen in Figure 6.9 where the results from the laser-smoke flow visualisation of planes downstream of the wheel are presented. Close to the wheel a single vortex core is visible but this merges into a general region of swirling flow which is present downstream of the wheel.

It has been shown from the vorticity data that this ‘hump-like’ structure is formed



(a) $Y = 400mmFS$



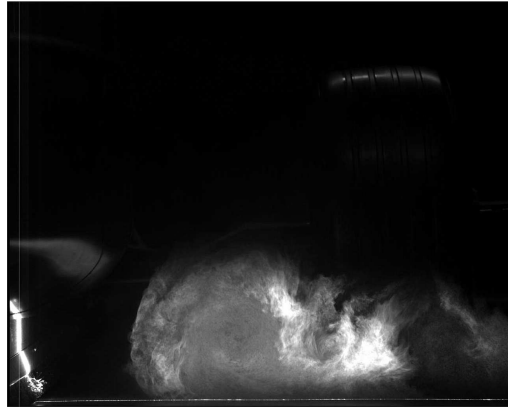
(b) $Y = 500mmFS$



(c) $Y = 600mmFS$



(d) $Y = 700mmFS$



(e) $Y = 800mmFS$

Figure 6.9: Laser smoke flow visualisation of flow downstream of wheel of McLaren model at a ride height of $h/c_{mp} = 0.48$ with rotating wheel ($V_\infty = 12.5m/s$)

as a result of the interaction between the main and footplate vortices. However the time-averaged vorticity values associated with these structures presented in Figures 6.6 and 6.7 diminish below the plotted iso-surface value of $\omega_y D/V_\infty = -8$. Vorticity fields downstream of the wheel with reduced contour levels are plotted in Figure 6.10, from which it is also possible to examine the effect of the trailing vortex system on the wake of the wheel.

As can be seen from this figure there is still significant vorticity associated with the main and footplate vortices in these planes downstream of the wheel. Upstream of the planes shown in Figure 6.10(a), the vortices were rotating about one another as independent structures. However, as can be seen from this data the vortices have begun to merge together which results in the large region of swirling smoke seen in the flow visualisation.

The presence of the trailing vortices significantly affects the topology of the wheel wake. Downstream of an isolated wheel two counter-rotating vortical pairs are generated (Section 5.2). One pair located near the top of the wheel (termed the upper vortices), and the other pair near the ground plane (termed the lower or ‘jetting’ vortices). As can be seen from Figure 6.10(c) the outboard lower vortex has been substantially displaced inboard and the inner vortex is no longer visible. The two merging vortices from the wing trailing vortex system may have merged with this vortex. Of the upper-pair, only the inner vortex is visible due to the limited field of view and its position has also been affected by the wing trailing vortex system.

6.2 Effect of Modifying Ride Height

The previous section has shown how the behaviour of the McLaren trailing vortex system at a moderate ride height ($h/c_{mp} = 0.48$), is dominated by the interaction and merging of the main and footplate vortex. Downstream of the wheel this forms a ‘hump-like’ region of swirling flow whose presence has a large affect on the wake generated from the rotating wheel.

In this section the flow structure downstream of the McLaren front wing at varying ride heights with the rotating wheel will be investigated. In similarity to

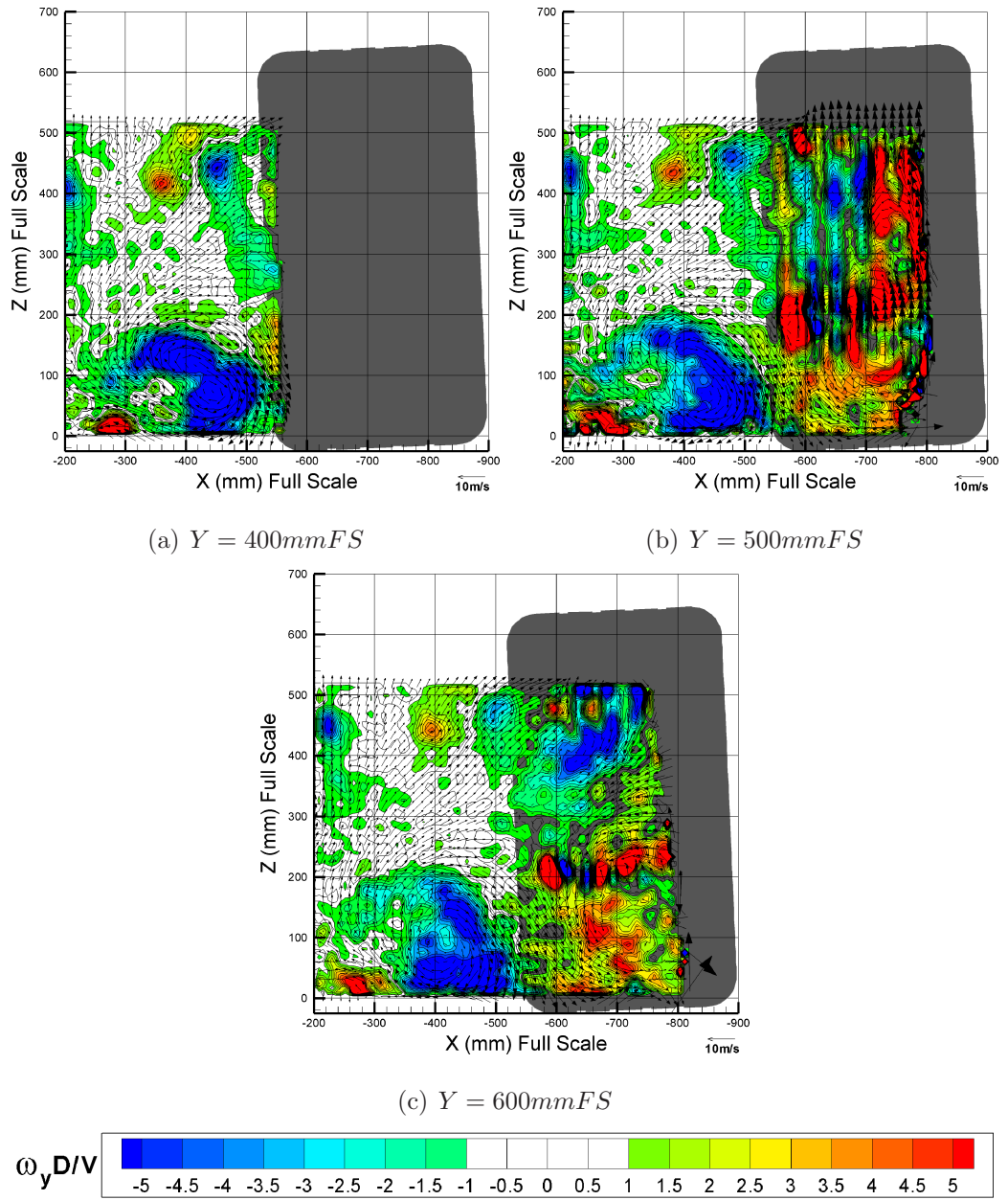


Figure 6.10: Non-dimensional time-averaged vorticity in planes downstream of wheel of McLaren model at a ride height of $h/c_{mp} = 0.48$, with the rotating wheel and reduced contour levels ($V_\infty = 25m/s$)

the previous section, this will be undertaken by examining the flow structure at different points downstream of the front wing.

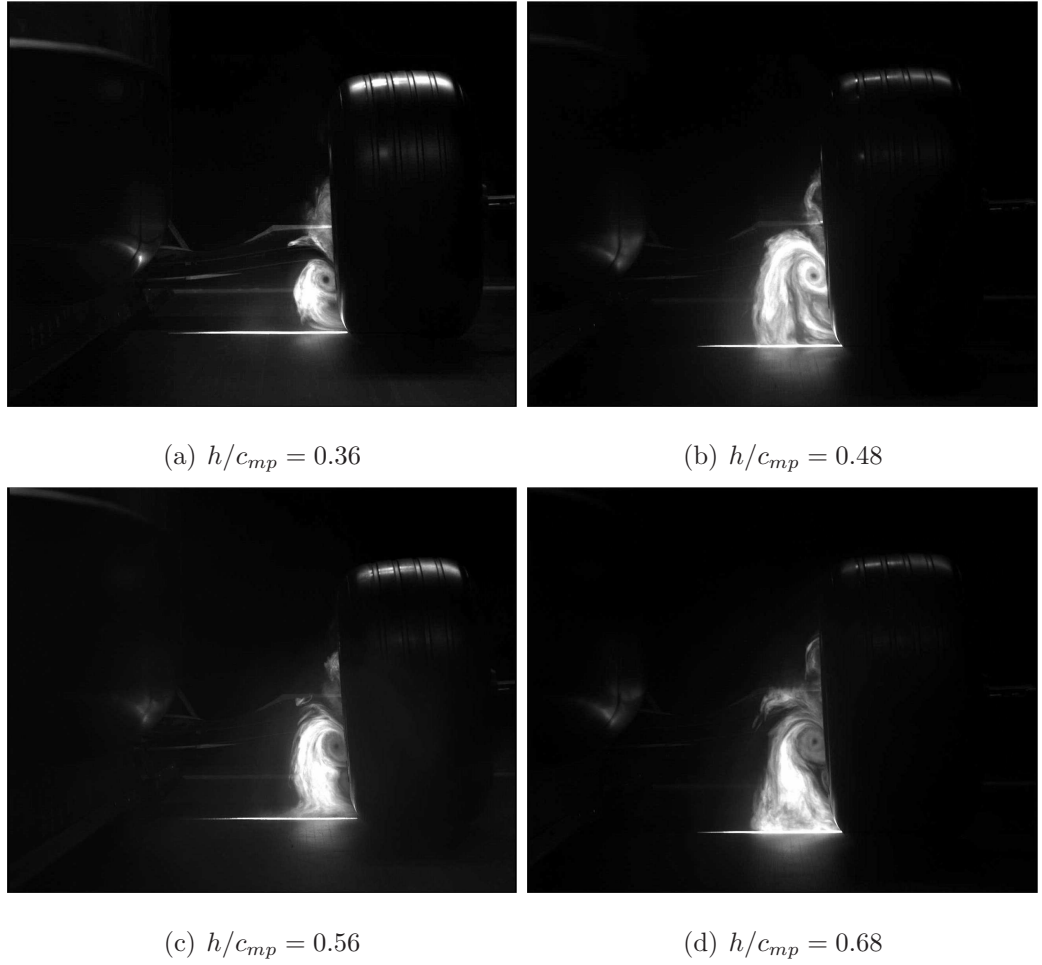


Figure 6.11: Laser-smoke flow visualisation at $Y = -250mmFS$ downstream of McLaren model at varying ride height with the rotating wheel ($V_\infty = 12.5m/s$)

6.2.1 Near-Field

Figure 6.11 shows results of the laser-smoke flow visualisation just downstream of the wing at $Y = -250mmFS$, for all of the ride height configurations.

From these images the consequences of changing the ride height of the wing can be seen. A clear trend in the vertical position of the main vortex is observed with its core being displaced in accordance with the height of the wing. However, the behaviour of the footplate vortex is less obvious with its presence not visible at the highest ride height (Figure 6.11(d)). As the wing is brought closer to the ground the smoke particles show the footplate vortex moving further inboard and it is clearly



Figure 6.12: Laser-smoke flow visualisation at $Y = -100mmFS$ downstream of McLaren model at varying ride height with the rotating wheel ($V_\infty = 12.5m/s$)

identifiable in the view of the camera, at the lowest ride height (Figure 6.11(a)). The amount of lateral displacement of the footplate vortex with ride height is greater than was observed without the wheel (Chapter 4). Hence it is thought that it is the influence of the flow ahead and about the front of the rotating wheel which causes this difference.

6.2.2 Inboard of the Wheel

Figure 6.12 shows the flow visualisation of the vortex system at all of the ride heights, after it has navigated about the front of the wheel. The cores of the main

and footplate vortices are clearly apparent in these figures and it can be seen that the separation distance between these two structures varies with ride height. With the wing furthest away from ground the separation between the vortices is reasonably large (Figure 6.12(d)). As the wing is lowered this distance reduces and at the lowest ride height the two structures can be seen to be interacting strongly (Figure 6.12(a)).

These qualitative observations are reinforced by the results presented in Table 6.1. This table gives the estimations for the centres of each vortex together with the calculated distance between the two cores obtained from PIV data. Note that these results were obtained from the time-averaged velocity data obtained by PIV at a plane of $Y = -100mmFS$ for all of the ride heights except for the lowest configuration, which was undertaken at $Y = -200mmFS$, because further downstream the vortices were in the process of merging.

Ride Height and Y-plane	Main Vortex		Footplate Vortex		Separation (mmFS)
	X(mmFS)	Z(mmFS)	X(mmFS)	Z(mmFS)	
$h/c_{mp} = 0.36$ Y=-200mmFS	-516.8	105.9	-511.7	34.5	71.6
$h/c_{mp} = 0.48$ Y=-100mmFS	-491.5	143.4	-466.0	56.3	90.8
$h/c_{mp} = 0.56$ Y=-100mmFS	-496.0	162.1	-500.2	61.5	100.7
$h/c_{mp} = 0.68$ Y=-100mmFS	-491.1	203.2	-516.8	84.3	121.6

Table 6.1: Table of the centres of the main and footplate vortices and the relative separation after having passed about the front of the wheel at different ride heights

These quantitative results confirm the observation that the separation distance reduces in accordance with the ride height.

The reasons for this trend is thought to be partly due to the shedding of the

vortex system in different parts of the flow travelling about the wheel and partially a consequence of the varying strengths of the vortices as the height of the wing is changed. As has been discussed in the literature review (Section 2.4) and in Chapter 5, the aerodynamics about a rotating wheel are complex with the flow being affected by both the rotation and profile of the wheel. As was observed from the results presented in Chapter 5, the trajectory of a vortex travelling about the wheel is strongly dependant on its upstream formation position. If two or more vortices are released in front of the wheel then their relative positions may also vary due to the variance in the local velocity about the wheel. Hence the effect of varying the ride height of the McLaren front wing not only changes the global position of the vortex system but may also modify the relative positions of the individual vortices. The separation distance of the vortices may also be affected by the varying strength of the main vortex which decreases with ride height.

Further downstream at $Y = 0mmFS$ Figures 6.13 and 6.14, containing both the flow visualisation and PIV results at the two lowest and highest ride height configurations respectively, show the flow structures that are formed as a result of the differing separation between the main and footplate vortices.

With the wing at the highest ride height the separation between the cores of the main and footplate vortices is the greatest, and as a result it can be seen from both the flow visualisation and the PIV vorticity contours (Figures 6.14(c) and 6.14(d) respectively) that the two vortices show very little signs of interaction and the main vortex travels about the wheel almost vertically above the footplate vortex.

As the height of the front wing and endplate is reduced to the two moderate configurations ($h/c_{mp} = 0.48$ and $h/c_{mp} = 0.56$), the interaction between the vortices appears to increase. The smaller separation and the increase in strength of the main vortex induces the vortices to orbit about one another, with the rotation greater when at the lower ride height.

With the wing in the lowest ride height configuration of $h/c_{mp} = 0.36$, Figure 6.13(a) and Figure 6.13(b) show the consequences of the smallest separation distance between the cores of the main and footplate vortices. At this point in the flow only a single core is visible and the remnants of the footplate vortex appears to orbit about

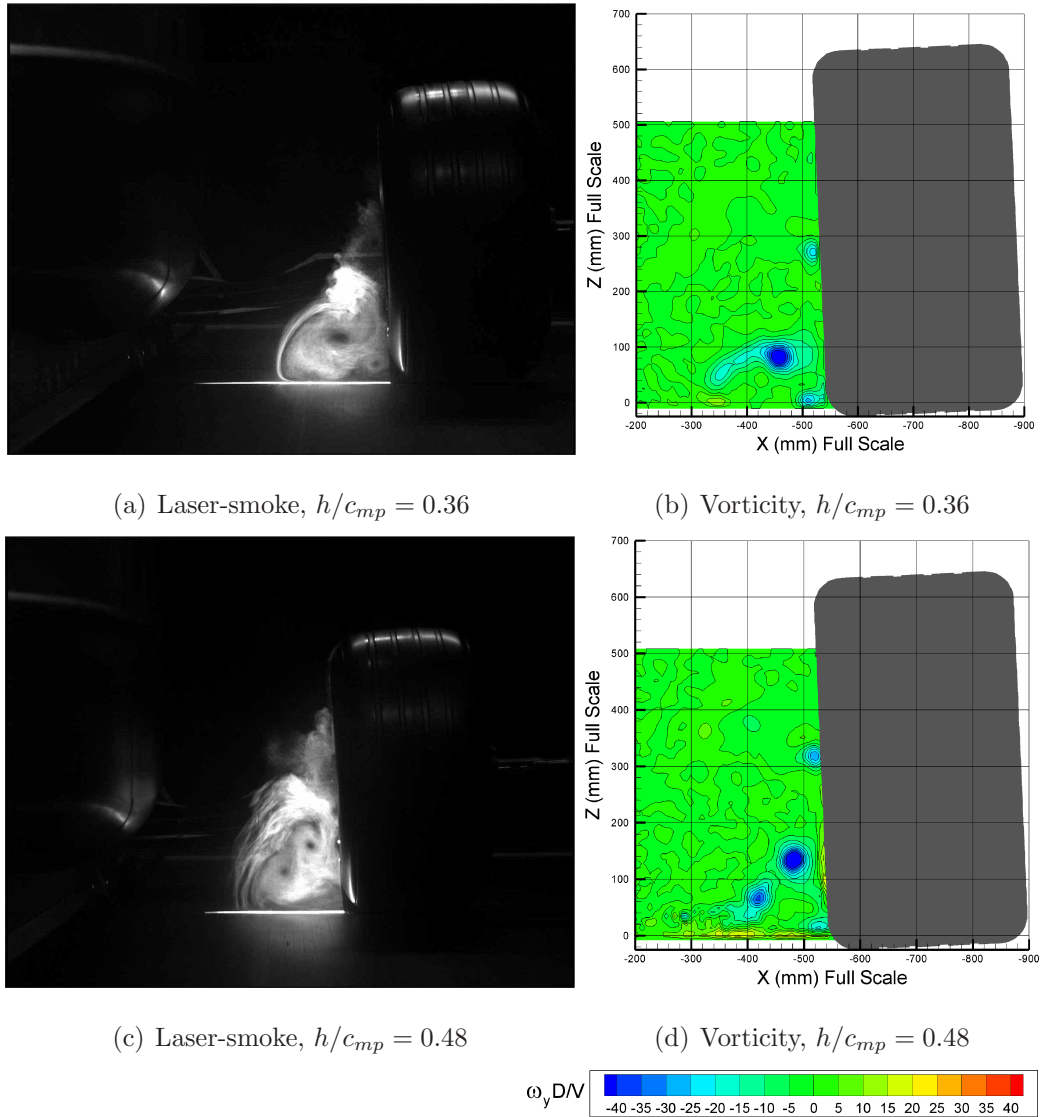


Figure 6.13: Comparison of laser-smoke flow visualisation ($V_\infty = 12.5m/s$) and non-dimensional vorticity contours obtained from PIV ($V_\infty = 25m/s$) at the two lowest ride heights behind the McLaren model with the rotating wheel

this core as an arm of vorticity. This structure is characteristic of two unequal co-rotating vortices undergoing the merging process (refer to Section 2.3.1.1).

As was discussed in the review of literature associated with the interaction of co-rotating vortices (Section 2.3.1.1), when separation distance is large the vortices will tend to orbit about one another due to the induced velocity field. If the separation distance is reduced or the strength of the vortices increased then the rotation of

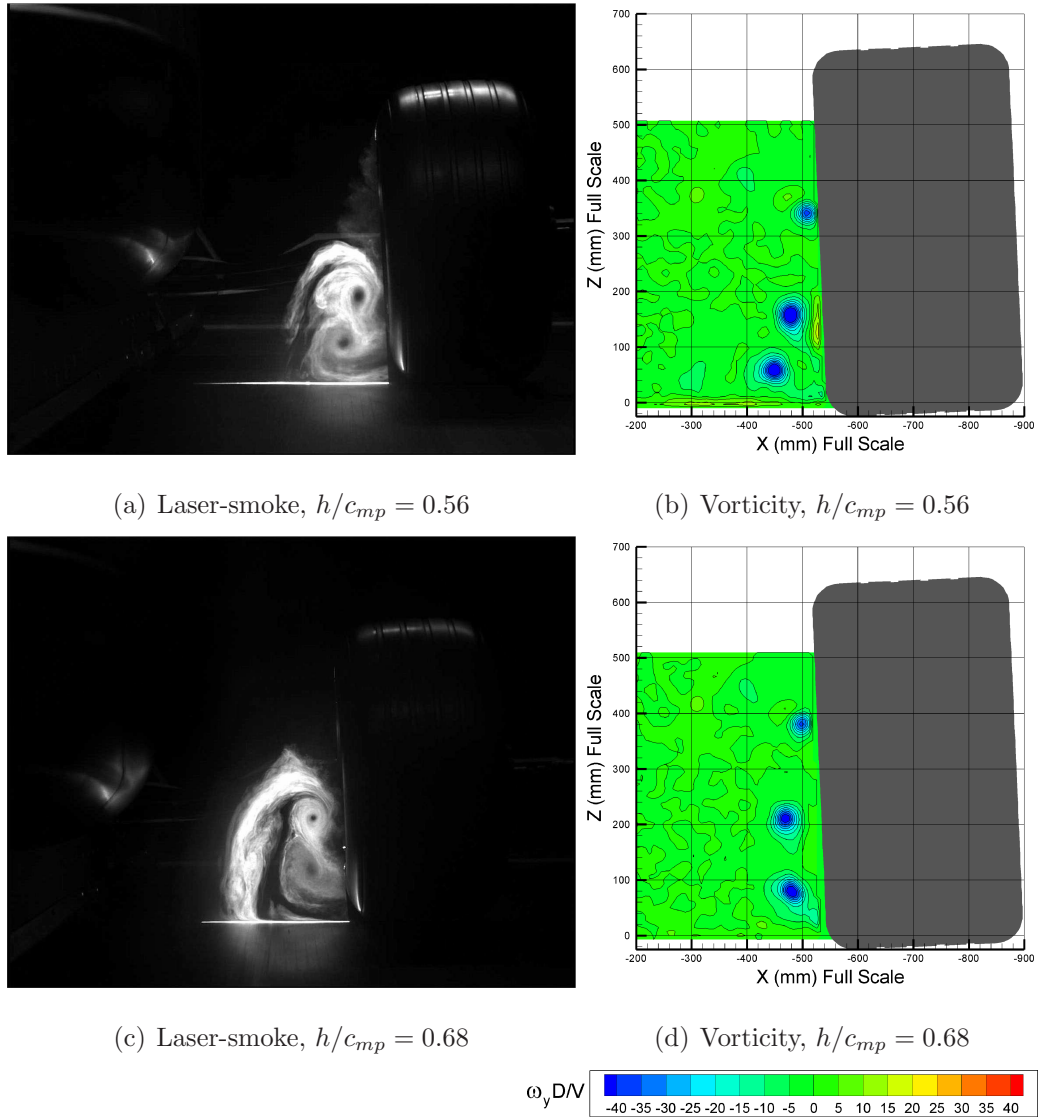


Figure 6.14: Comparison of laser-smoke flow visualisation ($V_\infty = 12.5m/s$) and non-dimensional vorticity contours obtained from PIV ($V_\infty = 25m/s$) at the two highest ride heights behind the McLaren model with the rotating wheel

the vortices is greater. This trend continues until a critical ratio of core size (r_c) to separation distance (b) has been met (Note that other researchers have referred to the core size as a, however to maintain the notation r_c will be used here). Once this has occurred, the behaviour of the co-rotating vortices changes dramatically, with the distance between the cores diminishing. Termed the ‘heart of the merging process’ by Cerretelli & Williamson (2003) this process is generally accepted to occur

when the ratio of core radius to separation exceeds $(r_c/b)_{crit}$ which is thought to be in the region $0.2 \leq (r_c/b)_{crit} \leq 0.326$ (refer to Section 2.3.1.1).

By parameterising the vortices from the time-averaged velocity fields, this ratio has been estimated for each of the different ride height configurations and is presented in Table 6.2. Note that at $Y = -200mmFS$ the vortices in the ride height configurations of $h/c_{mp} = 0.56$ and $h/c_{mp} = 0.68$ were partially obscured by the wheel from the view of the camera and hence no results are available. Also note that this ratio is based on two co-rotating vortices of equal strength with the same core radius. Therefore to take into account the two different sized vortices in these experiments, the mean of the core radii is used.

	Y=-200mmFS	Y=-100mmFS	Y=0mmFS
h/c_{mp}	r_c/b	r_c/b	r_c/b
0.36	0.21	N/A	N/A
0.48	0.13	0.16	0.15
0.56	N/A	0.13	0.12
0.68	N/A	0.10	0.11

Table 6.2: Table of the estimated vortex core radius to separation distance ratio (r_c/b) for the main and footplate vortices at each of the ride heights in various planes downstream of the McLaren model with the rotating wheel

From these results it can be seen that only at the lowest ride height do the vortices exhibit a core radius to separation ratio which is of the order of the critical ratio. Therefore this explains the different levels of interaction seen in the both the laser-smoke and PIV results shown in Figures 6.13 and 6.14.

The structure and interaction of the main and footplate vortices measured by these two different techniques, appear to be in good general agreement with one another. However, one difference between the two sets of results is the lack of the top vortex in the images from the flow visualisation. In obtaining these images the smoke was released in a position that provided the best visualisation of the interaction between the main and footplate vortices. Hence it is thought that there

was not sufficient smoke near the top vortex for it to appear in the images.

From the PIV data it can be seen that the peak vorticity of the top vortex increases as the ride height of the front wing is raised above the ground. This is indicative of an increase in circulation of this feature and is consistent with the results from Chapter 4 which showed that the strength of this vortex increased with ride height without the wheel.

The increased strength of the top vortex with ride height provides an explanation for its presence further downstream as the ride height of the front wing is increased, as presented in the time-averaged vorticity data shown in Figure 6.15 and from the different perspectives of Figures 6.16, 6.17 and 6.18.

The increased circulation prolongs the existence of this vortex in the time-averaged vorticity data by reducing the effect of the interaction with the flow close to the wheel. However, in all of the configurations the vortex appears to peter out as the centreline of the wheel is passed.

These plots clearly demonstrate the different merging characteristics of the main and footplate vortex inboard of the wheel in the four ride height configurations. As a result of this behaviour the vortices form different flow structures downstream of the wheel.

6.2.3 Downstream of the Wheel

The different structures described in the previous section can be seen in Figures 6.19 and 6.20 where the results from the laser-smoke flow visualisation and the total pressure surveys have been plotted at the lowest and highest ride heights.

As can be seen from these figures, the agreement between the two techniques for locating vortices is extremely good. Figures 6.19(a) and 6.19(b) show the flow downstream of the wheel generated by the vortices shed from the wing at the lowest ride height. The close interaction and merging of the main and footplate vortices generates a structure which consists of a single core in the centre of a large swirling volume of air which appears to be fairly axisymmetric.

As the ride height is increased, the amount of merging interaction decreases due

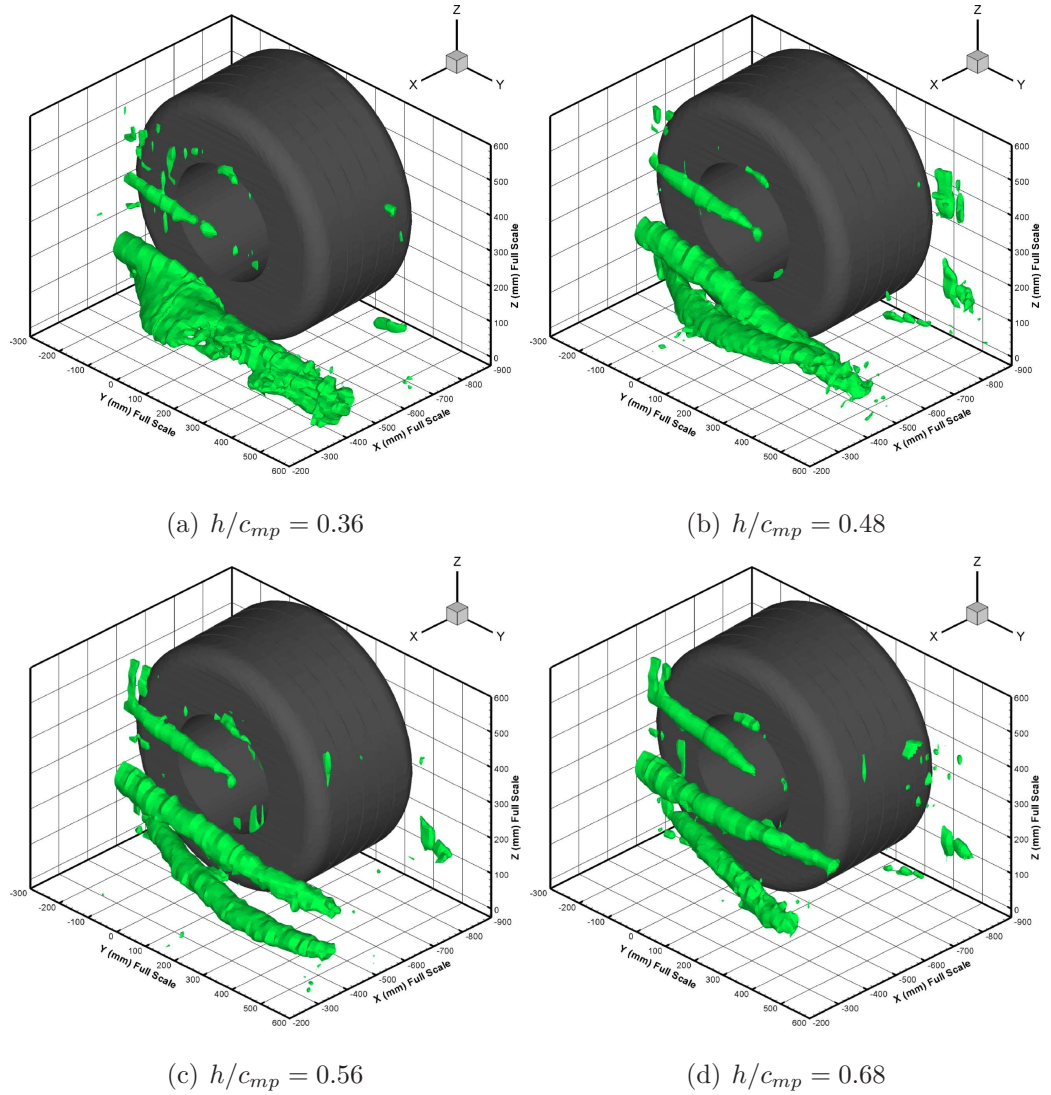


Figure 6.15: Iso-surface of non-dimensional time-averaged vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at varying ride heights with the rotating wheel ($V_\infty = 25m/s$)

to the changes in the relative positions and strengths of the vortices in the near-field. As was discussed in the previous section, with the gap between the wing and the ground plane at $h/c_{mp} = 0.48$ the vortices orbit about one another and form a ‘hump-like’ structure downstream.

With the wing raised further to $h/c_{mp} = 0.56$ a similar structure to the previous configuration is generated. The shape differs only slightly due to the amount of orbiting which has taken place ahead of this plane.

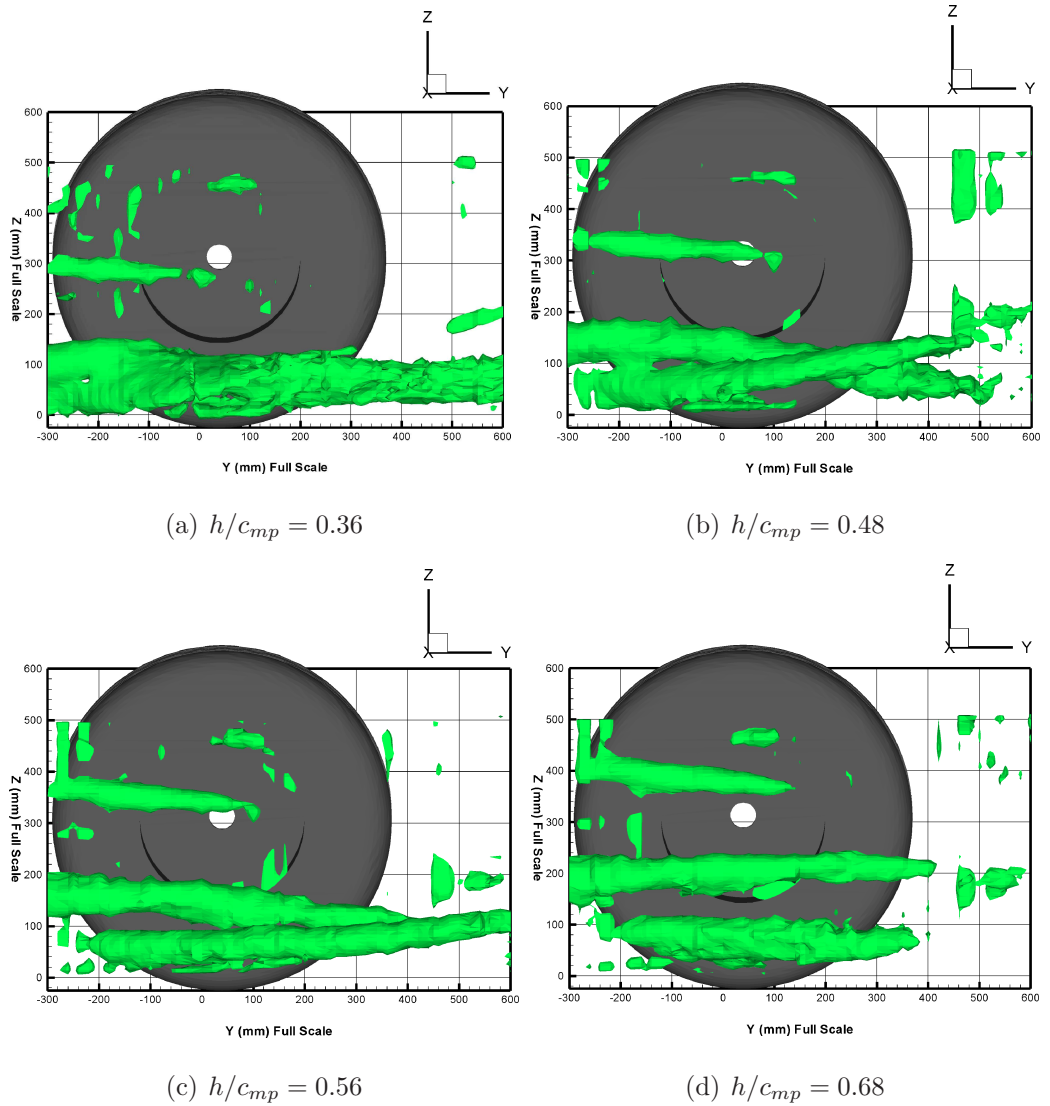


Figure 6.16: Iso-surface of non-dimensional time-averaged vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at varying ride heights with the rotating wheel as viewed in the Y-Z plane ($V_\infty = 25\text{m/s}$)

At the highest ride height of $h/c_{mp} = 0.68$ it can be seen from the iso-surfaces of vorticity plotted in Figures 6.15, 6.16, 6.17 and 6.18, that all of the three vortices travel about the wheel with very little interaction with one another. As a result the vortices appear to behave as isolated vortices and follow trajectories that are similar to those seen in the previous chapter. Downstream of the wheel the time-averaged vorticity of the main and footplate vortices decreases substantially which suggests that these two structures are affected by the large scale fluctuations which exist in

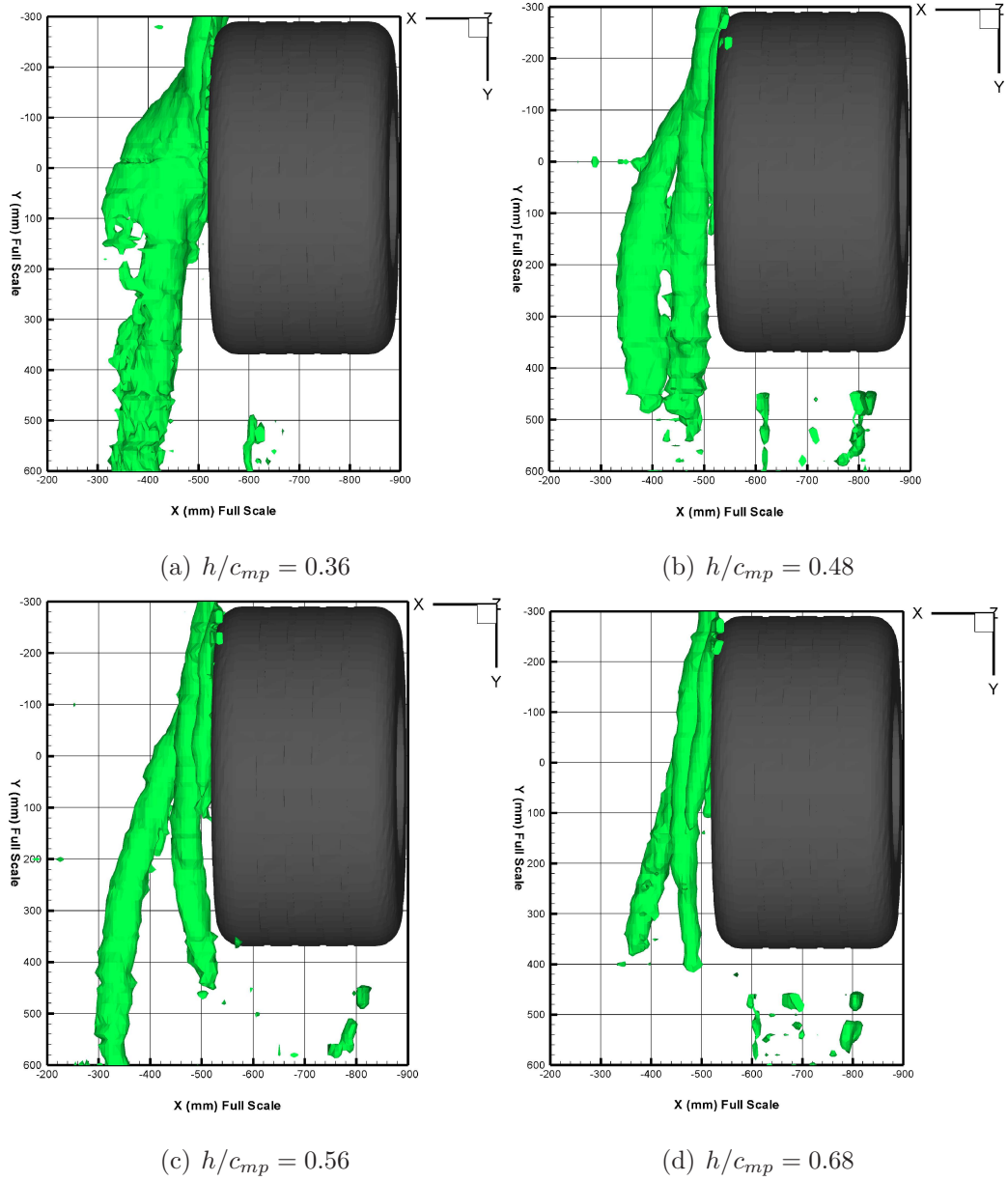


Figure 6.17: Iso-surface of non-dimensional time-averaged vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at varying ride heights with the rotating wheel as viewed in the X-Y plane ($V_\infty = 25m/s$)

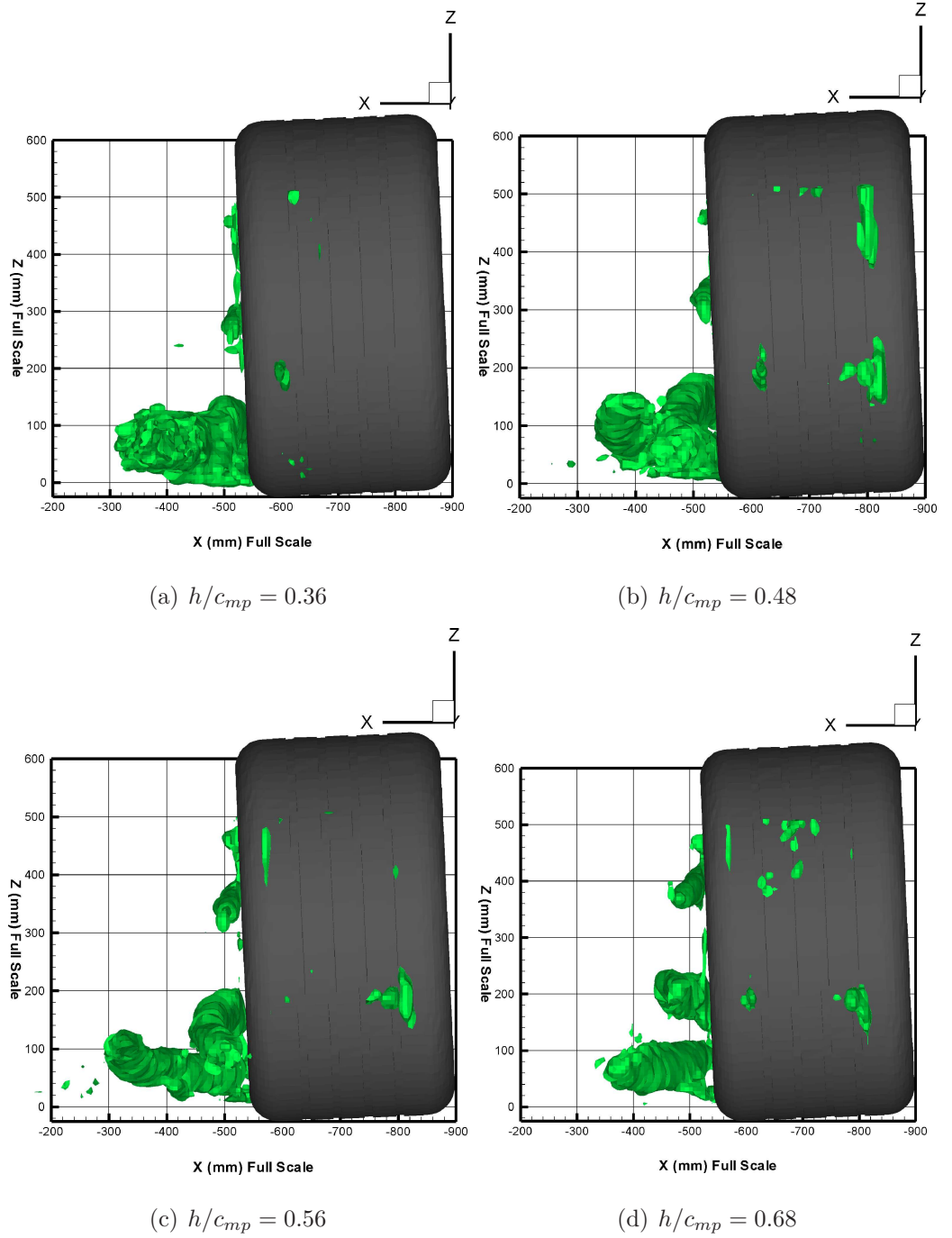


Figure 6.18: Iso-surface of non-dimensional time-averaged vorticity ($\omega_y D/V_\infty = -8$), downstream of McLaren model at varying ride heights with the rotating wheel as viewed in the X-Z plane ($V_\infty = 25m/s$)

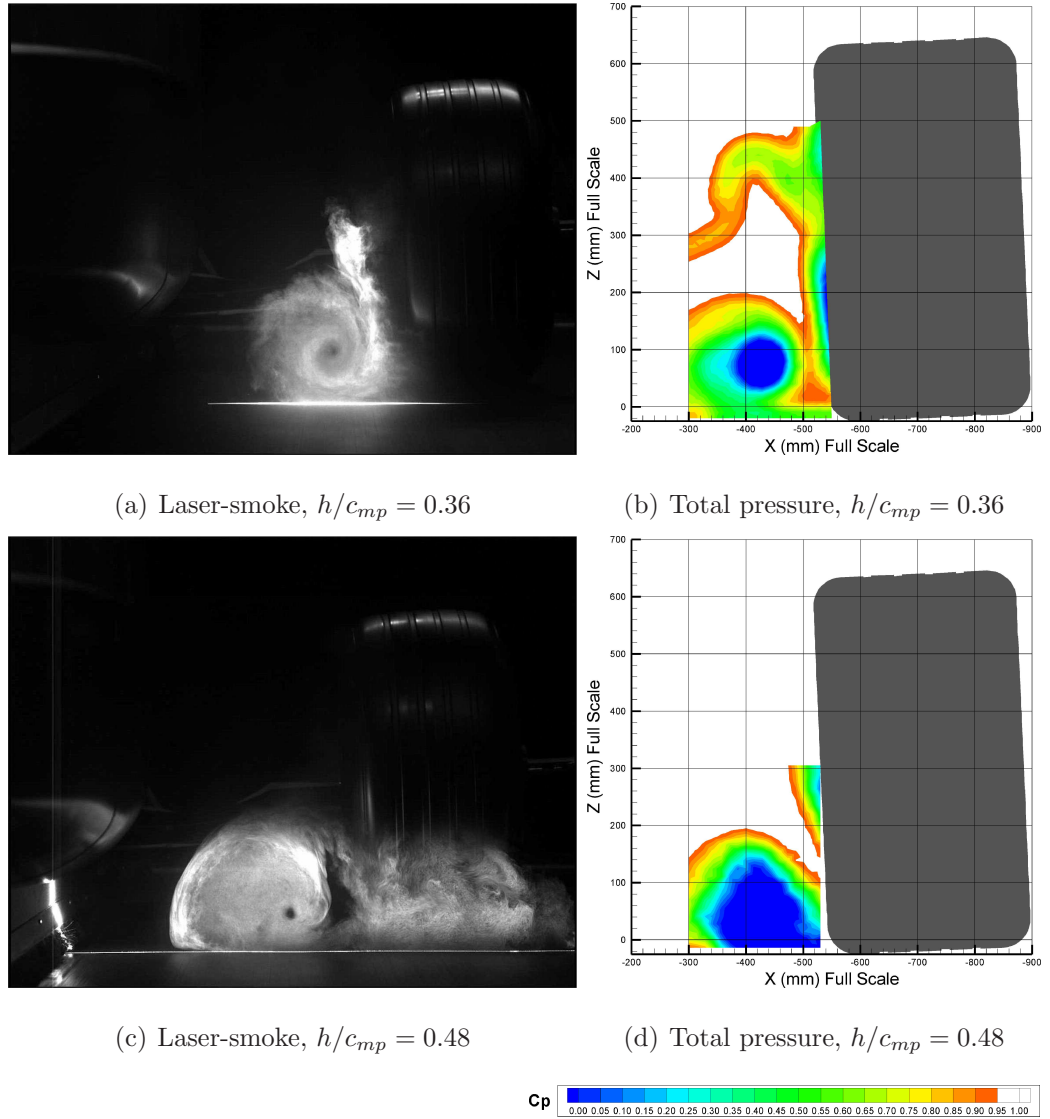


Figure 6.19: Laser-smoke flow visualisation ($V_\infty = 12.5m/s$) and total pressure ($V_\infty = 25m/s$) contours at $Y = 400mmFS$ downstream of McLaren model at the two lowest ride heights with the rotating wheel

the wake of the wheel. The resulting flow structure at $Y = 400mmFS$ can be seen in Figures 6.20(c) and 6.20(d). Both of the experimental techniques have found that the flow structure resembles the shape of these two weak vortices.

Further downstream of the wheel at $Y = 600mmFS$, the axisymmetric flow structure formed by the McLaren wing at the lowest ride height affects the wake that is generated by the wheel. This can be seen when the vorticity is plotted with reduced contours, as presented in Figure 6.21.

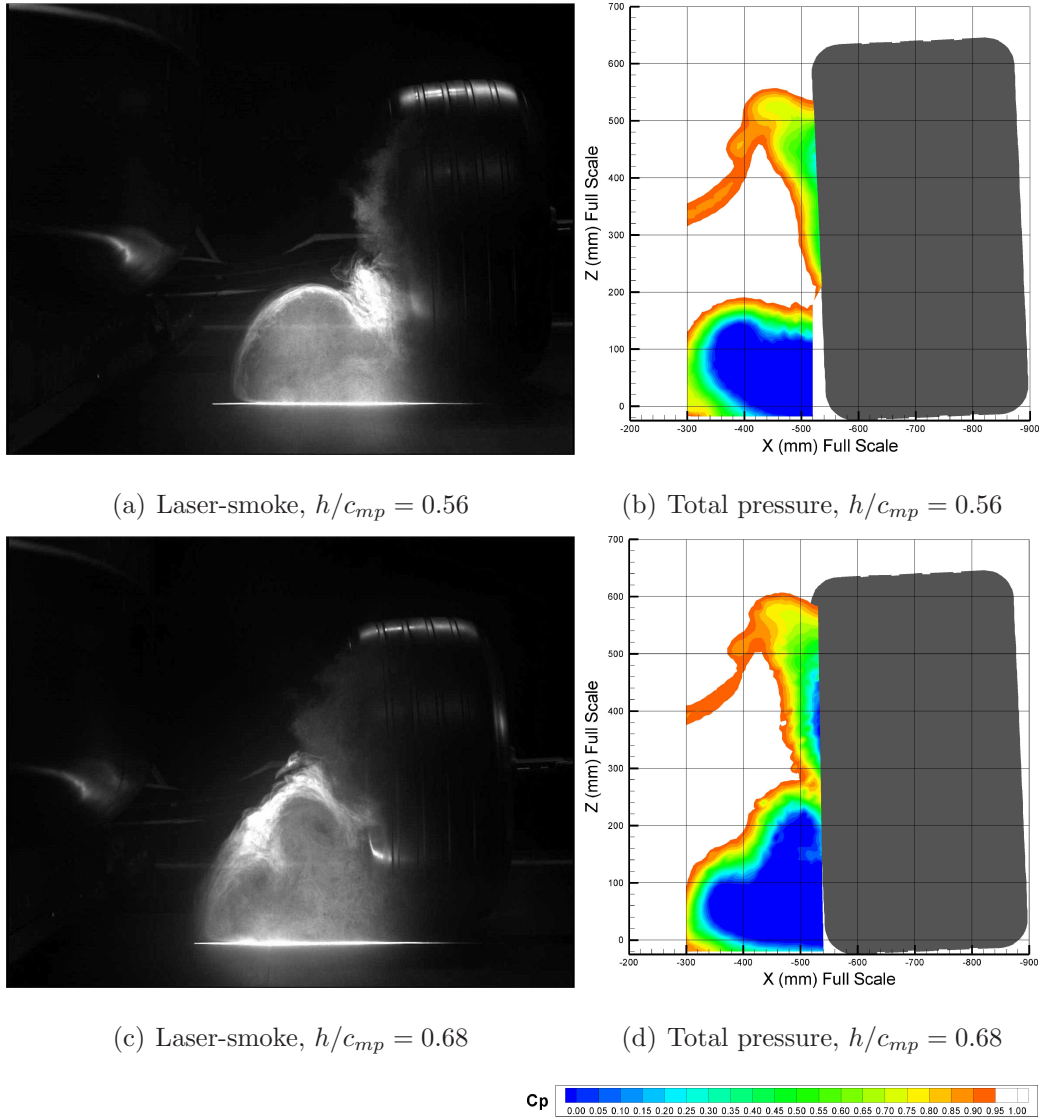


Figure 6.20: Laser-smoke flow visualisation ($V_\infty = 12.5m/s$) and total pressure ($V_\infty = 25m/s$) contours at $Y = 400mmFS$ downstream of McLaren model at the two highest ride heights with the rotating wheel

In similarity to the ride height configuration of $h/c_{mp} = 0.48$ discussed in the previous section and shown in Figure 6.21(b), the presence of the trailing vortex system shed from the wing in the lowest configuration, prevents the inner lower vortex from forming. It is uncertain whether this structure has merged with the trailing vortices or the aerodynamics associated with its formation have been affected.

At a ride height of $h/c_{mp} = 0.56$, the two trailing vortices have not completely merged together and the rotation about the footplate vortex has positioned the main

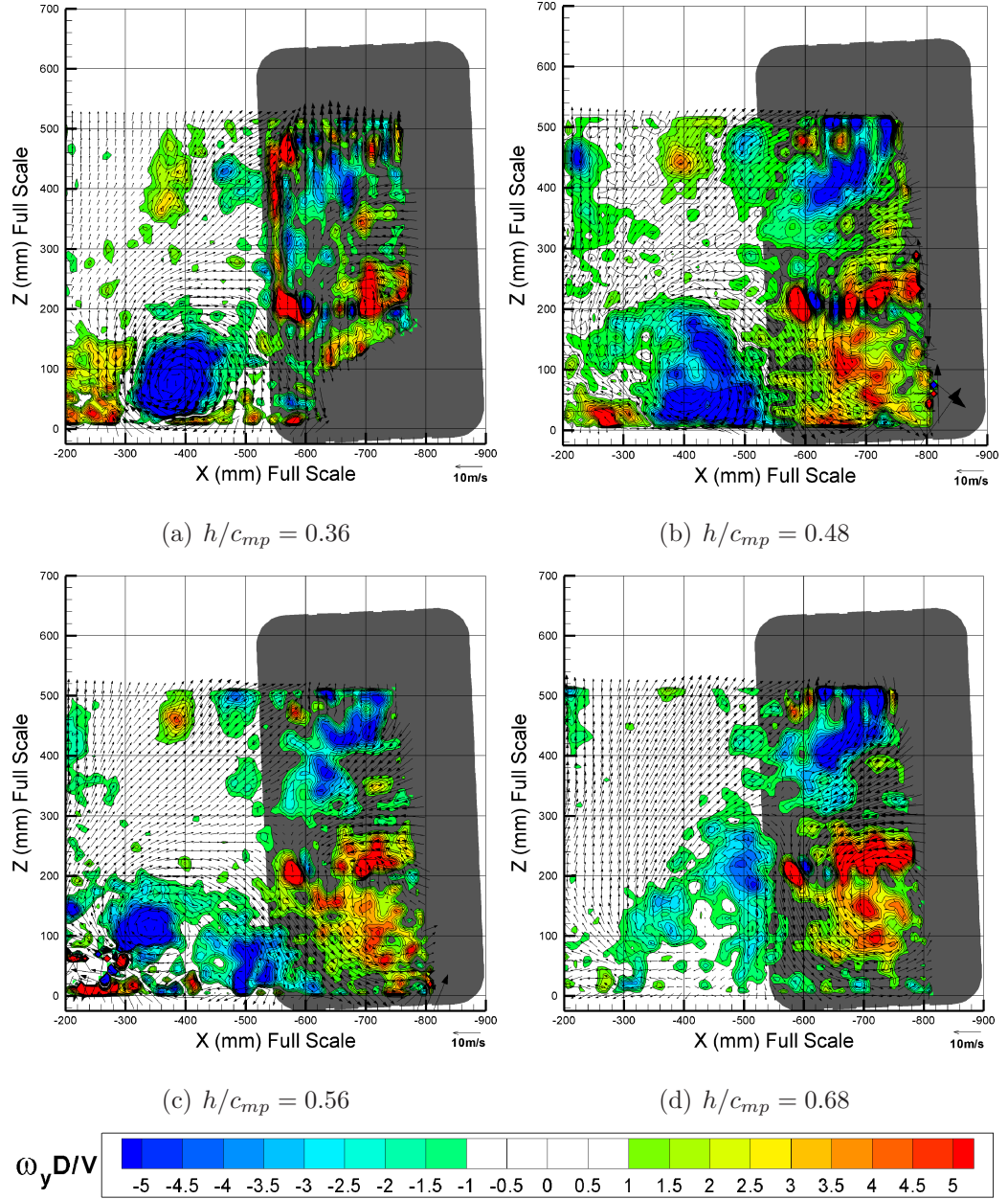


Figure 6.21: Non-dimensional time-averaged vorticity in planes downstream of wheel of McLaren model at varying ride heights with the rotating wheel and reduced contour levels ($V_\infty = 25m/s$)

vortex in a similar location to the inboard lower vortex of an isolated wheel. Hence it is thought that these two like-signed vortices have merged together.

With the McLaren wing at the highest distance above the ground, the time-averaged vorticities associated with the main and footplate vortices can be seen to be substantially reduced from those at the lower ride heights due to the interaction with the wheel wake. In this configuration the outboard jetting and inboard upper wheel vortices can be identified. However the presence of the inboard jetting vortex can not be determined. In the region where it would be expected to exist there are weak patches of negative vorticity near to the lower inboard edge of the rotating wheel. It may be that the unsteady buffeting of the wing vortices in this plane due to the large fluctuations in the wake have prevented a steady, coherent wheel vortex from being formed.

6.3 Comparison with McLaren CFD Results

Previously in this thesis the results of the McLaren CFD (McLaren 2003a) have been mentioned as part of the motivation for this research. Hence it is prudent to compare the results from the numerical technique with that obtained experimentally. The McLaren CFD was performed on the flow downstream of the front wing geometry at a ride height of $h/c_{mp} = 0.36$ and the results of this study are shown as total pressure contours with the equivalent experimental results in Figures 6.22 and 6.23. It should be noted that in the McLaren CFD the axis system is fixed with the car and the ground plane angled to model the car pitch. Hence the location of the ground plane varies with distance in the flow direction. In the experimental results the axis system is fixed with the ground plane (at $Z = -25mmFS$) and the model is pitched. This only affects the Z-axis with the X-axis being the same in both cases. Also note that the contour levels used to plot the results from the two techniques are identical.

In spite of the differences in Reynolds number of the results from these two different techniques ($Re_{c_{mp}} = 5.7 \times 10^5$ for the CFD compared to $Re_{c_{mp}} = 2.0 \times 10^5$ for the experimental results), the two flow structures shown in Figures 6.22(a) and

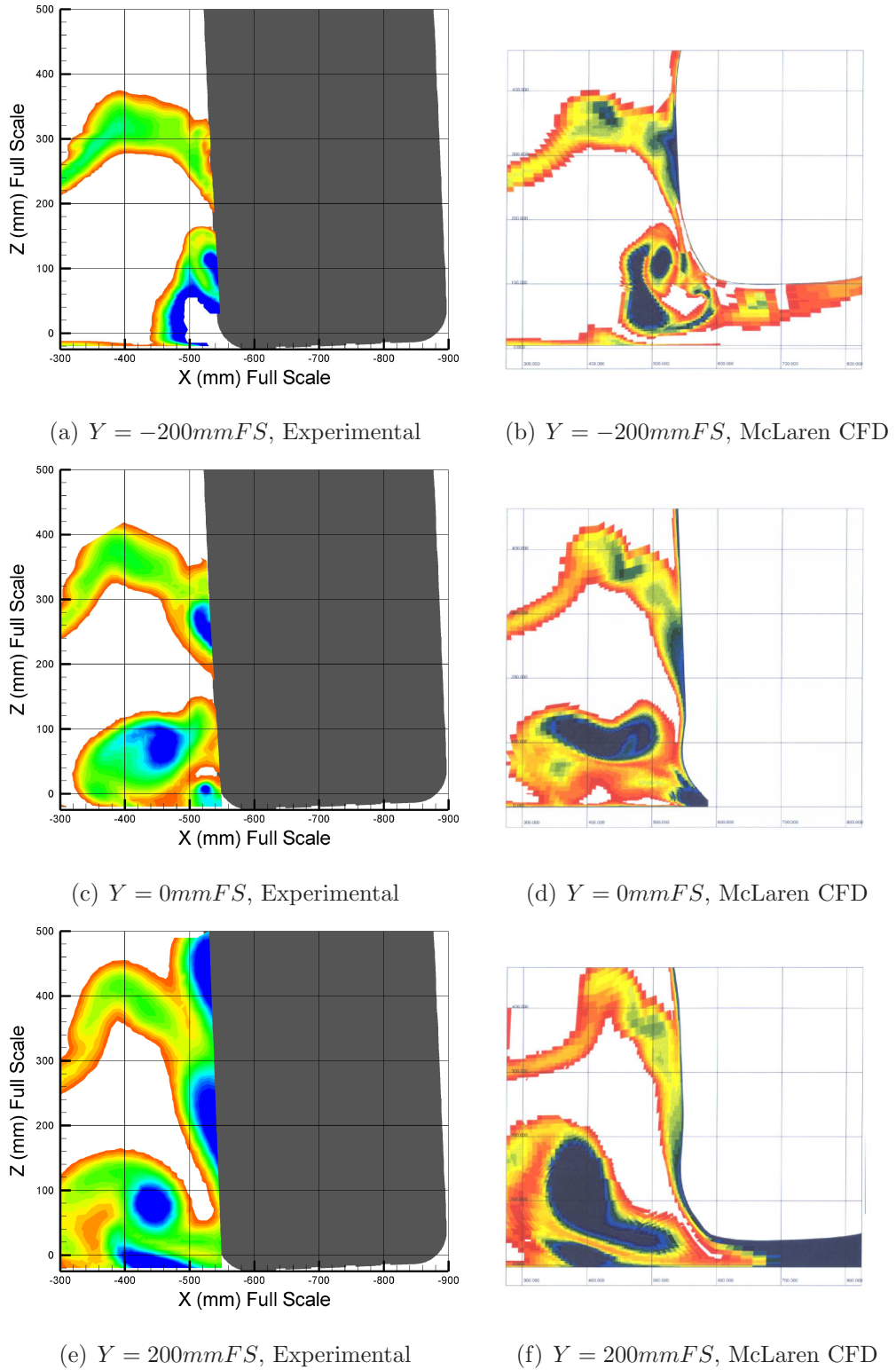


Figure 6.22: Comparison of total pressure contours obtained from experimental wake-surveys and McLaren CFD (McLaren 2003a), downstream of McLaren model at a ride height of $h/c_{mp} = 0.36$ with a rotating wheel

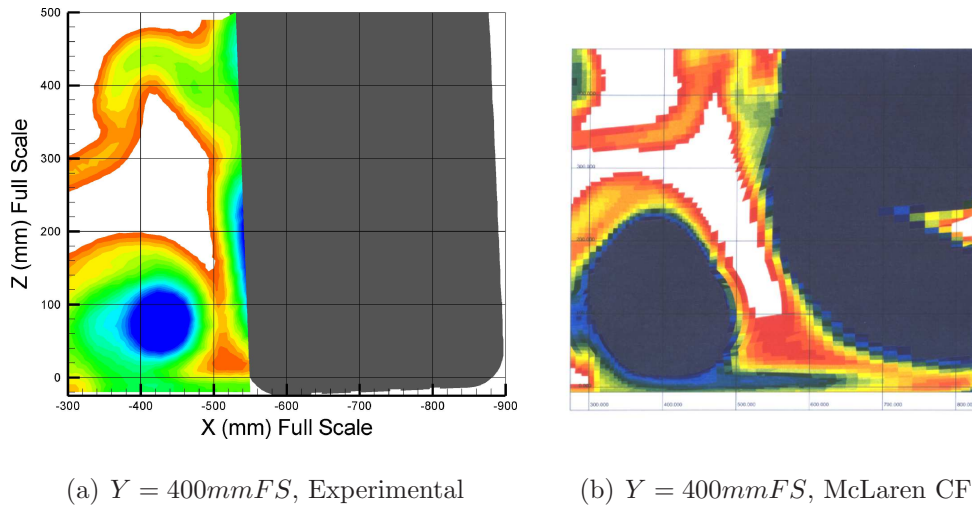


Figure 6.23: Comparison of total pressure contours obtained from experimental wake-surveys and McLaren CFD (McLaren 2003a), downstream of rotating wheel of McLaren model at a ride height of $h/c_{mp} = 0.36$

6.22(b) at a plane of $Y = -200mmFS$ exhibit good similarity. The energy loss associated with the cores of the vortices are of similar dimensions and positions (note that in Figure 6.22(a), a region of the plot has been removed due to erroneous data from the yaw insensitivity of the probe being exceeded due to the large cross-flows in this region). With distance downstream, the two vortices begin to merge and this can be seen from both sets of data. However, the details of this process revealed by the two techniques are slightly different. In general, the McLaren CFD predicts a bigger region of high total pressure loss ($C_p < 0$, indicated by the blue regions in each set of data). Downstream of the wheel at $Y = 400mmFS$ (Figure 6.23), the experimental data also indicates a region of energy loss which has a more circular shape than that predicted by the numerical technique. Previously it was shown that this was attributed to a large volume of air swirling about a single core. Therefore due to this difference in shape, it is thought that the CFD may be predicting a different structure to that shown experimentally at this point.

6.4 Concluding Remarks

The results presented in this chapter have shown that the flow downstream of the McLaren geometry with the rotating wheel, is dominated by the behaviour of the main and footplate trailing vortices. The presence of the wheel affects the positions and strengths of the vortices in the near-field resulting in different flow structures being formed as the ride height of the wing is varied.

When the front wing is set in the lowest ride height configuration, it has been shown the separation distance between the cores of the main and footplate vortices is sufficiently small so that the merging of these two structures occurs at a certain distance downstream. This results in a flow structure consisting of a region of air swirling about a single axisymmetric core.

As the front wing and endplate are raised above the ground, the increased separation between the two vortices diminishes their interaction and the flow forms a downstream ‘hump-like’ structure as a result of the orbiting of the main and footplate vortices.

With the wing raised to the highest distance off the ground there is a large separation distance between the main and footplate vortices causing the vortices to pass about the wheel with very little interference from one another.

The presence of the top vortex was also observed inboard of the wheel. As the ride height of the wing was increased the strength of this structure increased. However, due to the trajectory of this vortex near to the sidewall of the rotating wheel, the vorticity associated with this feature diminishes with distance downstream and it thought to have been affected by the local flow rotating with wheel.

The behaviour of the fourth vortex in the trailing vortex system has not been confirmed due to a lack of near-field information as a result of the inclusion of the wheel. The presence of this vortex has not been identified by any of the experimental techniques used in this study and is thought to have either interacted and merged with the other vortices ahead of the wheel or has not been able to navigate about the wheel itself.

It has also be shown that the different behaviour of the trailing vortex system

affects the wake that is generated by the rotating wheel. The principle interactions of the wheel wake and trailing vortices occur with the lower vortex pair whilst the positions of the other wheel vortices are also affected.

From the results presented in this chapter there is little evidence of vortex breakdown. The adverse pressure gradients in front of the wheel do not invoke a dramatic change in the structure of the vortices and the flow structure about the wheel is governed by a merging process. Downstream of the wheel the vortex system is affected by the fluctuations of the wake. The structure of the vortices past this point is difficult to visualise in the laser-smoke images. A change in the structure may have occurred due to the buffeting of the wake. However it is not possible to accurately determine whether this has taken place from these results.

Chapter 7

Conclusions and Suggestions for Further Work

7.1 Conclusions

The overall aim of this research project was to enhance understanding on the behaviour of the trailing vortex system shed from a Formula 1 front wing as it passes downstream about a wheel. To achieve this aim and to meet the specific objectives that were stated in Section 2.5, several different experimental techniques have been used to examine the flow downstream of a 50% wind tunnel model both with and without the wheel. Also to investigate the influence of the wheel, the behaviour of a single vortex when placed in varying positions and strengths about the wheel has been analysed. The following conclusions have resulted from these investigations:

1. The wake downstream of the Formula 1 front wing and endplate consists of four co-rotating vortices. The strongest features in the system are the wing trailing vortex (referred to here as the main vortex) and the vortex which is shed from the top of the endplate. The other two weaker vortices are the canard vortex, formed by the appendage on the outboard edge of the endplate, and the vortex which is generated by the flow about the footplate
2. As the front wing is raised above the ground plane, the circulations of the vortices varies. The strength of the main vortex diminishes as the ride height

is increased whilst the circulation about the top vortex increases. This trend causes the top vortex to be the strongest feature when the front wing is operated at its highest ride height. The circulation about the weaker canard vortex remains relatively constant whilst the strength of the footplate vortex peaks at a moderate ride height.

3. Modifying the ride height of the wing in the case where the wheel is not present causes the vertical positions of the structures within the vortex system to be displaced accordingly. Except for the slight outboard movement of the footplate vortex with ride height, the lateral positions of the vortices are maintained.
4. Without the wheel, as the system travels downstream, the flow structure is dominated by the relative strengths of the main and top vortices. In all ride height configurations the footplate and canard vortices interact with the main vortex which at the lowest ride height maintains a separation with the top vortex to form a ‘figure of eight’ structure downstream. As the ride height is raised the separation distance between these vortices is reduced and all four vortices appear to interact with one another at the highest ride height.
5. In contrast to other researchers the investigation into the flow downstream of the front wing without the wheel has shown that there are no abrupt changes in flow structure or disorder which would be indicative of vortex breakdown. Instead the structure is determined by the merging of the four co-rotating vortices. It is noted that previous research where breakdown has been observed was undertaken on wings operating at lower ride heights than those examined in this project.
6. Examination of the flow about an isolated wheel has shown that the aerodynamics about this component are complicated. The ‘jetting’ flow that was first described by Fackrell (1974) has been observed close to the contact patch of the wheel and the wake structure of two pairs of counter-rotating vortices has been identified.

7. It has been shown that the behaviour of a single vortex travelling downstream about a rotating wheel is strongly dependant on the initial position and strength of the vortex ahead of the wheel. When released in a position similar to that of the main vortex in the McLaren system, the vortex follows an arc-like trajectory as it travels with the local flow about the wheel. The curvature of this trajectory is dependant on the circulation of the vortex and height above the ground plane, due to the induced velocity from its image in this solid boundary.
8. If a single vortex is released from such a position that its trajectory passes close to the ground plane then a viscous interaction with the flow near this boundary may occur. This was seen when the vortex was released in a location representative of the footplate vortex with secondary vorticity being generated. As a result the trajectory of the single vortex was deflected vertically upwards.
9. As the single vortex is moved further outboard (across the face of the wheel towards its centreline), then the presence of a steady, coherent structure downstream of the wheel is extremely unlikely. A vortex passing close to the side-wall of a rotating wheel may be affected by the flow rotating with it and may interact with the boundary layer on the wheel.
10. When a single trailing vortex travels downstream of the wheel then its proximity to the wheel will cause it to interact with the wake which is generated behind a rotating wheel. The fluctuations which are present in the wake can also cause the position of the vortex to become unsteady. Also, if the vortex is close to one of the like-signed wheel vortices then an interaction will occur causing the wheel and trailing vortices to either be displaced or merge together.
11. When examining the flow downstream of the front wing the inclusion of the rotating wheel not only substantially affected the behaviour of the trailing vortex system but its physical presence limited the information that could be obtained experimentally on the near-field flow structure.

12. Just downstream of the front of the rotating wheel the flow structure is dominated by the behaviour of the main and footplate vortices. The top vortex is present near the sidewall of the wheel but its time-averaged vorticity diffuses with distance downstream. There is no evidence on the presence of the canard vortex inboard of the wheel and it is thought that the flow from the canard has either interacted with the other vortices or has not been able to navigate around the front of the wheel.
13. By raising the front wing above the ground, the separation distance between the main and footplate vortices is increased. At the lowest ride height this results in the merging of the vortices to form a region of air swirling about a single core. As the wing is raised the vortices orbit about one another resulting in the formation of a ‘hump-like’ structure. In the highest configuration the separation is the greatest and the vortices pass about the wheel with little interaction between one another.
14. Part of the motivation for this research was based on results from numerical computations performed by McLaren Racing (McLaren 2003a). It has been shown that the comparison between this numerical data and the experimental results is reasonably good, with a qualitatively similar flow structure being predicted downstream of the wheel. Only small differences are present during the generation of this structure.
15. The presence of the wing trailing vortices also affects the topology of the wheel wake, with the lower inboard wheel vortex interacting with the trailing vortices. The other wheel vortices are also affected and their positions vary as the height of the front wing is modified.

In summary the behaviour of a trailing vortex system travelling about a rotating wheel is complicated. Without the wheel the vortex system interacts and merges together, the characteristics of which are dominated by the relative strengths of the main and top vortices as the strongest features in the flow. The inclusion of the rotating wheel has been shown to dramatically affect the behaviour of the vortex

system. Modifying the ride height of the wing results in different flow structures being formed downstream of the wheel due to the amount of interaction that has taken place between the vortices. By examining the behaviour of a single vortex as it travels about the wheel, an insight into the main influences of the rotating wheel has been achieved and the strong dependence on the initial position and strength of the vortex ahead of the wheel noted. It has also been shown that the presence of the trailing vortex system may influence the characteristics of the wake that is formed downstream of the wheel.

7.2 Suggestions for Further Work

This study has been focussed on providing an insight into the flow physics relevant to the behaviour of a vortex system from a Formula 1 front wing, as it passes about a rotating wheel. The results of this research have generated a number of suggestions for further investigation in this area.

1. Aerodynamics about an isolated wheel

Previous investigations carried out into the aerodynamics of a rotating wheel have focussed on the general flow about the wheel, its pressure distribution and the topology of the wake. It is thought that this work could be furthered by examining other features relevant to the wheel of a race-car. Such parameters as camber, wheel squash, hub flow and overall shape could be examined together with an investigation into their effect on the wing vortex system.

2. Investigation into behaviour of two vortices about a rotating wheel

An investigation was undertaken into the behaviour of a single vortex passing about the rotating wheel. However it has been shown that the flow downstream of the McLaren front wing is dominated by the interaction between two vortices. Hence a study into the behaviour of two vortices passing about the wheel would be beneficial to the understanding of the problem. Parameters such as relative strength and position could be evaluated together with an analysis of the vortices as they travel about the front of the wheel.

3. Further analysis into the influence of wing vortices on the characteristics of the wheel wake

Results from this research have shown that the wake is affected by the presence of a single vortex or system of vortices. Further investigation is required to fully examine the interaction between these structures. Also a large proportion of the drag on a Formula 1 car is generated by the wheels and an investigation into the link between the wheel wake and drag may be beneficial.

4. Investigation into the interaction of the wing vortices and wheel wake with other downstream aerodynamic components

Downstream of the wheel of a race-car are several aerodynamic devices such as the sidepods, radiators and underbody flow (including the diffuser). Hence the flow from the front wing and wheel may interact with these components and affect their performance. Garrood (2004) investigated the interaction between upstream generated vortices and diffuser performance but an extension of this analysis to include the multiple trailing vortex system, wheel wake and the influence of ride height on other downstream components may aid the design process.

Bibliography

A L Chen, J. D. J. & Savaş, O. (1999). Dynamics of corotating vortex pairs in the wakes of flapped airfoils. *Journal of Fluid Mechanics* 382, 155–193.

Agathangelou, B. & Gascoyne, M. (1998). Aerodynamic Design Considerations of a Formula 1 Racing Car. *SAE Technical Paper Series* (980399).

Althaus, W., Brücker, C., & Weimer, M. (1995). *Fluid Vortices*, Chapter Break-down of Slender Vortices, pp. 373–426. Kluwer Academic Publishers.

Anderson, Jr., J. D. (1991). *Fundamentals of Aerodynamics* (2nd ed.). McGraw-Hill, Inc.

Barker, S. J. & Crow, S. C. (1977). The motion of two-dimensional vortex pairs in ground effect. *Journal of Fluid Mechanics* 82(4), 659–671.

Barlow, J. B., Rae, Jr., W. H., & Pope, A. (1999). *Low-Speed Wind Tunnel Testing* (3rd ed.). John Wiley and Sons Inc.

Batchelor, G. K. (1964). Axial flow in trailing line vortices. *Journal of Fluid Mechanics* 20(4), 645–658.

Batchelor, G. K. (1967). *An Introduction to Fluid Dynamics*. Cambridge University Press.

Bearman, P. W., de Beer, D., Hamidy, E., & Harvey, J. K. (1988). The Effect of a Moving Floor on Wind-Tunnel Simulation of Road Vehicles. *SAE Technical Papers* (880245).

- Bearman, P. W., Harvey, J. K., & Gardner, C. M. (1976). Preliminary Calibration of the 4.5' x 4.0' (1.37m x 1.21m) Low Speed Wind Tunnel. Technical Report I.C. Aero Report 76-01, Imperial College, Department of Aeronautics.
- Bearman, P. W., Harvey, J. K., & Stewart, J. N. (1999, March). Two and three component velocity measurements in a wind tunnel using PIV. *The Aeronautical Journal* 103(1021), 167–173.
- Benjamin, T. B. (1962). Theory of the Vortex Breakdown Phenomenon. *Journal of Fluid Mechanics* 14, 593–629.
- Brandt, L. K. & Nomura, K. K. (2006). The physics of vortex merger: Further insight. *Physics of Fluids* 18(5).
- Cerretelli, C. & Williamson, C. H. K. (2003). The physical mechanism for vortex merging. *Journal of Fluid Mechanics* 475, 41–77.
- Cogotti, A. (1983). Aerodynamic Characteristics of Car Wheels. *International Journal of Vehicle Design, Special Publication SP3*, 173–196.
- Cutler, A. D. & Bradshaw, P. (1993a). Strong vortex/boundary layer interactions: Part I. Vortices high. *Experiments in Fluids* 14, 321–332.
- Cutler, A. D. & Bradshaw, P. (1993b). Strong vortex/boundary layer interactions: Part II. Vortices low. *Experiments in Fluids* 14, 393–401.
- Dee, F. S. & Nicholas, O. P. (1968). Flight Measurement of Wing Tip Vortex Motion near the Ground. *British Aeronautical Research Council, London, England CP 1065*.
- Delery, J. M. (1994). Aspects of Vortex Breakdown. *Progress in Aerospace Sciences* 30(4), 1–59.
- Devenport, W. J., Rife, M. C., Liapis, S. I., & Follin, G. J. (1996). The structure and development of a wing tip vortex. *Journal of Fluid Mechanics* 312, 67–106.

- Earnshaw, P. B. (1962). An Experimental Investigation of the Structure of a Leading-Edge Vortex. *Ministry of Aviation, Aeronautical Research Council, Reports and Memoranda*.
- Escudier, M. & Zehnder, N. (1982). Vortex flow regimes. *Journal of Fluid Mechanics* 115, 105–121.
- Fackrell, J. E. (1974). *The Aerodynamics of an Isolated Wheel Rotating in Contact with the Ground*. Ph. D. thesis, Imperial College, London.
- Fackrell, J. E. & Harvey, J. K. (1973). The Flowfield and Pressure Distribution of an Isolated Road Wheel. In H. S. Stephens (Ed.), *Advances in Road Vehicle Aerodynamics*. BHRA Fluid Engineering.
- Fackrell, J. E. & Harvey, J. K. (1975). The Aerodynamics of an Isolated Road Wheel. In B. Pershing (Ed.), *Proceedings of the Second AIAA Symposium of Aerodynamics of Sports and Competition Automobiles*.
- Faler, J. H. & Leibovich, S. (1977). Disrupted states of vortex flow and vortex breakdown. *Physics of Fluids* 20(9), 1385–1400.
- Flefl, H. & Singer, N. (1998). *Aerodynamics of Road Vehicles*, Chapter 8 – High Performance Vehicles, pp. 365–414. Society of Automotive Engineers, Inc.
- Garrood, B. (2004). *Aerodynamic Interaction Mechanisms Relevant to the Underbodies of Formula 1 Cars*. Ph. D. thesis, Imperial College, London.
- Green, S. I. (1995a). *Fluid Vortices*, Chapter Introduction to Vorticity, pp. 1–34. Kluwer Academic Publishers.
- Green, S. I. (1995b). *Fluid Vortices*, Chapter Wing Tip Vortices, pp. 427–470. Kluwer Academic Publishers.
- Gursul, I. (2005). Review of Unsteady Vortex Flows over Slender Delta Wings. *Journal of Aircraft* 42(2).

- Gursul, I. & Xie, W. (1999). Origin of Vortex Wandering over Delta Wings. *Journal of Aircraft* 37(2).
- Hall, M. G. (1972). Vortex Breakdown. *Annual Review of Fluid Mechanics* 4, 195–218.
- Harvey, J. K. (1962). Some Observations of the Vortex Breakdown Phenomenon. *Journal of Fluid Mechanics* 14, 585–592.
- Harvey, J. K. & Perry, F. J. (1971). Flowfield Produced by Trailing Vortices in the Vicinity of the Ground. *AIAA Journal* 9(8), 1659–1660.
- Jeong, J. & Hussain, F. (1995). On the identification of a vortex. *Journal of Fluid Mechanics* 285, 69–94.
- Jørgensen, F. E. (2002). How to measure turbulence with hot-wire anemometers. Dantec Dynamics. Publication no. 9040U6151.
- Katz, J. (1995). *Race Car Aerodynamics, Designing for Speed*. Bentley Publishers.
- Katz, J. (2006, January). Aerodynamics of Race-Cars. *Annual Review of Fluid Mechanics* 38, 27–63.
- Kellar, W. P., Pearse, S. R. G., & Savill, A. M. (1999). Formula 1 Car Wheel Aerodynamics. *Sports Engineering* 2, 203–212.
- Kiel, G. (1935). Total-Head Meter with Small Sensitivity to Yaw. *NACA TM 775*.
- Knowles, R., Saddington, A., & Knowles, K. (2002). On the Near Wake of Rotating, 40 %–Scale Champ Car Wheels. *SAE Technical Paper Series* (2002–01–3293).
- Lamb, H. (1932). *Hydrodynamics* (6th ed.). Cambridge University Press.
- Lambourne, N. C. & Bryer, D. W. (1962). The Bursting of Leading-Edge Vortices – Some Observations and Discussions of the Phenomenon. *Ministry of Aviation, Aeronautical Research Council, Reports and Memoranda* (3282).

- Lear, C. J. (2003). *Controlling the Break-Up Distance of Aircraft Trailing Vortices*. Ph. D. thesis, Imperial College, London.
- Leibovich, S. (1978). The Structure of Vortex Breakdown. *Annual Review of Fluid Mechanics* 10, 221–246.
- Leibovich, S. (1984). Vortex Stability and Breakdown: Survey and Extension. *AIAA Journal* 22(9), 1192–1206.
- Lowson, M. V. (1991). Visualization Measurements of Vortex Flows. *Journal of Aircraft* 28(5), 320–327.
- Lucca-Negro, O. & O'Doherty, T. (2001). Vortex breakdown: a review. *Progress in Energy and Combustion Science* 27, 431–481.
- McLaren (2003a). Imperial College Research Program CFD Case for FW5 Isolated Front Wing (fw7392). McLaren Racing.
- McLaren (2003b). Imperial College Research Program CFD Case for FW5 Isolated Front Wing Without Wheel (fw7392-nw). McLaren Racing.
- McManus, J. & Zhang, X. (2006). A Computational Study of the Flow Around an Isolated Wheel in Contact With the Ground. *Journal of Fluids Engineering* 128, 520–530.
- Mears, A. P., Dominy, R. G., & Sims-Williams, D. B. (2002). The Air Flow About an Exposed Racing Wheel. *SAE Technical Paper Series* (2002-01-3290).
- Melander, M. V., Zabusky, N. J., & McWilliams, J. C. (1988). Symmetric vortex merger in two dimensions: causes and conditions. *Journal of fluid mechanics* 195, 303–340.
- Merker, E. & Berneburg, H. (1992). On the simulation of road driving of a passenger car in a wind tunnel using a moving belt and rotating wheels. *3rd International Conference of Innovation and Reliability, Florence, April 8-10*.

- Meunier, P., Dizès, S. L., & Leweke, T. (2005). Physics of Vortex Merging. *Comptes Rendus Physique* 6(4–5), 431–450.
- Milne-Thomson, L. M. (1952). *Theoretical Aerodynamics* (2nd ed.). MacMillan and Co. Ltd.
- Moore, D. W. & Saffman, P. G. (1973). Axial flow in laminar trailing vortices. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 333(1595), 491–508.
- Moseley, R. P. (1999). *The Application of Particle Image Velocimetry to Wing Vortex Flows*. Ph. D. thesis, Imperial College, London.
- Peckham, D. H. & Atkinson, S. A. (1957). Preliminary Results of Low Speed Wind Tunnel Tests on a Ghotic Wing of Aspect Ratio 1.0. *British Aeronautical Research Council CP CP*, 508.
- Phillips, W. R. C. (1981). The turbulent trailing vortex during roll-up. *Journal of Fluid Mechanics* 105, 451–467.
- Piola, G. (2005). *Formula 1 Technical Analysis 2004–2005*. Giorgio Nada Editore.
- Puel, F. & de Saint Victor, X. (2000). Interaction of Wake Vortices with the Ground. *Aerospace Science and Technology* 4, 239–247.
- Raffel, M., Willert, C. E., & Kompenhans, J. (1998). *Particle Image Velocimetry, A Practical Guide*. Springer.
- Saffman, P. G. (1992). *Vortex Dynamics*. Cambridge University Press.
- Saffman, P. G. & Baker, G. R. (1979). Vortex Interactions. *Annual Review of Fluid Mechanics* 11, 95–122.
- Sarpkaya, T. (1971a). On stationary and travelling vortex breakdowns. *Journal of Fluid Mechanics* 45, 545–559.
- Sarpkaya, T. (1971b). Vortex Breakdown in Swirling Conical Flows. *AIAA Journal* 9(9).

- Tremayne, D. (2004). *The Science of Formula 1 Design*. Haynes Publishing.
- Trieling, R. R., Velasco Fuentes, O. U., & van Heijst, G. J. F. (2005). Interaction of two unequal corotating vortices. *Physics of Fluids* 17(8).
- Türk, L., Coors, D., & Jacob, D. (1999). Behavior of wake vortices near the ground over a large range of Reynolds numbers. *Aerospace Science and Technology* 3(2), 71–81.
- Versmissen, J. J. (1974). Some Experiments on the Performance and the Drag Penalty of Various Distributed Roughness Bands used for Boundary Layer Transition Fixing. *NLR TR 74009 U*.
- Wright, P. (2001). *Formula 1 Technology*. Society of Automotive Engineers, Inc.
- Wright, P. G. (1983). The influence of aerodynamics on the design of Formula One racing cars. *Int. J. of Vehicle Design, Technological Advances in Vehicle Design Series, SP3*.
- Zhang, X., Toet, W., & Zerihaan, J. (2006, January). Ground Effect Aerodynamics of Race Cars. *Applied Mechanics Reviews* 59, 33–49.
- Zhang, X. & Zerihaan, J. (2003). Aerodynamics of a Double-Element Wing in Ground Effect. *AIAA Journal* 41(6).
- Zhang, X. & Zerihaan, J. (2004). Edge Vortices of a Double-Element Wing in Ground Effect. *Journal of Aircraft* 41(5).