Application of Particle Image Velocimetry and Laser Doppler Anemometry to a STOVL Ground Vortex Flow

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ABSTRACT

Impinging jets in cross flow form an unsteady feature called a ground vortex. This paper presents particle image velocity (PIV) and laser Doppler anemometry (LDA) measurements taken from the ground vortex region of a scaled supersonic impinging jet flow. PIV measurements were made for nozzle pressure ratios (NPRs) of between 2 and 4, nozzle height-to-diameter ratios \( \frac{h}{d_n} \) of between 3 and 10 (where \( d_n = 12.5 - 25.4 \text{mm} \)) and cross flow velocities \( V_\infty \) of between 10 m/s and 20 m/s. Selected LDA measurements were also taken from the ground vortex core and compared to a PIV time-series. Spectral analysis of the PIV time series showed the ground vortex position to fluctuate longitudinally by an rms distance of up to 4.47\( d_n \) with a peak amplitude at frequencies between 2.5 – 5 Hz while the LDA data showed the velocity to fluctuate by peak frequencies ranging from between 1-30 Hz. With the PIV frame rate limited to 15Hz, a major conclusion from the work is that further PIV studies are required which utilise a higher frame-rate camera system. As a minimum this frame rate should be 60 Hz although higher frame rates would allow studies of features on the edge of the ground vortex, nearer the jet.
NOMENCLATURE

\( d_n \) \( \) nozzle exit diameter
\( h \) \( \) height of nozzle above ground
\( p \) \( \) pressure
\( \text{NPR} \) \( \) nozzle pressure ratio \( = \frac{p_n}{p_\infty} \)
\( v \) \( \) y-direction velocity
\( w \) \( \) z-direction velocity
\( V_\infty \) \( \) cross-flow velocity
\( V_e \) \( \) effective velocity ratio \( = \sqrt{\frac{1}{2} \frac{\rho_v V_t^2}{\rho_\infty V_\infty^2}} \)
\( y \) \( \) horizontal streamwise direction from nozzle centre line
\( z \) \( \) vertical distance below nozzle exit
\( z' \) \( \) vertical distance above ground \( = (h - z) \)
\( \rho \) \( \) density

SUBSCRIPTS

\( n \) \( \) nozzle
\( o \) \( \) nozzle stagnation conditions
\( p \) \( \) vortex penetration (see Figure 1)
\( v \) \( \) vortex core position (see Figure 1)
\( \infty \) \( \) ambient
\( 1 \) \( \) equivalent fully-expanded jet exit conditions

1. INTRODUCTION

Impinging jet flows can be found in many engineering systems. One example, which can have a cross flow component with both stationary and moving impingement surfaces, is found in aerospace engineering around short take-off and vertical landing (STOVL) aircraft [Cimbala et al (1989), Cimbala et al (1991), Knowles and Bray (1991), Bray (1992), Knowles et al (1992), Knowles and Bray (1993), Knowles and Kirkham (1998), Knowles and Myszko (1998)]. This type of flow generates an unsteady, three-dimensional flow field called the ground vortex (see Figure 1) [Kuhn (1982), Cimbala et al (1989), Cimbala et al (1991), Knowles et al (1992), Bray (1992), Knowles and Bray (1993)]. This flow field occurs for a range of geometries and conditions and is positioned around the aircraft in a horseshoe shape. Observation of the ground vortex has shown that periodically fluid is shed upwards, in the case of vertical take-off aircraft, toward the engine intake [Kuhn (1982), Behrouzi and McGuirk (1996)]. This can cause hot gas ingestion (HGI), resulting in a loss of thrust and, in severe cases, causes the compressor to surge producing a total loss of power and vertical lift.

Previous experimental studies of the ground vortex formed with nozzle flows have included measurement of ground-plane mean pressure data [Bray (1992), Knowles et al (1992), Knowles and Bray (1993)] and flow visualisation [Cimbala et al (1989), Cimbala et al (1991), Behrouzi and McGuirk (1993), Behrouzi and McGuirk (1996)]. These studies have allowed extensive parametric investigations into the factors affecting ground vortex position. Other work using smoke for flow visualisation has focussed on determining the ground vortex instability for a low-speed jet and cross-flow condition [Cimbala et al (1989), Cimbala et al (1991)]. Limited hot-wire anemometry measurements were also included but did not map the 3-dimensional flow field. Experiments conducted in water-tunnels have mapped the 3-dimensional ground vortex using LDA and laser induced fluorescence (LIF) [Barata et al (1987), Behrouzi and McGuirk (1993), Behrouzi and McGuirk (1996)]. Some of the studies made in water tunnels have included transient data. At present there have been no data presented which define the 3-dimensional flow-field or its unsteadiness for a compressible jet in a cross-flow impinging on a moving ground plane.

flow field. Visualisation of the flow using the smoke-wire technique clearly shows the unsteadiness of the flow. However, the exact mechanism of the shedding or “puffing” phenomenon is still not clear, due mainly to a lack of detailed transient flow-field data. The development of suitable transient numerical models for computational fluid dynamics (CFD) modelling has been restricted as a result. The majority of numerical studies investigating the mean flow have used Reynolds-Averaged Navier Stokes (RANS) codes and suitable turbulence models [Barata et al (1989), Knowles and Bray (1991), Behrouzi and McGuirk (1993)b].

The utilisation of optical flow measurement techniques enables non-intrusive investigation of the flow field [Durst et al (1981), Adrian (1991)]. Particle Image Velocimetry (PIV) for example, will provide instantaneous two-dimensional velocity maps of the flow, which can be processed and run sequentially to enable cinematic analysis [Oakley et al (1996)]. Data obtained by the application of PIV to the ground vortex flow, could be used to refine current numerical codes applied to STOVL aircraft and impinging jet flows.

This paper presents mean and instantaneous PIV results from a series of ground vortex flows. To the authors’ knowledge these are the first such non-intrusive measurements of an unsteady ground vortex produced with a choked jet. The use of a moving ground plane is also unique to this series of experiments.

2. EXPERIMENTAL SET-UP AND METHOD

The experimental set-up is outlined in Figure 2. A pair of Howden screw-type compressors running in series deliver 0.9 kg/s of dried air at 3 bar (gauge) feed into the small rectangular settling chamber via a 34m³ storage tank. The settling chamber contains filter material and a perforated plate to achieve a symmetrical nozzle velocity profile. As in previous tests [Bray (1991), Knowles and Myszko (1998)], a “long half inch” nozzle was used with a 12.7mm exit diameter and a length of 10 diameters. The pressure in the settling chamber was controlled using a pair of Compair A119 – 20x20 control valves, connected in series. Seeding for the nozzle flow was supplied by a custom-designed atomiser, which contained 60 atomising jets in two banks of 30 (individually selectable). The supply pressure to the atomiser came from the main air line and was regulated using a third control valve, the atomiser outlets were connected to the settling chamber by four, ½” diameter hoses. A 5% glycerol/water mix was used as seeding material.
2.1 Wind Tunnel

An open-jet wind tunnel with nozzle dimensions of 1.14m x 1.52m produced the cross flow. A boundary layer removal system and rolling road was used to provide a moving ground plane along the length of the working section. The rolling road has a platen suction system to ensure the belt remains flat during operation. A Jem Hydrosonic 2000 fog generator, placed inside the wind tunnel diffuser section, seeded the tunnel flow.

\[ d_n = 12.5 \text{mm}, \; \text{NPR} = 2.36, \; \frac{h}{d_n} = 10 \; \text{and} \; V_\infty = 10 \text{ m/s}. \]
2.2 PIV

The PIV equipment consisted of a Dantec Flowmap 500 data acquisition box, a Kodak ES1.0 megapixel CCD camera and a New Wave Gemini Nd:YAG double-pulsed laser. The optical array used to produce the light sheet was mounted at the top of the wind tunnel nozzle to avoid any disturbance to the air flow in front of the ground vortex. Plane surface-mirrors fixed to adjustable mounts, steered the beam from the laser to the light sheet optics. The optics were mounted on an adjustable rail and consisted of a plano-cylindrical lens with focal length $f = 75$ mm, followed by two plano-concave lenses with focal lengths $f = -100$mm and $f = -50$mm. The resulting light sheet enabled an area of approximately $250 \text{mm} \times 250 \text{mm}$ to be imaged. The Kodak ES1.0 CCD frame rate and the laser allowed 15Hz cinematic PIV data to be recorded for analysis of the ground vortex. Data post-processing was performed using TSI UltraPIV software. The software was configured to use the Hart algorithm [Hart (2000)] with a $16 \times 16$ pixel area. These settings produced, on average, 10000 vectors per image with a spatial resolution of $2 \text{mm} \times 2 \text{mm}$ over the $250 \text{mm} \times 250 \text{mm}$ image area. Figure 3 shows a typical PIV image.

2.3 LDA

The LDA equipment consisted of a Lexel Model 95 water-cooled Argon-ion laser, a Dantec 60X41 transmitter with 60X24 fibre optic manipulators, a 2D FiberFlow probe and a 1m focal length lens with a 2x beam expander. The 514.5nm (green) and 488nm (blue) beams were used for the two components and alignment of the four beams was completed using a $35\mu\text{m}$ pinhole. The probe was mounted on an $x$-$y$-$z$, traverse to facilitate positioning of the measurement volume. Dantec burst spectrum analysers (BSAs), one 57N20 master and a BSA Enhanced 57N35 slave unit, filtered and amplified the Doppler burst. Dantec Burstware data processing software was used to process the data.

2.4 Experimental Method

Initial PIV runs were carried out with the CCD camera mounted on a conventional tripod. This proved unsatisfactory since the vortex position changed for each of the test conditions, and could not be imaged with the camera fixed in one position. The camera was therefore transferred to the $x$-$y$-$z$ traverse used for the LDA measurements. This allowed the camera to be moved accurately and since the traverse had already been aligned with the tunnel axis, only small focus corrections were necessary for each camera position change. A calibration image was also recorded about the centreline of the nozzle, lying on the edge of the image. Thus by knowing the distance moved by the traverse for each test condition, the different vortex positions could be accurately calculated.

Adequate seeding of the wind tunnel free-stream was achieved using a Jem Hydrosonic 2000 fog generator. However, seeding the jet flow, at 10% of the total volume flow rate based on nozzle area, necessitated the design and manufacture of a new device. The design consisted of a stainless steel vessel (155mm internal diameter and 500mm long) with a flange at either end, two banks of atomising jets and a baffle plate. The atomising jets were fed from the main compressed air line and operated at 3 bar above the settling chamber pressure. To set the correct NPR and seeding density required balancing the flow from the seeder and the main compressed air line. When too much seeding entered the settling chamber, the resultant PIV image was over exposed, as can be seen at the bottom of Figure 3. Thus the balance of flow was different for each NPR and was adjusted by turning a number of the seeding jets off when required.

3. EXPERIMENTAL CONDITIONS

PIV measurements were made between NPRs 2 and 4, nozzle height to diameter ratios ($h/d_n$) of between 3 and 10 and cross flow velocities ($V_\infty$) of 10 m/s, 15m/s and 20 m/s (see Table 1). In all these cases the rolling road was running at the freestream velocity. LDA measurements were made at NPR 3.72, $h/d_n = 10$ and $V_\infty = 10$ m/s.
Table 1 – Summary of experimental conditions

<table>
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<tr>
<th>Run</th>
<th>NPR</th>
<th>(h/d_n)</th>
<th>(V_\infty) (m/s)</th>
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<tr>
<td>9</td>
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4. RESULTS AND DISCUSSION

The instantaneous PIV vector maps captured for each of the conditions in Table 1, were processed to obtain mean vector maps and AVI animations. Additionally the mean vector maps were used to determine the vortex centre co-ordinates to position the LDA measurement volume. The results from these analyses will now be discussed in greater detail.

4.1 PIV Vector Maps

Figures 4a and 4b show instantaneous and mean vector maps of the ground vortex for NPR = 2.36, \(h/d_n\) = 10 and \(V_\infty\) = 10 m/s. In each plot the ground vortex is clearly visible with the centre of rotation at \(y_v/d_n = 12.4\) and \(z'/d_n = 4.7\) for the instantaneous vector map and at \(y_v/d_n = 10.88\) and \(z'/d_n = 3.64\) for the mean vector map.

The fluctuation of the vortex centre position could also be observed on the AVI files. Typically, the vortex would shift between 2 – 5\(d_n\) in \(y\) and 1\(d_n\) in \(z'\), where the change in position appeared random with no obvious frequency. Further investigation of the PIV time series data and the corresponding power spectrum, presented in a later section, confirmed these initial observations.

![Figure 4](image_url)  
*Figure 4 – a) Instantaneous b) Time averaged PIV vector map (NPR = 2.36, \(h/d_n\) = 10, \(V_\infty\) = 10 m/s)*

Figures 5a and 5b show instantaneous and mean vector maps of the ground vortex for NPR = 3.72, \(h/d_n\) = 10 and \(V_\infty\) = 10 m/s. Again, the ground vortex is clearly visible with the centre of rotation at \(y_v/d_n = 15.9\) and \(z'/d_n = 4.3\) for the instantaneous vector map and at \(y_v/d_n = 15.8\) and \(z'/d_n = 4.35\) for the mean vector map.

![Figure 5](image_url)
4.2 Changes in the time-averaged vortex position

Figures 6a, 6b and 6c show mean vortex core positions for a range of $h/d_n$, NPR and $V_\infty$ respectively. To understand the relative changes for the different variables we must first consider the definition of the major scaling parameter “effective velocity ratio” ($V_e^{-1}$). Effective velocity ratio is primarily dependent on nozzle exit velocity $w_1$ and cross flow velocity $V_\infty$. Thus in Figure 6a, for changes in $h/d_n$ the effective velocity ratio is fixed at $V_e^{-1} = 38.1$ and it can be seen that the mean vortex position moves less than 2 $d_n$ in $y$ and less than 1 $d_n$ in $z'$. This insensitivity

to h/d0 is consistent with the parameter $V_e^{-1}$. Conversely in Figure 6b with increasing NPR there is a significant change in the mean vortex position of around 5 d0 in y and around 1 d0 in z'. This result occurs since the increases in NPR will directly increase the equivalent exit velocity $w_t$ with a corresponding increase in $V_e^{-1}$, which in this case ranges from $V_e^{-1} = 25.5 – 32.1$. Figure 6c also shows a significant change in the mean vortex position of more than 5 d0 in y and 1 d0 in z' for changes in cross-flow velocity, $V_\infty$. Again this high sensitivity of yv is related to the change in effective velocity ratio $V_e^{-1}$, which changes from $V_e^{-1} = 38.1 – 19.1$ for these cases.

4.3 Instantaneous PIV Results

A computational data processing program was developed to calculate the vortex core position of instantaneous PIV vector maps. The program was based on a local search of the vector data given an a priori mean vortex core position and an estimated radius of search. Using this processing method, approximately 80% of the core positions were determined. The remaining vortex positions were found by manual examination using Tecplot.

![Figure 7 - Instantaneous PIV ground vortex core position (15Hz frame rate, NPR = 3.72, h/d0 = 10, V_\infty = 10 m/s)](image)

![Figure 8 - Instantaneous PIV vector map time series (15Hz frame rate, NPR = 3.72, h/d0 = 10, V_\infty = 10 m/s)](image)
Figure 7 shows a typical time series for NPR = 3.72, \( h/d_n = 10 \) and \( V_\infty = 10 \) m/s, where the mean vortex core position is \( y/d_n = 15.5 \), \( z'/d_n = 4.48 \) and the rms movement is \( y_{\text{rms}}/d_n = 4.47 \), \( z'_{\text{rms}}/d_n = 2.18 \). The camera frame rate in this case is 15Hz. This result illustrates the significant movement in both \( y \) and \( z' \) directions that the ground vortex undergoes. The fluctuations appear from initial analysis to be erratic occurring in bursts as the vortex grows and then shrinks. This can be seen by examining a time-series of six PIV vector maps over 0.4s as shown in Figure 8, where the selected cases have been highlighted in Figure 7. These results show secondary vortices forming, in conjunction with an increase in \( z'/d_n \). The vortices then collapse as the ground vortex reduces in size. The flow-field appears to be highly unsteady with flow structures appearing and disappearing at frequencies greater than 15Hz.

4.4 Analysis of LDA Data

To supplement the spectral analysis of the PIV data, limited LDA data were recorded from the mean vortex core position. Figure 9a shows a typical \( v \) component LDA time-series where NPR = 3.72, \( h/d_n = 10 \) and \( V_\infty = 10 \) m/s and the sample size is 10000. In this case the mean velocity is \( v = 0.519 \) m/s and the rms velocity is \( v_{\text{rms}} = 8.75 \) m/s or 87.5% of free stream. These data illustrate the highly turbulent nature of the ground vortex, with peak velocities at this point of 25 m/s or 2.5 times free stream velocity. The LDA data rate was of the order of 1kHz. Therefore, significantly higher spectral resolution was possible from the power spectrum than from the PIV data. The corresponding power spectrum is shown in Figure 9b. Here it can be seen that the majority of the spectral power occurs below 5 Hz, which is consistent with the PIV results. There are, however, significant peaks in the spectrum up to approximately 30Hz. Above 46Hz the spectral amplitude decays to less than 10% of the peak amplitude. For a more complete analysis of this particular phenomenon, a PIV system with a minimum sampling rate of 60 Hz would be required. However, to study the shear instabilities of the main jet, which are of the order of kHz, a significantly higher sampling rate would be necessary. Such high frame rate PIV systems are becoming available, based on cameras such as the NAC HiDCAM and high repetition rate Nd:YLF lasers such as the Photonics Industries GM30-527. Application of a high-speed system is the subject of a further study.

![Figure 9 – LDA velocity data about main vortex core position a) time series b) spectral distribution (NPR = 3.72, h/dn = 10, V_\infty = 10 m/s)](image)

5. CONCLUSIONS

PIV and LDA data have been presented from a scaled, compressible, ground vortex flow with a moving ground plane. The flow-field generated for these conditions can be compared to a STOVL aircraft hovering or carrying out low-speed manoeuvres in ground effect. The use of a compressible choked jet with a moving ground plane and the use of PIV and LDA systems to study this flow is thought to be unique.

Analysis of the mean PIV data from 72 vector maps showed the ground vortex to be most sensitive to changes in cross flow velocity \( V_\infty \) and to be least sensitive to changes in \( h/d_n \). The
instantaneous PIV results have also shown the jet to fluctuate chaotically in one case by RMS movements of up to $y_{rms}/d_n = 4.47$ and $z'_{rms}/d_n = 2.18$. No clear period of oscillation was apparent and subsequent spectral analysis of the PIV data found the majority of the spectral energy to be concentrated at between 2.5 – 5 Hz. Further spectral analysis of LDA data, taken from the mean vortex core, showed the majority of the spectral energy to be present up to around 30 Hz. This result therefore indicates that the present PIV system with a frame rate of 15 Hz has insufficient capability to capture the majority of the transient flow features from the ground vortex. This was confirmed from observations of secondary vortex formation in the instantaneous PIV data.

It is recommended that further PIV studies use a higher frame rate system, operating at a minimum of 60 Hz to ensure that the majority of unsteady flow features in the ground vortex are recorded.

ACKNOWLEDGEMENTS

The authors would like to thank the Engineering and Physical Sciences Research Council for support on this project from Grant GR/N02504. The authors would also like to acknowledge support and advice from the workshops of the Engineering Systems Department during this work.

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