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A PIV and LSV Study in the Wake of an Aircraft Model

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***Abstract*:** An experimental investigation was undertaken of the wake aerodynamics of a 1/12.81 model of a commercial passenger aircraft. The tests were undertaken in the 3.05 m by 3.66 m working section of a closed-return wind-tunnel. The program made use of laser sheet visualization (LSV) and particle image velocimetry (PIV) in planes, normal to the mean flow, to obtain images of flow-following, seed particles. The images were processed to obtain raw velocity vectors, flow divergence, vorticity, cross-flow energy and high quality visualizations. Image sequences obtained under identical incident flow conditions were used to conceptualize the variability of principal wake features, such as regions of fluid of high vorticity.

***Keywords*:** PIV, LSV, animation, aircraft model, large wind-tunnel.

1. Introduction

A knowledge of the behavior and persistence of vorticity trailing from the wing tips and flaps of aircraft wings is essential in prescribing conditions for safe, close proximity flying (Fig.1, after Crowder, 1983). The present study addresses this topic using LSV and PIV (Grant, 1997) to measure the complex flow fields at various downstream positions in the wake of a model aircraft. Wet film methods were used in recording the raw flow images in a large laser illuminated zone since the conflicting requirements of image size, spatial resolution and dynamic range meant that direct digital imagery was inappropriate (Adrian, 1997). The use of digital PIV (DPIV) to obtain the velocity field in the present circumstances would also require the combining of sub-images obtained at unrelated times and since the aim was to investigate the significant meandering motion of the vortex filaments this was an unsuitable approach. The work further develops the authors' work in the application of PIV to aerospace studies (Hurst et al., 1997).

Fig. 1. Complex environment behind a wing illustrated by pressure losses contour plot (after Crowder, 1980).

2. The Experiment

A full span, 1/12.81 scale, model of a representative passenger aircraft was mounted in the BAe Airbus Ltd, 3.05 m by 3.66 m, closed-return, wind-tunnel at Filton. The model was tested in a number of high lift configurations (i.e. with slats and flaps deployed) but without nacelles and pylons fitted. Flow field measurements were made normal to the free stream at five stations downstream of the wing by means of particle image velocimetry with the stream velocities being typically 60 $m.s^{-1}$ (Table 1).

Table 1. Position of laser sheets relative to the starboard wingtip.

sheet position number	distance downstream from the wing tip
1	87 mm
2	244 mm
3	492 mm
4	985 mm
5	1250 mm

The wind-tunnel was seeded with polycrystalline powder of high scattering efficiency with a specific gravity of 1 and an average diameter, by number, of 6 μm. The particles were introduced into the wind-tunnel through a small diameter rake placed in the contraction, well upstream of the model. The rake was lowered after particle introduction to minimise upstream flow disturbance. The powder was allowed to make a tunnel circuit before the PIV images were captured since this allowed the wind tunnel turning vanes, fan, fan alignment blades and screens to thoroughly disperse the powder. The use of seeding particles for quantitative flow visualisation relies on the use of particles which are of a suitable size and density such that they efficiently follow the flow characteristics (Grant, 1997).

Two frequency doubled Yag:Nd lasers were aligned to have the same optical beam path and the beam shaped to produce an expanding, vertical illuminated sheet which was introduced through a small slot in the wall of the wind-tunnel working section. The sheet was aligned normal to the flow and positioned at each of the five downstream planes of interest in separate tests. The double-YAG arrangement was adopted in these tests since it allowed for greater flexibility in the pulse separation time and offered the capacity for greater illuminating power. The lasers provided stroboscopic illumination with a frequency of 10 Hz with a time delay between the laser pulses of 60 - 80 μs. The second laser was triggered synchronously using an initiation pulse from the power supply of the first laser.

The images were captured by a 35 mm Nikon camera fitted with a flat field lens. The camera was mounted on a rigid strut which was shielded by a streamlined fairing. The strut was mounted on the wind-tunnel floor, 2.6 m downstream of the model.

The seeding density was chosen such that either correlation or tracking methodology could be implemented. The implicit smoothing and spatial averaging of one-step correlation was considered undesirable in the present case and the tracking method adopted. The availability of statistical (Grant and Liu, 1989) and neural network (Grant and Pan, 1997) tracking algorithms, both offering 'super-resolution,' and sub-pixel accuracy, recommended the adoption of this approach. This returned individual velocity measurements with errors typically of less than one per cent.

The generation of vorticity within the wake of the aircraft is dominated by the variation in cross-flow velocity. Therefore emphasis was placed, during the tests, on the examination of flow field characteristics in transverse planes.

Since a single camera was used to record the velocities in the transverse plane it was necessary to correct the measurements for the effect of through-plane velocity. As shown elsewhere (Grant et al., 1994) this parallax effect can be compensated for, providing an estimate of through sheet velocity is available. In the present tests through sheet velocity was estimated from PIV measurements made in a laser sheet having the mean velocity vector and the vertical axis in-plane. In this instance cameras were mounted on the floor and in the wind-tunnel working section roof space.

The velocities in the cross-flow, illuminated planes were measured at the 5 stations downstream of the starboard wing detailed in Table 1. The cross-wind horizontal (U) and vertical (V) velocity vector components were measured throughout a region of 800 mm by 400 mm. This area allowed full examination of all the flow features relevant to this investigation. The aircraft was in high-lift, landing configuration with double slotted flap deployed.

3. Data Processing

3.1 Raw Data

A typical data set obtained from a single PIV transparency is presented in Fig. 2.

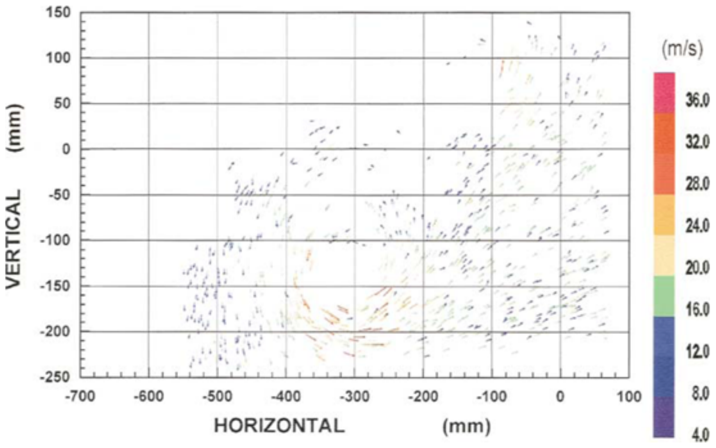

Fig. 2. Example raw velocity plot obtained from PIV data.

3.2 Interpolation

Interpolation onto a regular grid is a common post data-extraction procedure in PIV studies. It is advantageous to present the data on a regular grid since it makes comparison with CFD packages easier.

Interpolated data were obtained in a linear, distance weighted, interpolation scheme utilising between 4 and 30 surrounding measurements by means of a least squares procedure (Fig. 3).

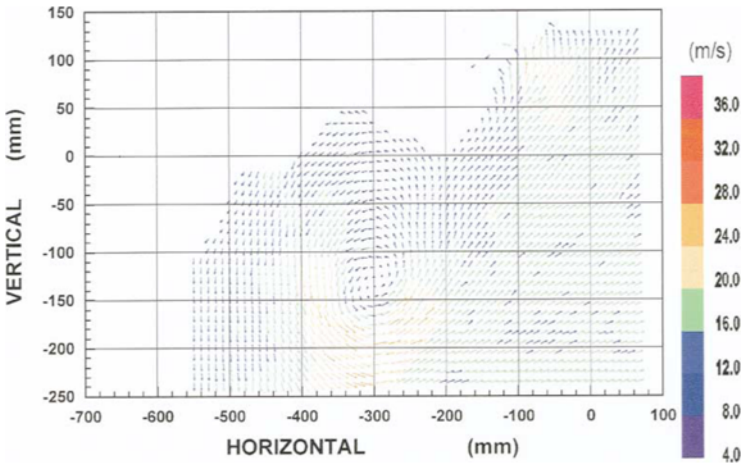

Fig. 3. Example interpolated velocity vector plot derived from PIV data.

3.3 Derived Quantities

(i) cross-flow velocity $V_\theta = \sqrt{V_y^2 + V_z^2}$

(ii) cross flow energy $E_\theta = \dfrac{V_y^2 + V_z^2}{V_\infty^2}$ (Fig. 4)

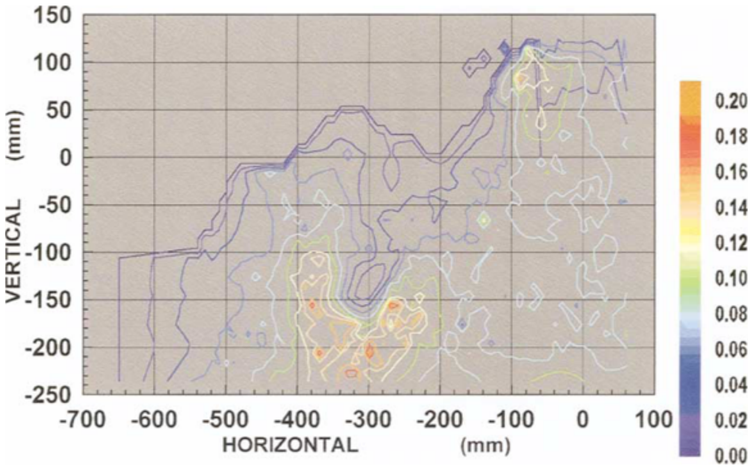

Fig. 4. Example cross flow energy plot obtained from PIV data.

(iii) streamwise component of vorticity vector $\left(\frac{\partial V_z}{\partial y}-\frac{\partial V_y}{\partial z}\right)\times\frac{b/2}{V_\infty}$ where $b/2$ is the model half span, 1.325 m, and the freestream velocity, V_∞ is 60 m.s $^{-1}$ (Fig. 5)

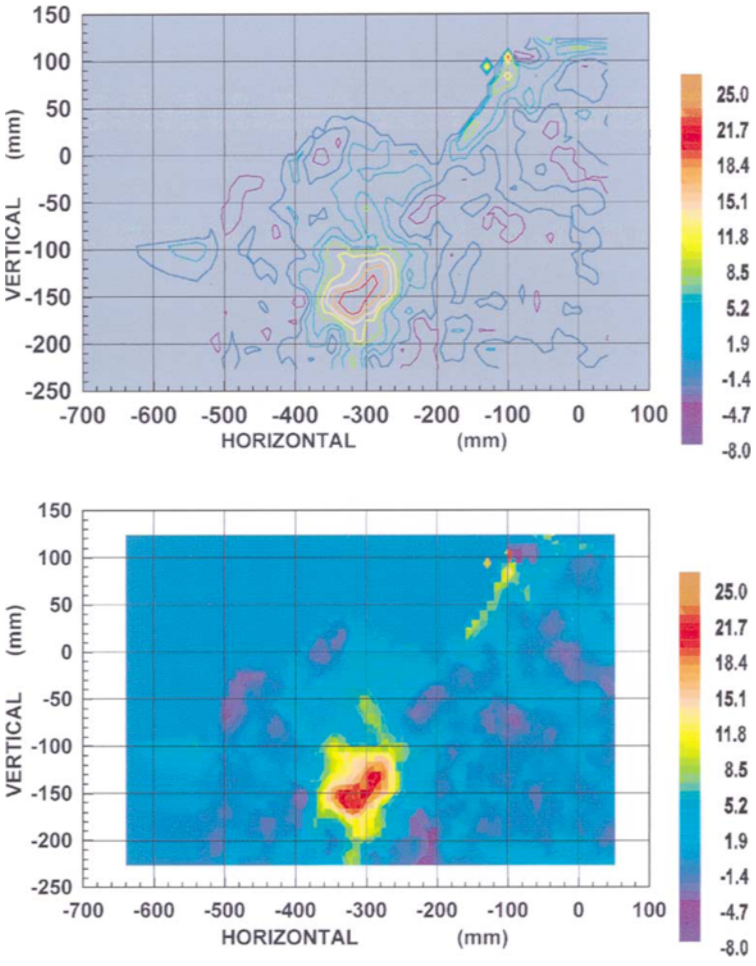

Fig. 5. Example vorticity plot obtained from PIV data.

This was obtained using the equivalent integration formulae $\frac{1}{area}\oint\left(V_y dy + V_z dz\right)\times\frac{b/2}{V_\infty}$

(iv) streamwise component of divergence. This was obtained using the integration formulae $-\frac{1}{area}\oint\left(-V_z dy + V_y dz\right)\times\frac{b/2}{V_\infty}$ (Fig. 6)

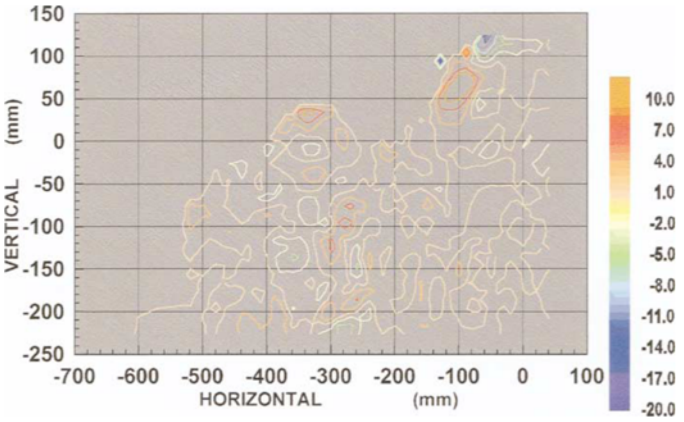

Fig. 6. Example divergence plot obtained from PIV data.

4. Discussion

The use of high image density visualisation provided the opportunity for improved conceptual appreciation of the variability of the dynamic wake. Two sets of images captured at random times are presented.

At one downstream position, 985 mm, example images, each containing around 100 raw velocity estimates are shown (Fig. 7). The measured velocity vectors are superimposed on the raw image of the particles. This gives an indication of vortex wander and clearly illustrates the limitation of time averaged data, experimental or numerical, in representing the flow.

One record from each of the first four downstream positions was then chosen (Fig. 8). This gives an indication of the vortex wander with downstream position and coupled with Fig. 7 again emphasizes the importance of the time dependence of the spatial distribution of shed vorticity.

Examination of the velocity field in the full data set showed that the trailing vortex dominated the flow field. The downwash and upwash induced by the flap vortex, in the inboard and outboard sections of the wing respectively, can be clearly observed. Cross flow velocities up to typically 30% of the streamwise velocity were generated, as shown in Fig. 2 with maximum values approaching 50%.

A further indication of the variability of the trailing vortex filaments was demonstrated by animating the digitised particle images. As reported by the authors elsewhere (Grant et al., 1998) the dynamic display of such raw particle images can be used to obtain quantitative information regarding vortex dynamics in wake flows (see also Coton et al., 1997 and Hurst et al., 1998). The vortex spins the seeding particles outwards leading to a void which can be used to accurately locate the vortex centre. In addition to defining wake properties, feedback from the trailing vortex of the wing is one of the important features producing the unsteady load so full field animation is a useful diagnostic tool in the present environment.

The measurement of this vortex movement is important to enable a full understanding of the flow field mechanics downstream of the wing to be obtained. Time averaged spatial measurement techniques, e.g. pressure probe, hot wire anemometry or LDA, would not provide this unsteady flow field information. This clearly demonstrates the advantages provided by PIV which allow the measurement of instantaneous velocities throughout a flow field. These detailed flow field data are very important in the development and validation of CFD techniques which can predict the full characteristics of the flow field.

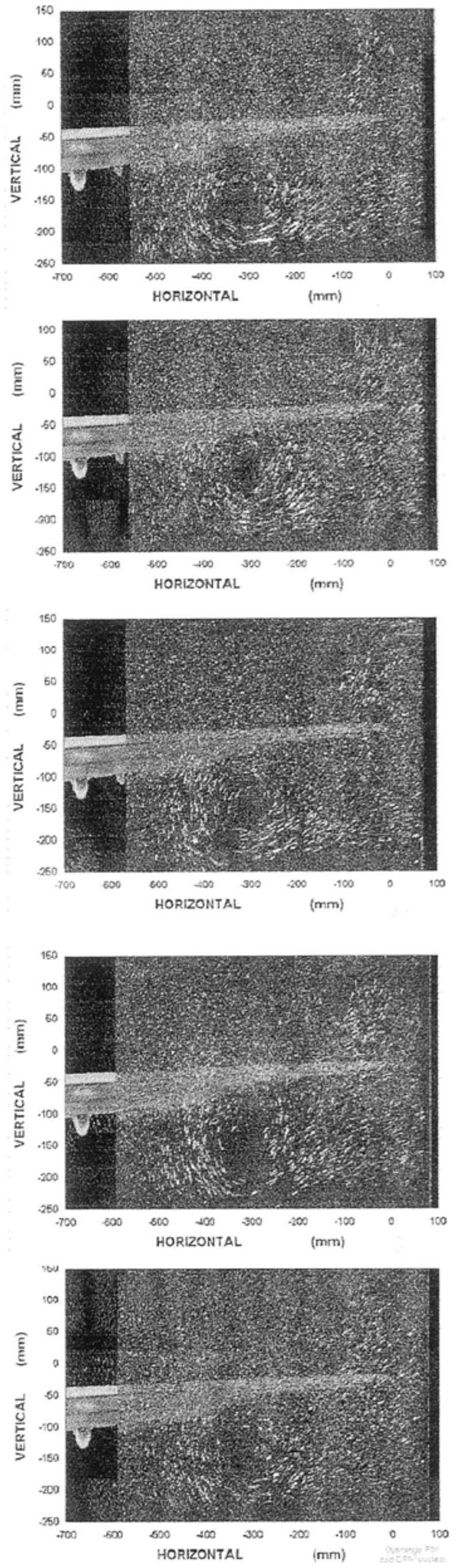

Fig. 7. Typical PIV vector plots at one downstream position.

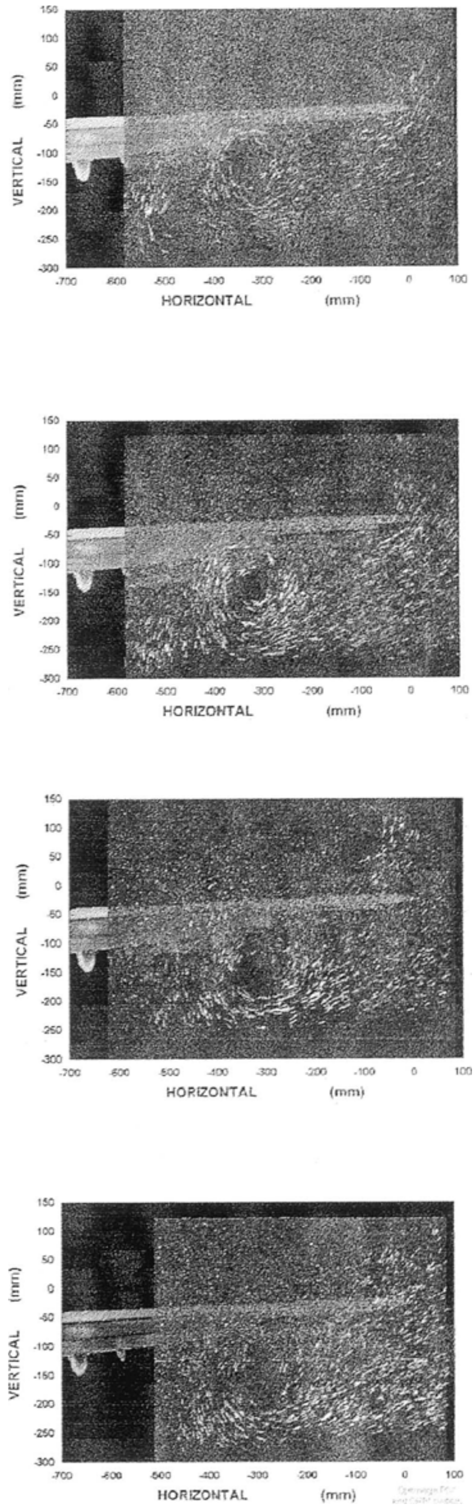

Fig. 8. Typical PIV vector plots at first four downstream positions.

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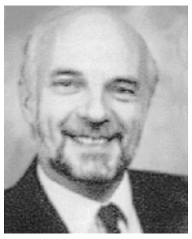
Authors' Profiles



Ian Grant : He obtained a degree in Physics from the University of Edinburgh in 1969 and a Ph. D. in 1972. He holds a personal chair at Heriot-Watt University. His main area of work is the development and application of optical, image processing, PIV and neural techniques in engineering. He has published more than 140 papers and was Editor of the SPIE Milestone Volume on PIV. He is founding editor of the e-journal 'Optical Diagnostics in Engineering', was joint editor responsible for electronic proceedings at the 8th International Symposium on Flow Visualization (Sorrento, 1998) and will be Chairman and joint editor of the 9th Symposium (Edinburgh, 2000).

Minggang Mo : He is a graduate of the Beijing Polytechnic University, Beijing, PRC. He joined the Fluid Loading and Instrumentation Centre at Heriot-Watt first as an Academic Visitor. After a short period as a Research Associate he was successful in obtaining an ORS scholarship to allow him to continue his studies as a research student at Heriot-Watt in the area of PIV.

Xiaobo Pan : She obtained a PhD from Heriot-Watt University in 1996. Her research has included the development and application of stereogrammetry in particle image velocimetry, the evolution of neural network techniques for image analysis, particularly particle tracking velocimetry, and the development of control systems for laser scanning.

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