A DIGITAL IMAGE PROCESSING APPROACH
TO LARGE-SCALE TURBULENCE STUDIES

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SUMMARY

An image processing approach to turbulence studies has been developed. The approach employs a structure tracking technique to quantify the movement of coherent, large-scale turbulent structures. The 'structure tracking' technique has been applied to the shear layer of a low speed jet issuing into a low speed crossflow. A study of the characteristics of the turbulent flow within this region involved comparative measurements with hot-wire anemometry measurements within the same flow regime and fractal analysis of the flow visualisation images used by the tracking routine. Fractal analysis was applied to flow visualisation images to educe a range of length scales made apparent by the flow visualisation equipment.

The results obtained with the structure tracking technique included the instantaneous velocity of the structures and a measure of their length scales. The instantaneous velocity measurements were used to calculate a turbulence characteristic associated with the structures. Further analysis revealed subsets of this turbulence characteristic involving the variation in average velocity of individual structures as well as variations in the instantaneous velocity of individual structures.

Where possible, the results of the structure tracking technique were compared to those achieved by hot wire anemometry and good correspondence was found between the mean flow characteristics measured by both techniques. The results of the two techniques began to diverge in the regions of the flow where conventional hot-wire anemometry was unable to discriminate between the flow associated with the jet and that associated with the crossflow. In such regions, time-averaged hot-wire anemometry produced results which combined the measurements in both flow regimes and therefore attenuated any characteristics of the jet which were significantly different from those of the crossflow. In the same flow regions the structure tracking technique was able to measure those characteristics specifically associated with the jet, producing results, which reflected the behaviour of the jet more accurately.
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NOMENCLATURE

a,b - Jet trajectory curve-fitting parameters
A,B - King’s law calibration constants
D - Jet nozzle diameter (13mm)
E - Hot-wire bridge voltage
E(f) - Energy coefficient of frequency, f
h - Width of box used in box counting method
k - Axial cooling coefficient
l - Integral length scale of the flow
L - Primary length scale of the flow e.g. the flow width
M - Magnitude of instantaneous velocity projected in X-Y Plane
M1 - Magnitude of instantaneous velocity measured by wire1 projected in X-Y Plane
M2 - Magnitude of instantaneous velocity measured by wire2 projected in X-Y Plane
N - Total number of samples
n - King’s law calibration exponent constant (0.45)
N(h) - Number of boxes of width, h, encompassing boundary
nt - Number of samples for which flow is turbulent
P - Depth of jet penetration in the X-Direction
R - Ratio of jet exit velocity to crossflow velocity
R(τ) - Autocorrelation coefficient of time lag τ
S - Jet nozzle separation
St - Strouhal Number
u - Instantaneous velocity in the X-direction
u' - Fluctuating component of velocity in the X-direction
u'' - Fluctuation of instantaneous u-component velocity from local mean
u' - Fluctuation of local mean u-component velocity from ensemble mean
\bar{U} - Average Velocity in the X-Direction
\bar{U}_f - Average freestream velocity in the X-direction
v - Instantaneous velocity in Y-direction
v' - Fluctuating component of velocity in the Y-direction
Instantaneous velocity in the Z-direction
Fluctuating component of velocity in the Z-direction
Thickness of deflected jet
Horizontal distance from the jet exit in the downstream direction
Vertical distance from the jet exit, measured from the ground plane
Horizontal distance from the jet exit in the normal to the downstream direction
Angle of velocity vector to X-axis
Dissipation
Kinematic viscosity of air $1.5 \times 10^{-6} \text{ m/s}^2$
Kolmogorov length scale
Kolmogorov time scale
Statistical standard deviation
Taylor microscale length scale
Displacement along the centre-line of the deflected jet
Correlation coefficient in Tutu & Chevray correction method, $\frac{\langle -uv \rangle}{\sqrt{u^2} \cdot \sqrt{v^2}}$
Time lag
Effective angle of crossed hot-wire 1 (nominally 45°)
Effective angle of crossed hot-wire 2 (nominally 45°)
CHAPTER ONE

1. INTRODUCTION

1.1 GENERAL INTRODUCTION TO THE THESIS

Conventional measurement techniques such as hot-wire anemometry (HWA) and more recently, Laser Doppler Anemometry (LDA) have been used extensively in the study of turbulent flows. Whilst these techniques provide a great deal of data concerning the time history of flow behaviour, they fail to provide information reflecting the instantaneous characteristics of the flow. The foundation of such techniques is point-based and as such, they fail to provide a 'picture' of the flow. The random nature of turbulence makes instantaneous point-measurements meaningless unless they are collectively analysed in a time averaged or ensembled manner. This then requires that turbulence is viewed statistically rather than in physical terms. Flow visualisation overcomes this restriction by allowing global representations of a flow regime at instantaneous points in time.

Flow visualisation is a powerful investigative tool, increasingly used in studies of fluid dynamics. Qualitatively, the nature of many complex flows may be revealed immediately with the use of simple flow visualisation techniques. The development of techniques for the quantitative analysis of flow visualisation images, however, opens up a wide range of research tools for the analysis of large-scale or full-field flow behaviour.

Established flow visualisation techniques, such as Particle Image Velocimetry (PIV), produce full-field quantitative data concerning a flow field. However, such techniques require very high resolution imaging for accurate data acquisition and, as a result, the field of analysis is generally small and does not reflect the large-scale behaviour of the flow. Such techniques are very effective when studying small-scale turbulent structures but are not viable for studies of large-scale turbulence as will be presented here.

The work presented in this thesis is a discussion of the author's contribution to the development of full-field image processing techniques for the quantification of turbulence
characteristics within complex flows. The technique developed has been applied to a low speed, incompressible flow regime which has been seeded with a passive contaminant. The technique demonstrates that useful and effective quantitative flow visualisation studies are achievable with relatively low cost equipment, without the need for complex illumination systems. The ease of use and the ready availability of the equipment required for the technique, should highlight the advantage and accessibility of image processing methods to all researchers in the field. The work presented here will demonstrate that there is little reason for most experimentalists in fluid mechanics not to augment their laboratory facilities with even the most basic flow visualisation equipment.

1.2 SCOPE OF THE PRESENT WORK

The primary study presented in this thesis, is the development of a technique for studying large-scales of turbulence. The technique that has been developed is capable of tracking the movement of a large-scale structure within the shear layer of a turbulent flow. Testing was carried out in an open return wind tunnel within the Civil Engineering Department of the University of Surrey. Measurements were taken in the centre-plane of a single jet issuing normally at a velocity of 6 m/s into a transverse crossflow with a velocity of 1 m/s. The location of measurements was chosen to minimise the out of plane effects of what is a predominantly 3-dimensional flow.

The aim of the experimental programme was to demonstrate a quantitative flow visualisation technique that could elicit characteristics of flow behaviour that were not available with conventional point measurement techniques. HWA measurements were taken throughout the centre-plane of the jet, yielding instantaneous velocities. Average velocities, turbulence characteristics and other higher order moments were calculated, based on these measurements. Image processing techniques were used to measure the velocities, length scales and turbulence characteristics of large turbulent structures from a series of instantaneous images acquired within the shear layer of the jet in a crossflow. The digital imaging approach requires the acquisition of a large number of images of the turbulent / non-turbulent interface between the jet and the crossflow. The acquisition of these images, combined with the image processing equipment available, made it possible for the relatively
new field of fractal analysis to be applied to the stored images. Fractal analysis was used for the purpose of estimating the range of turbulent length scales within an instantaneous ‘picture’ of a turbulent flow boundary.

1.3 THE FLOW REGIME

The aim of the current work is the development of a new approach to the study of turbulent flows and, as such, the flow under investigation is secondary to the technique that has been developed. However, the selection of the flow regime for study was based on a number of criteria. Whilst it may seem unusual that a complex three-dimensional flow was selected for the development and validation of a two-dimensional technique, the following section will demonstrate the suitability of the jet in a crossflow phenomenon to the current study. It was important to be able to seed the flow at source, as the image processing routines relied on the ability of the seeding medium to accurately follow the large-scale turbulent structures within the flow. This was particularly straightforward with the jet in crossflow as the seeding medium could be introduced at the inlet of the fan supplying the jet fluid. In this way, the flow under investigation became in reality, the behaviour of the seeded jet, whereby the introduction of smoke was an integral part of the study. Other flow regimes considered for the current work were those such as bluff body flows, boundary layer flows or flows around cylinders producing a Von Karmann vortex street. These ideas were rejected, because under such circumstances, the seeding medium would have had to been introduced to the flow within the wind tunnel. The method by which this was performed would have had an effect on the resulting flow behaviour. Admittedly it would have been possible to bleed the seeding medium into the flow regime under investigation. However, the need for a high delivery rate of the seeding medium to achieve good flow illumination and definition, would have required that the method of introduction of the seeding medium would have changed the configuration of the experimental model considerably. Pressure fields created by an intrusive seeding technique would have been a major consideration in the experimental analysis. Whilst the introduction of the seeding medium at the inlet of the jet supply fan, changed the inlet pressure to the jet, varying the fan speed so that the resulting jet velocity could be set to its required value could accommodate this effect. The result was an essentially non-intrusive
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seeding technique which did not affect the overall behaviour of the flow and would allow a high density of the seeding medium to effect good flow visibility.

The crossflow velocity was selected to be as low as was sustainable by the wind tunnel apparatus (1 m/s). The jet velocity was selected at 6 m/s as previous workers; Keffer and Baines (1963) have shown that with a jet to crossflow velocity ratio above 4, the position of the jet could be described by a single function with a virtual source. It was decided that for best comparisons with other researchers, a point well above that limit be chosen, without being so high as to be severely affected by the blockage effects of the jet penetration.

1.4 ORGANISATION OF THE THESIS

The next chapter of this thesis, Chapter Two, presents a review of literature relevant to this thesis. It begins by examining aspects of fluid mechanics studies relevant to the current work. Included within this is an examination of flow measurement techniques, a study of current methods for the identification of vortical structures and an outline of the aspects of jet in crossflow studies that have a bearing on the current analyses. Following this is a survey of current image processing techniques associated with object recognition and tracking. The chapter concludes with a review of the previous work in the field of fractal analysis of turbulence.

Chapter Three provides a detailed description of the apparatus used during the experimental programme associated with this thesis. This section starts by describing the wind tunnel and jet rig, which provide the flow regime for measurement, including the flow characteristics of the apparatus. Next, the conventional hot-wire apparatus is detailed including the data acquisition apparatus along with the probe characteristics. The apparatus fundamental to this study is that of the image processing equipment and this is also described in detail by breaking it down into its separate components of the image processing module, the smoke generator, the Charge Coupled Device (CCD) camera and the light sheet apparatus.

The experimental programmes of the preliminary studies that support the current work are detailed in Chapter Four. The first section details the experimental procedure of a
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quantitative image analysis study that provided the background for the current investigation. The subsequent sections describe the hot-wire anemometry and fractal analysis techniques which provide the comparative data for the current work. The results of each phase of the preliminary work are presented with each section.

Chapter Five describes the structure tracking technique central to this thesis. The chapter is divided into three sections. The first section describes the implementation of the structure tracking technique, describing the operation of the software written specifically for this project. The second section describes the analysis techniques used to calculate the characteristics of the large-scale turbulent structures, including velocity, turbulence characteristic and length scales. The final section presents the results of the technique, analysis of these results is reserved for Chapter Six.

The results are discussed in Chapter Six beginning with a comparison between point measurement techniques and the digital image processing techniques presented herein. In many cases, a direct comparison between the results achieved by the different techniques is not possible due to the varying nature of the data acquisition for all techniques presented. In general, the results of the hot-wire anemometry are discussed in terms of the way they support the image processing results. There is little analysis of the hot-wire results as independent statistics describing the flow behaviour. However, hot-wire anemometry measurements are compared to those of previous researchers to demonstrate the validity of the reference data. The bulk of the analysis is confined to implications that can be made from the new and unique data made available by the current structure tracking technique. The fractal analysis technique is generally described in terms of its augmentative benefits to the current image processing technique but there is also a degree of discussion of the fractal analysis approach and results as a stand-alone method of acquiring quantitative data from flow visualisation images. The main aim of this chapter is to discuss the relevance of the image processing results in terms of the behaviour of the jet in a crossflow.

Chapter Seven outlines and discusses further developments of the structure tracking technique as it is applied to alternative flow regimes. Results and observations from a number of experiments are discussed. The modification of the technique to look at different
planes within a flow is outlined, and results of this developmental work with the structure tracking technique are presented.

As a conclusion, Chapter Eight outlines the concepts and motivation behind the new image processing technique. The achievements of the current programme of work are summarised and the essential differences between the current technique and other flow measurement techniques are outlined. The outcome of the experimental programme is summarised and recommendations for the development of the techniques described herein are proposed.

Diagrams are included within the main body of the thesis to clarify the concepts being discussed. Figures that demonstrate results or numerical data are included in Appendix A, and pictures which of relevant apparatus and flow visualisation images are included in Appendix B.

1.5 SUMMARY

This chapter has highlighted the need for the development of quantitative flow visualisation techniques. It reinforces the belief that flow visualisation is a powerful analytical tool which is being underused in its current applications. It highlights the difference in the results achievable with point measurement techniques and quantitative flow visualisation techniques. Additionally, the scope of the current work is described along with an outline of the flow field under investigation, a jet in a crossflow (JICF) and the reasons for its selection. Finally, the organisation of this thesis has been outlined with a brief description of the content of each chapter.

The following chapter is a review of the work that has been carried out in fields related to the current project, both in terms of the flow regime and flow measurement techniques. It summarises the knowledge and understanding which was required for the execution of this work.
CHAPTER TWO

2. LITERATURE REVIEW

2.1 INTRODUCTION

The work presented here is primarily concerned with the application of image processing techniques to studies of the behaviour of large-scale turbulent structures. Flow visualisation techniques have been used for studies of a wide range of fluid dynamics phenomena. However, early studies were essentially qualitative in their nature and used to aid the interpretation of results measured using conventional, intrusive, point-measurement techniques, such as hot-wire anemometry or pressure measurement methods.

Advances in image processing and analysis within recent years have now made quantitative image analysis possible. However, few techniques have been established well enough to be used as mainstream experimental tools. The benefits of a quantitative flow visualisation method can be demonstrated by applying it to a classical flow regime to elicit data that would not be immediately apparent using conventional flow measurement techniques. To demonstrate the validity of a new technique, it is necessary to first demonstrate the limitations of conventional methods then to outline the way in which a new technique can be used to augment the analysis tools available.

The work presented here concerns large-scale, full-field image analysis techniques, applied to the shear layer region of a low-speed, single jet issuing normally, into a low-speed crossflow. The image processing techniques are those of turbulent structure tracking and fractal analysis. The following review will be divided into three sections. The first section will discuss the fluid mechanics aspects of the current study, including conventional flow measurement techniques. The second describes current techniques in use over a wide range of image processing applications and the third will discuss the relatively new field of fractal analysis, specifically with its application to turbulence studies.
2.2 FLUID MECHANICS STUDIES

This section, concerning the fluid mechanics aspect of the current study, will first describe conventional flow measurement techniques and their applications and limitations within the current research field. Current work concerning the identification and measurement of large-scale turbulent structures will then be discussed and finally the current state of understanding of the behaviour of a jet in a crossflow will be presented.

2.2.1 Measurement Techniques

The following section briefly mentions point measurement techniques particularly Laser Doppler Anemometry (LDA). The multi-point measurement technique of Particle Image Velocimetry (PIV) is reviewed in somewhat greater detail, outlining early drawbacks in the technique and the methods by which they have been overcome. The reason PIV is given more attention, is that, latest developments of the technique have the capability of time resolution of flow characteristics, which is a feature of the current image processing technique.

2.2.1.1 Point Measurement Techniques

Optical methods are routinely used in studies of fluid mechanics to measure quantities such as velocity, density and scalar concentration. Laser Doppler Anemometry (LDA) or Laser Doppler Velocimetry (LDV) as described by Durst, Melling & Whitelaw (1976), Greated & Durani (1977) and Adrian (1983) are well-established techniques. For an in-depth study of the technique, the reader is referred to the work of those authors. LDA techniques typically allow a spatial resolution in the region of 1-2mm, with accuracy in the range of 0.1% to 1%, Adrian (1986). LDA, however, is essentially a point measurement technique, as is hot-wire anemometry which has been long established and need not be reviewed here. Whilst these techniques have been modified and developed to allow multi-point measurements, they have in the main been merely a move towards the use of an array of single point measurements, such as hot-wire rakes and multipoint LDV systems, which measure a limited number of points such, as Nakatani et al. (1985).
2.2.1.2 Particle Imaging Velocimetry (PIV)

For many years, a great deal of interest was shown in the development of a technique that would allow a large number of point measurements to be achieved. It was not until the early to mid-1980's that the advances in computer technology and image processing equipment allowed the development of techniques which were able measure the motion of thousands of points within a two or three-dimensional region. These methods yielded instantaneous pictures of a flow field that were unobtainable with single-point measurements. The technique of tracking the movement of particles within a flow is known as Particle Imaging Velocimetry (PIV) or Particle Tracking Velocimetry (PTV). The basis of PIV techniques is that a fluid is seeded with a marker that is presumed to follow the flow. Typically, the marker is of some medium that has good optical scattering properties. In two-dimensional PIV, illumination takes the form of a thin light sheet, usually between 1mm and 10mm thick. Some form of double exposure is then used to record two image fields of the markers, with the interval between exposures being accurately recorded as the period for velocity calculation.

Some early measurements such as Shiraishi et al. (1985) relied on manual measurements to extract quantitative velocity data. However, the increased use and quality of computers and image processing equipment, now allows images to be either recorded digitally or converted to a digital format so that the analysis can be automated. The most common analysis method for double exposure techniques is that of image correlation, whereby the images of the interrogation field are shifted to find the position at which the markers of each image best overlap with each other. In effect, this is the matching of image pairs within an image region to ascertain the average displacement of the fluid markers. The description of PIV given here is that in its most basic form. Development work in recent years, has involved the modification of the technique to improve accuracy, eliminate directional ambiguity, encompass three-dimensional displacement and measure the temporal development of the flow field.
2.2.1.2.1 Elimination of Directional Ambiguity

Landreth & Adrian (1988), proposed a technique in which the photographic image field was displaced by a known distance between illumination pulses. By making this displacement greater than the maximum displacement of all markers over the pulse interval, so that even the most negative velocities produced a positive. The actual fluid velocities were then found by mathematically subtracting the image shift. The method proposed in this work used an electro-optical technique to obtain the image shift, however, previous methods used by the authors and others, which involve mechanical techniques for image shifting, were described. The electro-optical technique was applied to a stationary flow field and yielded results with an RMS error of ~0.8% of the full scale. A further test of the system was carried out on a test section of nearly quiescent water displaced with a uniform velocity. A small transient velocity was present in the flow during translation. The electro-optical shifting approach clearly revealed the transient velocities within the mean flow field.

A different technique for resolving directional ambiguity was shown by Grant & Liu (1990). The recorded size of a marker within an image is proportional to the impinging light intensity and duration. Using this phenomenon, the authors employed a technique, in which a short ‘tagging’ pulse of illumination was fired either immediately before or immediately after each illumination pulse. The resulting image was that of a double image, slightly ‘blurred’ in the direction of motion. The direction of a marker could then be extracted from information concerning the position of the principal marker image, relative to its tagging image. The technique was applied to a variety of flow-fields. These were the flow behind a cylinder, the flow behind a step and a wave-current interaction. The interval between the tagging pulse and the main pulse was dependent on the velocities within the flow field being measured. A longer pulse interval was required with low-velocity flows to avoid overlap of the principal image and the tagging image. With high velocity flows, the pulse interval was required to be shorter so that there was no difficulty in the pairing of the principle image and the tagging image. The technique was found to be capable of high accuracy and dynamic range. Velocities in the range 0.01 m/s to 20 m/s were measured with some cases in which the turbulence intensity was as high as 100%. The advantage of this technique over that proposed
by Landreth & Adrian (1988) was its experimental simplicity. Illumination pulses could be created by use of a ‘chopper’ and standard laser sheet apparatus.

The problem of directional ambiguity in marker and fluid velocity has been addressed in a number of other ways, Goss et al. (1989) used a two colour approach and Coupland et al. (1991) used a holographic technique, amongst others. The reader is referred to these publications for a more detailed discussion of the techniques. One of the advances in PIV over the last ten years has been due to the development and advancement of digital electronics. Willert & Gharib (1991) used digital image processing approach to acquire two consecutive flow field images to separate storage areas. This allowed the cross-correlation of two images rather than an auto-correlation of a double-exposed, single image. The acquisition of the images to separate storage areas removed the dimensional ambiguity associated with uncorrected double exposure images. The Willert & Gharib (1991) work established the validity of a digital PIV (DPIV) technique. The restrictions of image processing equipment available to the authors at the time meant that the greatest image acquisition rate achievable was only 30 Hz. This meant that the technique could only be applied to low speed flows. The case presented in this paper was that of a low Reynolds’ number vortex ring in water. The lower limit of velocity with this technique, depended on the spatial resolution of the image processing equipment available, and not the overlap of the particle images as is common with double-exposure PIV. The drawbacks of this DPIV technique were mainly those associated with the lack of sophistication of the equipment available at the time. Conceptually, DPIV is a sound idea and as the cost of high speed imaging equipment continues to fall along with an increase in the spatial resolution of the equipment, the merit of the technique will continue to grow.

The development of digital PIV (DPIV) is economical and efficient method of implementing a well-established flow measurement technique. DPIV systems compared to analogue systems require non-specialised electronic equipment and are able to take advantage of the rapidly developing technology of computing hardware.
2.2.1.2.2 Three-dimensional PIV

One of the major sources of error in PIV and associated techniques is the out of plane movement of a marker. Under such circumstances, the degree of error is related to the angle between the out of plane vector and the measurement plane. Conventional PIV techniques would measure the projected displacement of the marker within the image plane.

Nishino et al. (1989) developed a three-dimensional PIV approach. The technique employed three TV cameras, with effectively orthogonal viewing angles and a digital image processing system to track nylon particles within an unsteady Couette flow between two concentric cylinders. The image acquisition rate of the image processing equipment used was 30 Hz and so, with three cameras, the interval between plane acquisitions was 0.1s. This restricted the applicability of the technique to very low speed flows. Illumination pulses in the measurement volume were triggered at 30Hz by the timing signal from the cameras. The use of the three cameras allowed all three velocity components in the measurement volume to be calculated. Whilst the three camera technique lent the advantage of three-dimensional velocity measurement to PIV, the reduced acquisition rate and increased experimental complexity, limited the value of the technique. Even so, the approach used was declared to be successful and application of the same technique to a stirred water tank demonstrated its applicability to turbulent flows.

The effect of out of plane movement with PIV techniques was addressed by Arroyo & Greated (1991). A stereoscopic approach was suggested, with the use of either two cameras or one camera with a mirror arrangement. The single camera and mirror technique effectively split the camera into two imaging areas. With this technique, the angle of viewing the image source was split into two viewpoints, no longer normal to the illumination plane. As a result, the out of plane movement projected to each imaging plane varied according to the viewing angle and the degree of out of plane movement could be detected by a reconstruction from the two image recordings. The technique was applied to a flow field of Rayleigh streaming with velocity of 2.6 mm/s. A laser light sheet of 40mm width and 0.7mm thickness intersected the flow field. The paper reveals no details about the accuracy of the technique but stresses that its implementation was very similar to that of conventional PIV. The
Chapter Two - Literature Review

the nozzle. This finding was in agreement with that of Sykes, Lewellen & Parker (1986), who stated that, for large velocity ratios, the source of the stream wise vorticity in the vortex pair could readily be traced back to the original stream wise vorticity of the emerging vertical jet.

The horseshoe vortices were found by Fric & Roshko (1989) to have their source in the approaching crossflow boundary layer, whereby the separated boundary layer ahead of the jet supplied the 'horseshoe' type structures with vorticity and the 'horseshoe' vorticity created a pressure gradient at the wall thereby generating even more vorticity.

A key point of the Fric & Roshko paper concerned the wake vorticity of the jet, where previously analogies had been made between the wake formation behind the jet and those behind a circular cylinder in a flow. Fric & Roshko declared that because vorticity could only enter a flow through imposed initial conditions or at wall boundary conditions and, as these did not exist at the jet / crossflow interface, it was not possible for the jet to shed vortices. The essential difference between a jet and a cylinder was the non-existence of a 'no-slip' condition on the jet surface. Smoke flow visualisation was used to show that the source of the wake vorticity was the crossflow boundary layer.

Of the four vortex systems outlined above, the vortices of greatest interest to the current study is that of the shear layer vortices as these are vortical structures under investigation with the current image processing techniques. Accordingly, the following section will concentrate on the shear layer vortices associated with a jet in a crossflow and discuss the previous findings and observations made in this flow regime.

2.2.3.3 Shear Layer Vortices

A series of flow visualisation experiments were carried out with a jet in a crossflow by Kelso et al. (1996). In these experiments, dye streaks were injected into a water-based jet in crossflow at a variety of injection points. Dye injection into the upstream side of the jet nozzle clearly highlighted that the ring vortices in the shear layer of the jet, had their origin within the jet nozzle. Analysis of video images allowed the authors to imply that the ring-like vortices were formed by a 'roll-up' of the shear layer around the entire perimeter of the jet.

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Photographic images showed the collapse of the clearly defined ring-like vortices on the upstream side of the jet as they met with the rings formed on the downstream side of the jet. This collapse resulted in a less well defined, but nevertheless coherent structure in the outer shear layer of the jet.

Fric & Roshko (1994) developed their earlier work from 1989, with particular attention to the wake vortices. However, within their paper, smoke seeding flow visualisation techniques were used to emphasise the shear layer vortices. Two different seeding sources were used, one with the seeding of the jet and the other with the seeding of the centre-plane of the crossflow from a point upstream of the jet exit. In both cases, a jet to crossflow velocity ratio of 2 was used.

A study conducted by Huang & Chang (1994) into the structures within a combusting jet noted that two types of organised flow structure could be observed within this flow regime. These were the stream wise counter-rotating vortices and the coherent structures on the upstream surface of the jet, near the exit region. Schlieren visualisation techniques were employed which clearly defined the ring-vortices on the jet boundary in a region within 6 diameters downstream of the jet exit. Images were presented for a range of jet to crossflow velocity ratios from 0.75 to 2.8. The observation was made that as the jet to crossflow velocity ratio increased, the direction of the vorticity changed from positive in the stream wise direction to negative. This effect was attributed to the fact that at low velocity ratios the momentum of the crossflow was dominant, whilst at high ratios, it was the momentum of the jet that dominated. An example was shown of a transitional case where both momentum effects were equal and, in this case, the vortices could be seen to take a ‘mushroom’ type structure. With a velocity ratio of about 2.8, corresponding to a momentum flux ratio of approximately 3.5, the organised coherent structures, previously visible, broke down and were no longer distinguishable. The work went on to analyse the frequency of the passage of the coherent structures using the point measurement technique of single hot-wire anemometry. Results were presented concerning the trajectories of the turbulent structures using a time-averaged long exposure shadowgraph technique. These results were compared to those presented by Pratte & Baines (1967) using a jet path equation similar to that of Keffer & Baines (1963).
A multi-point pattern recognition technique was used by Eiff & Keffer (1997) to characterise the coherent structures within the near wake region of an elevated turbulent round jet in a crossflow, such as may occur with a chimney issuing into the atmosphere. A rake of crossed-wire probes was used in conjunction with a pattern recognition technique in the horizontal and vertical planes of the jet wake. The pattern recognition technique used, was a development of the one introduced by Mumford (1982) and Ferré & Giralt (1989) detailed above.

The results of Eiff & Keffer (1997) suggested that the vorticity due to the structures in the wake of an elevated jet in a crossflow made a contribution to the contra-rotating vortex pair within the jet body because their top portion remained attached to the jet.

In a recent paper, Smith & Mungal (1998) used Planar Laser Induced Fluorescence (PLIF) to acquire two-dimensional images of a jet in a crossflow. In these visualisations, the shear layer vortices were clearly visible through the bending and downstream region of the jet. The study was concerned with the quantification of the scalar field within the jet images. Results showed a significant difference between the concentration field acquired from ensemble images and those from instantaneous images. This highlighted the need for an instantaneous approach to the study of turbulent flow regimes.

An instantaneous approach of analysis of shear layer structures was attempted by Gruber et al. (1997), using a flow seeding visualisation technique in an attempt to track the turbulent structures in the near-field shear layer of a high speed jet in a high speed crossflow. Tests were carried out at jet to crossflow velocity ratios of 1.71 and 0.61 for two jet injection geometries, circular and elliptical with two jet fluids, helium and air. The investigation region extended to a downstream position of X/D = 4. This places the higher velocity ratio measurements within the ‘zone of maximum deflection’ as defined by Pratte and Baines (1967). Unfortunately, the jet to crossflow velocity ratio is below 4 and thus the deflection of the potential core of the jets means that trajectory results could not be compared to the established empirical equations. The technique proposed by Gruber et al. involved the acquisition of images, temporally separated by an interval between 1μs and 2μs covering a fixed region in the centre plane of the deflected jet. The resulting images were subject to
significantly different signal to noise ratios, with the second of the two images of such poor
definition that mathematical cross-correlation of the two images was inconclusive. Analysis
was eventually carried out manually, whereby the centres of particular structures were
identified in each image. Velocity vectors were then calculated by the displacement of the
feature over the period between image acquisitions. Conclusions were drawn about the effect
of nozzle injector geometry on the near field behaviour of the jet structures. Even with a
rather optimistic estimate of ±1 pixel error in the location of the centre of a structure, the
results involved an uncertainty of ±47 m/s, roughly 10% of the convection velocities
involved. The manual method of measuring the displacement and the high degree of error
involved, undermines the technique such that the results are more qualitative than
quantitative.

An unusual, if not unique, opportunity for the study of combusting jets in a crossflow was
seized upon by Mungal & Lozano (1996) in which they managed to obtain news footage of
numerous scenes of oil wells on fire as a result of the 1990 Persian Gulf War. The burning
jets were deflected by ambient crosswinds. Whilst, the environment was hardly conducive to
the quantification of experimental conditions, it was considered that the rarity of such
opportunities to study this flow condition on such a scale made it a worthwhile investigation.
The video images were digitised to 8 bits on a PC-based image processing system where the
difference in light levels between the burning jet and the background provided excellent
contrast. Consecutive X-Y planes of the jet were rendered into a three-dimensional X-Y-t
image by computer generation. In this manner, large-scale structures on the upstream surface
of the jet were observed as they moved from the jet direction to the crossflow direction. This
was observed to occur at a constant speed. There was however, no attempt to try to explain
the reasons for this other than to say that despite its complex three-dimensional nature, the jet
in a crossflow displays some underlying organisation.

Numerical simulations of a jet in a crossflow have been presented by many authors, Sykes,
Lewellen & Parker (1986) being among those who presented results concerning the shear
layer vortices. Their numerical analysis involved the solution of Reynolds averaged Navier-
Stokes equations using a turbulence model (Mellor Yamada 2.5). Their results concerning the
essential features of the flow were compared to the established experimental results of Keffer
& Baines (1963), Kamotani & Greber (1972), Mousa et al. (1977) and Andreopoulos & Rodi (1984) and found good correspondence. The Sykes et al. (1986) work presented a numerical simulation of the tracking of the development of the shear layer ring vortices, by describing the initial jet as a vortex cylinder and tracking the trajectory of a ring of fluid particles starting slightly above the boundary of the jet nozzle. This work produced clearly defined ring vortices at jet to crossflow velocity ratios of 8, 4 and 2. The same general distortion was shown at all velocity ratios, with only the highest velocity ratio case displaying relatively undistorted rings at a distance greater than 1 diameter downstream of the jet exit. The work concerning the development of these vortices was only a small part of a greater body and little emphasis is made on it. However, it does show that the greater part of the distortion of the vortices occurs in the ‘bending’ region of the jet.

Work by Yuan, Street & Ferziger (1999) reported on a series of Large Eddy Simulation (LES) studies for a round jet issuing into a crossflow with velocity ratios of 2.0 and 3.3. The mean and turbulent statistics produced matched well with the experimental data of Sherif & Pletcher (1989). Furthermore, the simulation reproduced some of the large-scale coherent structures made visible by flow visualisation. The effect of these structures on the mean velocities, Reynolds’ stresses and turbulent kinetic energy along the jet centre plane were discussed within the paper. However, the vortical structures examined were restricted to those near the jet exit. Whilst instantaneous contours of vorticity highlighted the shear layer vortices up to 2.5D downstream of the jet exit, there was no progression to examine the convection of these structures nor was there analysis of the same structures at a farther downstream location. The extent of the computational area at most only reached to 8D downstream of the nozzle.

2.3 IMAGE PROCESSING TECHNIQUES

One of the major areas of development in digital image processing and computer vision has been that of object recognition and tracking. Many techniques and approaches have been developed for this purpose for a range of applications.
2.3.1 Image Recognition

Two of the most common forms of feature extraction in current use are those of mathematical shape recognition and template matching. These two techniques are briefly discussed here, with reference to their applicability to the current study.

2.3.1.1 Mathematical Approximation Techniques

The mathematical approximation of shapes is an important aspect of image processing. It is useful for applications such as data compaction, noise filtering and, more relevant to the current application, feature extraction.

The approximation of simple shapes can be achieved with polynomial descriptors or spline approximations. However, the continuity requirements of such techniques are not compatible with most image recognition techniques, where discontinuities are inherent in the images. Pavlidis & Horowitz (1974) described a method of segmentation of curves into sections, which could be described by a series of low order polynomials. The demonstrated cases were in fact linear segments. The contribution of Pavlidis & Horowitz (1974) was that of an algorithm to find the break points between the linear segmentations that achieve the least error between the original image and the approximation. Developments in the field of shape recognition and description include the work of West & Rosin (1992), in which a combination of arc and line fitting techniques were used to achieve a greater fidelity between an image and its mathematical approximation. Initially, edge detection was performed on an image and the edges were approximated by straight lines. The original edges were then approximated by arcs of recursively fewer pixel points until a minimum of three pixels was reached. At each recursion the error between the image and its approximation was assessed and compared with the straight-line approximation. The best fit was the one selected for the final approximation. This technique was more computationally intensive than that described by Pavlidis & Horowitz (1974), but it had the advantage of a more faithful reproduction of images.
Another method of image approximation by mathematical means is the Hough transform. The Hough transform is the most common technique for the detection of known shapes within images, Proctor (1998). For a detailed description of the algorithm by which it is implemented the reader is referred to image processing texts such as Ballard & Brown (1982). A brief description of the Hough transform is that it is a mathematical transformation that is applied to an image outline to reduce it to a series of lines described by their orientation and distance normal to an origin, Hough (1962). The Hough transform approach has been very popular over the years and been used for the detection of a variety of objects such as lines, circles, ellipses and other shapes.

The object recognition techniques for feature extraction described above, rely on the use of low-level features such as edges, lines, curves and ellipses. They are reliant on an idealised line drawing approximation of real shapes and require excellent image segmentation and edge detection routines. The mathematical shape approximation techniques described are better suited to feature extraction applications in which there is prior knowledge of the parameters of the shape to be detected, such as aspect ratio or some constant polynomial description of the shape. This is not the case in the current application and as a result, a review of the limitations of such techniques has recognised that, under the current conditions, outline detection is not a suitable process for the tracking of large-scale turbulent structures.

2.3.1.2 Template Matching

Template matching is a simple method of detecting a particular feature in an image. Provided the appearance of the feature is known accurately, one can try to detect it with a template, Ballard & Brown (1982). The template is in effect a sub-image that resembles the feature to be detected. A measure of similarity is calculated for how well an image area matches the template and the point of maximum similarity is selected as the location of the feature. The template matching technique is carried out by shifting the template across the image to different offsets and calculating the similarity in each case. In the current application, the appearance of a turbulent structure was not known accurately and so this technique could not be used to locate and identify it in the first instance. However, once the structure had
identified by some method, the image section encompassing it could be stored and used as template for locating it in subsequent images.

Ballard & Brown (1982), state that the appearance of the feature must be known accurately for template matching to be effective. However, because a ‘best match’ is all that is required under the current circumstances, the similarity criteria can be relaxed to accommodate the slight changes in shape of the structure from one image to the next.

2.3.2 Image Tracking

Although the template matching method seemed to be an appropriate technique to apply to the tracking of the turbulent structures in the current application, a range of other image tracking techniques were reviewed with the aim of optimising the structure tracking technique.

Typical of the techniques in use in image tracking applications, are those presented within a volume summarising two week course of lectures which was presented in July 1993 at the Isaac Newton Institute for Mathematical Sciences at Cambridge University. The lecture series of the latest developments in image tracking was published in 1994. This section provides a brief summary of the relevant lectures presented during those two weeks.

Blake et al. (1994) presented work concerning the tracking of visual contours. The work presented a mathematically intensive technique which was capable of tracking a shape through six degrees of freedom; translation in two dimensions, rotation, and horizontal, vertical and diagonal scaling. The technique could accommodate minor deformations of the shape and out of plane rotations. However, in its application, the technique required that the contour edge being tracked was clearly defined and discrete from any background image. The technique used a curved search region based on the estimated contour of the object to be tracked and was demonstrated to track efficiently the movement of a hand, against a well contrasted background, through many degrees of freedom. Unfortunately, with the current work, the image field contained more than one shape or structure. In searching through the image field for similar shaped contours, the technique would have produced many ambiguous
results, as often two structures within an image field would be of similar enough a shape to confuse the tracking technique. If the current work were concerned with the visualisation and tracking of isolated turbulent structures, the work by Blake et al. (1994) would certainly have been very relevant and worthy of further investigation.

Work presented by Shapiro et al. (1994) concerned the tracking of moving heads. The technique employed for this has similarities to PIV methods used in flow measurement. Characteristic points of high contrast were selected within a shape or structure to be tracked. In the case presented, faces were used, with facial characteristics such as nostrils or lips being used as markers. These markers or ‘corners’, which were distinctive point features, were matched from image to image and from this, the overall movement of the face could be implied. The turbulent structures within the flow regime under investigation in the current project, however, did not contain characteristic points, either internal to the structure or externally on the structure boundary. Whilst a point characterisation of the structures was considered, the method was not found to be practical for current purposes.

Murray et al. (1994) showed a tracking method based on the corners or edge sections of a shape moving in front of a camera. Whilst translation and rotation could be measured with this technique, it suffered in its application to turbulent structure tracking, from the same problems as the previous two approaches. The turbulent structures deformed in such a way and at such a scale, that small sections of the structure were not necessarily recognisable from one image to the next.

2.4 Fractal Analysis

Fractal analysis is a relatively new field of mathematics, which has enjoyed great popularity over the last ten years or so. This has been due to the publicity surrounding the ability of the science to describe many of the patterns that occur within nature such as clouds, mountains and leaves. These descriptions were previously unobtainable with conventional geometry and, as such, a new perspective on previously impenetrable phenomena has been gained.
The discovery or rediscovery, and development of fractal geometry can be attributed to B.B. Mandelbrot and his text, Mandelbrot (1982) is highly recommended to those wishing a wider understanding of the subject.

The similarity in shape of turbulent structures of different scales, indicates that fractal analysis could be applied to an instantaneous image field to extract information concerning the range of scales over which self-similarity occurs. Thus, indicating the range of length scales of the turbulent structures within a flow visualisation image.

2.4.1 Fractal Analysis of Turbulence

In his rather comprehensive paper, Sreenivasan (1991) discusses the use of fractal analysis applied to lines, surfaces and volumes in turbulent flows. He notes that in liquid flows, with dyes used as passive scalars, the Schmidt number, which is the ratio of kinematic viscosity of the seeding medium to the particle diffusivity of the suspending medium, is of the order of 1000. Schmidt numbers greater than unity imply that the seeding medium will always stay within the turbulent flow. The results show two distinct scaling regions, the first being the K-range, occurring between the integral length scale and the Kolmogorov scale, $\eta$, and the second being the B-range, occurring between the Kolmogorov scale and the Batchelor scale, $\eta_b$. Reference is made to Prasad & Sreenivasan (1990a) where a turbulent interface of a volume of the order of $700\eta \times 600\eta \times 32\eta$ with resolution of the order of $4\eta$ was used for analysis in the K-range and a fractal dimension of $2.35 \pm 0.05$ was found for jets and wakes. The Sreenivasan paper also mentions that for a free jet in water, a histogram of the fractal dimension of the boundary in images yields a mean dimension of 2.36 with a standard deviation of 0.3.

Davis & Li (1996) presented work on the fractal dimension of schlieren images of a heated air jet at 17.2 m/s an 40°C above ambient air temperature, mixing with quiescent flow and of a diffusion flame from a coannular jet with an inner velocity of 2.5m/s surrounded by an outer velocity of 2.0m/s. Tests were carried out on the flame in its natural state and when excited at frequencies of 40Hz and 420Hz. The camera speed was set at 1/2000s so that the displacement of the diffusion flame was in the region of 1mm during image acquisition.
Fractal dimensions of 2.31 and 2.4 were found for the heated jet flow and diffusion flame respectively, using the box-counting method. This result agreed well with those published by other researchers. Davies & Li included in their paper a summary of the fractal dimensions in a variety of flows measured by other researchers. This is reproduced below to allow measurements in the current study to be compared with existing results. The dimension shown is the fractal co-dimension. This is the difference between the topological dimension of the image and the measured fractal dimension. For example, a fractal dimension of 1.3 measured from a line contour is the same result as a fractal dimension of 2.3 measured with a plane surface.

<table>
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<tr>
<th>Method</th>
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<td>Sreenivasan et al. (1989)</td>
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<td>0.35</td>
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<td>Prasad &amp; Sreenivasan (1989)</td>
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<td>Prasad &amp; Sreenivasan (1990b)</td>
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<tr>
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<td><strong>Plumes</strong></td>
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<td>Lane-Serff (1993)</td>
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<td><strong>Mixing Layers</strong></td>
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<td>Sreenivasan &amp; Meneveau (1986)</td>
<td>HW velocity signal</td>
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<td><strong>Pre-mixed Flames</strong></td>
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<td>0.05-0.36</td>
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Table 2.1 - Previous Measures of Fractal Dimensions of Turbulence
2.5 Summary

The background understanding required for the development of the current work covers a wide range of disciplines. A review of the aspects of fluid mechanics and flow measurement that are relevant to the current work has been provided. The capabilities of full-field measurement technique of PIV has been outlined this technique has a greater similarity to the image processing technique which has been developed. A range of techniques used in various image processing applications has been described, along with an analysis of their relevance to the current work. A brief review of fractal analysis, as applied to turbulence studies has been provided with emphasis on the quantifiable measure of fractal dimension, which is necessary for comparison with the current work.

The next chapter will describe the equipment used in the current work. This will cover the apparatus used to create the jet in a crossflow flow regime. The flow measurement apparatus and supporting computer hardware and software used in the comparative hot-wire anemometry will be described, as well as the image processing equipment used in the development of a new technique for turbulence studies.
3. EXPERIMENTAL FACILITIES

3.1 INTRODUCTION

The current study involves the development of a novel image processing technique, used to study the classical flow configuration of a jet in a crossflow. The study involved the application of a modern digital image processing system, to traditional flow visualisation techniques. Conventional hot-wire anemometry methods were used to provide comparative experimental results for the validation of the new image processing approach.

The following sections of this chapter describe the apparatus used within the study. In broad terms, these descriptions have been divided into three categories. The details of the wind tunnel and associated jet equipment are described in the first section. The hot-wire anemometry apparatus used in the comparative study, and its configuration are presented in the second. The third section outlines the equipment used in the acquisition and analysis of the flow visualisation images.

3.2 WIND TUNNEL AND JET FACILITIES

The description of the apparatus used to create the regime of a jet in a crossflow has been divided into two sections. The first section, outlines the equipment used, with detailed descriptions of the components, which make up the wind tunnel and jet apparatus. The second section, describes the preparation and commissioning of the equipment. It outlines how the flow regime was created and its key characteristics measured prior to experimentation.

3.2.1 Apparatus

The description of the wind tunnel and jet apparatus can be split into three separate sections. In the first section the wind tunnel that is used to create the crossflow for the flow regime, is
described in terms of its dimensions and characteristics. The next section describes the equipment and pipework used in the creation of the jet, which issues into the wind tunnel crossflow. The last section describes the pressure measurement equipment used to establish the velocities of the jet and the crossflow.

3.2.1.1 Wind Tunnel Apparatus

A schematic diagram of the wind tunnel used in the experimental programme is shown above (Diagram 3.1). The wind tunnel was an open-return, blow-down type with a working section of 0.624m width, 0.75m height and 3.6m length. A photograph of the tunnel is provided in Picture 1.

The tunnel was capable of freestream velocities of up to 12 m/s using a Carter Howden 900A backward airfoil centrifugal fan, powered by a 15kW 160T Bull electric motor. Freestream velocity was controlled by a KTK Newton 6P15-CUB thyristor drive, which allowed
continuous velocity control between approximately 0.7 m/s and 12 m/s. During operation the flow produced by the fan issued into a wide-angle diffuser, which contained four mesh screens. This, in turn, led to a settling plenum chamber, which contained a honeycomb flow straightener, and two mesh screens to reduce large-scale turbulence. The flow was accelerated into the working section by a 9:1 area ratio contraction, which produced a uniform flow regime.

High efficiency smoke filters were fitted at the outlet of the tunnel to remove almost all the smoke introduced into the flow. The filters used were of type E66WK/5 manufactured by Vokes Ltd. of Guildford. They were folded glass paper filters that rated at 98.5% efficiency for a particle sizes between 0.01 and 4.0 μm and 100% efficiency for larger particle sizes. The tunnel included a removable glass floor section and a ‘Perspex’ side panel to allow optical access to the working section. During normal operating conditions, with a freestream velocity of 1 m/s, the thickness of the uninterrupted boundary layer at the jet ground plane in the test section was found to be 36 mm which was 2.77 times the jet nozzle diameter (Figure 3.1 and Figure 3.2.). The location of measurement was 20 mm upstream of the jet exit. Displacement thickness and momentum thickness were 5.16 mm and 3.18 mm respectively. Freestream turbulence in the working section was measured at an average of 0.9%. Velocity and turbulence intensity profiles of the freestream within the working section are shown in Figure 3.3 and Figure 3.4.

3.2.1.2 Circular Jet

The jet apparatus was designed keeping in mind that future work may be carried out with multiple jet configurations. In this case it may be necessary to seed only one of the jets, and so, the jet inlets were designed to be separate. The same design was applied to the pipework for both jets. Criteria for the jet issuing into the crossflow were that its velocity profile was uniform with a minimum boundary layer thickness. To this end, the jet pipework was terminated in a contraction. The shorter the contraction length, the smaller the boundary layer at exit would be. However, with a contraction that was too short, the chances of flow separation would have been greatly increased.
Previous work within the research group had developed a number of possible nozzle designs and one of these was selected. A nozzle exit diameter, D, of 13 mm was selected as this corresponds to the exit dimension used in previous work within the department. This work investigated twin jet configurations with jet separations of 1D, 3D, and 5D, Savory et al. (1992), Toy et al. (1992), Toy et al. (1993a), Toy et al. (1993b), Toy et al. (1993c). Unfortunately, the necessity of the contraction meant that a 1D separation between the two jets could not be accommodated with the new design. With the correct contraction ratio, the 3D separation case could be accommodated. Copper piping of 32.5mm internal diameter was selected for the nozzle supply pipework, which allowed a contraction area ratio of 6.25:1. The velocity profile at the exit of the jet is shown in Figure 3.5.

Space restrictions forced the positioning of the jet pipework on the roof of the wind tunnel. The original design included the placement of an orifice plate flow-meter in the pipework as a means of measuring the jet velocity. To accommodate the flow disturbance that this would cause, and allow a resettlement zone, the jet pipework would have required a section of 10 D length upstream of the orifice plate and at least 6D length downstream. It was not practical to design a 0.52m length of pipe to stand vertically on the tunnel roof, as this would produce problems with connections for the air supply to the pipework. This problem was addressed by placing a bend in the pipework so that the section necessary for the orifice plate was placed horizontally. The inclusion of a bend in the pipework brought with it its own considerations. Bends which have a centre-line radius to pipe radius ratio of less than 0.8 incur serious flow separation, those with a ratio between 0.5 and 1.5 result in pressure losses in the region of 80%, Miller (1976). Minimum losses are incurred with a radius ratio of about 3, but the minimum that could be achieved with the engineering equipment available, was a bend with radius ratio of 4. This is the bend radius that was placed in the pipework. The pressure gradient in the pipe is severely affected by the bend and a straight length of up to 30D is required, downstream of the bend, for the flow to re-establish a steady state pressure gradient. However, the pressure gradient is adequately settled after only 12D. Thus, a 12D section was placed after the pipe bend. This is the section that led into the 6.25:1 area ratio contraction. The contraction was embedded in a Perspex disc which was fitted to the roof of the tunnel, such that the jet issued into the tunnel at a right angle to the mean flow direction.
During the preliminary experimental stage, it was found that the orifice plate flow-meter did not respond adequately as it was susceptible to fouling by the deposition of the smoke oil. The meter was removed from the pipe but the same basic configuration remained.

3.2.1.3 Pressure measurement equipment

The freestream velocity of the tunnel was measured with a conventional pitot-static tube to allow calibration of the hot-wire apparatus and to monitor the tunnel freestream velocity during the set-up stage of the experiments. The pitot-static tube was connected by 'flexitube' to a micromanometer placed outside the tunnel. The micromanometer (Picture 2) was a dial type and allowed measurements to an accuracy of ± 0.00125mm WG. Pressure measurement devices of the sort used here are not appropriate for measuring the rapidly fluctuating pressures associated with a turbulent flow. However, it has been shown that the freestream turbulence of the wind tunnel was less than 1%, and as such, the pitot-static tube was deemed adequate for measuring the mean pressures of the tunnel crossflow. The work of Keffer & Baines (1963), has shown that, at its exit, the velocity profile of a jet is essentially uniform and of low turbulence intensity. Therefore, the simple pitot-static tube could also be used for pressure measurements of the velocity at the jet exit.

3.2.2 Operating Environment

3.2.2.1 Commissioning of wind tunnel and jet apparatus

Ambient conditions within the smoke tunnel laboratory were strongly affected by the running of the tunnel itself. It was necessary to allow the fan to run at medium speed, to bring the laboratory conditions up to a steady state level, before starting any practical work. This warm-up time was usually between 1 and 2 hours.

It was necessary to set the jet exit velocity and the crossflow velocity prior to the acquisition of data by image processing or hot-wire anemometry. The exit pressure at the jet nozzle was strongly affected by the flow condition in the wind tunnel and, so the jet exit velocity was measured with the crossflow running. A pitot tube was placed at the centre of the jet exit.
nozzle at a distance, no greater than 5mm from the exit plane. This region is within the potential core of the jet which, with an exit velocity of 6m/s, is essentially unaffected by the surrounding crossflow, Keffer & Baines (1963). A pitot-static tube was placed in the flow at the same downstream location as the jet exit to measure the static pressure within the tunnel. The pitot static tube was used to measure the crossflow velocity within the tunnel freestream. The jet velocity was calculated by the difference between the total pressure at the jet exit and the static pressure in the tunnel measured with the pitot-static tube.

3.3 Hot-Wire Anemometry Equipment

The complexity of the hot-wire anemometry hardware and software used in the comparative study of the current project requires that its description is broken down into four main sections. The first of these will deal with the hot-wire apparatus and the equipment required to support it. The second section deals with the operating environment of the hot-wire equipment. It outlines the considerations and precautions which were required for accurate and efficient use of the hot-wire anemometry equipment. The calibration of the various components of the hot-wire anemometry system are dealt with in section three and the operational software used in data acquisition is detailed in section four.

3.3.1 Apparatus

The apparatus required to support the hot-wire anemometer consisted of three main components. These were; the PC-based analogue to digital converter card (ADC), used to convert hot-wire bridge voltages to numerical values, the traverse equipment, used to position the crossed hot-wire probe within the flow regime and the hot wire anemometer itself, along with its bridge balancing equipment.

3.3.1.1 Analogue Digital Converter

The analogue / digital converter used throughout the experimental programme, for both hot-wire anemometry and flow visualisation, was a PC-based PC30AT MULTIFUNCTION ANALOGUE AND DIGITAL I/O BOARD, supplied by Amplicon Liveline Limited. It
provided a 16-channel 12-bit analogue to digital converter as well as a 2-channel 12-bit Digital to analogue converter. In addition, a facility for 8-bit digital input/output along with on-board counter timers was included. The board was controlled through custom written software by direct memory addressing and by interrupt control.

3.3.1.2 Traverse Equipment

A diagram of the traverse equipment is shown below in Diagram 3.2. The traverse system was constructed with a 15V stepper motor, directly connected to a threaded stainless steel bar with thread pitch of 1.00mm. The stepper motor has rotational resolution of 400/360 steps per degree of rotation. The combination of threaded bar and stepper motor, therefore gave a minimum single displacement of the order of $2 \times 10^{-3}$ mm.

Diagram 3.2 - Hot-Wire Probe Traverse Equipment
3.3.1.3 Hot-wire apparatus

Constant temperature anemometry was used throughout the experimental programme. A schematic of the hot-wire apparatus used is shown overleaf in Diagram 3.3. For all hot-wire experimentation an overheat ratio of 0.8 was used, i.e.

\[
\frac{\text{hot resistance} - \text{ambient resistance}}{\text{ambient resistance}} = 0.8
\]
Diagram 3.3: Hot-Wire Apparatus and Configuration

- Amplifier
- Power Supply Board
- Ground
- Signal Amplifier
- Analog Voltage
- Digital I/O Port
- Clamp Stand
- Hot-Wire Holder
- Crossed Hot-Wire Probe + Holder
- Controller
- Stepper Motor
- Threaded Bar
- Crossed Hot-Wire Probe + Holder
- Disa 56601 CTA Unit
- +2 x 5616 CTA General Purpose Bridge
- +56100 CTA Standard Bridge
- 56105 Power Pack
- Disa 56801 Main Unit
register. This process was repeated until the whole image field had been read out to the diode of the differential amplifier.

During the image acquisition phase, the camera input pulses were held stationary whilst charge collection was carried out for a period of up to near 20ms. At the same time, the storage pulses were triggered at TV line rates clocking the image in the storage area, out to the readout registers. When the last line had been read out, the counter triggered the storage pulses to start downloading the image in the acquisition area to the storage area. This capability of the CCD to operate under image acquisition and image transfer simultaneously allowed the independent operation of the two processes. Though the image readout was carried out at TV rates of 50 non-interlaced fields per second, the image acquisition period could be set as low as 2ms. This reduced problems associated with blurring.

3.4.1.3.2 Image Acquisition

Whilst CCD cameras are digital devices, the readout registers converted the image to a TV image, which is essentially an analogue signal. Hence, the 385 x 288 pixel array recorded by the image sensor was displayed at the resolution and refresh rate of the device to which the image was sent. In the case of the current experimental programme, this was the image processing equipment that operated with an image array of 512 x 256 pixels in a non-interlaced mode at 50 images per second. The digital processing equipment used was capable of operating at 16 bits per pixel, offering 65536 grey levels. However, the signal to noise of the image sensor would render resolution of this scale meaningless. Furthermore, the current technique did not rely on high resolution of shading but rather on a single bit level, black or white image. The only requirement for good grey scale resolution was that the user could adequately identify the boundaries of a turbulent image. The human eye is capable of resolving only about forty shades of grey and thus, the equipment operating as an 8-bit digitiser offering 256 grey levels was adequate.
3.4.1.4 Light sheet apparatus

The discussion of the light sheet apparatus has been split into two sections. The first section deals with the apparatus used in the creation of the light sheet. The next section describes the configuration and procedures used with the hardware to create a high intensity light sheet that was synchronised with the image acquisition frequency of the camera.

3.4.1.4.1 Lighting Arrangement

A schematic of the arrangement for creating a light sheet is shown above, in Diagram 3.10. The main challenge to be met in creating the light sheet was that of creating a sheet of sufficient intensity so that the seeded flow could be well illuminated. The highest powered laser light source available for the project was a 50mW diode laser with a wavelength of 790nm producing a parallel elliptical beam of 1.5mm width and 3mm length. Beam splitting would have so greatly diffused the light intensity that it would not have been practical. The alternative method was to scan the light beam using an oscillating mirror.
To achieve a sharp, clear image it was necessary to scan the mirror through the field of view of the camera only once during the image acquisition. Any more sweeps would result in a double image on the CCD receptors. This was achieved by coupling the output of the camera, via an amplifier, to the input of the A/D converter on the PC30AT board, as well as to its normal destination of the VCR. The laser was directed at the mirror, which was mounted on a stepper motor, which was positioned so that the beam was reflected along a path out of the range of view of the camera. The custom written software continuously sampled the output from the camera, waiting for the severe voltage drop associated with the blanking pulse of the camera output. The end of this blank was used as the trigger for the mirror to start moving. This was controlled by the PC30AT card previously used for hot-wire anemometry. When the end of the blanking pulse was detected, signals were sent via the digital I/O port, to the stepper motor control box to turn the stepper motor through its sweep and stop it when the beam had passed through the camera viewing field. Again, the software waited for a blanking pulse before returning the mirror to its starting position in the same manner, and so completed one cycle during which two images were acquired. In this way the sweep of the laser was synchronised with the acquisition period of the camera. The details of this technique are presented in section following section.

3.4.1.4.2 Light Sheet Details

The difference between the voltage output from the camera during image transfer and that during a blanking period was in the region of 1.5V. This output was passed to an amplifier box with programmable gain and offset settings. The amplifier offset was programmed such that the digital conversion of the blanking voltage was zero and the gain of the amplifier was used to fully utilise the 0-10V conversion range of the ADC. The software routine continuously sampled and converted the camera output voltage at a rate of 12kHz and the resulting digital value was compared to zero. A timing diagram of the light sheet operation is shown in Diagram 3.11 on the following page.
Chapter 3 - Experimental Facilities

Camera Output Signal

Vertical Blank Period

Instantaneous Low Output Signals

End Of Vertical Blank Period

20ms Sustained Low Output Signals

Horizontal Blank Periods

Time

ADC Sampling

Diagram 3.11 - Timing Diagram of Light Sheet Mirror Operation
If the value returned by sampling was greater than zero, the routine continued to sample the voltage. If, however, the digital value was equal to zero, a blanking period was registered. Three subsequent samples were then inspected to decide if the blank was a horizontal blank associated with the end of one line of an image or a vertical blank associated with the end of an image field. A horizontal blank had a period of the order of $10\mu s$ and so at the current sampling rate, could not return more than one zero digital value. The vertical blank, however, had a period of about $1.5\text{ms}$, which corresponded to 180 digital samples and conversions. When a vertical blank was detected, sampling and conversion of the camera output continued until a large increase (1.5V) in the camera output voltage associated with image data transfer was registered. At this point the software routine wrote values to the output ports of the ADC to control the stepper motor movement. These output port voltages were 5V and could be set to two states, ‘on’ or ‘off’. Two output ports were written to. These were in turn wired to the clock input and the direction control of the stepper motor control box. The direction control voltage, was set either ‘on’ or ‘off’ depending on the sense in which the stepper motor was required to rotate, clockwise or anti-clockwise. The clock signal from the PC was used to move the stepper motor through its angle of rotation. For each switch of the signal going from ‘off’ to ‘on’, the stepper motor rotated by one step. Four hundred steps resulted in a 360-degree rotation. The switching operations of the motor and control box require a settling time and this restricted the rate at which the motor could turn. The time interval between each ‘off’ to ‘on’ transition controlled the motor speed. This interval included the time for the motor to move, settle, be switched from ‘on’ to ‘off’ and then settle again. Typically, this period was $800\mu\text{s}$ per step. It was essential that the motor be moved on as quickly as possible after each step so that the effect was that of a continuous sweep. This avoided any banding of the light caused by the reflected beam being at rest for significant periods of time.

For the experiments described here, the light sheet was created by moving the motor through 10 steps ($9^\circ$) per sweep in a period of 8 ms and the results showed an even sweep of well defined images.
3.4.2 Operating Environment

A ‘Perspex’ wall panel on the side of the tunnel provided optical access to the working section of the tunnel. This panel covered a region starting upstream of the jet down to 40 jet diameters downstream. The camera was positioned on a tripod 1m from the jet exit plane, perpendicular to the main flow direction. A lens for the camera was chosen such that the field of view encompassed a region of approximately 15 jet diameters square in the jet exit plane.

All ambient lighting was switched off and the optical path from the camera to the tunnel was enclosed in a wooden frame canopy, covered with blackout cloth. This was to ensure that the only light impinging on the camera, was that reflected or refracted from the laser sheet. The canopy was used to eliminate any light emitted from the PC screen and video display monitor and any associated electrical or electronic equipment. The efficiency of this method of elimination of background lighting effects was tested by recording the images from the camera with the seeded flow in place but without the laser sheet illumination. The resulting image showed no significant variation in the zero pixel intensity across the whole of the acquired image. Furthermore, all the internal walls of the working section were painted matt black to ensure that there were no reflective surfaces within the image recording area to eliminate errors caused by light reflection within the tunnel itself. Once again a test was carried out, this time with the laser sheet in operation but with no smoke delivered to the tunnel. The test sought to show that with no smoke in the tunnel the CCD camera sensed no significant illumination. This was indeed shown to be the case. On this basis, it could be affirmed that with the seeded jet being delivered into the crossflow, the only source of light impinging on the CCD receptors of the camera, was reflected and refracted from the laser sheet towards the camera by the smoke seeding particles.

3.4.3 Calibration

Prior to the acquisition of jet images for analysis, a calibration grid was placed in the X-Y plane of symmetry of the jet. This consisted simply of a grid of lines, at 5 diameter intervals, accurately drawn on a piece of rigid card. The origin of the grid was placed at the jet exit
nozzle. The image of the grid was then recorded to videotape, for use in the analysis process, to convert pixel-based locations or displacements to standard units of measurement.

3.4.4 Software

The software developed for the image processing techniques used in the current study is described fully in Chapter Five.

3.5 Summary

This chapter has detailed the experimental apparatus used within this project. It has discussed the procedures required to prepare the apparatus for use and the calculations carried out to ensure the adequacy of the hot-wire apparatus. The details of the software used for the hot-wire-anemometry experimental programme have been included, but because the structure tracking software used for this project was a novel development, its discussion is reserved until Chapter Five where it can be considered in the context of its application.

The next chapter details how the apparatus described in this chapter was used in the preliminary experimental programme associated with this project.
CHAPTER FOUR

4. PRELIMINARY MEASUREMENTS

4.1 INTRODUCTION

This chapter details the preliminary measurements that were undertaken in order to provide a context in which the development of the new image processing technique for tracking turbulent structures could be placed. Initial experiments were carried out to establish the validity of quantitative image processing techniques applied to flow visualisation images. This was followed by an experimental programme using conventional point measurement techniques to provide comparative data for the study with the structure tracking technique. The relatively new discipline of fractal analysis of turbulence was then employed to establish the capability of the current image processing equipment in resolving large-scale flow features within instantaneous flow visualisation images. The following chapter details the analysis techniques and results of each phase of the preliminary programme.

4.2 QUANTITATIVE FLOW VISUALISATION EXPERIMENTS

Preliminary measurements were made in which the overall penetration behaviour of a number of jet in crossflow configurations was studied using time-averaged image processing techniques. The motivation for these experiments was to study the viability of the use of image processing techniques to achieve quantitative results from flow visualisation images.

Time-averaged, full-field, jet path images were recorded and a thresholding technique was used to elicit the penetration behaviour of the jet. The case of a single jet was studied, along with a range of twin jet configurations at a variety of angles of orientation to the crossflow. Tests were carried out for a range of jet to crossflow velocity ratios and nozzle separations. Results were compared with those achieved by previous researchers, Bradbury (1981) and Pratte & Baines (1967) amongst others, using more conventional techniques. These comparisons with previous results allowed certain assumptions to be made concerning the characteristics of the smoke tunnel facility and the image processing equipment. These
characteristics were taken into account during the execution of the main body of the current work.

The preliminary study proved valuable in finding a suitable jet to crossflow velocity ratio that would produce a flow regime essentially unaffected by blockage effects, yet providing a degree of similitude in terms of jet path behaviour, so that well established empirical analysis could be applied.

The results of the preliminary study were valuable in their own right when considering the interaction between twin turbulent jets and a crossflow, Toy et al. (1993c). A summary of the apparatus and measurements associated with the preliminary investigation is presented here, along with the results and conclusions that were made concerning the penetration behaviour of single and multiple jets in a crossflow.

4.2.1 Apparatus

The wind tunnel and image processing apparatus used in the preliminary study was the same as that which has been described within the main body of this thesis. The only differences in the experimental apparatus used were the method of jet delivery and the illumination technique.

4.2.1.1 Jet Apparatus

The jet was created by a small centrifugal fan supplying a plenum chamber that contained two straight copper pipes, which produced the jets. A schematic diagram of the plenum is shown on the following page.
This configuration was mounted on the top of the smoke tunnel facility such that the jet exits were flush with the ceiling of the tunnel. The jet exit velocity was coarsely controlled by the speed of the centrifugal fan and fine adjustments and adjustable cones at the inlet to the jet.
exit pipes controlled jet balancing. Closing one of the outlet pipes of the plenum chamber created the single jet.

4.2.1.2 Light Sheet Apparatus

A constant 1kW halogen lamp was used, with a 10mm slit on the floor of the tunnel, to provide an illuminated volume of the flow. The time-averaged nature of the study being carried out meant it was not necessary to provide a synchronised light source to illuminate the seeded flow. The divergence of the halogen lamp resulted in the illuminated section being a volume of the order of 20mm thick, along the centre plane of the deflected jet, rather than a sheet. This did not create a problem in the analysis, as the work studied the region of maximum penetration of the jet, which on average, occurred along the centre plane.

4.2.2 Measurements

With both outlet pipes of the plenum chamber opened, two parallel jets were created, which issued at right angles into the crossflow. The orientation of the jets to the crossflow was adjusted by rotating the plenum chamber. Configurations of jet alignment axis to crossflow axis, angles of 0°, 30°, 45°, 60° and 90° were tested with jet to crossflow velocity ratios of 4, 6, 8 and 10 in each case. The study was extended by varying the separation between the jets for each velocity and angle. A set of measurements was taken with a single jet configuration to provide comparative data.

Flow visualisation images of the entire jet were recorded to video tape via a CCD (Charge Coupled Device) camera with a field of view encompassing the whole jet from its exit to a region about 40 jet diameters downstream of the jet exit. The video images were then played back through the image processing equipment, which used a pixel addition technique along with bit shifting to produce a result that represented the average light intensity of the field of view. In this technique, the image processing equipment was used to sum the full-field pixel intensities of 256 consecutive images of the seeded jet in real-time. The images summed were eight bit images with 256 grey scales. The resulting pixel intensity map was stored across two 8-bit frame buffers as a 16-bit image. A digital shift of eight bits was performed.
on this image, this being equivalent to a division by 256. The result therefore, was an average of the 256 images acquired during the sampling period. Previous work by other researchers, Toy & Wisby (1988) has shown that the presence of seeding represented the presence of the jet. As it was the seeding which reflected and refracted the light towards the camera, the illuminated regions of the flow could be taken to be regions at which the jet was present. A thresholding technique based on pixel intensities within the image was, developed to discriminate between the jet and any background lighting effects. As a result, the extent of the jet was clearly delineated. The stream wise location of this delineation was identified by an edge detection technique based on the gradient of pixel intensities within the image and an image scanning routine that produced the pixel co-ordinates of the edge.

4.2.3 Results and Discussion

Comparisons between the initial sections of the paths of the top edge of twin jet arrangements, with that of the single jet showed that the trajectory of the upstream jet is unaffected by the downstream jet until the point in the flow where the downstream jet issues into the crossflow (Figure 4.1). However, the upstream jet has the effect of sheltering the downstream jet as it issues into the crossflow. This is most apparent at the widest jet separation of 5D. The interaction between the two jets is very clear over the whole range of velocity ratios tested. The initial trajectory of the upstream jet can be seen to be identical to that of a single jet until it coincides with the downstream jet.

The flow of the downstream jet can be seen to penetrate through the upstream jet, resulting in a ‘kink’ in the profile of the top edge of the jet. The same effect is visible at a separation of 3D, but only at the higher velocity ratios of 6, 8, and 10. In all other cases, the profile of the combined jets looks similar to that of a single jet. Investigation of the power law relating penetration to downstream distance \( \frac{P}{DR} = a \left( \frac{X}{DR} \right)^b \), shows that the log-log gradient of penetration against downstream distance, is constant, only for a single jet or when separation is 1D and the orientation to the flow is 0° or 90°, i.e. in-line or parallel.
Within this constraint, the results compared well to those recorded by other researchers (See Table 4.1).

<table>
<thead>
<tr>
<th></th>
<th>( a )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Jet</td>
<td>1.441</td>
<td>0.393</td>
</tr>
<tr>
<td>In-Line (Separation=1D)</td>
<td>2.298</td>
<td>0.369</td>
</tr>
<tr>
<td>Side-by-Side (Separation =1D)</td>
<td>1.464</td>
<td>0.34</td>
</tr>
<tr>
<td>Abramovich (1963) (Centre-line)</td>
<td>0.87</td>
<td>0.33</td>
</tr>
<tr>
<td>Bradbury (1981) (Centre-line)</td>
<td>0.9</td>
<td>0.333</td>
</tr>
<tr>
<td>Pratte and Baines (1967) (Outer Edge)</td>
<td>2.63</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 4.1 - Comparison of Jet Parameter Values

The value for the scaling constant, \( a \), was generally larger than previously published, this was because other researchers had based their results on centre-line profiles and the current work was based on the outer edge profile. Pratte & Baines (1967) described their apparatus as having a much greater tunnel cross-section to jet area ratio than those used in the preliminary test, which would have resulted in a smaller blockage effect. This highlighted the fact that blockage effects may be a problem with future work, if high jet velocities were used.

The complete set of side-by-side jet results showed the greatest penetration occurring with a separation of 1D followed by the 5D separation then the 3D separation (Figure 4.2). These findings were in line with those of Toy and Savory (1991) and Kamotani and Greber (1972). The differences at a velocity ratio of 4 were so small, it could be stated that at low velocity ratios, the effect of jet separation has little effect on the overall penetration of the jets. At higher velocity ratios, however, the differences in penetration become quite significant, with increases in penetration of the order of 3D at about 20D downstream.

At a jet separation of 5D, varying the angle of incidence of the jets shows a maximum penetration occurs with the in-line case followed by the case with the jets aligned at 30° to the crossflow (Figure 4.3). Penetration profiles for the 45°, 90° and single jet cases are all very similar, with the 90° and single jet cases giving almost identical results, with a slightly
smaller penetration than the 45° case. The minimum penetration occurs with the jets aligned at 60° to the crossflow.

With a jet separation of 3D, maximum penetration again occurs with the in-line case, followed by the 30° case. The reduction in jet spacing results in a similarity in penetration profiles for all other alignments, such that it could be said that beyond 45°, the effect of varying the angle of incidence to the crossflow is minimal. However, these variations are not negligible as when the velocity ratio is increased, the scaling of the variations also increases. In general, the effect of varying the incidence angle at a jet separation of 3D is less marked than that at a separation of 5D. With a separation of 1D, there are clear differences in the penetration profiles for all jet alignments, with a decrease in penetration as the angle to the flow increases. This indicates behaviour similar to a slot jet in that, as the cross-sectional area presented to the flow increases, the bending effect of the crossflow also increases.

The similarities between the penetration profiles for each velocity ratio at all angles for a given nozzle spacing, indicate that the effect of increasing the velocity ratio is predominantly one of scaling (Figure 4.4).

The case of velocity ratio of 6 was further investigated to obtain information concerning the growth rate of the jet. Results show that a variation in jet alignment angle does not affect the rate at which the jet grows in the plane of symmetry (Figure 4.5). The jet width does vary according to the angle, but this is due to the initial spacing of the jets in the stream wise direction. The separation of the jets affects the growth rate of the jet, with the width increasing rapidly at a separation of 1D but less so at 3D and 5D (Figure 4.6).

With a constant alignment angle of 30° and a jet separation of 5D, the velocity ratio of the jets was varied to investigate the effect this had on the growth rate of the width of the jet (Figure 4.7). Results show that in the early stages of development the widths of the jets remained very similar, regardless of initial velocity. The divergence of the growth rate from this initial trend was dependent on the velocity ratio of the jets. The lower the velocity ratio, the earlier the divergence occurred. The implication of this is that the crossflow influences the jet development more significantly after an initial depth of penetration that increases as
velocity ratio is increased. Comparison with single jet data shows that width development is more rapid when twin jets are involved.

4.2.4 Conclusions

Maximum penetration of the jets occurred with the jets in-line, separated by 1D. This may be because the behaviour of the jets in this configuration is more like that of a single jet delivering twice the momentum of a single jet case, but with the same cross-sectional area presented to the crossflow.

Minimum penetration occurred with a separation of 5D at an angle of 60° to the crossflow. It has been found by Savory and Toy (1991) that when twin jets are separated by large spacing, there is little interaction between the two jets and their behaviour is similar to that of independent single jets. When the spacing between the jets decreases, the interaction between the two jets causes a decrease in their penetration. This has been observed by Savory and Toy (1991), Holdeman and Walker (1977) and Kamotani and Greber (1974). Kamotani and Greber also found that as the spacing between the jets becomes very small, the crossflow no longer passes between the jets and the inner vortices of the contra-rotating pairs do not develop, or do so only weakly. As a result, little or no interference takes place between the jets and their momentum is conserved, so the penetration of the combined jet is increased. It would seem that at a separation of 5D and alignment of 60°, the effective spacing of the jets is such that the upstream jet offers little or no protection from the crossflow to the downstream jet. Furthermore, the jet separation is such that the interaction between the jets is at a maximum so the overall penetration is at a minimum. The effect of varying the angle of the jets brings two factors into consideration. At smaller angles, the upstream jet shelters the downstream jet from the crossflow. This effect is decreased as the angle of alignment increases. The other effect of increasing the angle is to increase the effective spacing between the two jets and therefore vary the interference between them. The point at which the latter effect becomes more dominant is dependent on the actual spacing between the jets.
It is not possible to define equations to predict the trajectory for twin jet configurations based on the single jet in a crossflow equation. In most cases, there is not a constant log-log gradient relating penetration to downstream position.

When the jets are in-line and separated by more than 1D, the downstream jet has no effect on the upstream jet until the point at which the jets merge.

When the jets are separated by 1D, they behave in a similar manner to a single circular jet. However, a direct comparison cannot be made, since the overall penetration of the twin jets varies as their angle to the crossflow is altered.

This preliminary programme of tests, established the effectiveness of image processing techniques in eliciting quantitative results from flow visualisation images on a time-averaged basis. The progression from this was to study the feasibility of an image processing approach applied to instantaneous and time resolved flow visualisation images. Before advancing to this stage, it was necessary to obtain results concerning the flow regime under investigation, using established measurement techniques to provide comparative data for the new technique under development. To achieve this, a series of hot-wire anemometry tests was carried out within the flow regime of single jet in a crossflow.

4.3 Hot-Wire Measurements

This discussion about the current use of hot-wire anemometry begins by describing the details of the experimental procedure and data acquisition. It then goes on to describe the mathematical techniques used in the analysis of the data, including description of the application of the Tutu and Chevray (1975) method of correction for hot-wire anemometry measurements in turbulent flows. The discussion concludes with a description of the results achieved with hot-wire anemometry. Discussion of the relevance of these results is reserved till the Chapter Six where they are discussed in relation to the results of previous researchers and those achieved with the new image processing technique.
4.4.2.4 Additive Law

In the fractal analysis of turbulence, data are generally limited to that acquired from one or two dimensions only. Sreenivasan (1991) described the relationship between the dimension of a fractal object and the fractal dimension of a line or plane intersecting that object. Sreenivasan stated that, assuming that the intersecting line or plane is of a width less than the smallest scales of the turbulence and that the result is independent of orientation, the fractal dimension of a line should be 2 less than that of the original object and the fractal dimension of a plane should be 1 less than that of the original object. This ‘additive law’ allows comparisons of measured fractal dimensions from different intersections of an object to be compared. Results from special case studies of this relationship are cited by Sreenivasan (1991), such as Mandelbrot (1982) and Falconer (1984).

4.4.2.5 Implementation of box method

A large number of instantaneous images of a jet in a crossflow were captured for analysis with the new image processing technique under development. Prior to analysis with the new technique, an established method of fractal analysis was applied to these images to ascertain the range of turbulence length scales that could be visualised within an instantaneous image of the flow regime. To effect this, the image of the section of a jet in a crossflow was stored in a binary form with the threshold chosen so as to define the interface between the smoke seeded jet and the background ambient illumination level. An instantaneous image of a section of the shear layer of a jet in a crossflow is shown in Diagram 4.7. Binary reduction has been omitted to aid clarity.
An initially large grid of boxes was overlaid on the binary image and the number of boxes that contained an interface region was counted (Diagram 4.8).

This was achieved by software that read the intensity of a pixel at an arbitrary starting point within the box and then scanned through to find if all pixels within the box were of the same intensity. If this was not the case, it was concluded that the box encompassed a region containing both a seeded and a non-seeded region of the flow, and as such the box was said to contain an interface. The box size and number of boxes containing an interface were
recorded and stored. The grid resolution was then increased and the process repeated () until the resolution was such that each box was of side 2 pixels long.

The results were plotted in log-log form with the number of interface encompassing boxes against the box size. The overall image size was 512 x 256 pixels. If the fractal grid were required to fully encompass the image area without extending beyond the range of the image, it would have been necessary to use box sizes that were a factor of 256. Whilst this would have been the most accurate method, it would have resulted in sparse results as only 8 different box sizes could have been used. Instead, a range of box sizes of width between 2 and 250 pixels was chosen, with an aspect ratio of 2. The individual box sizes were selected such that a decrease in box width would result in a change of the number of boxes that would fit within the image field. Boxes which extended beyond the boundary of the image and contained a smoke / no-smoke interface were not counted as whole boxes, but as the fraction of the box which remained within the image field. This approximation allowed a greater number of data points to be used for analysis. A ‘best fit’ straight line was fitted to the data in the form, \( \log N(h) = d \log h \), where, the gradient of this line was the negative of the fractal dimension of the interface. The regions, where the gradient of the curve was constant, were considered to be the regions where the image could be said to be fractal in nature. The size range over which the image was a fractal, was taken to be the range of the size of the structures within the image, averaged in their X and Y directions.
The fractal analysis technique presented here, aimed to elicit quantitative information concerning the complete flow visualisation image. More specifically, the fractal analysis approach was designed to produce results concerning the range of structure sizes on the jet / crossflow interface, defined by the smoke / no-smoke boundary.

Whilst the result for an ideal fractal is a straight line, the gradient of which is the fractal dimension of the image, ideal fractals are theoretical models, which do not exist in nature. Even in the ideal case, a straight line fit can only be achieved if the box scaling coincides with the fractal dimension of the image. The current application of this technique provided a guide or indicator to the range of length scales that existed within the images.

The smoke / no-smoke interface of an image field within a seeded flow was treated as a line containing many discontinuities, these were the irregularities caused by the protuberance of a turbulent structure. As the resolution of the grid increased, the accuracy with which the boxes defined the edge was increased.

The relationship between the resolution and the number of boxes which encompassed a section of the smoke / no-smoke boundary tended towards being squared, when the box size was much larger than the scales within the image. This was because, with very coarse resolution, even a small section of the boundary within a box qualified the box to be counted, as did the slightest 'noise' component in the image. At such scales, the error of an extra box being counted, constituted a significant percentage error. As such, the fractal dimension returned when using a box size much larger than that of the largest irregularities in the boundary, tended towards 2.

In cases where the resolution was very high, i.e. the box size is smaller than the smallest irregularities within the boundary, the number of boxes that encompassed the interface, increased linearly with resolution, resulting in a fractal dimension of 1. The area of interest with the current technique was that which returned a constant fractal dimension between 1 and 2. In this region, the change in number of boxes encompassing the jet edge, as a result of a change in resolution, was a reflection of the number of structures within the image of the order of the box size.
4.4.3 Error associated with the fractal analysis technique

The current technique returned an approximate estimation of the length scales within the image. The reason the estimation was approximate, was that the pixels within the frame buffer had an aspect ratio of about 1.4. This restricted the scaling of the box size to a standard measurement. With the current technique, there was no accommodation for the direction in which the number of boxes increased, be it horizontally or vertically. The result was that the estimation of the size of structures within an image could have been in error by a factor of 1.4. For the current study, this error was acceptable as the technique was only required to estimate the range of the structure sizes within the images.

4.4.4 Results

The results of the fractal analysis technique are presented in Figure 4.34 to Figure 4.39. The results for each location are presented separately and based upon the average results of 40 images. There are two key points of interest within the data presented. The first of these is the slope of the log-log data of number of boxes against box size. The negative of the gradient of this slope is the value of the box-counting fractal dimension of the flow visualisation images. The second point of interest is the positions at which the data points diverge from the fractal dimension gradient. These positions indicate the limits of length scales within the images.

4.4.4.1 Box-Counting Dimensions

The gradient of the slope in all the cases presented in Figure 4.34 to Figure 4.39 are consistently around -1.3. The gradients at positions farther downstream than X/D=10 are closely centred on 1.32. This indicates a consistency of the fractal dimension within the images. There is therefore a similarity in the convolutions of the edge of the shear layer images at all downstream locations.
Chapter Four - Preliminary Measurements

4.4.4.2 Length Scales

The box sizes at which the data points diverge from the fractal dimension slope are similar for all cases presented. The lower limit of conformity between the fractal slope and the data points is of the order of 0.2D in all cases. This implies that the smallest scales that can be measured at all locations are constant. The upper limits of conformity vary slightly. There is a general increase in the box size, h, at the limits from h=1.5D in the X/D=10 case to h=2D in the X/D=35D case. This indicates a general increase with downstream position, in the size of the largest scales within the images.

4.5 Summary

The programme of work for the preliminary stages of the current project has been detailed. The initial investigations into jets in a crossflow using time-averaged image processing techniques have been described along with an analysis of the results achieved and insights gained. The work with hot-wire anemometry, to provide comparative data has been detailed, with a description of the results obtained. This provides an understanding of the flow characteristics of a jet in a crossflow. The theory and application of fractal analysis to the instantaneous flow visualisation images have been outlined and the results of this have shown the range of length scales discernible within the images.

The following chapter will concentrate specifically on the new image processing technique for the tracking of turbulent structures. The implementation of the technique will be described in detail and an overview of the results will be presented.
CHAPTER FIVE

5. THE STRUCTURE TRACKING TECHNIQUE

5.1 INTRODUCTION

This chapter will describe in detail the new image processing technique that has been developed for the investigation of the behaviour of coherent large-scale turbulent structures. The technique is based on the tracking of the movement of these structures as they pass through a field of view. This development of a technique for studying the behaviour of large scales of turbulence is the major contribution of this thesis. The new technique allows a study of coherent structures that is not subject to the restrictions of point-based, time-averaged analysis. The behaviour of turbulent structures can be inspected as they move downstream. The analysis is quantitative and yields information about the turbulence characteristics of the structures which has not been previously available.

This discussion of the techniques used in the tracking of large-scale turbulent structures has been subdivided into two sections. The first section details the implementation of the structure tracking technique including the methods used for the analysis of the flow visualisation images. The second section provides a description of the results achieved with the technique. Analysis of the results is reserved for the following chapter, so that where appropriate, they can be compared to the results of the hot-wire anemometry study.

5.2 IMPLEMENTATION OF THE STRUCTURE TRACKING TECHNIQUE

The implementation of the structure tracking technique is divided into several sections. The first of these concerns the tracking procedure. In this section, the method by which turbulent structures are identified and tracked is detailed. It is in effect, a description of the operation of the software that has been developed for this project. The limits of the structure tracking technique are outlined in the second section. The third section concerns the acquisition of the instantaneous flow visualisation images. It describes the range of structures selected for tracking, within the limits described in the previous section. The next three sections describe
the quantitative measurements that were made possible by the development of the structure tracking routine. These are the velocities of the structures, a turbulence characteristic of the structures and an estimation of their length scales. Following this is a discussion on the error margins inherent in the structure tracking technique, their effect on quantitative measurements, and the methods used to minimise or overcome them.

5.2.1 Tracking Procedure

The first stage of the tracking process was that of the image acquisition and storage. This was a user controlled and validated process. The videotape was played continuously through the image processing equipment and the user pressed a key to initiate the image acquisition routine that grabbed four consecutive images at 20ms intervals, such as those shown below.

![Diagram 5.1 - Four consecutive images of a turbulent structure at the edge of a jet in a crossflow (20MS intervals)](image)

These images were then replayed frame by frame for the user to identify a discrete turbulent structure to be tracked. Once a structure had been identified, the user employed a binary Look Up Table (LUT), which reduced the image area to a simple black or white display. The user set the threshold limit for this LUT by stepping up or down the threshold limit using the keyboard, to eliminate any noise interference with the image signal whilst maintaining fidelity with the jet image. Once the threshold limit had been identified, the image was reduced to its binary LUT values and the pixel co-ordinates of an area encompassing the structure to be tracked were entered and stored in a data file on the hard disk of the PC. The series of four images were then stored as an image file and a file compression routine was executed on the image file to save storage space on the PC. This was carried out for all forty of the image series before any structure tracking was carried out.
The image files and their associated data files were all named with consecutive numeric titles so that they could be accessed easily by a simple loop counting routine within the structure tracking software. The structure tracking software began by initialising the image processing equipment then decompressing the compressed image files and writing the stored images to the frame buffers of the image processing equipment. The actual tracking routine was then used to identify all four consecutive locations of the turbulent structure as it moved through the image field. This whole routine required no interaction other than for the user to pass to the machine the numeric title of the first and last files containing the compressed images. This allows the time consuming tracking process to be carried out overnight without any supervision. The resulting data was written to an output file that contained the pixel co-ordinates of the centroids of the turbulent structure. This data was then imported to a spreadsheet package where it was compared with the calibration grid information, and actual positions and sizes were calculated and stored for analysis.

The principle behind the structure tracking technique was that of shape recognition. However, in the current application, the problems associated with such a technique were compounded by the fact that the shapes to be tracked did not remain constant in terms of size and shape. The routine began with the acquisition of four consecutive images at 20ms intervals, from a plane section of the flow within the shear layer of the JICF. All four images were displayed for the user to identify the distinct turbulent structure to be tracked. During the development of the current technique, a machine-automated process for structure identification was created. This process relied on the comparison of the acquired image to a series of primary shapes to identify a distinct, trackable structure. However, it was found that such a technique was very time-consuming. The location of a suitable structure took up to 5 minutes of processing time to identify. The same could be achieved almost immediately by eye. Therefore, the machine-automated routine was rejected as an appropriate solution for the analysis of the images.

Once the first instance of the structure had been identified and located, the co-ordinates of an area encompassing the structure were passed to the PC. To assist in the location of the structure, the raw image of the edge of the JICF was overlaid with a coarse grid with a pitch of 32 pixels (See Diagram 5.2 and Diagram 5.3).
Diagram 5.2 - Raw image of shear layer of a jet in a crossflow (pseudo-coloured)

Diagram 5.3 - Coarse grid overlay on raw image of shear layer of a jet in a crossflow (pseudo-coloured)
The pixel intensities of the selected area were written to the PC memory and stored as the primary image. The routine then searched a near region of the second image to find the location at which a shape with the closest resemblance to the primary image could be identified. If there was some foreknowledge of the approximate location of the structure, this information could be used to restrict the search region and therefore increase the processing speed. When the second instance of the structure had been located, a pixel map of the surrounding area was written to the PC memory and this was used for searching for the same structure in the third image. This process was repeated until the location of the structure was identified in all four of the consecutive images. A pixel counting routine was then carried out on the areas identified as containing the structure and, from this, the centroid of the structure could be calculated along with the structure height and width. Although the shape and size of a turbulent structure varied between the first and fourth images, the routine was able to track it, as long as individual changes between any two consecutive images were not too great.

The method of image recognition operated by reducing the jet images to a binary format of black and white which defined the boundary between the seeded and non-seeded flow. The routine then effectively overlaid the section containing the primary structure onto a series of locations within the secondary image, finding the extent of mutual overlap between the two sections. The position of greatest overlap was identified as the location of the secondary structure.

To begin with, the separation between the search areas in the secondary image was very coarse, with a grid of 8 x 8 search regions separated by 32 pixels, centred on the location of the original structure. The position at which the highest overlap correlation occurred with this grid was used as the centre for a search with a more refined grid, still of 8 x 8 locations. However, this time the resolution of the grid had been doubled, with a positional separation of 16 pixels, the process was iterative, with the final grid searching through locations separated by only 1 pixel. This technique provided a high-resolution scan of the search area without the need for high-resolution searches in those areas that could be dismissed by a cursory search.
Refined techniques were developed for image matching. In the first of these, the images were not binarised and the differences between the pixel intensities were interrogated, however, in practice, this technique did not yield any great advantage. The number of 'mistracked' images, where the results were divergent, was comparable with the binarisation method and the processing time was greatly increased. The second most effective refinement, in terms of minimisation of 'mistracked' images, occurred with a technique that looked at the fluctuation in the difference between the pixel intensities of two unenhanced images. This technique allowed for the change of pixel intensities within an image due to expansion or lighting anomalies. However, the processing overhead required to accommodate this, far outweighed the slight advantage gained in tracking fidelity.

All things considered, the favoured technique was that of binary reduction of the image, used with a threshold of image correlation that allowed images to be matched with a high degree of confidence. Typically, deformation of the structures was such that, with any two matched structures, 85-95% of pixels within a structure image were found to overlap with its partner.

Once the location of the structure in all four images had been identified, its centroid was ascertained by a routine that counted bright pixels within the area of interest. For a final qualitative assessment of the image tracking efficiency, an edge detection routine was used to draw the outlines of the structure at all four locations onto a display frame buffer where they could be superimposed and the development of the structure could be seen (Diagram 5.4).

**Diagram 5.4 - Enlarged Reconstruction of Outlines of the Structure in Diagram 5.1**

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The programming code relevant to the structure identification and location, and a flow chart of the execution of the complete structure tracking routine are included in Appendix C.

5.2.2 Limits of the technique

The structure tracking routine described here was limited with regard to the size of structures that it could track. The upper limit of structure size was dictated by the field of view of the image processing equipment and this could be adjusted by careful experimental procedure. The lower limit however, was dependent on the out-of-plane velocity of the structures being tracked and this is a result of the flow regime under investigation.

5.2.2.1 High size limit of trackable structures

A rather obvious requirement of the structure tracking technique is that any structure that is being tracked needs to remain fully within the image field through all four image acquisitions. During the experimental stage of the current project, video footage was acquired, typically, using a field of view of 15D square in the XY plane of the jet. This related to an area of 195mm x 195mm. A reasonable assumption was that the turbulent structures within the edge of the jet were convected at a rate near the crossflow velocity of 1m/s. With a sampling interval of 20ms, a typical structure would have moved 20mm in the period between image acquisitions resulting in an overall horizontal displacement of 60mm between the acquisition of the first and the last images. Therefore, for a structure to be wholly visible through all four image acquisitions, its width must be no greater than 195mm - 60mm = 135 mm or 10.4D (See Diagram 5.5). This maximum size was based on a structure first appearing at one edge of the limit of the image field and then moving to the opposite edge during the acquisition period.
5.2.2.2 Low size limit of trackable structures

To find the lower limit of the structure technique, a turbulent structure was approximated by a spherical shape of radius $r_0$, as shown below.
Areas A₀ and A₁ within the diagram above, are those illuminated by two consecutive light sheets separated by an interval of 20ms. The out-of-plane displacement during this interval is dZ. During the developmental stage of this project, it was found that efficient tracking occurred with structure area overlaps of 85% and above. So it could be assumed, that a structure could be tracked if the out-of-plane displacement was such that the area ratio a₁/a₀ is 0.85 or greater, i.e. \( \pi r₁^2/\pi r₀^2 \geq 0.85 \) and at the limit, \( \pi r₁^2/\pi r₀^2 = 0.85 \). Thus \( r₁^2 = 0.85 r₀^2 \)

Geometrically, it can be seen that: \( -dZ^2 + r₁^2 = r₀^2 \)
and so: \( -dZ^2 = 0.15 r₀^2 \)

Therefore, at the limit for efficient tracking, the maximum tolerable out of plane movement of a structure, dZ, was, dZ = 0.39 r₀

Another assumption to be made in this analysis was that of the average out-of-plane velocity of the structures. Work by previous researchers, Toy et al. (1993a), Andreopoulos and Rodi (1984), indicated that near to the centre plane of the jet, the mean horizontal component of velocity in the Y-Z plane is in the region of 20% of the freestream velocity. This compares well with the hot-wire anemometry results associated with this project which indicate a stream wise turbulence intensity of around 20%. Assuming the turbulence within the structures is isotropic, a reasonable estimation of the out-of-plane fluctuation in velocity, was in the region of 0.2 m/s when the crossflow velocity was 1 m/s. Furthermore, during development, the structure tracking routine had indicated that the average vertical velocity of structures in the X-Y plane was also about 0.2 m/s. Based on this supporting evidence an approximation of the out-of-plane velocity of the turbulent structures being tracked was 0.2 m/s.

Using this assumption of the out-of-plane velocity of the structures, it was possible to calculate a minimum size of structure, which could be tracked. Given that the interval between image acquisitions was 20ms, the out-of-plane displacement, dZ, of a structure would be in the region of 4mm or 0.31D. The limit of dZ was 0.39 r₀, as shown above, and so the minimum value for r₀ was, r₀ = 4mm/0.39 = 10.3mm or 0.8 D. This established the lower size limit of the structures that could be tracked with the current technique.
5.2.3 Data Acquisition

The structures to be tracked were selected within a range from about 1D, the minimum size of structure that could be tracked with the current technique, up to the largest size of structures detected by HWA. The distribution of the sizes of structures to be tracked was selected to be similar to the distribution implied by the hot-wire anemometry technique, over the same range of length scales. Preliminary tests had shown that a sample of 40 structures was adequate for convergence of the structures' average velocity and turbulence characteristic and as such the study was carried out with this sample size at each downstream location. In practice a much larger sample was selected, with less attention paid to the size of the structures but rather more to their capability to be tracked by the current technique. A post-processing routine, described in Chapter Five, was carried out, to measure the length of each structure within the sample, so that appropriate structures could be selected to achieve the required distribution.

5.3 Measurement Techniques

5.3.1 Velocity and Turbulence Characteristic

Instantaneous structure velocities in the stream wise direction, \( u \), were calculated by, the displacement of the structure over the period between image acquisitions.

With reference to the schematic diagram of a convecting turbulent structure, shown in Diagram 5.7, instantaneous velocities, \( u \), were calculated by.
The reason for measuring displacement from non-consecutive structure locations is explained later in this chapter in the section on timing errors.

The four locations of the structure, \( x(t_1), y(t_1) \), were used to yield two structure velocity measurements. The two velocity measurements were then combined to produce an average velocity for the structure. The symbol, \( u \), is introduced at this stage, to denote an average velocity, local to an individual turbulent structure.

Thus

\[
\bar{u} = \frac{x(t_3) - x(t_1)}{2(t_3 - t_1)} + \frac{x(t_4) - x(t_2)}{2(t_4 - t_2)}
\]

As with conventional measurement techniques, the average velocity of a number of structures was calculated by the average of all the individual structure velocities.

Average Velocity, \( \bar{U} = \frac{1}{N} \sum_{n=1}^{n=N} u_n \)
Conventional turbulence intensity calculations are based on the quantification of the fluctuating component of velocity, where the instantaneous velocity is considered to be a combination of the average velocity plus the fluctuating component, i.e. \( u = \overline{U} + u' \). When considered over time, this allows the quantification of the fluctuating component, \( u' \), which, when normalised by the average velocity, yields the turbulence intensity, essentially the standard deviation of the data set.

A similar approach was used for the quantification of the turbulence characteristic of the tracked structures, such as those shown in the schematic diagram above.

The instantaneous velocities of the structures, \( u \), were used as a velocity data set for which a standard deviation, and therefore, a turbulence characteristic associated with the structures could be calculated.

\[
\text{Turbulence Intensity, } u' = \sqrt{u^2 - \overline{U}^2}
\]

Further consideration revealed that there were essentially two causes of the measured fluctuations in the velocity of the structures. The variation in the average velocities, \( \overline{U} \), of all the structures within the sample from the ensemble mean, was just one of the contributory factors in the turbulence characteristic calculation. To the author's knowledge, this is a previously unquantified value, and so the notation, \( \overline{u}' \), is used here to symbolise it.

Where

\[
\overline{u}' = \sqrt{(U - \overline{u})^2}
\]

The other contributory factor was the deviation of the two instantaneous velocity measurements from the calculated mean velocity of each structure. The instantaneous velocity of a structure comprised of the mean velocity and some fluctuating component. Again, this requires new notation to symbolise the fluctuation of a localised velocity from a localised mean. For this purpose the symbol, \( u^* \), is used.
Hence, the instantaneous velocity, $u$, of a structure is made up of the mean velocity of all structures, the deviation of the average velocity of the structure from the ensemble mean and the deviation of the instantaneous velocity of the structure from its local mean.

This is shown by;

$$ u = \overline{U} + \overline{u}' + u'^* $$

Where $\overline{u}'$, is the fluctuation of the local mean from the ensemble mean and $u'^*$ is the fluctuation of the instantaneous velocity from its own local mean.

Thus the overall turbulence characteristic is a combination of the fluctuation in average velocities of the ensemble of all structures and the local fluctuation in velocity of each individual structure.

The standard deviation, $\sigma$, of the complete data set is, $u'^* = \sqrt{u'^{2} - \overline{u}'^{2}}$

This allows $u'$ to be calculated as follows

$$ u'^* = \sqrt{u'^{2} - \overline{u}'^{2}} $$

Rearrangement gives:

$$ u'^{2} = \overline{u}'^{2} + u'^* $$

Therefore

$$ u'^{2} = \overline{u}'^{2} + 2u'^* \overline{u}' $$

Over a large data set

$$ \sum u'^{2} = \sum \overline{u}'^{2} + \sum u'^*^{2} + 2 \sum u'^* \overline{u}' $$

Because $u'$ and $\overline{u}'$ are fluctuations about a mean, in ensemble, they evaluate to zero and the result is

$$ \sum u'^{2} = \sum \overline{u}'^{2} + \sum (u'^*)^{2} $$

So on average

$$ \frac{\sum u'^{2}}{N} = \frac{\sum \overline{u}'^{2}}{N} + \frac{\sum (u'^*)^{2}}{N} $$

Therefore

$$ \overline{u}'^{2} = \overline{u}'^{2} + (u'^*)^{2} $$

And with standardised notation

$$ u'^* = \sqrt{u'^{2} - \overline{u}'^{2}} $$
The value of $u'$ can be calculated from the standard deviation of the local average velocities of the structures and the value of $u'$ can be calculated from the standard deviation of the instantaneous velocities of the structures in the conventional way. This allows the local deviations from the local average, $u^*$, to be quantified. Hence a new measure of the turbulent content of a flow has been developed.

5.3.2 Length Scale Estimation

The length scale estimation was carried out automatically by the software routine. The structure tracking technique identified the centroid of each turbulent structure under investigation. Once the location of a structure had been identified, its overall size could be established by a routine to count the number of 'bright' pixels within the image section. Length and width of the structure were estimated by a routine, which counted the number of pixels bound by the leading and trailing edges of the structure. The line at which the pixel counting took place was centred at the middle of the structure. The routine defined the edge of a structure as the location at which the pixel intensity started to be consistently zero. The routine searched along a line for a zero pixel intensity and when one was found, it interrogated the five pixels adjacent to this point, to ensure that the zero value was indeed the edge of the structure and not some anomaly arising from image ‘noise’ or inconsistency in the shape of the structure.

5.3.3 Errors associated with the structure tracking technique

One of the errors associated with the current structure tracking technique was essentially due to the light sheet creation method. By using a swept beam to create a sheet, not all parts of the field of view were illuminated at the same time. Treatment of a swept light sheet as an instantaneous full-field illumination method, would have led to a number of errors associated with the timing of the illumination pulses. This, in turn, would have led to errors in the calculated velocity of the structures within the illumination field. Another area of uncertainty existed in the accuracy of location of the centroids of the structures. The effects of these margins for error are discussed in the following sections along with the quantification of the errors and techniques for their minimisation.
5.3.3.1 Timing Errors

The nature of the light sheet creation technique resulted in the final image being a composite of a time averaged light beam. The light sheet illuminated different sections of the flow at different times, and this factor had to be taken into consideration when calculating the velocities of structures within the flow. Shown below, are diagrams of the position and timing of the laser as it sweeps through a plane to create a light sheet.

DIAGRAM 5.8 - SCANNING LASER POSITION AND STRUCTURE POSITION DURING FIRST OF FOUR CONSECUTIVE IMAGES SEPARATED BY 20MS
DIAGRAM 5.9 - SCANNING LASER POSITION AND STRUCTURE POSITION
DURING SECOND OF FOUR CONSECUTIVE IMAGES SEPARATED BY 20MS

DIAGRAM 5.10 - SCANNING LASER POSITION AND STRUCTURE POSITION
DURING THIRD OF FOUR CONSECUTIVE IMAGES SEPARATED BY 20MS
The sweep direction alternated from forwards to backwards with each image acquired. Thus the time interval between two consecutive illuminations of the same part of the flow was dependent on the position of the section, relative to the beam centre position. If a section of the flow was illuminated early in one sweep of the beam, it would naturally be illuminated late in the return sweep and the same is true for the converse. This could have introduced significant errors into the calculations of instantaneous velocities. Consider the structure displacement shown between the first and second images above. Without error correction, the velocity of the structure may be taken as the displacement of the structure between the two images, divided by the 20ms interval between sweeps. However on closer inspection, it can be seen that although the sweeps start 20ms apart, the time at which the sweep covers the area of interest is delayed according to the position of the structure. With sweeps in two alternate directions this time delay varied according to the direction of the sweeps and the position of the structure. The worst possible case would have occurred with areas of interest at the extremities of the image field.
A structure of typical size of 2.5 D (32.5mm) within the first image field (Diagram 5.8) is illuminated by a sweep in the direction opposing that of the flow, between about 4.8ms and 6.4ms after the start of the sweep. If the structure continues to travel at a velocity roughly equal to the crossflow velocity of 1m/s, it can be expected to have reached an area starting 20mm farther downstream by the time it is illuminated by the second sweep (Diagram 5.9). The time required for the second sweep, now travelling in the direction of the flow, to cover this region could be seen to be between 2.4ms and 4.0ms. Therefore, the actual interval between both measurements is nearer to (20ms + 2.4ms) - 6.4 ms = 16 ms, than the nominal period of 20 ms resulting in a significant error in timing of 25%.

Unfortunately, it was not possible to retrieve the direction of the sweep from the image data. However, even if this were possible the problem of error analysis is further compounded by the fact that the error margin depends on the position of the structures.

Under the same flow and sweep conditions as the latter case, an area which at x=20mm. is illuminated between 1.6 and 3.2 ms after the start of the sweep. On the second sweep, the area is covered between 4.0 and 5.6 ms after the start of the sweep. Thus, the time interval is in the region of 20ms + 5.6ms - 3.2ms = 22.4ms. Hence to apply corrections to the velocity data obtained from two consecutive images would require data concerning sweep direction and the position of the structure relative to the origin of the sweep, neither of which were available from the experiments conducted.

To obtain accurate instantaneous velocity data concerning individual structures, it was necessary to consider two alternate images, separated by 40ms, each with laser sweeps passing in the same direction. Under these conditions the error margin did not vary according to the structure position, as the starting position of the sweep was constant.

To perform error analysis on this technique, a structure in any position was considered. As before it is assumed that the structure has moved nominally 20mm in the interval between consecutive acquisitions. As the images under consideration were alternate images, the nominal displacement was 40mm and the nominal interval between images was 40ms. Either by calculation of the velocity of the sweep or by reference the diagrams above, it can be seen
that 40mm corresponds to about a 1.6 ms offset in the sweep time and so; the error in timing interval was about 4%.

This problem is exacerbated when it is considered that, with the calculated interval between images, the distance moved by the structure differs from the nominal 40mm, by the calculated percentage error in timing and, therefore, the structure is swept correspondingly earlier or later than initially estimated. The scale of this error in the timing interval is the velocity of the structure divided by the velocity of the sweep, which has been calculated to be about 4% of the first error calculation. Each adjustment in the timing correction requires an adjustment in the displacement, which again results in a change in the timing interval. However, this iterative process is shown below to be a continual addition of about 4% of the previous error correction.

The initial error estimation was based on a structure moving through the image field at 1m/s, the nominal period between sweeps is 40ms. During this time a structure would have moved 40mm. The speed of the laser sweep was calculated to be about 25m/s and if the laser sweep was in the same direction as that of the structure, the illumination of the structure in its second instance would have occurred after a period of the 40ms timing interval plus the time required by the laser sweep to cover the distance between the two structure locations, i.e.

\[
\text{Interval} = 0.04s + \frac{0.04m}{25\text{ms}^{-1}} = 0.0416
\]

So the initial estimate for the error in timing interval was 4.16%. However, this estimate was based on the displacement of the structure during the nominal timing interval of 40ms. It was now apparent that this interval was greater and as a result the structure would have moved further than initially assumed. The timing error on the second iteration was calculated using

\[
\text{Interval} = 0.04s + \frac{0.0416m}{25\text{ms}^{-1}} = 0.041664
\]

This relates to a 4.1664% error compared to the nominal values. It was clear that this
reassessment of the timing interval could have led to a further calculation to more accurately assess the error margin resulting from the assumption of a 40ms interval between image acquisitions. However, it was clear that the error margin diminished significantly with each iteration. The same analysis could have been applied to a structure moving in the opposite direction to the laser sweep and similar results would have been obtained. It was not possible to find the direction of the laser sweep, and so an error margin of 4%, was assumed for the timing interval between image acquisitions.

For each set of 4 images, two velocity results were obtained. These results could be combined to give an average velocity for individual structures or be considered en masse to calculate an average velocity for structures within a region of the flow. Whilst the velocity for a set of two images may have had an error of up to 4%, this margin was much less when the velocities were averaged either for a particular structure or an ensemble of all structures within a particular flow region. For velocities based on images acquired during a light sweep in the flow direction, the time interval was shown to be about 41.6ms, whereas with the sweep travelling in the opposite direction, the time interval was about 38.4ms. For each structure, one velocity was calculated during a forward sweep and one during a backward sweep. Whilst it was not possible to detect which velocity was calculated on which sweep, an average of the two results combined the overestimation of velocity on one sweep with the underestimation of the other. Thus when an interval of 40ms was assumed for the time between image acquisitions, the resulting error in the average velocity could be calculated to be:

\[
\frac{1}{38.4} + \frac{1}{41.6} - \frac{1}{40} = 0.00004 \text{ s}^{-1}
\]

With a mean flow velocity of 1m/s, this error in estimation of the time interval in a velocity calculation based on 40ms, resulted in an overall error of less than 0.1% in the velocity estimation. This degree of error was negligible under the current experimental conditions.
5.3.3.2 Accuracy of Structure Location

One further source of error in the tracking technique was the identification of the centroids of the turbulent structures. The difficulty lay in the identification of the turbulent structure, independent of its visualised connectivity to other adjacent structures. For the purposes of tracking the position of the structure, however, this was not a significant problem. Reference to the images below, shows that whilst there was significant distortion of the structure over the 60ms sampling period, there was little relative movement between the connectivity and the structure.

![Diagram 5.12 - Four consecutive images of a turbulent structure at the edge of a jet in a crossflow (20ms intervals)](image)

This allowed the structure and connectivity to be treated as one entity. As a result, the rate of convection of the structure could be assumed to be the same as that of the structure and connectivity combined. In cases where the deformation was significant, the tracking software could not recognise the flow structure in the second position and the routine returned the result of an 'untrackable' structure.

The location of a structure is measured as the centroid of the seeded region within the area encompassing the turbulent structure. This technique could not avoid enclosing some of the connectivity. As a result, all of the measured locations were, to some degree biased towards the direction of the connectivity. It is worth noting that in the worst possible case, where the connectivity section covered 25% of the enclosing box, the greatest error in calculation of the centroid of the structure was of the order of 8% of the structure length. In practice, any structure with such a high degree of connectivity was not selected for analysis and a realistic maximum for these errors was found to be in the region of 5%. Assuming an average
structure length of 2D (26mm) a typical maximum error would be in the region of 0.1D or 1.3mm. The implication of this is that there may be a rather large error margin in the measurement of the displacement between any two locations of a structure, which would result in an error in the calculation of the velocity of a structure. However, because the two elements move together, any error in the measurement of the absolute location of a structure in one instance, is repeated in the second. As such, the error in the measurement of the displacement of a structure is reduced considerably and is dependent on the minimal deformation of the object being tracked.

5.3.3.3 The Effect of Image Blur on Image Processing Techniques

The use of camera and image processing equipment will always lead to blur errors, caused by movement of the object during image acquisition. This can distort the perceived size of the image as the object in its starting and final positions is seen as single entity. In such a case, the blur ratio is defined as the maximum displacement of the object during image acquisition, divided by the true size of the image.

It should be noted that with the current technique, the result of the blur could be either to stretch or contract the image in the direction of the flow.

For the image processing experiments described in this thesis, it was necessary to quantify the value of this blur ratio, so that an assessment could be made concerning the fidelity of the recorded images. For conventional, constant light techniques, the blur ratio is dependent on the camera acquisition period and the velocity of the object in the field of view. The result is that all objects are blurred by the same length, defined by;

\[ \text{Blur} = (\text{Object Velocity}) \times (\text{Acquisition Period}) \]

This results in the blur ratio being dependent on the size of the object.

\[ \text{Blur ratio} = \frac{\text{Blur}}{\text{Object Size}} \]

\[ \text{Blur ratio} = \frac{(\text{Object Velocity}) \times (\text{Acquisition Period})}{\text{Object Size}} \]
In the experimental program described here, the light sheet was created by sweeping a laser line through the image field. When the laser line was absent, not enough light reached the CCD array of the camera to register an image. In such a case the acquisition period was the sweep period of the laser line. The blur length was dependent on the time required for the line to sweep an object.

\[
\text{Blur time} = \frac{\text{Object length}}{\text{Sweep Velocity}}
\]

\[
\therefore \quad \text{Blur} = \text{Object velocity} \times \text{Blur time}
\]

\[
\therefore \quad \text{Blur ratio} = \frac{\text{Blur}}{\text{Object Length}}
\]

\[
\therefore \quad \text{Blur ratio} = \frac{\text{Object velocity}}{\text{Sweep Velocity}}
\]

Thus the blur ratio was independent of object size and camera acquisition periods.

During the experimental program, the smallest length covered by a sweep was 3 jet diameters or 195mm. The complete image area was swept in 8ms. This resulted in a sweep velocity of 24.375m/s. The objects being measured were the turbulent structures in the shear layer of the jet, the velocities of which were, typically, of the order of 1 m/s. These conditions produced a maximum blur ratio of about 4.1% for the images acquired. The sweep was generated from what was essentially a point source, and so the sweep length varied with vertical displacement from the sweep centre. Thus, the blur ratio varied within the vertical axis of the image. Images were interrogated within a 10 jet diameter or 130mm range, starting 1.5m from the sweep centre. Thus, the length swept by the ‘far’ end of the sheet during the same period was equal to, \((0.195/1.5) \times 1.63 \text{ m} = 0.2119\text{m}\). Hence, the sweep velocity varied linearly from 24.375 m/s at the lowest point to 26.4875 m/s at the highest point. This resulted in an inverse relationship between the blur ratio and position from the sweep centre, with a 10% change in the ratio between the two extremes of the images.

Another factor to be taken into account was that, if the image moved during the sweep, the time required for the sweep to cover the image also changed according to the image velocity and so the process was iterative. This additional error was in effect a timing error and has been dealt with in the earlier section on timing errors, where it was shown that for the current situation, the timing error and therefore the blurring error for each progressive iteration was a
power of the previous iteration. The blur error of the second iteration was the original blur error squared and therefore total blur tended gradually towards a limit just above 4%. For the present case, the initial blur calculation was small enough to make further iterations unnecessary.

The blur effect applied equally throughout the image field, and as such had no effect on the location of the centroids of the turbulent structures, other than that already addressed in the section on timing errors. The blurring effect did, of course, influence the results of the fractal analysis technique. However, the approximate nature of the scaling of this technique, described in Chapter Four, made the 4% error caused by blurring negligible.

5.4 STRUCTURE TRACKING RESULTS

The structure tracking technique was concerned with the velocities of turbulent structures as they moved downstream. The statistics concerning these velocities were placed in context by consideration of their positions and their sizes. The following discussion details the results of tests carried out to measure the position, length scales and velocity characteristics of the turbulent structures in the shear layer of a jet in a crossflow.

5.4.1 Structure Positions

The general distributions of the centroids of the turbulent structures within the shear layer of the jet in a crossflow, are shown in Figure 5.1 to Figure 5.7. Figure 5.1 to Figure 5.6 show the location specific results, whilst Figure 5.7 shows the ensemble image of all the structures within a global image. It can be seen that the structure positions generally lie along the expected path of the outer edge of the jet.

5.4.2 Large-Scale Structure Comparisons

To allow valid comparisons between hot-wire anemometry and the current technique, a range of structures of a length comparable to those detected by hot-wire anemometry were selected for the tracking process. Comparative distributions for all measurement locations are shown
in Figure 5.16 to Figure 5.21. Towards the larger end of the scales, there were some cases in which structures of the appropriate size could not be found or the percentage of large-scale structures detected by hot-wire anemometry, were of such a low quantity that even tracking of a single structure of that scale might place an undue bias on the results. The distributions are, nevertheless, very closely matched. This implies that the range of structures chosen for tracking is a true reflection of the range of sizes of structures that exist in the measurement region, within the limits of the structure tracking technique. The effect of the length scale of the structures on the results is described in a later section.

5.4.3 Structure Velocities

Figure 5.8 to Figure 5.13 show the distribution of the stream wise and normal velocity components of individual structures at each measurement location. Overlaid on these distributions are lines indicating the average of both velocity components. It can be seen that, generally, the average stream wise velocity of the structures is very close to that of the freestream. However the variation in this velocity can be as much as 17% from the mean, with the most extreme cases occurring near the jet exit. The variation in the velocity of the structure, normal to the flow direction is also very evenly distributed with variations in velocity being of the same order as those in the stream wise direction. The individual velocities are evenly distributed within the limits with few anomalous measurements. A general trend can be seen in which the average normal velocity component can be seen to decrease with increasing downstream position, which is what may be expected as the jet is deflected towards the stream wise direction. There appears to be a transitional stage at the 25D location where the velocities in both directions are very closely packed before an increase in the variation of the stream wise velocity at locations farther downstream. From this point onwards the variation in the normal velocity component appears to remain fairly constant. The variation in velocities shown here are a reflection of the overall turbulence characteristic calculated at a later stage.

Figure 5.14 demonstrates that the number of structures tracked to elicit an average velocity measurement is adequate, in that the deviation from the mean, in the limit is of the order of 2%.
5.4.4 Turbulence Characteristic

The velocities measured by the image processing technique are not representative of the overall flow field, so it is not possible to extract a measure of turbulence intensity from the image processing velocity data set. Instead, an alternative measure, called the turbulence characteristic, is quantified. This is the RMS value of the velocity fluctuations of the large-scale structures. Again, as with the average velocity measurements, Figure 5.15 demonstrates that by tracking forty structures through four locations each, an adequate sample size for measuring the turbulence characteristic is achieved.

The calculated turbulence characteristic presented in Figure 5.15 is a reflection of the individual variations in velocity of the structures as well as the variation in velocity between discrete structures.

5.4.5 Effect of Length Scales on Results

Great care was taken to ensure that the data set chosen for analysis by the image processing technique, closely matched the results found by hot-wire anemometry. However, it becomes apparent from Figure 5.22 to Figure 5.33, that the size of the turbulent structure has little or no effect on the results produced by the current method. Figure 5.22 to Figure 5.27 show the variation in the average velocity of individual structures with their size. The only correlation between the two parameters can be seen in the X/D=10 case, where the correlation coefficient has been calculated to be just over 50%. The relevance of this result will be discussed in Chapter Six. In the general case, there is no indication that the size of the structure has any effect on its average velocity. The distribution of the structures seems uniform throughout the range of sizes and if a greater distribution of velocities can be seen at the smaller scales, this is a reflection of the number of samples chosen at each location rather than any fluid dynamic effect.

Figure 5.28 to Figure 5.33 show the fluctuations in the measured velocity in the stream wise direction of each individual structure. The change in velocity between the two measurements is represented as a turbulence characteristic as this is how the results of the ensembled
structures are presented. The values represented are in fact the normalised variation of the velocities from the mean for each structure. Once again, the distribution of the turbulence characteristic is so well spread, that no relationship between the size of a structure and its change in velocity can be implied.

5.5 SUMMARY

The methods used for the tracking of turbulent structures have been detailed. This included descriptions of the data acquisition and analysis techniques. A new measure of a turbulence characteristic has been introduced and the factors that affected this characteristic have been detailed.

The results achieved by the application of these analysis techniques have been introduced. However, the only analysis at this stage was to demonstrate the lack of dependence of the results on the length scale of the structures, in most areas of the flow under investigation.

The following chapter will provide a detailed analysis of these results. The hot-wire anemometry results relevant to the structure tracking work, will also be presented within the context of the current investigation. Insights into the flow behaviour and its effects will be proposed and the advantages of the new technique will be highlighted.
CHAPTER SIX

6. DISCUSSION OF RESULTS

6.1 INTRODUCTION

The aim of this chapter is to elaborate on the results presented in Chapters Four and Five. To begin, the validity of the hot-wire anemometry measurements is established by comparison with the results of previous research. Following this, where possible, comparisons are made between the results of the hot-wire anemometry study and those of the new structure tracking technique. These comparisons demonstrate that the flow regime under investigation was the same for both studies. Examples of results which differ, are used to highlight the different natures of the point based hot-wire anemometry technique and the global structure tracking technique. Finally, a series of measurements that are possible only with the new structure tracking technique are presented, along with insights into the behaviour of a jet in a crossflow, which the structure tracking results have made apparent.

6.2 HOT-WIRE ANEMOMETRY AND ESTABLISHED RESULTS

6.2.1 Measurement Location

The hot-wire results for turbulence intermittency can be seen to have undergone severe change at locations farthest from the jet floor plane (Figure 4.17). These results identified this region as the outer shear layer of the jet, as the intermittency could be seen to drop from the approximately 100%, (generally more than 90%) value expected within the main body of the jet to approximately 0% in the freestream. Further evidence to support this statement could be found in the results for the skewness and kurtosis of the velocity distribution in the same region (Figure 4.14 and Figure 4.15). These results showed a high deviation from a Gaussian flow distribution, as might be expected within the main body of the jet or within the freestream. The cause of this deviation was due to the fact that in the shear layer region, the probe was placed in a flow that fluctuated between the nominally non-turbulent (irrotational) freestream and turbulent regions of the jet. Statistical analysis of the time-history in that
region was the equivalent of trying to produce a sensible outcome by a combination of results from two completely different flow regimes.

6.2.2 Jet Trajectories

The extent of penetration of the JICF is clearly defined by the intermittency results presented in Figure 4.17. As stated above, the region in which the turbulent intermittency dropped from 90% to zero was identified as the shear layer region. The outer limit of this shear layer region could, therefore, be seen to be the outer limit of the deflected jet. The penetration of the jet at each measurement location within the X-Y plane of the jet was recorded and the data set of X and Y co-ordinates defining this outer edge were fitted to the jet path equation:

\[
\frac{P}{DR} = a \left( \frac{X}{DR} \right)^b
\]

Keffer & Baines (1963), Pratte & Baines (1967)

The co-ordinates of the points in this curve fit were used to calculate values for the parameters a and b. These parameters were used to construct a curve defining the theoretical extent of the deflected jet. Comparative trajectories of the current results and those of Pratte & Baines (1967) are shown in Figure 6.1. It is immediately clear that the penetration described by the Pratte & Baines (1967) parameters was greater than that defined by the parameters of the current experimental techniques. The experimental technique of Pratte & Baines delivered the jet into the crossflow, through a plate mounted 8" (20.32mm) above the floor of the tunnel. This minimised the effect of the boundary layer on the trajectory of the jet; therefore, the penetration of the jet was expected to be less when compared with the current results, because of the increased momentum acting on the jet. However, Pratte & Baines used a variety of jet diameters in their experiments, the largest of which was 0.362"(9.2mm). With tunnel dimensions of 47"(1.19m) high x 96" (2.44m) wide, the area ratio of the tunnel cross-section to the jet at exit was in the region of 43,000. With the current experiments, this area ratio was just 3526, therefore the blockage effect of the jet was significantly greater in the current work, which may explain the differences between the results.
Chapter Six - Discussion of Results

Other researchers, Abramovich (1963), Bradbury (1981) and Smith & Mungal (1998) have also carried out investigations to define the parameters of the jet path equation. Their work involved the description of the centre-line of the deflected jet. Their results have been compared with the current centre-line profiles, defined by the points of maximum turbulence intensity, in Figure 6.2. The centre-line profiles of Pratte & Baines (1967) are also included in these comparisons. This places the Pratte and Baines (1967) result in context. It would seem that their results for jet trajectories are high, compared with the greater body of work. The variability of experimental conditions in terms of boundary layer height and jet to tunnel area ratios is such that it is not surprising that there is a range of experimental results for the jet trajectory. However, the current centre-line trajectory agrees very well with that of Smith & Mungal (1998), who used jet to tunnel cross-sectional area ratios from 3712 to 34,093.

6.2.3 Velocity Measurements

6.2.3.1 Stream wise Velocity components

The u-component velocity profiles produced by hot-wire anemometry (Figure 4.11) only show significant data concerning the deflected jet in a region up to about X/D=20. Beyond this point the jet velocity, was dominated by the crossflow within the tunnel. This corresponds with the findings of Pratte & Baines (1967) in which the jet was described as containing two separate regions, the ‘zone of maximum deflection’ and the ‘vortex zone’. The ‘vortex zone’ was defined by Pratte & Baines as beginning at a point where the non-dimensionalised displacement along the jet axis, \( \xi/(DR) = 5 \), this is equivalent to \( X/(DR) = 3.2 \). With a jet to crossflow velocity ratio, \( R \), of 6, as used in the current experiments, this relates to a position of \( X/D = 19.2 \). The results of HWA within the current work are in keeping with that of Pratte & Baines, who observed that from this point forward, there was no relative longitudinal motion between the jet and the crossflow. In the vortex zone, jet velocity was essentially the same as that of the crossflow, implying that its initial nozzle velocity no longer drove the momentum of the jet.

 Throughout all downstream locations, the velocity in the shear layer was indistinguishable from that of the crossflow.
6.2.3.2 Normal velocity components

The v-component velocity profiles shown in Figure 4.12, measured by HWA, show a significant variation from zero within the main body of the jet at all downstream locations. However in the shear layer, the v-component velocity was significantly high, only in the X=5D to X=15D locations. This region was the 'zone of maximum' deflection, as defined by Pratte & Baines (1967). It started at the end of the initial region of the jet, where the jet was essentially unaffected by the crossflow, and extended to the start of the vortex zone, mentioned above. The intermittency of the shear layer region meant that the average value of the v-component velocities measured there, was based on averages within the jet and the crossflow, which had a zero v-component velocity. As such, the v-component velocities were not a true reflection of the velocities within the jet. Only in the regions where the v-component velocity of the jet was significantly higher than zero, would their effect have been noticeable. This is why it was only in the zone of maximum deflection where v-component velocities in the jet were detectable.

6.2.4 Turbulence Intensity and Higher Order Moments

Profiles of the higher order moments, which describe the velocity distribution of the u-velocity component with the jet in a crossflow, are presented in Figure 4.14 and Figure 4.15. It can be seen that within the main body of the jet, the results indicate that the distribution of u-component velocity variations was essentially Gaussian (skewness was near zero and kurtosis was 3). The skewness and kurtosis of the velocity distribution in the shear layer of the jet were clearly, far from Gaussian. A Gaussian distribution was one of the criteria required for the valid application of the Tutu and Chevray (1975) technique for corrections in high intensity turbulence. The turbulence intensity in the shear layer region can be seen to be very low, of the order of 5% (Figure 4.13). Thus, the Tutu & Chevray correction factor for results in regions of such low turbulence intensity was minimal. Turbulence intensities in the X/D=5 region were very high, approaching 50% in some cases. The degree of error involved in correcting such a highly turbulent region was so great that the results here are essentially qualitative. The criteria of a Gaussian velocity distribution was met in all regions of high
turbulence intensity and the effect of applying corrections to the ‘non-Gaussian’ regions was minimal, therefore correction could be applied to all the measurements within the jet.

6.2.5 Reynolds’ Stresses

The result for Reynolds’ stresses, which are indications of vorticity, measured within the jet are presented in Figure 4.16. They show that the vortex strength within the main body of the jet was diminished as the jet moved downstream. This was to be expected as the vortices were expanding as they moved downstream. The region of interest in the current study was particularly the shear layer of the jet. Here, there were no strong indicators of vorticity, which might have been expected to be associated with the turbulent structures in the shear layer. The reasons for this was that the ring vorticity associated with the upstream side of the jet in its initial region had interacted with the ring vorticity on the underside of the jet and collapsed, as observed by Kelso et al. (1996). Furthermore, by the time the turbulent structures reached a position 5-10D downstream, they had expanded to such an extent that any vorticity had been diminished. Finally, the intermittency of the flow in the shear layer region was such that the time averaging of the results attenuated any vortex signal, which may have been detected.

6.2.6 Conclusions of Hot-Wire Anemometry Study

The mean trajectory of the jet has been fitted to the empirical jet path equation of Pratte & Baines (1967) and the parameters produced, show good agreement with previous researchers. The trajectory of the current jet lies below the higher limit described by Pratte & Baines (1967) and above the lower limits shown by Abramovich (1963) and Bradbury (1981). The trajectory of the current jet compared well to that of Smith & Mungal (1998).

The mean u-component and v-component velocity measurements have shown the ‘zone of maximum deflection’ and the ‘vortex zone’ described by Pratte & Baines (1967). The transition between the two regions occurred near X/D=20, which was where Pratte & Baines identified it.
Chapter Six - Discussion of Results

The turbulence intensity, skewness and kurtosis indicated that, the distribution of flow velocities was such that the Tutu and Chevray (1975) correction for velocities, turbulence intensities and Reynolds stresses', could reasonably be applied. The reservation was that one of the criteria required by the Tutu and Chevray technique is that the mean v-component of velocity is zero. This was not the case in the current flow regime, however, the assumption was that the application of this correction method, went some way towards mitigating the errors associated with hot-wire anemometry in high turbulence regions.

Reynolds' stresses in the shear layer do not indicate any strong vorticity. The implication of this, is that the ring vortices that exist in the near-exit regions of the jet have collapsed, as observed by Kelso et al. (1996)

The degree of conformity between the results of other researchers and the HWA results presented in this thesis supports the validity of the hot-wire work and allows the comparison of results from the image processing techniques and HWA

### 6.3 Fractal Analysis Results

#### 6.3.1 Fractal Analysis + HWA results

<table>
<thead>
<tr>
<th>X/D</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
<th>-1 x Gradient (Fractal Dimension, d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.5D</td>
<td>0.2D</td>
<td>1.27</td>
</tr>
<tr>
<td>15</td>
<td>1.5D</td>
<td>0.2D</td>
<td>1.34</td>
</tr>
<tr>
<td>20</td>
<td>1.5D</td>
<td>0.2D</td>
<td>1.34</td>
</tr>
<tr>
<td>25</td>
<td>2D</td>
<td>0.2D</td>
<td>1.34</td>
</tr>
<tr>
<td>30</td>
<td>2D</td>
<td>0.2D</td>
<td>1.35</td>
</tr>
<tr>
<td>35</td>
<td>2D</td>
<td>0.2D</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table 6.1 - Ensemble Averaged Results of Fractal Analysis of Instantaneous Flow Visualisation Images
Chapter Six - Discussion of Results

A summary of the results concerning the upper and lower limits of conformity between the fractal analysis data and the slope of the general trends (shown in Figure 4.34 to Figure 4.39), are presented in Table 6.1. The gradient of the general trend is an indicator of the degree of irregularity of the jet edge. The results are based on averages from forty images and so do not represent the size of structures found in any one image.

When the grid resolution had reached such a size that the box size was smaller than the smallest irregularities within the image, halving the size of the box resulted in doubling the number of boxes that encompassed the jet edge. This produced a fractal dimension of 1, as the box-dimension, \( d \), was defined by \( N(h) = A(1/h)^d \), where, \( A \) was a constant, \( h \), was the box size and \( N(h) \) was the number of boxes of size, \( h \), which encompassed an edge section.

If the box size was larger than the smallest irregularities, a decrease in box size allowed the edge to be better approximated with boxes and the relationship between size and the number of boxes encompassing the edge was no longer linear. Based on this analysis, the region of the log-log graphs (Figure 4.34 to Figure 4.39) where the decrease in box size tends away from the main trend towards a gradient of 1 identifies the approximate size of the smallest irregularities or turbulent structures within the jet edge. In all cases presented, this limit occurs around a box size of 0.2D. Whilst the pixel resolution of the image processing equipment varied by downstream location, it was generally of the order of 35 pixels per jet diameter or 0.371mm/pixel. As such, the lower limit of conformity between the general trend and the data of 0.2D relates to about 7 pixels. It is clear that this lower limit was not a result of the resolution of the imaging equipment, but truly a reflection of the smallest size of length scales within the image. When compared with the hot-wire results for Kolmogorov length scales in the same region (Figure 4.32) it can be seen that the 0.2D limit is greater than the Kolmogorov length scales, which reached a maximum of 0.05D. Thus, it could be stated that flow seeding in this region did not distinguish structures of that scale within the region under investigation. The low limit of the fractal analysis indicates that the smallest size of turbulent structure identifiable within the smoke / no-smoke interface of the seeded jet in a crossflow, was of the order 0.2D.
Chapter Six - Discussion of Results

In cases where the box size was larger than the largest irregularities of the interface, it was expected that the fractal dimension would also be 1. However, in practice, the effect of any image noise within the field of view tended to force this dimension towards 2. This was because a halving of the boxes resulted in four times the number of boxes that encompassed some edge, be it noise or the jet. The fact that the smoke / no-smoke interface crossed the coarse boundaries of large boxes, further forced the fractal dimension towards 2.

The general trend of the relationship between box size and number of boxes is indicative of a range of scales over which there was a similarity. This is analogous with the energy cascade which can be identified with hot-wire anemometry (Figure 4.18 to Figure 4.31). Any deviation from this general trend at the larger scales indicates that the box size was greater than the size of the irregularity within the image. At the larger scales, the interval between changes in resolution increased and so the accuracy of the point at which divergence from the trend occurs, is diminished. Nevertheless, as the current technique sought only to provide an approximate estimate of the range of scales with an image field, the results are still valid.

The data presented show that there was a general increase in the size of the large turbulent structures at the jet edge it moved downstream. This was supported by the increase in the width of range of the length scales detected by the hot-wire anemometry technique (Figure 5.16 to Figure 5.21) Whilst the largest scales detected by the fractal analysis technique might not seem to reflect the larger scale structures (3D and above), it must be remembered that the current technique has an inherent factor of accuracy of 1.4 as this was the aspect ratio of the pixels. Furthermore, the current results are based on the average of 40 images and, to some degree, on the average size of structures within any one image. Within this degree of variation, the current results are a valid estimate of structure sizes within the jet edge, especially when compared with some hot-wire approaches such as measurement of integral length scale (Figure 4.33), the largest scale which can be measured by conventional statistical analysis. These hot-wire anemometry results return a length scale of the order of 1D in the shear layer region, when it could clearly be seen from flow visualisation that much larger structures existed.
Chapter Six - Discussion of Results

The range of structure sizes indicated by the fractal analysis method cannot be directly compared with those from hot-wire anemometry. The energy spectra shown in Figure 4.18 to Figure 4.31 are in terms of frequency, whilst the fractal analysis technique yields a length scale. To facilitate comparisons, length scales are converted to a frequency scale with a simple approximation of $U = f\lambda$, where, $\lambda$, is the length scale of the turbulent structures. In so doing, the length scale range for which the relationship $N(h/D) = (h/D)^d$ is valid, can be interpreted in terms of frequency. The upper limit of $2D$ is equal to 26mm, at a mean velocity of 1m/s, this approximates to a frequency of 35HZ. The lower limit of $0.2D$ (2.6mm) approximates to a frequency of 385 Hz. These limits, when compared to the frequency spectra in Figure 4.18 to Figure 4.31, place the structures in the jet edge image within the inertial subrange of the energy cascade.

6.3.2 Fractal Analysis and Previous work

The fractal dimension of the images was calculated from a line boundary of planar images. Comparisons with the work of Sreenivasan (1991) and others require that the additive law (Chapter Four) be applied. The resulting fractal dimensions of the turbulent structures acquired through image processing range from 2.27 to 2.35. This is in close agreement with the results of Sreenivasan (1991) and others cited in the literature review, who measured fractal dimensions of mixing jets by tomographic imaging and found dimensions in the region of 2.35.

6.3.3 Conclusions of Fractal Analysis Study

The fractal analysis techniques identified a range of turbulence length scales in the jet boundary, which could be made apparent with the current flow visualisation equipment. This range was placed in context within the inertial subrange of the turbulent energy cascade. In doing this, the limits of the ability of the seeding medium to resolve the small-scale structures within the current flow regime were identified and an indication of the average size of the large-scale structures was achieved.
This understanding of the range of the size of the length scales visible with the image processing equipment provided a basis for the following work on structure tracking.

**6.4 COMPARATIVE STRUCTURE TRACKING AND HOT-WIRE ANEMOMETRY RESULTS**

In this section, the contribution of the new image processing technique for studying large-scale turbulent structures is assessed. Initial results are presented to establish that the flow phenomena being studied is the same as that of the hot-wire anemometry technique. Following on from this, there is a section in which the difference in the nature of the techniques is emphasised and the advantages of the new technique are highlighted. The final section is an analysis of those results that are achievable only with the new image processing technique.

**6.4.1 Comparative Measurements**

**6.4.1.1 Measurement Location**

The nature of the present image processing technique required that the structures to be tracked were discrete and well defined. This required a low degree of intermittency so that turbulent structures were coherent and could be identified as separate from each other. Visual analysis of the flow visualisation images showed that these circumstances occurred only in the outer edge shear layer of the deflected jet and, as such, this was the region in which all structure tracking took place. *Figure 5.1 to Figure 5.7* show the location of the centroids of the structures that were tracked. The hot-wire results for turbulence intermittency and higher order moments, identified this as the shear layer region of the jet. Comparison between the location of the centroids of the turbulent structures and the location of the shear layer region identified by hot-wire anemometry showed that the structures which were tracked were clearly located in the outer edge shear layer of the deflected jet. Therefore, the characteristics of the large-scale turbulent structures on the edge of the jet were compared to hot-wire measurements within the shear layer, as defined by turbulence intermittency.
Jet Trajectory

A similar exercise to that used to define the trajectory of the jet from HWA results was performed to define the jet edge described by the locations of turbulent structures in the shear layer of the jet. Jet penetration co-ordinates were measured from Figure 5.7 at the same downstream locations as those used with the hot-wire anemometry data. These results were fitted to the empirical jet path equation of Pratte & Baines (1967). The trajectory implied from the location of the structures is compared to that implied from HWA in Figure 6.1.

The trajectories defined by the hot-wire anemometry results compare very well with those defined by the location of large-scale turbulent structures in the shear layer (Figure 6.4). The structure tracking technique indicates a trajectory of about 1D less in penetration than the HWA technique. This could be accounted for by the fact that whilst the HWA technique defined the extreme boundary of the jet, the boundary defined by structure identification technique was based on the centroids of the structures, and, as such one might expect this to be an underestimation of the overall extent of the jet. The degree of underestimation would be in the region of half the average length scale of the turbulent structures. This half-length, based on the distribution of structure sizes (Figure 5.21) was about 1.4D.

6.4.1.2 Velocity Measurements

<table>
<thead>
<tr>
<th>X/D</th>
<th>Average Structure Velocity In Downstream Direction $\bar{U} / \bar{U}_r$</th>
<th>Average Shear Layer Velocity In Downstream Direction $\bar{U} / \bar{U}_r$ (HWA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.996</td>
<td>0.992</td>
</tr>
<tr>
<td>15</td>
<td>1.005</td>
<td>1.001</td>
</tr>
<tr>
<td>20</td>
<td>1.033</td>
<td>1.001</td>
</tr>
<tr>
<td>25</td>
<td>0.978</td>
<td>1.000</td>
</tr>
<tr>
<td>30</td>
<td>1.021</td>
<td>1.017</td>
</tr>
<tr>
<td>35</td>
<td>1.020</td>
<td>0.991</td>
</tr>
</tbody>
</table>

Table 6.2 - Comparison of u-Component Velocities
The structure velocities measured by the image processing technique are compared to those in the shear layer of the jet in Table 6.2. The freestream velocity in both cases was 1m/s. Perhaps unsurprisingly, there is little difference between the two sets of results. The convection of the structures was the same as the velocities within the shear layer. However, it is significant that crossflow conditions were the same for both the smoke seeded jet used with image processing and the unseeded jet used in the HWA experiments. This similitude of the stream wise velocities supports the validity of the comparison of studies in which the results contrast.

Before embarking on further analysis of the results of the structure tracking technique, it is important to establish, with reference to Figure 5.16 to Figure 5.21, that the range of structure sizes analysed with this new image processing approach, was representative of the range of large-scale structures detected in the shear layer by hot-wire anemometry.

6.4.1.3 Conclusions of Comparative Study

It has been established that the main characteristics of the jets studied by both techniques are the same. The jet to crossflow velocity ratios were 6, in both cases, with a crossflow velocity of 1m/s. The trajectory of the outer edge of the jet was shown to be the same for both studies and therefore whilst results from both techniques might not be directly comparable, they were at least both based on the same flow regime.

6.4.2 Comparison of Contrasting Structure Tracking and HWA Results

Direct comparisons between the values measured by HWA and those measured by structures tracking are not possible. The structure tracking results are not localised to a point as the hot-wire measurements are. Nevertheless, an approximate comparison is made by assuming that all structures located at X~10D, for example, are at X=10D. A further assumption is that a representative value of the results that vary with displacement in the Y-direction within the shear layer can be found by taking the mean of the results in the range.
6.4.2.1 Velocity Vector Measurements

Measurements of the u and v-components of velocity in the shear layer region of the jet are presented in the tables below.

<table>
<thead>
<tr>
<th>X/D</th>
<th>Average Structure Velocity In Downstream Direction $\overline{U} / \overline{U}_f$</th>
<th>Average Structure Velocity In Normal Direction $\overline{V} / \overline{U}_f$</th>
<th>Resultant Velocity $\sqrt{\overline{U}^2 + \overline{V}^2} / \overline{U}_f$</th>
<th>Resultant Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.996</td>
<td>0.316</td>
<td>1.044</td>
<td>17.60</td>
</tr>
<tr>
<td>15</td>
<td>1.005</td>
<td>0.232</td>
<td>1.031</td>
<td>12.99</td>
</tr>
<tr>
<td>20</td>
<td>1.033</td>
<td>0.201</td>
<td>1.052</td>
<td>11.01</td>
</tr>
<tr>
<td>25</td>
<td>0.978</td>
<td>0.173</td>
<td>0.993</td>
<td>10.03</td>
</tr>
<tr>
<td>30</td>
<td>1.021</td>
<td>0.145</td>
<td>1.031</td>
<td>8.08</td>
</tr>
<tr>
<td>35</td>
<td>1.020</td>
<td>0.138</td>
<td>1.029</td>
<td>7.70</td>
</tr>
</tbody>
</table>

Table 6.3 - Velocities Measured by Structure Tracking

<table>
<thead>
<tr>
<th>X/D</th>
<th>Average Shear Layer Velocity In Downstream Direction $\overline{U} / \overline{U}_f$</th>
<th>Average Shear Layer Velocity In Normal Direction $\overline{V} / \overline{U}_f$</th>
<th>Resultant Velocity $\sqrt{\overline{U}^2 + \overline{V}^2} / \overline{U}_f$</th>
<th>Resultant Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.01</td>
<td>0.134</td>
<td>1.019</td>
<td>7.56</td>
</tr>
<tr>
<td>15</td>
<td>1.00</td>
<td>0.103</td>
<td>1.005</td>
<td>5.88</td>
</tr>
<tr>
<td>20</td>
<td>1.00</td>
<td>0.090</td>
<td>1.004</td>
<td>5.20</td>
</tr>
<tr>
<td>25</td>
<td>0.999</td>
<td>0.083</td>
<td>1.002</td>
<td>4.75</td>
</tr>
<tr>
<td>30</td>
<td>1.014</td>
<td>0.072</td>
<td>1.017</td>
<td>4.06</td>
</tr>
<tr>
<td>35</td>
<td>0.992</td>
<td>0.069</td>
<td>0.994</td>
<td>3.98</td>
</tr>
</tbody>
</table>

Table 6.4 - Table of Shear Layer Velocities from HWA
Chapter Six - Discussion of Results

As established earlier, the average u-component velocity of the structures in the shear layer of the jet in a crossflow remained reasonably constant as the jet moved downstream. The mean of the averages at all locations was within 1% of the crossflow velocity with a standard deviation of less than 2%. The mean of the magnitude of the velocity vector also remained generally constant at an average of 3% above the crossflow velocity with a standard deviation also under 2%. However, over the same spatial region the v-component velocity of the structures dropped from 0.316 to 0.183. There is variability in the averages of the velocity vector and the u-component velocity, probably due to small variations in the crossflow velocity, thus, it is not possible to establish whether the downstream convection velocity of the structure remained constant, regardless of the normal velocity component or the magnitude of the velocity vector remained constant.

The stream wise velocities measured by both techniques yield the same result, since the turbulent structures were being convected at the same velocity as the crossflow. However, the normal velocities, give markedly differing results. The reason for this is, the magnitude of the normal velocity component measured by HWA within the jet was attenuated by its intermittency in the crossflow. As a result of the attenuation of the v-component velocity, the calculated velocity vector was affected in magnitude and direction.

The structure tracking results are based only on fluid within the jet, since no measurements were taken in the crossflow. The two techniques measured different aspects of the flow regime, the structure tracking measured velocities associated with the jet and HWA measured velocities associated with a point that was intermittently within the jet.

The direction of the ensemble average of the turbulent structures is shown in Figure 6.3 along with the gradient of the outer edge of the jet, implied by differentiation of the jet path equation. There is a good agreement between the directional data of the structure and the gradient of the jet trajectory, although the structure velocities show a slightly shallower angle of trajectory than the jet path. The reason for this is that the jet trajectory was measured from the extreme extents of the structure centroid locations. The calculated direction of the structures at each location was based on the average of an ensemble of a number of structures.
at an approximate downstream location within the shear layer, regardless of their location in
the X-Y plane.

By contrast, the time averaged hot-wire measurements, in the same region, fail to reflect the
trajectory of the jet due to the inability of the technique to discriminate between the jet and
the crossflow. Some form of conditional sampling would be required and the technique
would therefore be subject to the conditioning criteria.

6.4.2.2 Turbulence Measurements

Turbulence measurements with hot-wire anemometry produce a result which is the statistical
standard deviation of velocities at a point in the flow. Therefore, in an intermittent region
such as the one under investigation here, the measured turbulence intensity is based on the
velocity statistics of a combination of the turbulent and non-turbulent regimes. A point
measurement in a flow regime that is made up of high but infrequent turbulence would return
a low overall turbulence intensity. The structure tracking on the other hand, measured only
the velocity fluctuations in the turbulent regions of the flow. The contrast between the two
techniques is well illustrated by such a case.

In an attempt to provide comparative data, the turbulence intensities measured by hot wire
anemometry are divided by their local intermittency. This, to some degree, provides a
measure of turbulence intensity of the turbulence regions only and is termed the turbulence
characteristic measured by HWA.

The problems associated with the comparison of mean flow characteristics are exacerbated
when fluctuating components are considered. Whilst the structure tracking technique has the
advantage of being able to measure velocities of the jet itself, this is only at a large-scale. The
fluctuations in velocity within the structure itself cannot be measured with the current
 technique. Therefore, the turbulence measure of the structures is termed a turbulence
characteristic. It represents the turbulence due to the large-scale fluctuations in the flow and
is the standard deviation of the structure velocities, normalised by the average.

6-15
Chapter Six - Discussion of Results

The results of the HWA turbulence characteristic are presented with the turbulence characteristic of the structures in Table 6.5.

<table>
<thead>
<tr>
<th>X/D</th>
<th>Turbulence Characteristic (%)</th>
<th>HWA Turbulence Characteristic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Std Dev of Structure Velocity</td>
<td></td>
</tr>
<tr>
<td>u'/U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-------------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>10</td>
<td>7.29</td>
<td>15.1</td>
</tr>
<tr>
<td>15</td>
<td>5.12</td>
<td>14.0</td>
</tr>
<tr>
<td>20</td>
<td>5.95</td>
<td>12.8</td>
</tr>
<tr>
<td>25</td>
<td>5.78</td>
<td>11.7</td>
</tr>
<tr>
<td>30</td>
<td>7.08</td>
<td>12.6</td>
</tr>
<tr>
<td>35</td>
<td>6.97</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Table 6.5 - Comparative Table Turbulence Characteristics

The turbulence characteristic of the structure tracking method is significantly lower than that of the HWA method. This is due to the nature of the measurement methods. The turbulence characteristic of the structure tracking technique is a measure of the fluctuation of the velocities of the structures, whereas the HWA turbulence characteristic is a measure of the fluctuations in velocity within the structures as well as the structures themselves. The difference in the values obtained by the two techniques, is an indication of the turbulence of the smaller scales within the large-scale turbulent structures.

6.5 Results Particular to the Structure Tracking Technique

This section concerning the results of the structure tracking study is divided into two halves. In the first half, the results that were presented in Chapter Five are discussed in greater detail. General trends are highlighted and the interpretation of the results is outlined. The second half of this section presents an analysis of the results concentrating specifically on the various flow regions within the jet.
6.5.1 Discussion

6.5.1.1 Relationship between structure size and structure velocity

It has been detailed in Chapter Five, that there is generally no relationship between the size of a structure and its convection velocity. However, in the case of structures recorded at X/D=10, a weak correlation can be seen in which the velocities of structures increase with their size. Within the data set presented, there is a statistical correlation of about 50% between the two parameters. These results raise two issues, the first is why this correlation should exist and the second is why it is only apparent in the X/D=10 region. To address these issues, it is necessary to consider the region of the jet in which the measurements took place. At X/D=10 the jet is still in the zone of maximum deflection.

In the zone of maximum deflection, the structures nearer the centre of the jet are more strongly governed by the jet momentum than those towards the outer edge of the jet, which are more strongly subject to the crossflow conditions. Large structures within the jet shear layer tend to be found nearer the centre line of the jet. The smaller structures tend to be attached to the outer extent of the larger structures. Thus, the apparent correlation between the size of a structure and its velocity is more likely to be a reflection of the effects of structure position relative to the centre-line, as opposed to a length scale characteristic.

As the jet moves towards the freestream direction, the deflection of the jet is dominated by entrainment of crossflow fluid into the jet. As a result, the velocity of the large-scale structures, which play an important role in the entrainment process, are convected at the velocity of the crossflow, regardless of their size and position relative to the jet centre-line. Therefore, the structure tracking technique recorded no size dependency within the velocity of the turbulent structures beyond the X/D=10 region.

To further support this relationship between structure size or position and structure velocity within the near exit region of the jet, it would have been useful to have a comparative set of data from the X/D=5 location, however for the reasons outlined below, these results were not available for the current study.
6.5.1.2 Measurements in areas of high shear stress

Images of turbulent structures in the shear layer of the jet were recorded at series of locations from X/D \sim 5 to X/D \sim 35. However, the current image processing technique was not capable of tracking the structures in the regions of the jet nearest its exit. The high shear stresses in this region, which cause the deformation of the jet into its characteristic ‘kidney’ shape also severely affect the turbulent structures in the shear layer. The forces to which the turbulent structures are subjected are strong enough to deform them to such an extent, over a 20ms interval that they are barely recognisable by eye. The structure tracking routine was not able to track structures that had changed shape and size so dramatically. As such no result of the velocity or the turbulence characteristic are available from this region of the jet.

6.5.1.3 Details of Turbulence Characteristics from Structure Tracking

The results presented in this section concern the turbulence characteristics of the structures recorded in the shear layer of the jet in a crossflow. This turbulence characteristic is based on the fluctuations of velocities of the turbulent structures as they move downstream. Each turbulent structure yields two velocity measurements from which the average velocity of the structure can be ascertained. The turbulence characteristic, is therefore, made up of two components. The first is the average of the fluctuation of the mean velocity of the structures, $\bar{u}$ from the ensemble mean, $\bar{U}$, and the second is the average of the fluctuations in velocity of individual structures $u$, from their own local mean, $\bar{u}$. These fluctuating components are denoted by $u'$ and $u^*$, respectively. The method of quantification of these two separate characteristics is detailed in Chapter Five.

Whilst the lines in Figure 5.8 to Figure 5.13 indicate the average velocities of the structures at each location, the distribution of the instantaneous velocities within the graph give an indication of the turbulence characteristic of the structures at each location. A wide distribution would indicate a high turbulence characteristic and conversely a closely grouped set of results would indicate a low turbulence characteristic. The overall results for turbulence characteristic are presented in Table 6.6
The pattern of variation in turbulence characteristic with downstream location is not the same as that resulting from the hot-wire investigation of turbulence intensity. The image processing results indicate that the fluctuations in structure velocity are highest at the X/D = 10 location, which is in concord with the hot-wire results. However, rather than decreasing gradually with increasing downstream distance, the turbulence characteristic reaches a low point at X/D = 15 then generally increases with downstream displacement. Though this seems unusual, it does indicate a sensitivity of the structure tracking technique to the deflection zone and vortex zones discussed earlier. It is interesting to investigate the contributions to the turbulence characteristic as described in the introduction to this section.

The calculation of the turbulence characteristic contribution based on the individual average velocities of the structure, $\overline{u}'$, is subject to a very small error margin, of the order of $\pm 0.1\%$ of the average velocity as this is the minimal degree of error associated with the assessment of the average velocity of an individual structure (See Chapter Five). The error margin in the turbulence contribution associated with the deviation of the instantaneous velocities of a structure from its own local mean is much greater. The error in the estimation of the instantaneous velocity of a structure is of the order of 4% of the mean. This results in an error margin of similar magnitude to the actual turbulence characteristic contribution itself. Whilst this may seem to invalidate the calculations, it may be safely assumed that the homogeneity of the data sets and each location would impose the same degree of error at each location.
Thus, whilst there may be reasons for a lack of confidence in the magnitude of the contribution to the turbulence due to local velocity fluctuations, the general trend can be assumed to be valid.

It can be seen that in the vortex zone region of the deflected jet, the major contributing factor to the turbulence characteristic was the variation in the average velocities of the structures. The fluctuation in the structure velocity as it passed through the measurement region was less significant. Whilst the turbulence characteristic at $X/D=15$ was significantly lower than that at $X/D=10$, the contribution of the differing sources of the turbulent characteristic were equal. As the deflected jet moved farther downstream, the effect of the fluctuation in the velocity of individual structures became progressively more significant until $X/D=30$, where this effect was the more dominant of the two.

### 6.5.2 Analysis

#### 6.5.2.1 Zone of Maximum Deflection

At the $X/D=10$ location the turbulence characteristic was at its highest. This reflected a high degree of fluctuation in the velocity of structures passing through this region. As stated earlier, this was within the zone of maximum deflection of the jet, nearest the jet exit. It was to be expected that the influence of the initial jet momentum here was stronger than at any of the other locations analysed in this work. The contribution of the fluctuation of the average velocities in this region was at its highest here, both in absolute value and as a percentage of the overall turbulence characteristic. The comparatively low fluctuation in velocity within individual structures implied that the velocity of a structure remains comparatively constant as it moves into the crossflow. The contra-rotating vortices are not yet dominant and do not appear to have had a strong effect on the shear layer structures. This suggested that the source of the fluctuations in the velocity of the structures was within the jet.
6.5.2.2 Transitional Region

As the jet fluid moved to the X=15D location, there appears to have been a transitional point, the turbulence characteristic here, was at a minimum. The effect of the jet momentum was reduced as it moved downstream, due to expansion. The effects of the crossflow and the contra-rotating vortices had not yet become dominant and as such, fluctuations in the velocity of individual structures was small. This decrease of the influence of the jet in a region where the contra-rotating vortices were not yet established, appears to have resulted in a zone of 'relative tranquillity' between the zone of maximum deflection and the vortex zone.

6.5.2.3 Vortex Zone

As the jet fluid moved out of the zone of maximum deflection into the vortex zone, from X/D=20 onwards, the turbulence characteristic began to increase. There was a general consistency in the turbulence characteristic due to the variation in the average velocity of structures. However the fluctuations in the instantaneous velocities of the structures increased with downstream displacement, becoming the more dominant effect by X/D=30. In this region the contra-rotating vortices start to dominate the jet behaviour. It is likely that it was the influence of vortices, which affected the instantaneous velocities of the turbulent structures on the edge of the jet. In regions where the vortices were secondary to the influence of the initial jet momentum, the instantaneous velocities of individual structures remain relatively constant. Within the vortex zone of the jet, the momentum of the jet is governed by the entrainment of the crossflow; this may be another source of the increased fluctuation in the instantaneous velocities of the structures.

6.6 Summary

The structure tracking technique has been able to detect a relationship between the size of turbulent structures near the nozzle of a jet in a crossflow and their velocity. It has been suggested that this is a result of the break down of large eddies. This result was not tested at regions very near the nozzle as shear stresses deformed the eddies to such an extent that they could not be tracked with current techniques. The velocity vectors of structures within the jet
were shown to closely resemble the angle of deflection of the jet. Such results were not achievable with conventional hot-wire anemometry methods. This highlighted the advantage of the current structure tracking technique, in that it was able to measure characteristics within the jet itself rather than averaged characteristics which reflect the behaviour of the crossflow, as well as that of the jet. The technique for measurement of velocities of turbulent structures within the jet was developed to allow a treatment of the instantaneous velocities of the turbulent structures. This development resulted in the definition of a turbulence characteristic associated with the large-scale structures. Further investigations with the structure tracking technique allowed an insight into the factors contributing to this turbulence characteristic. A trend was identified in which the movement of the structures was observed to be significantly different in the zone of maximum deflection and the vortex zone of the jet. A transitional zone was identified between these two zones, in which the turbulence characteristic was at a minimum as the flow moved from a region in which it was dominated by the jet velocity to one in which the contra-rotating vortex effects and the entrainment of the crossflow fluid, became dominant. This treatment of the global characteristics of the jet yielded results that were not obtainable with conventional point measurement techniques.

The next chapter of this thesis describes the applications of the structure tracking technique to alternative flow fields and details the preliminary phase of an adaptation of the current technique to allow the tracking of even larger-scale flow features.
Chapter Seven - Further Applications and Developments of Structure Tracking

CHAPTER SEVEN

7. FURTHER APPLICATIONS AND DEVELOPMENTS OF STRUCTURE TRACKING

7.1 INTRODUCTION

Throughout the current programme of work, there has been a continual awareness that the application of the technique under development was in no way restricted to the flow regime investigated in the main body of this thesis. Opportunities have been taken to apply the current technique to a variety of other flow regimes, in particular that of a vertical free jet and those of road vehicle aerodynamics. The work with the free jet led to a further development of the technique to allow the tracking of horizontal cross-sections of the jet to try to deduce information concerning velocities in the shear layer of the jet.

7.2 ROAD VEHICLE AERODYNAMICS

Techniques, which had been developed for studies of the shear layer of a jet in a crossflow, were applied to the study of the wake behaviour of road vehicle models, McCusker et al. (1996a). The aim of the work, was to produce quantitative data concerning the behaviour of discrete turbulent structures within the wakes of a number of vehicle body types, from the essentially ‘bluff’ body shape of commercial vans or MPVs to a highly streamlined, low drag, prototype model

7.2.1 Apparatus

The vehicle models tested are shown below. A modified version of model 1 was also tested, in which the front section of the model was removed to allow a different face configuration.
Experiments were carried out in the same smoke tunnel facility used for the jet in crossflow experiments, using the same image analysis equipment and procedures described earlier. The main difference in the experimental technique was that of illumination. Due to the blockage of the light path caused by the experimental models, it was found to be preferable to use a 1kW halogen lamp light source, in concert with a 10mm slit along the centreline of the
model. The tunnel flow velocity was set to 1 m/s corresponding to a Reynolds' number of about 1.4 x 10^4 based on model length. Smoke was introduced into the flow by bleeding in immediately upstream of the model so that it attached to the model front surface.

7.2.2 Measurements

Average images of smoke concentration in the wake of models 1 and 2 were generated by the image processing equipment, in the way described in Chapter Four, for the production of the averaged jet in crossflow images in the preliminary study. However, in this case, this technique was further developed to produce contour plots of smoke intensity. Work by Ohba (1995) had shown that there is a linear relationship between the image intensity recorded within a seeded flow and the concentration of the seeding medium within the image plane. As a result, image intensity contours can be assumed to be similar to the smoke concentration contours. To produce the image intensity contours, the number of grey scales within the image was reduced to produce the required contour bandwidth. In the case presented, the pixel intensities within the image field were normalised by one tenth of the maximum intensity within the field, to produce 10% bandwidths. This resulted in a banding effect on the averaged image so that an edge detection routine could be performed to highlight the interfaces between the bands, thereby producing a contour plot. The contoured image was then stored on a frame buffer where the pixel intensities could be accessed via the PC and converted to a standard graphics file format, accessible by most spreadsheet packages. Scales were then drawn about the image and the contour plot was produced without the time consuming processes usually associated with such graphical representation (Figure 7.1 and Figure 7.2).

7.2.3 Results and Discussion

The structure tracking technique showed a minimal deformation of the turbulent structures under the experimental conditions, implying a negligible velocity gradient within the turbulent structure. The streamwise velocity of the structures was consistently in the region of 75% of the freestream velocity. This contrasts with the close matching of structure velocity and freestream velocity found with a jet in a crossflow. Structure locations were very
centralised in the vertical direction indicating a consistency in the penetration of the turbulent structures into the freestream. Comparisons were made between the time-averaged data based on image averaging and the instantaneous images for the unmodified model 1 in particular. Time-averaged results indicated that the wake height extended to about 0.6 times the model length (Figure 7.1). However, instantaneous images (Figure 7.3) showed structures that penetrated well beyond this, demonstrating that the wake was, in fact, larger than indicated by time-averaged results. The same analysis was performed on all vehicle models. However, in these cases a much smaller data set was used, purely for a qualitative comparison of results. The streamlined model produced turbulent wake structures which were much closer to the ground plane than the other ‘bluff’ models, also these turbulent structures were generally much smaller than those produced by the other models. The vertical components of velocity was generally constant and close to zero with the three ‘bluff’ models, with a slightly positive component, though there were some structures with negative vertical velocity components. The structures in the wake of the streamlined model (model 3) were generally smaller and more often with a negative vertical velocity component, reflecting a general decrease in the size of the wake region and a tendency for the wake flow to reattach to the ground plane.

The aim of this application of the structure technique was not to provide a definitive, comprehensive study of road vehicle aerodynamics. Rather it was to demonstrate that the technique that has been developed has scope to be used in a variety of turbulence studies.

The results were to be of interest to vehicle manufacturers seeking to gain a better understanding of the nature of turbulence generated by vehicle bodies at a global instantaneous level, both for validation of numerical simulation codes and for quantitative experimental techniques.

7.3 Vertical Free Jet Study

The application of the structure tracking technique to the flow field of a free jet was instigated by the FRS (Fire Research Station), McCusker et al. (1996b). It was an investigative feasibility study, using the image processing techniques that had been developed
during the execution of the experimental work associated with this thesis. The aim of the study was to determine the suitability of the current work for the analysis of the behaviour of smoke originating from a fire. The impetus for this was the hazards associated with indoor fires such as the noxious and toxic products of combustion, as well as the problems caused by the obscuration of vision leading to the impediment of escape and hindrance to fire-fighting. The heat generated by fire causes the rapid movement of the gases that contain ‘smoke’ so that they quickly occupy a building. The movement of smoke is a fluid dynamics problem and so the structure tracking technique which had been applied to previous fluid dynamic phenomena, was proposed as an experimental technique to be used for smoke movement studies. A preliminary study of a free jet was set up as a model for a smoke plume, to test the ability of the technique to track turbulent structures within such a flow.

7.3.1 Apparatus

The experiments were carried out in a spacious laboratory environment with the ambient flow conditions minimised during experimentation. The jet apparatus consisted of a smoke generator and centrifugal fan configuration described in chapter 3, and a 1m length of 20mm internal diameter pipe connected to the fan outlet by flexible hose. A photograph of the arrangement is shown in Picture 8.

The light source used in this set of experiments was a 4W water-cooled, argon-ion laser, producing a beam of 1.5mm diameter with 0.5mrad divergence. This afforded far more illumination than previously available with the 50mW diode laser. With the increased power available, it was no longer necessary to scan a laser line because there was now enough power to allow a light sheet to be created by beam splitting, through a cylindrical lens. All other experimental instrumentation was the same as has been previously described.

A novel illumination technique using solenoid driven mirrors was employed, which allowed three planes of illumination at a variety of heights.

The apparatus used for the mirror arrangement and beam splitting is shown diagrammatically in Diagram 7.4 and photographically in Picture 9.
A small front-silvered mirror was mounted on a self-returning solenoid, at an angle of 45°. The mirror and solenoid were both fixed to a ‘Perspex’ faceplate, which was in turn mounted on a ‘Perspex’ base plate. The faceplate and base plate were both made with machined slots that allowed the faceplate two degrees of freedom, relative to the base plate. This design allowed a multiple mirror arrangement, as shown in Picture 10 to be easily aligned. The base plate had a central section removed so that it was possible for a light beam to pass through it and onto the next arrangement (Picture 11). The base plate was attached at one end, to a length of standard scaffold pole, at the other end was a small glass rod of 10mm diameter, acting as a cylindrical lens. The laser beam was shone horizontally, over a distance of 12m, from one end of the laboratory to the other (Picture 12), whereupon it hit a stationary mirror angled at 45°, placed directly below the solenoid controlled mirrors. This mirror deflected the beam vertically, in the direction of the solenoid controlled mirrors. As the solenoid of the first mirror was activated, the mirror moved into the path of the beam, again deflecting it through 90° and directing it through the cylindrical lens that split the beam into a sheet (Picture 11). When the solenoid was deactivated, the mirror sprang back out of the beam path and allowed the beam to pass through the base plate onto the next arrangement, so a
sheet could be created at the next location. The solenoids were controlled via the same Amplicon PC30-AT data acquisition card and PC configuration used for the hot-wire anemometry experiments described in Chapter Three. Software controlling the mirror arrangement was written by the author specifically for this project.

The jet outlet velocity was set between 3.5 m/s and 6.25 m/s and light sheets were generated for a variety of periods between 100ms and 30s. A camera placed in parallel with the nozzle configuration recorded the image of the illuminated cross-sections. A sketch of the experimental configuration is shown below.

![Diagram 7.5 - Free Jet Investigation Apparatus](image)

7.3.2 Measurements

Initially, the structure tracking technique described throughout this thesis was applied to the problem, and large turbulent structures moving in the jet direction were tracked. As a development of the current work, a second approach was applied. Cross-sections of the jet at
three heights were recorded and qualitative shape recognition applied to the images in order to try to recognise when a particular horizontal cross-section of the jet moved from one level to the next.

Preliminary work using image-averaging routines was used to establish the variation in smoke concentration and smoke intermittency throughout the plume. The current technique sought to identify the presence of smoke only, as the work was of interest to fire research. The smoke illumination and image recording technique used, clearly defined the smoke presence within the image field. By reducing the images to a binary format, wherein the smoke presence was displayed as ‘white’ and all else as ‘black’, the image was simplified at the cost of gradation of intensity within the seeded region. As the aim of the work was merely to detect the presence of smoke regardless of concentration, this binary reduction was deemed an appropriate technique to use. The image recorded by the camera, was displayed in real-time on the output monitor, via the image processing equipment. The user then selected an intensity threshold value that clearly defined the threshold between smoke and no-smoke. This value could be adjusted in real-time until the required limit was found. The software then acquired 250 consecutive images of the flow at a 50Hz acquisition rate, representing 5 seconds of sampling. The images were acquired to a frame buffer that was initially blank, with each image the buffer was incremented by one grey scale level at each location where the incoming image was above the threshold value. The resulting image represented a full field image of the proportion of the sampling time for which smoke was present. Contour bands were then imposed on the image by a reduction of the grey scale range as described in the previous section on road vehicle aerodynamics. The resulting image was pseudo-coloured to highlight bands of intermittency.

7.3.3 Results and Discussion

The standard structure tracking routine was employed first, and applied to cross-sections of the jet parallel to the flow direction so that structures in the outer edge of the smoke plume could be tracked. The results in this region showed that the structures were severely affected by the shear forces between the surrounding air and the plume, resulting in considerable deformation over the 20ms interval between acquisitions. Furthermore, the structures were
Chapter Seven - Further Applications and Developments of Structure Tracking

seen to move very little over this period as may be expected on the boundaries of a free jet. An increase in the delay between image acquisitions would have resulted in a more significant movement of the turbulent structures. However, the deformation of the structures would have been so severe as to make them unrecognisable to the structure tracking routine.

To obtain some reliable data concerning the velocity of the smoke plume, a ‘wavefront’ tracking technique was developed, the results of which are shown in Picture 13 to Picture 17. Horizontal cross-sections of the plume were acquired with the first image being taken at the illumination plane nearest the jet exit. Subsequently, images were acquired at an illumination plane 3 nozzle diameters above the initial plane at 20ms intervals. The results showed that whilst the overall shape of the cross-section of the plume changed considerably over an acquisition period, individual changes between any two consecutive cross-sectional images was slight. Closer inspection showed that by considering the appropriate time frame of cross-sectional images, similarities could be seen between the initial cross-section at t=0, in the primary plane and those acquired at the elevated position after a particular time lag. As such, because the time lag between the image acquisitions could be calculated along with the vertical displacement of the illumination planes, the transport period of the structure could be calculated, as could the velocity of the outer region of the plume. A refinement of this process was added by which the image acquisition at the second level was delayed until the cross-section was expected to traverse the interval between the acquisition planes. The period of this delay was calculated based on the velocity of the outer edge of a free jet using the velocity decay rate along the central axis of a free jet and the velocity profile across a free jet as outlined by Abramovich(1963). Using this method, the technique was used to track a cross-section of a plume as it moved through three elevations, 12.5D, 15.5D and 21.5D. Comparisons were made between the theoretical analysis of free jet velocities and the experimental image processed results and proved to be valid, producing a velocity for the outer edge of the plume, which was within 10% of the theoretically expected result.

7.4 SUMMARY

The structure tracking technique developed within the main body of this thesis has been applied to flow fields associated with the aerodynamics of road vehicles. This demonstrated
that the technique is independent of the flow regime and could equally be applied to any study of coherent turbulent structures that can be visualised. Furthermore, the preliminary work associated with complete cross-sections of a free jet, has shown the potential for a grand-scale image processing technique, developed along the lines of the current technique.
8.1 INTRODUCTION

The central concept behind the development of the structure tracking technique was that it would allow the treatment of turbulent structures on an individual basis. The technique centred on a particular flow feature, rather than a point or region within the flow regime. This introduced a Lagrangian rather than Eulerian analysis of turbulence. The use of flow seeding as a discriminator allowed the analysis of characteristics associated specifically with the seeded flow, without the measurement of extraneous quantities from the surrounding flow regime.

8.2 CONCLUSIONS

The primary objective of the work presented in this thesis was the development of a quantitative analysis technique for the study of large-scale turbulent structures. This has been accomplished by the application of flow visualisation techniques to intermittently turbulent flows. Where possible, the results have been compared to those measured by traditional hot-wire anemometry techniques, with a good correlation between the bulk characteristics of the flow measured by both techniques. The structure tracking technique presented here was used to measure flow characteristics that are not obtainable with point measurement techniques. The specific characteristics of large-scale turbulent structures that were measured were the velocity vector and the turbulence characteristic.

8.2.1 Velocity Vector

The structure tracking technique applied to the shear layer of a jet in a crossflow was able to distinguish coherent turbulent structures. This allowed the measurement of velocities associated with the jet, without the inclusion of velocities associated with the crossflow.
Therefore, the velocity vectors produced as a result were a realistic representation of the characteristics of the jet flow regime. When compared to the time-averaged point-based measurements of hot-wire anemometry, the velocity vectors produced by the structure tracking technique were found more closely resemble the trajectory of the jet. This highlighted the difference in nature of the two techniques, in that the structure tracking routine produced results that were specifically associated with the behaviour of the turbulent structures within the shear layer of the deflected jet.

8.2.2 Turbulence Characteristic

The measure of turbulence characteristic presented here represented the fluctuations in velocity of the large-scale turbulent structures. This measure was broken down into two aspects, that of the variation in the average velocity of structures passing through a section of the flow regime and that of the fluctuation in velocity of individual structures as they passed through the section. The variation in these quantities as the jet moved downstream showed the distinctly different characteristics of the ‘zone of maximum deflection’ and the ‘vortex zone’ identified by previous researchers. It was implied that in the zone of maximum deflection, the influence of the initial jet momentum dominated the behaviour of the large-scale turbulent structures. The variation in velocity between individual structures was found to be higher here than anywhere else measured in the jet, and the fluctuation in velocity of individual structures was found to be small by comparison. Beyond this region a transitional zone was identified in which the influence of the initial jet momentum was reduced and the effects of the crossflow and the contra-rotating vortices were still relatively weak. This resulted in a region where the variation in the average velocity of the structures was comparatively small and the fluctuation in velocity of the structures had not yet reached the levels it would farther downstream. Farther downstream, within the vortex zone, the fluctuation in average velocity of the structures appeared to reach a steady level. In this region the dominant contribution to the turbulence characteristic came from the fluctuations in the velocity of the individual structures, this fluctuation was attributed to the effect of the contra-rotating vortices that dominate the flow in this region.
Chapter Eight - Conclusions & Recommendations for Future Work

The results concerning the variation in velocity of the turbulent structures could not have been achieved with other flow measurement techniques and are unique to the type of study presented here. The results presented here demonstrate the contribution that this thesis has made in providing a new tool for turbulence studies. Whether used independently, or as an augmentative tool for existing techniques, the advantage of a method of studying specific turbulent structures has been demonstrated. The relatively low cost and simplicity of the equipment required to implement such a technique is one further argument for its assimilation into laboratories where conventional flow measurement techniques are used.

8.3 RECOMMENDATIONS FOR FUTURE WORK

The work described in this thesis is the early development of a new approach to turbulence studies, and so the scope for future development is large. There are a number of areas that are worthy of further investigation. Some suggestions for this developmental work are listed below.

1) A technique for tagging each frame acquisition such that the direction of the laser sweep is known would eliminate a source of error or uncertainty in the estimation of the velocity of the structures. In situations such as the current one, where the hardware configuration of the image processing equipment and the ADC used to control the laser sweep prohibited their being used in the same PC simultaneously, this could probably be achieved by the use of a low power LED placed discreetly in the field of view. The state of the LED could be linked with the direction in which the oscillating mirror is swept.

2) The structure tracking study has so far only been applied in depth, to one flow regime and preliminary studies of two others. There is obviously scope for testing the solution with a number of other flow fields such as multiple jets, bluff body flows and boundary layer flows. It would be of interest to test the current technique to identify the flow regimes in which it was not suitable and find the reasons why.

3) The major area of interest would be to develop the current two-dimensional technique into a three-dimensional one. This would require more elaborate equipment, capable of much
higher image acquisition rates and light sheet intensity. A proposed area of research would be to use a rapidly scanning light sheet passing through a seeded flow. If the image acquisition rates and sheet scanning speeds are high enough, it should be possible to use the acquired images to reconstruct an instantaneous three-dimensional image of the flow regime. The problem inherent in such a technique would be the movement of the flow during the period between the acquisition of the first and last images. However, current commercially available equipment is capable of acquiring images at rates of more than 1000 frames per second, albeit at a premium. Assuming a coarse reconstruction field based on images from 10 light sheets, for example, the period between the first and last images would only be 10 ms, which, with the current flow regime would relate to an offset of about 10mm, which would be acceptable for the scale of the proposed study. The natural progression of this reconstruction technique would be to acquire a series of reconstruction fields separated by some time interval such that large-scale turbulent structures could be tracked three-dimensionally through the flow field. This would yield information about all three planes of movement of the structure and allow accurate quantitative data about the way in which the size and shape of the structure changes as it moves downstream.

The fractal analysis technique detailed within this thesis could equally be applied to this 3-dimensional approach, the only criteria being that the separation between the image reconstruction planes is comparable to the pixel resolution of each two-dimensional image field.

The application of the techniques discussed here would make available data concerning the scales and development of large-turbulent structures, which would be of great interest and benefit to researchers involved in numerical simulation studies or those studying entrainment. They would also provide useful data for alternative forms of turbulence analysis that do not rely on conventional statistical methods.
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Appendix A

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Intermittency (HWA): \( a = 2.27 \), \( b = 0.270 \)

Pratte + Baines (1967): \( a = 2.63 \), \( b = 0.393 \)

\[
\left( \frac{P}{DR} \right) = a \left( \frac{X}{DR} \right)^b
\]
Figure 6.2 - Comparison of Jet Path Parameters (Centre Line)
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\[
\frac{P}{DR} = a \left( \frac{X}{DR} \right)^b
\]

- Intermittency (HWA): \(a = 2.27 : b = 0.270\)
- Imaging: \(a = 2.22 : b = 0.245\)
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(Pseudo-Coloured) Time = 0.70s; Height = 15.5D

Jet Exit Velocity = 4.75 m/s
Appendix C
Programming
STRUCTURE TRACKING ROUTINE FLOWCHART

Start

Grab 4 Consecutive 512 x 256 Images

Display First Image

Is Image Accepted By User?

Yes

Compress All 4 Images and Display Simultaneously

Is Image Sequence Accepted buy User?

Yes

A
A

Read Intensity Threshold Value

Apply Look Up Table (LUT) To Compressed Image With All Pixels Above The Threshold Value Displayed As White And All Those Below Displayed as Black

Is Threshold Acceptable To User?

Yes

Fix Threshold By Rewriting Pixel Intensities On All Images According To LUT

B
Display First Image In Full Size

Overlay Image With 16 x 16 Grid Of Cells Of 32 x 16 pixels

Read Grid Co-ordinates Of Top Left Corner Of Area Encompassing The Turbulent Structure

Read Box Height And Box Width

Overlay Image With Box Defined By Starting Co-ordinates And Size
C

Is Box Accepted By User?

Yes

Set Box As Template By Reading All Pixel Intensities Within Box Into Memory Array

Start Loop #1 Counter

Move To Next Image

D

Return To Start
Step Size = 64
Correlation Maximum=0

Start Loop #2
Counter

Step Size = (Step Size) / 2

Select Area Of Interest (AOI) With Y-Position
4 x Step Size Pixels Less Than Template Y-Position

Start Loop #3
Counter

E
Select Area Of Interest (AOI) With Y-Position 4 x Step Size Pixels Behind Template Position

Start Loop #4 Counter

Is AOI Within 512 x 256 Pixel Image Area

Set Pixel Interrogation Position To X=0, Y=0 Of AOI

X
F

Start Loop #5 Counter

Set Pixels Interrogation Position To Far Left Of AOI

Start Loop #6 Counter

Read Image Intensity At Pixel Position

G
Is Pixel Intensity Equal To Intensity Of Template At The Same Position?

Yes

Correlation = Correlation + 1

Has Entire Horizontal Line Of AOI Been Interrogated?

Yes

No

Increment Pixel X-Position

Continue Loop #6
Has Entire AOI Been Interrogated?

Yes

Max Correlation = Correlation
Store AOI Position

No

Is Correlation Greater Than Max
Correlation?

Yes

Is AOI X-Position >=
Template Position +
4 x Step Size?

No

Increment Pixel Y-Position

Continue Loop #5

J

I
I

Increment AOI X-Position By Step Size

Continue Loop #4
Is AOI Y-Position >= Template Position + 4 x Step Size?

- Yes
  - Increment AOI Y-Position By Step Size
  - Continue Loop #3
- No
  - K
K

Is Step Size = 1?

Yes

No

Set New Template Position To AOI Position At Max Correlation

Continue Loop #2

Write AOI Position At Max Correlation To File Set Max Correlation = 0

L
L

Has Final Image Been Interrogated?

Yes

No

Continue Loop #1

Perform Edge Detection On AOIs Associated With Max Correlation Positions And Copy Edges To Output Buffer.

END
STRUCTURE IDENTIFICATION AND TRACKING SUBROUTINES

find_corr(xpos,ypos,xloffset,yloffset){
/*Finds maximum correlation between primary image and sample region in secondary image*/
low=18355840.0; /*Sets number of pixel mismatches to 'high' value*/
lowy=ypos;
lowx=xpos; /*Initialises structure location in primary image as start point of search region in secondary image*/
p=128; /*Initialise p, extent of search area*/
r=32; /*Initialise r, step intervals in search area*/
while(r>=1){ /*Loop until step interval is one pixel (Loop #1)*/
low=18355840.0; /*Sets number of pixel mismatches to 'high' value*/
sum=0; /*Initialises mismatch counter*/
for(y=lowy-p;y<=lowy+p;y=y+r){
/*Loop to interrogate areas in region up to p, pixels in front of and behind primary position at step intervals of r (Loop #2)*/
for(x=lowx-p;x<=lowx+p;x=x+r){
/*Loop to interrogate areas in region up to p, pixels above and below primary position at step intervals of r (Loop #3)*/

if(((x<=xpos)&&(x+x<=511))&&(y>=0)&&(y+y<=511))&&(x>=0)){ /*Condition to read only 'even' lines of interlaced image (Condition #1)*/
compare_areas(x1offset,y1offset); /*Call routine to compare search region with primary image*/
if(sum<=low){ /*Condition that number of mismatches is minimum (Condition #2)*/
low=sum; /*Minimum value redefined*/
lowx1=x;
lowy1=y; /*Start point of search region redefined as region containing least mismatches*/}
/*End of ‘mismatch minimum’ conditional instruction set (Condition #1)*/
/*End of ‘even lines’ conditional instruction set (Condition #2)*/
/*End of loop to scan interrogation areas vertically (Loop #3)*/
/*End of loop to scan interrogation areas horizontally (Loop #2)*/
p=p/2; /*Reduce extent of search region */
r=r/2; /*Reduce step interval in search region */
lowx=lowx1;
lowy=lowy1; /*Store best match location*/
} /*End of loop #1*/

} /*End of correlation routine*/

******************************************************************************

compare_areas(x2offset,y2offset){

/* Finds correlation between primary image and search interrogation area*/
sum=0;
pos=0;
num=0;

/*Routine to pixels in interrogation area into an array*/
for(ycomp=0;ycomp<=ys;ycomp++){ /*Loop to increment vertical pixel location (Loop #1) (ys:vertical size of interrogation area)*/
if(((y2offset+y+ycomp)%4==0)||((y2offset+y+ycomp-1)%4==0)){ /*Condition to read only ‘even’ lines of interlaced image (Condition #1)*/
for(xcomp=0;xcomp<=xs;xcomp++){ /*Loop to increment horizontal pixel location (Loop #2)*/
bright2[pos]=fb_rpixel(B1,x2offset+x+xcomp,y2offset+y+ycomp);
/*Reads pixel intensities within interrogation area into an array*/
pos=pos+1; /*Increments index*/
num=num+1; /*Counts size of array*/
} /*End of horizontal increment loop (Loop #2)*/
} /*End of Conditional instruction set (Condition #1)*/
/* End of vertical increment loop (Loop #1) */

/* End of area comparison routine */