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VELOCITY MEASUREMENTS NEAR AN AUTOMOTIVE COOLING FAN

by

Michael Brown

A Thesis
Submitted to the Faculty of Graduate Studies and Research through the Department of Mechanical, Automotive and Materials Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada
2001
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ABSTRACT

Due to the increased competition for engine compartment space in automobile
design, an increased emphasis has been placed on automotive cooling fan performance.
The goal of this study was to design and execute an experiment to measure all three
components of the phase-averaged velocity field on planes upstream of an automotive
cooling fan. The measurements were conducted with the use of a single component,
backward-scatter, fibre optic Laser Doppler Anemometer (LDA).

The fan was located in a fan test facility, designed so that the fan speed and flow
rate could accurately and independently be controlled. The facility was also designed so
that the boundary conditions were symmetrical and the flow upstream and downstream
could be characterized as being unbounded. The results of this experimental study are to
be used for validating a Computational Fluid Dynamics (CFD) model of a fan that has
been developed independently and has the same design and flow conditions.

To perform this experiment, a fixture and traverse were designed and constructed
so that a single component probe could be set in three different locations to allow
measurement of all three components of velocity at the same location in space. The
traverse was designed to locate the measurement position along a radial line, which
extends to the fan blade tip. By grouping measurements according to the phase angle of
the fan, phase angle averaged velocities were determined over the measurement plane,
which is normal to the fan axis. Such measurements were made for six different
operating conditions. These were comprised of two fan speeds and three flow rates.
Three different fan designs were tested, for a total of 18 experiments.
The data collected was used to create velocity contour plots, which were analyzed. The variation in contour plots as a result of a change in flow rate, fan speed, and fan design are discussed.
To my wife Andrea for her faith, support and friendship.
ACKNOWLEDGEMENTS

The author wishes to express his deep and sincere gratitude to Dr. G.W. Rankin for his guidance, unceasing help and generous aid during this study.

Technical assistance rendered by Mr. R. Tattersall in constructing the probe traverse and fixture is greatly acknowledged. As well, thanks are due to Mr. P. Seguin for his assistance with all the electronic equipment used in this project. Special thanks go to Keith DeGroot, an undergraduate student who wrote the control program that integrated the traverse controller with the Dantec measurement software as a part of his co-op work term.

Dr. D.L. Harrington’s assistance in determining the seed particle size was invaluable and much appreciated.

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# NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<td>F</td>
<td>Focal Length</td>
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<tr>
<td>d</td>
<td>Beam Spacing</td>
</tr>
<tr>
<td>D_L</td>
<td>Beam Diameter</td>
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<tr>
<td>E</td>
<td>Expansion Ratio</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength</td>
</tr>
<tr>
<td>f_D</td>
<td>Doppler Frequency</td>
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<tr>
<td>U_x</td>
<td>Velocity component in X direction</td>
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<tr>
<td>U_1</td>
<td>Velocity component measured when probe is in position 1</td>
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<tr>
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<td>t</td>
<td>Tangential velocity component</td>
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<tr>
<td>Mag</td>
<td>Velocity Magnitude</td>
</tr>
<tr>
<td>P_Mag</td>
<td>Precision uncertainty in the velocity magnitude</td>
</tr>
<tr>
<td>P_r</td>
<td>Precision uncertainty in the radial velocity component</td>
</tr>
<tr>
<td>P_a</td>
<td>Precision uncertainty in the axial velocity component</td>
</tr>
<tr>
<td>P_t</td>
<td>Precision uncertainty in the tangential velocity component</td>
</tr>
<tr>
<td>θ</td>
<td>Angle between two laser beams emitted from the transmitting optics</td>
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<tr>
<td>N_f</td>
<td>Number of fringes in the measuring volume</td>
</tr>
<tr>
<td>d_f</td>
<td>Distance between two adjacent fringes</td>
</tr>
<tr>
<td>φ</td>
<td>Phase shift angle</td>
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X  Distance between two measuring volume locations
R  Radial location of measuring volume
CHAPTER 1 - INTRODUCTION

The emphasis placed by automotive vehicle design engineers on increasing the interior space of the vehicle has led to a reduction of the available underhood space. This, coupled with the continual addition of new components and the use of larger engines, creates a very adverse thermal environment under the hood. This trend has lead to an effort by DaimlerChrysler to develop an underhood numerical simulation process that will help guide the design and packaging of current and future vehicles. The development of such an overall numerical simulation process depends upon the successful development of a number of subsystems.

DaimlerChrysler and the University of Windsor are collaborating on a project that focuses on the development of a new approach for simulating the fan performance in the case of under the hood installations. The ultimate objective is to develop and implement a completely new fan model, which can be used in the cooling module simulation, to predict the components of the velocity and the pressure rise. This project involves three main stages:

- Develop a comprehensive Computational Fluid Dynamics (CFD) model of an automotive cooling fan.
- Develop a fan test facility and validate the comprehensive model with the use of experimental data.
- Develop a new and simplified model based on conservation laws and fan geometry and validate with the use of the comprehensive model.

This study is concerned with the second stage of the overall project. The objective is to conduct a detailed experimental investigation of the flow field near an
automotive fan at a location upstream of the fan. The velocity measurements are to be made with sufficient accuracy on a grid of suitable spacing to allow detailed velocity contours to be constructed from the data for comparison with existing CFD predictions. A Laser Doppler Anemometer (LDA) was used for this study. A recently constructed fan test facility, located at the University of Windsor in a Mechanical, Automotive and Materials Engineering Fluid Dynamics laboratory, was used for this purpose. This facility was originally constructed to study the details of the velocity field of an automotive fan at downstream locations and to obtain fan performance characteristics. The study of the “open air” condition upstream of the fan required the design and construction of a traverse mechanism and its installation onto the facility in order to obtain these measurements.

The measurements were taken at a single plane upstream from three different fans that operated at six different operating conditions for a total of 18 experiments. The six conditions consisted of three flow rates and two fan speeds. The operating conditions were chosen based on the design of the first fan. For each fan speed, measurements were taken at the design flow rate. As well, a high flow rate and medium flow rate were used. The same operating conditions were used for the two other fans.

The experimental data was used to create velocity component and magnitude contour plots, which were investigated and compared. Changes in the contour patterns due to a change in fan design, fan speed or flow rate were identified and recorded.
CHAPTER 2 - LITERATURE SURVEY AND DETAILED OBJECTIVES

The literature survey is grouped into two main sections: (a) Laser Doppler Anemometry (LDA) and (b) turbo-machinery measurement techniques.

2.1 Laser Doppler Anemometry

2.1.1 History and General Information

Goldstein [1] gives a very good overview of Laser Doppler Anemometry. As well, Durrani and Great [2] and Rinkevichius [3] have published books describing the Laser Doppler Anemometer including optical configurations and signal processing. The LDA technique has been in use since Yeh and Cummins [4] published a paper describing the use of lasers for fluid velocity measurements in 1964. Since that time, many advances in optical configurations and electronic processors have made the LDA a very desirable method of measuring velocity. The method is non-intrusive, which means the flow will not be disturbed, as it would if a measurement probe, such as a hot wire anemometer, were used. It also has the ability to measure velocity in hostile environments such as combustion chambers and inter-blade regions in turbine rotors. The LDA also offers a good spatial resolution and is able to track very high frequency velocity fluctuations in fluid flow.

Lasers can be used to measure flow velocity by making use of the Doppler principle, which describes how the observed frequency of a wave changes due to the relative velocity of the wave source and observer. This principle can be applied to light and sound since both display a wavelike characteristic. If a sound or light source is moving, an observer will observe a different frequency depending on whether the
observer is moving with the source, or is stationary. The difference in perceived
frequency is proportional to the relative velocity between the observer and the source. If
both the observer and source are stationary, but the emitted wave intercepts a moving
object, which then scatters the wave, an observer also detects a difference in frequency
between the wave from the emitted stationary source and the wave scattered by the
moving object. This information combined with knowledge of the angles between the
source, object and observer can be used to determine a component of the velocity of the
object.

The Doppler principle mentioned above allows a single laser beam (source) to be
used to determine the velocity of a particle (moving object) that passes through the beam
and scatters light. The scattered light is detected by a photodetector (observer). Laser
light is used because the light is monochromatic. The problem with this configuration is
the very high frequency of the laser beam relative to the shift in frequency caused by the
moving object. Although this measurement can be taken, its accuracy will be low. An
alternate approach is to perform a function called optical heterodyning of the laser beam.
If two waveforms of different frequencies are combined, a beat frequency will result,
which is the difference between the frequencies of the two original beams. Three
methods have been used for optical heterodyning; reference beam, dual beam and dual
scatter. Only the dual beam has found widespread use. It is the method employed in this
study and hence is further explained below.

The dual beam method uses two beams of similar intensity. The easiest way to
get this configuration is to start with a single beam and then split it using a beam splitter
and mirror arrangement so that the beams are parallel. The two parallel beams are then
passed through an optical lens that focuses the beams to a point where they will cross, called the measuring volume. The dual beam configuration is shown in Figure 2.1. The scattered light from both beams combine to give a scattered wave that has a frequency equal to the difference of the two Doppler frequencies. This wave is converted to an electrical signal using a photodetector.

The relationship between the Doppler frequency, $f_D$, and the velocity component in the x direction, $U_x$, is given by equation (2.1). The angle between the two approaching laser beams is $\theta$ and the wavelength of the beam is $\lambda$.

$$f_D = \frac{2 \cdot U_x \sin(\frac{\theta}{2})}{\lambda} \quad (2.1)$$

This method has become the most widely used because the orientation of the receiving optics is not critical. The two most common orientations are to have the receiving optics directly opposite the transmitting optics, called forward-scatter, and to have the receiving and transmitting optics both housed in the same probe, called back-scatter. As long as the receiving optics are focused on the measuring volume, however, any orientation will work.

Durst et al. [5] describe Mie scattering theory, which states the intensity of scattered light is much stronger for a forward-scatter configuration. A forward-scatter configuration, therefore, is more desirable if the Doppler signal is weak. The disadvantage of a forward-scatter system is the need to ensure the receiving optics are properly focused. This requirement becomes more cumbersome if the measuring volume must be moved often. A forward-scatter configuration also requires more space than a back-scatter configuration. A back-scatter configuration is shown in Figure 2.2
An alternate physical explanation of the dual beam operation that does not involve the Doppler technique, has been given by Rudd [6]. When the two beams cross, their wave patterns cause constructive and destructive interference regions, called fringes, as shown in Figure 2.3. When a particle passes through the measuring volume, the velocity component parallel to the u vector shown in Figure 2.3 can be measured. As the particle passes through the measuring volume, it will scatter light only when it passes through an area of constructive interference. Knowledge of the angle between the two beams as well as the wavelength of the light can be used to determine the fringe spacing. By measuring the frequency at which the fringes are passed, the velocity component of the particle can be determined. The relation between the frequency and the velocity is the same as that determined using the Doppler principle.

One problem associated with the LDA technique, as it has been described, is directional ambiguity. Referring to Figure 2.3 and the fringe model previously described, the output from a particle travelling in the positive u direction and one travelling in the negative u direction would be the same. In order to overcome this problem, the frequency of one beam is shifted with the use of a Bragg cell, which uses a piezoelectric transducer. The result of a shifted frequency is that the fringes in the measuring volume will move (either in the same or opposite direction of the u vector in Figure 2.3) at a constant rate proportional to the frequency shift. If the velocity magnitude of a particle is greater than that of the fringe, the measured velocity of a particle moving in the same direction as the moving fringes will be reduced by the velocity of the fringes. The velocity of the fringes will increase the measured velocity of particles moving in the
opposite direction. Therefore, the direction of the particle's velocity can be determined by its magnitude relative to the motion of the measuring volume fringes.

2.1.2 Optical Parameters

In Figure 2.4 and Figure 2.5, the beam and measuring volume geometry are shown with the various dimensions labeled. With knowledge regarding the characteristics of the laser beam and the optics, the dimensions of the measuring volume can be determined. The optical lens is used to redirect two parallel beams so that they cross. The point where the two beams cross is known as the measuring volume, which has a length ($\delta_z$), width ($\delta_y$), and height ($\delta_x$). The perpendicular distance from the lens to the measuring volume is called the focal length (F) and the angle between the two beams after they pass through the lens is $\theta$. The diameter of the beams before they pass through the lens ($D_L$) as well as the expansion ratio (E) must also be known. The expansion ratio is the diameter of the beam before it passes through the lens divided by the diameter after it passes through the lens.

The length of the measuring volume is calculated using equation (2.2).

$$\delta_z = \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L \cdot \sin\left(\frac{\theta}{2}\right)} \quad (2.2)$$

The width of the measuring volume is given by equation (2.3).

$$\delta_y = \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L} \quad (2.3)$$

The height of the measuring volume is calculated using equation (2.4).

$$\delta_x = \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L \cdot \cos\left(\frac{\theta}{2}\right)} \quad (2.4)$$
As well as the dimensions of the measuring volume, information regarding the number of fringes (N_f) in the measuring volume as well as the fringe spacing (δ_f) is important. This information can also be calculated with knowledge of the laser wavelength and geometrical parameters. The number of fringes can be determined using equation (2.5).

\[
N_f = 8 \cdot F \cdot \frac{\tan \frac{\theta}{2}}{\pi \cdot E \cdot D_L}
\]  

(2.5)

The spacing between the fringes is calculated using equation (2.6).

\[
\delta_f = \frac{\lambda}{2 \cdot \sin \left( \frac{\theta}{2} \right)}
\]  

(2.6)

### 2.1.3 Seed Particle Size

The previous description of the Doppler principle shows how the velocity of an object can be measured. If the object is suspended in a fluid flow, and is small enough to follow the flow precisely, the fluid flow can be measured using an LDA. For gas flows, particles, called seed particles, are often introduced into the flow, while most liquid flows have enough small particles naturally occurring in the flow to take accurate measurements. The diameter of the particle is a critical parameter in measuring fluid flow using an LDA system. Selection of the correct particle size is actually a compromise between a large particle that generates a good signal and a small particle that follows the flow. Various techniques have been used to measure particle size. For example, with the use of a supersonic wind tunnel, Olejak et. al [7] have shown that particle sizing can be accomplished by measuring the relaxation length of particles as they pass through a shock wave. Saffman [8] describes a method of measuring particle diameter with the aid of a
phase Doppler anemometer. Unlike an LDA, the fringe spacing in the measuring volume of a phase Doppler anemometer must be much smaller than the particle. As a particle passes through the measuring volume, it scatters the light from many fringes. The light from the various fringes will be scattered in different directions depending on the location of the particle intersection with the fringe. The direction of the scattered light is modeled assuming the particle is spherical. Saffman also describes the upper and lower limits of particle diameters that can be measured. These limits are a function of the equipment optics and the laser wavelength.

Menon and Lai [9] describe the parameters to consider when choosing the type of the seed particle. They mention that no single physical parameter describes the light scattering ability of a particle. For this reason, no single seed particle selection will result in optimum results for all flow situations.

The signal to noise ratio (SNR) should be as great as possible. A low SNR could result in the inability of the processor to distinguish the noise contribution from the actual signal, resulting in erroneous velocity measurements. Current LDA signal processors have a method of rejecting a measurement when the SNR is too low. This solution, however, does not improve the data rate. Two physical characteristics affect the SNR; the particle size relative to fringe spacing and the light scattering ability of the particle. Menon and Lai give evidence that indicates the optimum ratio of particle diameter to fringe spacing for a high SNR is close to unity. Scattered light is a combination of reflection, refraction, and diffraction. The importance of each component is a function of the location of the receiving optics. For a forward-scatter configuration, refraction and diffraction are the methods by which the receiving optics sense the particle. For this
configuration, a small refractive index is important. For back-scatter techniques, reflection and a high refractive index is ideal.

2.2 Turbo-machinery Measurement

2.2.1 LDA in Turbo-machinery and Fan Studies

The use of Laser Doppler Anemometry (LDA) in turbo-machinery measurement has become very common. A detailed knowledge of the flow field near rotating machinery is desirable because it can lead to a better understanding of characteristics such as efficiency and performance. In high performance machinery, phenomenon such as unsteady fluid loads and the interaction of flow fields with structural elements may not be recognized in the design stage, but can be measured in actual operating conditions. Because of the non-intrusive nature of the LDA, velocity measurements can be made between blades of rotating machinery without destroying a probe. A number of studies have used the LDA for this purpose.

Menon and Hoff [10], as well as Menon [10,12] have used two and three component LDA’s to acquire phase averaged measurements in the inter-blade region of a rotor. In both experiments, an encoder that generates a signal once per revolution along with a clock are used to determine the phase angle of the rotor at the time a particle passes through the measuring volume. The number of angle bins is rather large at 1000 per revolution in [10] and 9000 in [10]. This configuration allows for a high degree of accuracy, but requires a long running time in order to acquire a sufficient number of particles in each angle bin. Because these two experiments use multi-component measuring systems, higher order statistics can be calculated as well as the average velocity.
Lepicovsky [13] investigated two methods for data reduction while making phase averaged measurements in turbo-machinery. In general, LDA measurements are used for comparison with a Computational Fluid Dynamics (CFD) model. When modeling a fan, symmetry is often used because the space between the blades, the channel, is the same for all blades. When making an LDA measurement a researcher, by extension of the CFD model, need only measure the flow through a single channel. Alternatively, one could average the measurements from each channel. Lepicovsky noted, however, that geometric variation between channels, as a result of manufacturing and assembly tolerances, can lead to a large variation in flow fields from channel to channel. For this reason, comparison between CFD code and LDA data must be made very carefully.

Although Lepicovsky does not offer a method for making this comparison, he does suggest a proper data acquisition method and phase averaging technique.

Lepicovsky describes two methods of data sampling. The first is ‘blade channel conditional sampling’ in which an encoder is reset at the beginning of every blade passage. For the other option, called ‘rotor conditional sampling’, the rotary encoder is reset at the beginning of every revolution. In the first method, every sample is weighted equally and in the second, every channel profile is weighted equally. Lepicovsky recommends the use of ‘rotor conditional sampling’ so that channel to channel variation is not lost. This method is more demanding on computer memory and data rate than ‘channel conditional sampling’ because a statistically significant number of samples must be collected for every rotor channel. Lepicovsky does not suggest a method for averaging the data from each channel for comparison with CFD data, however.
In the current study, measurements are taken upstream of the fan, not between blades. The measured flow field, however, shows periodicity with some variation, similar to the data presented by Lepicovsky. A ‘rotor conditional sampling’ technique was used, but the data was not averaged to form a velocity profile for a ‘typical’ channel. Instead, velocity measurements for each fan blade are considered separately. For this reason, velocity contours from this study may not appear symmetrical, as they would from a CFD study.

In an application similar to the current study, Morris et. al. [14,15] measured flow fields downstream of an automotive cooling fan using a hot wire anemometer. The purpose of Morris’ study was to test an ‘aerodynamic shroud’ device used to overcome the effects of large tip clearances required on cooling fans in trucks. The large tip clearance is required because of the relative motion between the fan and the surrounding shroud.

Very little work has been published concerning three component measurement techniques using a single component Laser Doppler Anemometer. Generally, a three component system is used for making three component measurements for two reasons. Researchers are often interested in measuring turbulence quantities as well as time averaged velocity. Measurement of turbulence quantities requires all three components to be measured simultaneously. As well, many privately funded research projects have three component LDA systems available.

2.2.2 Facility Design

Morris [16] designed and built a fan test facility at Michigan State University, Lansing, Michigan. Nourse [17] used Morris’ work as a basis for the development of a
fan test facility at the University of Windsor. For the current study, this facility was
modified by adding an LDA on a traverse and fixture assembly.

Both theses describe a facility designed to control the speed of an automotive
cooling fan as well as the flow rate across the fan. With the fan conditions controlled,
velocity component measurements were taken downstream using a hot wire anemometer.
Both facilities can be basically described as a box that is large enough to simulate
external flow by having negligible velocity near the internal walls. The box is sealed
except for an inlet and outlet. The cooling fan is placed across the inlet and the flow
through the outlet is measured.

In Morris' study, the flow rate was measured using an integral technique that
involves the use of the force exerted by the flow on a turning vane. Nourse's study used
a more traditional orifice plate placed in ductwork at the outlet.

In both studies, the velocity measurements were phase averaged with respect to
fan angle. Both facilities made use of an optical encoder to measure fan angle and speed.
While Morris' encoder generated only a reset signal, Nourse's encoder generated a reset
signal as well as a signal for every 2° increment.

2.3 Detailed Objectives

The current study involves using an LDA to measure the three components of
velocity at a location upstream of an automotive cooling fan. The decision to use an
LDA is based on the fact that this measurement technique is non-intrusive. The LDA
does not alter the approach flow to the fan and hence fan performance. The LDA is
positioned using a mechanical traverse. The output signal is analyzed and recorded using
a Burst Spectrum Analyzer (BSA) and an accompanying BSA Flow software program.
With the use of an angular encoder arrangement, the data is phase averaged. Velocity contour maps are constructed on the measurement plane.

As a result of the literature survey, and considering the availability of equipment, the following detailed objectives have been formulated.

1. Utilize a single component fibre optic, back-scatter laser Doppler anemometer with frequency shifting to measure each of the three components of average velocity on a plane upstream of an automotive cooling fan.

2. Design, construct and implement a fixture mechanism that will insure proper positioning of the LDA probe such that the three components of average velocity are measured at the same location in space within an acceptable tolerance.

3. Design, construct and implement a traverse mechanism that will allow placement of the fixture and LDA probe such that the measuring volume will be placed at a number of positions on a radial line extending from the axis of the fan and in planes, which are perpendicular to the fan axis, upstream from the fan.

4. Acquire three component average velocity field data for one upstream plane, two shaft speeds, and three fan flow rates for three different fan designs.

5. Present the average velocity field data in the form of velocity contour plots suitable for comparison with CFD results.

6. Investigate the effect of fan design, speed and flow rate on the average velocity magnitude as well as the axial, tangential and radial components of average velocity.
Figure 2.1: Dual Beam Heterodyne Method

Figure 2.2: Typical Back-scatter Configuration
Figure 2.3: Fringe Pattern in a Dual Beam Measuring Volume

Figure 2.4: Beam Geometry

---

1 Reproduced from Dantec Slide presentation
Figure 2.5: Measuring Volume Geometry

\[ \delta_x \]

\[ \delta_f \]

\[ \delta_z \]

\[ Z \]

\[ X \]

\[ ^2 \text{ibid.} \]
CHAPTER 3 - EXPERIMENTAL APPARATUS

3.1 Laser Doppler Anemometer Setup

The block diagram in Figure 3.1 shows the components of the fibre optic LDA used for this experiment. The laser beam, which is linearly polarized, is emitted (1) and is then split into two beams of equal intensity (2). The beams are also modified so that they are polarized in directions orthogonal to one another. One of the beams is led through a Bragg cell (3) where it is shifted by 40 MHz. The other beam is passed un-shifted through the Bragg cell section through a reflecting prism and recombined with the shifted beam (4). The laser beam is now coupled into the fiber (7). The fibre used is a ‘high-birefringence’ fiber, which allows the laser light to pass without being affected by bends or twists in the fibre, as well as pressure or temperature changes. In the probe, the single beam is split with a beamsplitter (8) that differentiates between the two beams based on the orientation of their polarization. The beam that was previously rotated is rotated back in the rotator (9). The beams then pass through the transmitting/receiving optics and cross at the measuring volume (10). When a particle passes through the measuring volume, the scattered light is received through the transmitting/receiving optics and passes through the receiving fibre (11) to the photodetector (12) and photomultiplier (13). The resulting electrical signal is then analyzed with the use of the Burst Spectrum Analyzer.

A fibre optic back-scatter system was more desirable for this experiment due to the difficulty associated with traversing the measuring volume along the radius of the fan and ensuring proper focus of the receiving optics.
3.1.1 Optical Parameters

In Table 3.1, the laser characteristics and optical parameters required to compute the dimensions of the measuring volume are given for the LDA optics that were used in the current study. These parameters determine the geometry of the measuring volume and therefore have influence on an acceptable particle to use for seeding.

<table>
<thead>
<tr>
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<th>Symbol</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Focal Length</td>
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<td>50 mm</td>
</tr>
<tr>
<td>Beam Spacing</td>
<td>d</td>
<td>11 mm</td>
</tr>
<tr>
<td>Beam Diameter</td>
<td>$D_L$</td>
<td>0.27 mm</td>
</tr>
<tr>
<td>Expansion Ratio</td>
<td>E</td>
<td>1.0</td>
</tr>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>632.8 nm</td>
</tr>
</tbody>
</table>

Table 3.1: LDA Optical Parameters

The length of the measuring volume was calculated using equation (2.2). The length of the measuring volume was calculated as $\delta_z = 1.365 \times 10^{-3}$ (m) using the parameters in Table 3.1. The formula for calculating the width of the measuring volume is given in equation (2.3). With the values given in Table 3.1, the value of the width is $\delta_y = 1.492 \times 10^{-4}$ (m). The height of the measuring volume is calculated using equation (2.4). With the values given in Table 3.1, the value of the height is $\delta_x = 1.501 \times 10^{-4}$ (m).

As well as the size of the measuring volume, information regarding the number of fringes in the measuring volume as well as the fringe spacing is important. The number of fringes is calculated using equation (2.5). The number of fringes is calculated to be $N_r = 51$. The spacing between the fringes is calculated using equation (2.6) and is determined to be $\delta_r = 2.894 \times 10^{-6}$ (m). These calculations are presented in full in Appendix I.
3.2 Seed Generation

Seed particle generation was accomplished with the use of a standard special effects fog generator; Radio Shack Fogger Model Number 4203058. The fogger operation depends upon heating a solution of food grade glycols and water. The solution used for this experiment, ‘Slow Dissipating Fog Solution’ Model Number 42-8059, was also obtained from Radio Shack. This method of seed generation was attractive because the environment was not isolated from the surrounding laboratory facilities. Health and safety issues were therefore important. The average particle diameter was not provided by the supplier so an experimental investigation was conducted to obtain this information. This experiment and results are described in the section 4.1.4.

The back-scatter optical configuration was successful mainly because the optics, seed and laser used in this experiment combined to create a strong enough signal for valid readings and an adequate data rate.

3.3 Fan Test Facility

An existing fan test facility has been used in this study. The details have been reported in Nourse [17], however, general features are described below.

The facility consists of a 3m x 3m x 3m enclosure with the test fan mounted on a vertical shaft such that the fan diameter is in the plane of the ceiling. A cutaway view of the facility showing the fan, fan shaft, fan motor and location of the LDA is given in Figure 3.2. The fan shaft is turned by a variable speed DC motor through a belt drive. The effect of “ram air”, caused by vehicle motion, is experimentally simulated by drawing air from the room surrounding the enclosure, through the test fan, into the enclosure and back to the surrounding room using an auxiliary blower. The volume flow
rate of air through the fan is measured using an orifice type flow meter and controlled with a personal computer through an A/D and D/A converter.

Figure 3.3 shows a perspective view of the facility with the area of the ceiling around the fan, as well as the facility door, removed. The numbers in Figure 3.3 indicate the flow path through the facility. At a large distance from the fan (1), the flow is zero. The flow accelerates through the fan (2) and into the upper section of the facility. The facility was designed to be large enough that the flow at the inner side walls of the facility was negligible. The fan shaft and drive mechanisms are housed at a location downstream of the fan such that the fan performance and measured velocity field were not affected. The flow is kept approximately symmetrical by the use of grating in the four corners of the facility. Elsewhere the upper and lower sections of the facility are separated by plywood. A rectangular diffuser is located at the centre of the lower section of the facility. Air is drawn through the grating separating the upper and lower sections and into the diffuser with the use of a mechanical blower (3). The air then flows through the ductwork (4) and through an orifice plate (5), which is located at a sufficient distance from an elbow in the duct work to produce fully developed pipe flow. This orifice plate is used to measure the flow rate and provide a signal for its control. The flow then returns to the laboratory at a large distance from the facility (6). With this facility, the fan speed and flow rate through the fan are independently controlled.

Velocity components can be measured using an X-array hot-wire anemometer on planes in a region downstream of the fan.
This facility was modified by adding a traverse and fixture upstream of the exterior ceiling on which the LDA probe was mounted. The design of the traverse and fixture is considered next.

3.4 Fixture and Traverse Design

The goal of this experiment was to measure all three components of the air velocity at points on a plane upstream of a fan. The equipment used for this experiment consisted of a single component fibre optic, back-scatter laser Doppler anemometer arrangement. In order to perform the experiment, a traverse and fixture were required.

The traverse was designed to move the fibre optic probe along a radial line in a plane perpendicular to the fan axis. Motion of the traverse was in the horizontal direction along the traverse guide rails to allow positioning of the fixture at various radial locations. The traverse and fixture assembly is shown in Figure 3.4 and Figure 3.5.

The fixture was designed to accurately and repeatedly position the probe so that the laser beams will focus the measuring volume on the same point in space when the probe is located in any of the three orthogonal orientations. The probe fixture was also designed to move along the probe fixture guide rails, which are at an angle to the horizontal to allow positioning of the measuring volume on different horizontal planes.

The traverse and fixture were also designed for simplicity in manufacture and ease of use. Details are provided below.

3.4.1 Traverse Detail

The traverse details are shown in Figure 3.6 and Figure 3.7. The traverse can move a distance of 340 mm along its guide rails. Movement was provided and controlled by a drive screw and stepper motor.
The stepper motor resolution was 200 steps / revolution. The drive screw had a standard 6 threads / inch. These two values combined to give a step size of 21.2 μm / step. The traverse resolution, therefore, was ± 10.6 μm.

Control of the stepper motor was accomplished with the use of an auxiliary computer. When the probe is to be moved to the next measurement position, the BSA software sends a signal through a serial port connection, to the auxiliary computer, which then initiates the routine to move the traverse. When the probe is in the new position, the auxiliary computer responds to the BSA software and measurement resumes. Details of the auxiliary computer and associated hardware and software are provided by Degroot [18]. A modified version of this report is included in Appendix II.

The fixture was secured to the traverse with the use of the fixture guide rail bearings. As seen in Figure 3.7, these bearings are oriented 15° from the measurement plane. This orientation serves two purposes. First, this angle allows the measuring volume to be lower than the probe allowing measurements very close to the fan without damaging the probe. Second, this angle allows the vertical height of the measurement plane to be set. The placement of a set screw and collar on the fixture determine the height of the measuring volume. The fixture is kept in place by gravity. The distance of the measurement plane upstream of the fan can be set from 0 to 0.060 m.

3.4.2 Fixture Detail

Figure 3.8 shows a top view of the probe fixture. The fixture basically consists of two arms oriented 90° from one another and guide rails for connecting the fixture to the traverse.
The detail of the fixture arms is shown in Figure 3.9. The arm consists of a probe support, probe support bearings, and adjustment screw. The design allows the user to position the arms of the fixture and use set screws to lock the position.

The probe was connected to the probe support with the use of a probe collar, shown in Figure 3.10. The probe was locked into place with the use of a ball detent in the probe support that locates to a dimple in the probe collar. The collar was used only because a dimple could not be machined in the probe itself. The probe was arbitrarily set in the collar and then locked into place with a set screw. The ball detent assured accuracy and repeatability when rotating the probe about its axis in one arm and when moving the probe from one arm to the other. This design allowed the user, with the proper setup procedure, to ensure the measuring volume was in the same location in each orthogonal direction. As well, the fixture gave the user the capability to ensure the probe was aligned properly so that the probe measured three orthogonal components of velocity in the same location. The procedure for this setup is explained in Chapter 4.
Figure 3.1: Typical Fibre Optic Back-scatter LDA Arrangement

\[3\] Reproduced from FOLDA manual published by Dantec
Figure 3.2: Cutaway View of Fan Test Facility

Figure 3.3: Perspective View of Fan Test Facility
Figure 3.4: LDA Traverse and Fixture Assembly: Side View

Figure 3.5: LDA Traverse and Picture Assembly: Front View
Figure 3.6: Traverse – Perspective View

Figure 3.7: Traverse - Side View
Figure 3.8: Probe Fixture

Figure 3.9: Fixture Arm
Figure 3.10: LDA Probe in Collar
CHAPTER 4 - EXPERIMENTAL PROCEDURE

In this chapter, the procedure used for taking a measurement is explained. The experiment was conducted with care and efforts were made to eliminate any extraneous variables.

The procedure for this study can be divided into two categories; the preliminary setup and the actual velocity measurements. The preliminary setup involved assembly and alignment of the LDA optics and their connection to the BSA. As well, the software that controls the BSA was installed on a personal computer. The interface between the BSA and the personal computer was an IEEE 488 General Purpose Interface Bus (GPIB) purchased from National Instruments. The optical encoder in the facility was connected to the BSA using coaxial cable and a BNC connector.

Once the equipment described in Chapter 3 was ready, a series of preliminary experiments, as described in section 4.1 were conducted. The procedures described in section 4.2 were used to take the actual velocity measurements.

4.1 Preliminary Setup

The procedures followed in the preliminary setup were used to ensure the measurement procedure was appropriate and the results accurate. First, the probe fixture was aligned to ensure the measuring volume was correctly placed and an experiment was performed to validate the setup. Next, a procedure was followed in order to ensure the sample size was statistically significant. As well, an experiment was conducted to ensure the averaging time was adequate. Finally, a procedure was followed so that the seed particle size could be measured. These procedures were followed only once before the
velocity measurements were taken and proved that the measurement procedure was valid for this study.

4.1.1 Traverse and Fixture Setup

As explained in Chapter 3, the traverse and fixture design allow the user to ensure the measuring volume is in the same location in each orthogonal direction. In this section, the procedure used to set the measuring volume is explained. As well, the procedure for an experiment used to validate the location of the measuring volume is described and the results analyzed.

The following procedure was used to setup the probe fixture. With the probe in one arm, a cross-hair apparatus was positioned in the measuring volume. Without moving the cross-hair, the probe can then be set in the other arm. The probe support in this arm was then moved through the probe support bearings so that the measuring volume was again focused on the cross-hair. An adjustment screw was incorporated into the design so that the probe could be precisely positioned. The probe support was also capable of being rotated in each bearing. This degree of freedom gave the operator the ability to insure that the probe, while locked into the detent, was actually aligned so that horizontal and vertical velocity components could be measured. The fixture and cross-hair apparatus used in this experiment are shown in Figure 4.1.

Both probe fixture arms have detents so that the probe can be aligned to measure both horizontal and vertical directions. Measurement of the vertical component in both arms is redundant. This redundant component can be used to verify the location of the measuring volume when the probe is moved from one arm to the other. Figure 4.2 is a graph of the average velocity as measured from two redundant components, U1
(corresponding to the vertical component in the left arm), and U4 (corresponding to the vertical component in the right arm). This experiment was performed using a count of 50,000 for reasons described in the sections on sample size and averaging time. Also, the measurement was taken at a radius 20mm from the fan hub, or 85mm from the fan axis. This graph also shows the percent difference in the measured velocity between each component. This graph, as well as the data in Table 4.1, indicate the velocity difference fluctuates between −5.38% and +6.22% around a mean close to zero percent. The maximum uncertainty is 0.26m/s. The complete set of data for this experiment is presented in Appendix III.

<table>
<thead>
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<tr>
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<td>Average Value</td>
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</tr>
<tr>
<td>Standard Deviation</td>
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</tr>
</tbody>
</table>

Table 4.1: Redundant Velocity Component Data Analysis

This analysis shows the probe was phase shifted when it was moved from one arm to the other. A short analysis was conducted in order to quantify the phase shift.

In order to estimate the phase shift of velocity component U4 relative to U1, the data for each fan blade was averaged together to create a velocity graph for a ‘typical’ fan blade. The data for U1 and U4 were plotted on the same graph. The U4 plot was then phase shifted until it overlapped the U1 plot. This graph is shown in Figure 4.3, which shows U1, U4 and U4 shifted 1.4°.

Knowledge of the phase shift, \( \phi = 1.4^\circ \), and the radial position, \( R=85.0\text{mm} \), can be used to determine the distance between the position of the measuring volume for U1 and U4. Assuming the line joining U1 and U4 is perpendicular to a radial line from the fan
center, the distance between the two locations of the measuring volume, \( X \), can be related to the phase shift angle and the radius by the following equation:

\[
\sin(\phi/2) = \frac{X/2}{R}
\]  

(4.1)

Solving for \( X \), the distance is 2.1 mm. The uncertainty in the location of the measuring volume, therefor, is half of this distance or \( \pm 1.1 \) mm.

Since the above result is dependent upon a graphical analysis and the uncertainty created by the misalignment of the measuring volume is only \( \pm 6\% \), the setup was determined to be adequate for this experiment.

### 4.1.2 Determination of Proper Sample Size

LDA measurements can only be made when a particle passes through the measuring volume. The occurrence of a particle in the measuring volume is a random event. When a particle arrives, the BSA records the velocity of that particle as well as the time that the particle arrives (as determined by a clock internal to the Burst Spectrum Analyzer). This information, along with the output from the optical encoder was used to place the particle’s velocity into the appropriate angle bin. The setup has 180 bins each with a width of \( 2^0 \). The velocity from all particles in a bin were then averaged to generate the phase averaged velocity for that bin.

According to statistical theory, determination of a normally distributed population mean (i.e. the mean value of an infinite number of readings) can be accomplished with knowledge of the mean and standard deviation of a sample from that population if the sample size is large enough. The population mean can also be determined if the population standard deviation is not known. If the population standard deviation is unknown, the accepted minimum sample size is 30 [19]. The sample size is greatly
reduced if the population standard deviation is known. In order to determine the true mean value of the velocity in each bin in this experiment, enough data must be acquired to ensure that every angle bin has at least 30 samples.

The two parameters that may be set on the BSA that determine when data acquisition will end are the total number of counts recorded and the maximum length of time allowed for data collection. When either the desired count, or the running time are reached, the experiment will end. The software is not capable of using the number of counts in each angle bin as a running parameter, so the total number of counts must be large enough to ensure that each angle bin has at least 30 samples.

The problem is further complicated due to the fact that the BSA records the signal from the optical encoder as well at the arrival of a particle in the measuring volume as a count. With this configuration, an experiment could run long enough to allow the fan to cycle enough times to trigger the end of the experiment without a single particle passing through the measuring volume.

To ensure that each angle bin has a sample size greater than 30, a series of measurements were taken at one radial location, each with an increased count size. For each experiment, the number of particles that passed through the measuring volume in each angle bin was recorded.

Figure 4.4 shows the number of particles that were measured in each angle bin for an experiment that used 10,000 samples. The ordinate shows the counts in each bin and the abscissa shows the angle bin. This graph shows that very few particles passed through the measuring volume in each angle bin. Many bins have less than 30 particles and some have close to 10. For the next experiment, the count size was increased to
50,000. Figure 4.5 shows the number of particles in each angle bin, for this experiment. The data from the 50,000 count experiment shows that every angle bin has well in excess of 30 samples.

These sample sizes indicate that a smaller total count could probably be used in order to generate samples sizes closer to 30. Using a smaller total count may save time, but doing so would also increase the risk that the sample size in a bin may be below 30 for some experiments since particle arrival is a random event. For this reason, the total count was kept at 50,000.

Notwithstanding the above results the data was examined after every experiment to ensure that each bin had a sample size of 30. If an angle bin had fewer than 30 samples, the experiment was repeated for that radial location.

4.1.3 Determination of Phase Averaging Time

The sample size of 30 referred to in the previous section is only sufficient if the particle velocities are randomly distributed and conform to a normal distribution. The samples will conform to a normal distribution if the measurements are taken over a sufficient length of time. If the time period is long enough, the time mean velocity, which is steady, will be measured. This assumption allows the measurements of all three components of flow with the use of a single component LDA.

The best test to ensure the time mean velocity is actually measured is to conduct an experiment that measures the average velocity at a single radial position and then to repeat the measurement using a longer time period. The averaging time is sufficiently long when the results from one experiment are sufficiently close to the results from another experiment with a larger averaging time. Since the measurement of a single seed
particle is a random event, dependent upon the arrival of the particle to the measuring volume, the length of time required for a complete average velocity measurement at a single radial location cannot be directly controlled. This time period can be indirectly controlled, however, by increasing the count size. So an experiment similar to the one described in the above section was conducted. Instead of measuring the particle count in each bin, however, the average velocity measured in each bin was recorded. When the difference in the average velocity between two experiments is sufficiently small, the count size is large enough to ensure a sufficient averaging time.

Figure 4.6 shows phase averaged data for an experiment that used 10,000 samples. The abscissa shows the angle bin and the ordinate shows the average velocity. This graph looks fairly good. The data show 5 repeated humps, which corresponds with the number of blades on the fan used in the experiment. The humps are also fairly smooth. Figure 4.7 shows the average velocity for an experiment using 50,000 counts. This data appears to be improved from the data acquired in the previous experiment since the graph is smoother. As mentioned in the previous section, an experiment that incorporates a count of only 10,000 results in less than 30 samples in each angle bin. This data, therefore, may be improved because of the longer averaging time or because the sample size in each bin is larger.

Figure 4.8 shows the measured average velocity for an experiment using 100,000 counts. The velocity data is very similar to the data from the previous experiment.

The percentage difference of the average velocity in each angle bin between the data acquired in the 50,000 count experiment and the 100,000 count experiment was calculated. The data from these two experiments is presented in Appendix IV. With the
use of the data in Appendix IV, Table 4.2 was created. These values show that the
difference in data acquired using a larger sample size (which corresponds to a larger
averaging time) is clearly smaller than 2%.

<p>| | |</p>
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<tr>
<td>Standard Deviation</td>
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</table>

Table 4.2: Sample Size Data Analysis

Since the measured phase averaged velocity did not change from one experiment
to the next, the phase averaged flow was determined to be steady. A steady flow
indicates the averaging time for both experiments was sufficiently long to measure the
true phase averaged time mean velocity. Therefore, the experiment was run using a
50,000 count.

4.1.4 Determination of Seed Particle Size

The size of the particles generated by the Radio Shack Fogger was determined
with the use of an Aerometrics Phase Doppler Particle Analyzer (PDA). The PDA was
set up with a forward-scatter configuration. The equipment is located in the General
Motors Research and Development (GMRD) Thermal Energy Systems Laboratory,
Warren, Michigan. The fogger was moved to this location for testing. The tests were
conducted with the assistance of Dr. D. Harrington of GMRD.

Figure 4.9 depicts the output screen from a successful measurement of particle
diameter. The top figure shows a histogram of particle diameters and the bottom shows a
histogram of velocities measured. The PDA was configured to measure a velocity
component perpendicular to the actual flow of particles from the seed generator, so the
expected mean velocity was 0 m/s. The arithmetic mean diameter is 2.840 microns, the
median diameter is 2.489 microns. The sample size was 7579 particles.

4.2 Velocity Measurement Procedure

In this section, the procedure for taking the actual velocity measurements will be
explained.

4.2.1 Fan Operating Conditions

Completion of this experiment required taking measurements for three different
fans, each operating at three different flow rates and two different speeds for a total of 18
experiments. Table 4.3 is a test matrix that identifies the operating conditions used for
each set of measurements and labels each set with an identification code.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Flow Rate (CFM)</th>
<th>Fan Speed (rpm)</th>
<th>Fan ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
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<td>2300</td>
<td>1</td>
</tr>
<tr>
<td>B1</td>
<td>635</td>
<td></td>
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</tr>
<tr>
<td>C1</td>
<td>1123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>800</td>
<td>2700</td>
<td>2</td>
</tr>
<tr>
<td>E1</td>
<td>737</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>1327</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
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<td>2300</td>
<td>3</td>
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<tr>
<td>B2</td>
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<td>C2</td>
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<tr>
<td>D2</td>
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<tr>
<td>B3</td>
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<td></td>
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<tr>
<td>C3</td>
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<td>D3</td>
<td>800</td>
<td>2700</td>
<td></td>
</tr>
<tr>
<td>E3</td>
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</tr>
<tr>
<td>F3</td>
<td>1327</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Test Matrix
Fan 1 has five blades with a ring diameter of 0.3090m and a hub diameter of 0.1175m. The leading and trailing edges of the blades on Fan 1 rotate in a clockwise direction as the blade extends from the hub to the tip. Fan 2 and 3 each have nine blades. Fan 3 differs from fan 2 by the blade shape. The leading and trailing edges of the blades of Fan 2 are curved in the counter-clockwise direction. On fan 3, the leading edge is straight, but the trailing edge is curved. The ring and hub diameters for fans 2 and 3 are the same. The hub diameter is 0.1300m while the ring diameter is 0.3090m.

4.2.2 Velocity Data Acquisition

The following procedures include the steps taken to obtain one set of readings. For a more detailed explanation regarding the use of the BSA Software, refer to the proper manual [20].

As previously mentioned, this experiment involved measuring all three components of the velocity in a plane upstream of a fan with the use of a single component measurement system. Measurements were taken at the intersection points on a grid as shown in Figure 4.10. Once the appropriate amount of data was acquired, the traverse was moved to the next radial location and data collected. This procedure continued until all radial locations were completed.

Table 4.4 gives the location of the plane, as well as the radial positions measured for Fan 1. Measurements were taken on a total of 20 radial locations. The distance between each radial location was about 4.8mm. Because the fan hub extended upstream through the measurement plane, measurements could not be taken at this radial location. Instead, the innermost radial position measured was 4.8mm from the hub.
Table 4.4: Measurement Locations for Fan 1

Table 4.5 gives the location of the plane, as well as the radial positions measured for Fan 2 and Fan 3. The measurement locations are the same for these two fans since they have the same dimensions. Since the hub did not extend through the measuring volume, a measurement could be taken at the radius of the fan hub. For this reason, a total of 21 radial locations were used for these fans.

Table 4.5: Measurement Locations for Fan 2 and Fan 3

The general procedure for this experiment was to take measurements for a single component across the entire plane and then to traverse the plane again measuring the second component and then repeat measuring the third component. This procedure was more desirable than measuring all three components at one radial location before moving to the next location because the movement from one radial location to the next was automated, while moving the probe in order to change the measured velocity component was a manual operation.

The following steps were required for setting and running the experiment.

1. The power to facility fan and blower was turned on.
2. Using the facility controller computer and software, the desired fan speed and flow rate were set. Refer to Nourse [17] for this procedure.

3. The traverse was reset.

The BSA was capable of operating a traverse driver. The traverse itself could be operated independently of the BSA. The traverse guide rails had a stop at each end to prevent the traverse from coming loose. The guide stops have been set up so that the measuring volume is located at the innermost radius when the guide rail bearings hit the stop. The traverse was manually moved until it hit this stop. The BSA was then used to ‘reset’ the traverse as described in the operating manual. The BSA has a “wizard” that can be used to set up a grid. In this case the grid is a one dimensional grid that represents all the radial locations where measurements are taken. Twenty radial locations were set for Fan1 and twenty one were set for each of Fan2 and Fan3.

4. The desired LDA parameters were set:

- **Expected Minimum Velocity.** This value depends on the operating condition as well as the velocity component being measured. The value generally falls between 0.0m/s and -7.0m/s for the conditions measured.

- **Expected Maximum Velocity.** This value also depends on the operating condition as well as the velocity component being measured. The value generally falls between 2.0m/s and 12.0m/s for the conditions measured.

- **High Voltage:** 1400 to 1600 volts

- **Signal Gain:** 30 dB

- **Record Length:** 16 to 32
These values were determined by running an experiment using only 5 evenly spaced radial locations that span the fan and evaluating the results. If any of the locations yielded unsatisfactory results, the parameters were changed and the pre-experiment repeated.

In order to evaluate the pre-experiment results, a histogram of the velocities at each position was viewed. If any of the histograms appeared to be clipped, the expected velocities were inappropriate. If the data rate or the number of particles in an angle bin were too small, the high voltage, signal gain and record length had to be changed. This procedure requires practice and a trial and error approach. This pre-experiment was run at least once for every operating condition and every velocity component measured. For a complete set of the parameters used in each experiment, see Appendix V.

5. The Cyclic Phenomenon parameters were set:

The data collected was phase averaged according to the rotation angle of the fan. The data was phase averaged with the use of the optical encoder in the fan test facility as well as the BSA’s internal clock. The BSA Flow software included an option known as the Cyclic Phenomena add-on. This option is designed for measuring flows that have a cyclic phenomenon as a result of an external influence such as fan rotation. The fan angle was divided into angle bins of \(2^0\) width. The Cyclic Phenomenon add-on requires a signal to indicate the end of a revolution. This add-on can then phase average the data based on the information from the reset pulse and internal clock, or from the reset pulse and a signal for every angle bin from an encoder. For this project the data was averaged with the use of the internal clock and the reset pulse. The following parameters were set on the Cyclic Phenomena add-on:
• Cycle length: 360 deg
• Sub-cycles: 1
• Phase average bins: 180
• External/Internal clock: Internal
• Select channel: BSA 1
• Pulses per cycle: (not relevant for this setup)

6. Data Acquisition was begun.

One experiment was run for each velocity component on every operating condition. All velocity measurements were recorded in meters per second (m/s). At the end of each experiment, the BSA was to export a datafile with the average velocity for each of the 180 angle bins. The BSA was unaware of which velocity component was measured, so the exported data file was labeled specifically. Details of the labeling system are given in Chapter 5.

Once the measurement of one component was complete, the probe was positioned to acquire the data for the next component, the traverse was reset, the export datafile was renamed to reflect the next component and the data acquisition was repeated.

When the experiment was completed, the datafiles were checked. As well as containing the average velocity for each angle bin, the datafiles contain the number of particles that were used for calculating this average. This value was checked to insure it was greater than 30.
Figure 4.1: LDA Probe Positioning Setup

Figure 4.2: Redundant Velocity Measurements and Percentage Difference
Figure 4.3: Redundant Velocity Measurement Phase Shifted

Figure 4.4: Sample Size Measured for an Experiment using 10,000 counts
Figure 4.5: Sample Size Measured for an Experiment using 50,000 counts

Figure 4.6: Average Velocity for an Experiment using 10,000 Counts
Figure 4.7: Average Velocity for an Experiment using 50,000 Counts

Figure 4.8: Average Velocity for an Experiment using 100,000 Counts
Figure 4.9: Output Screen from Phase Doppler Particle Analyzer

Figure 4.10: Measurement Grid
CHAPTER 5 - EXPERIMENTAL DATA ANALYSIS

The method of post-processing the data will be described in this chapter. The post-processing includes transforming the coordinate system, and using FIELDVIEW to plot the contours presented. Only a description of the data analysis method is included in this chapter. The results will be presented and discussed in Chapter 6.

5.1 Transformation

The velocity components that are recorded using the LDA probe in the orientation described previously must be transformed into radial, tangential and axial velocity components relative to the fan shaft. Figure 5.1 shows the velocity components as they are measured by the LDA probe. All measurements are made somewhere along radial line A-A. The components U1, U2, and U3 have the same direction regardless of the radial location of the measurement. U1 is positive directed downwards in the direction of normal fan flow. This figure does not show that the components are also rotated 15° around line B-B. The development of the transformation requires two steps. First, U1, U2 and U3 are transformed into components U1', U2', and U3' as shown in Figure 5.2. This transformation is a 45° clockwise rotation around component U1.

Once this transformation is complete, components U1', U2', and U3' are rotated around line B-B in order to acquire radial (r), tangential (t), and axial (a) velocity components as shown in Figure 5.3.

From a point above the fan, the following directions are considered positive;

r>0 for motion directed towards the centre of the fan

t>0 for clockwise motion

a>0 for motion down through the fan
The following matrix equation describes the transformation from the components described in Figure 5.1 to the components described in Figure 5.2.

\[
\begin{bmatrix}
U1' \\ U2' \\ U3'
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(45) & -\sin(45) \\
0 & \sin(45) & \cos(45)
\end{bmatrix}
\begin{bmatrix}
U1 \\ U2 \\ U3
\end{bmatrix}
\]

The second step of the transformation involves rotating $U1'$, $U2'$, and $U3'$ $15^\circ$ around line B-B in Figure 5.2. The following matrix equation describes this transformation.

\[
\begin{bmatrix}
r \\ a \\ t
\end{bmatrix} =
\begin{bmatrix}
-\sin(15) & \cos(15) & 0 \\
\cos(15) & \sin(15) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
U1' \\ U2' \\ U3'
\end{bmatrix}
\]

The above two equations can be combined to form the following matrix.

\[
\begin{bmatrix}
r \\ a \\ t
\end{bmatrix} =
\begin{bmatrix}
-\sin(15) & \cos(15) & 0 \\
\cos(15) & \sin(15) & 0 \\
0 & \sin(45) & \cos(45)
\end{bmatrix}
\begin{bmatrix}
\cos(15) & \sin(45) \\
\sin(15) & \cos(45) \\
\sin(15) & -\sin(45)
\end{bmatrix}
\begin{bmatrix}
U1 \\ U2 \\ U3
\end{bmatrix}
\]

These transformations are accomplished by post-processing the data with a FORTRAN program. The algorithm appears in Appendix VI. This algorithm is also used to calculate the velocity magnitude using the three velocity components.

### 5.2 Post-Processing Data using FIELDVIEW

The contour plots were generated with the FIELDVIEW software program [21], which is commercially available from Intelligent Light, Lyndhurst, New Jersey. The data exported from the LDA must be organized so that FIELDVIEW can create the
appropriate contour plots. As well, the transformation generated in section 5.1 must be applied to the data.

Every time a measurement at one radial location is completed, the BSA software would save a datafile. The measurement of a single fan operating condition (flow rate and fan speed) involved 20 radial locations, and three components, for a total of 60 datafiles. Each datafile had a header indicating the radial location measured as well as the following information: The row number, angle bin, number of particles measured in each angle bin, and the mean velocity of those particles. The information from these files was then organized into a single file.

The BSA software allowed the user to specify the name of the exported datafile. If the LDA was setup to make measurements at more than one location, the BSA software would automatically append a sequential number to the datafile for each location. The datafiles were given names that indicated the operating condition, fan and velocity component measured. For example, datafile A1U1#001.txt was a file containing data for experiment A1 (as defined in Table 4.3) measuring component U1 (as shown in Figure 5.1). The “#001” is automatically appended by the software and indicates the first radial position (the position closest to the fan hub). Reading the header in this file, one can determine the location of each radial position.

Appendix VI contains the FORTRAN algorithm used for organizing this data into a file that can be read by FIELDVIEW. When this program is run, it will read the average velocity data from all 60 files (A1U1#001.txt to A1U3#020.txt). After transforming the data, the FORTRAN program will place the data into a single formatted
matrix and save the data along with a header indicating the number of components contained in the file for FIELDVIEW to read.

The data can be read into FIELDVIEW only if a proper grid has been generated. The grid is generated using a FORTRAN program. The algorithm for this program can be found in Appendix VII. FIELDVIEW used a Cartesian plane co-ordinate system. The FORTRAN program inputs the number of angle bins used in the experiment, as well as the number and location of radial locations and generates the locations of the grid points on a Cartesian co-ordinate system.

The algorithms in Appendix VI and Appendix VII were set up so that the data in the datafile corresponds to the proper ordered pair generated in the grid file.

The contour plots were generated in FIELDVIEW using the Computational Surface function. The minimum and maximum values for each contour plot correspond to the minimum and maximum value in the data. All contour plots contain 30 contours. As mentioned previously, all experiments included measurements at a maximum radius of 154.5mm. The data was only plotted for a maximum radius of 152.0 mm to correspond with the CFD data.
Figure 5.1: Velocity Components as Indicated by LDA Probe

Figure 5.2: Partially Transformed Velocity Components
Figure 5.3: Fully Transformed Velocity Components
CHAPTER 6 - EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results are presented and analyzed in this chapter. Figure 6.1 through Figure 6.72 show the contour plots created from the experimental data. The data for Fan1 are plotted in Figure 6.1 through Figure 6.24. Fan2 results are plotted on Figure 6.25 through Figure 6.48 and Fan3 results are plotted on Figure 6.49 through Figure 6.72. For each fan, the velocity magnitude is plotted as well as the axial, tangential and radial components. In all the plots, the contour range is dictated by the minimum and maximum values measured. All plots have 30 contours. Each contour represents a value of velocity measured in meters per second (m/s) and shows the velocity contours as one would see them from a position upstream of the clockwise turning fan.

In this chapter, the contour plots are contrasted and compared in order to identify the way contour patterns change when the fan speed, flow rate and fan design change. Since the purpose of this study is to create measurement contours that can be compared with CFD data and not to design a fan, a limited attempt is made to determine the physical phenomenon behind the contour pattern.

The data generated in this study has been saved on a compact disk and is available from the University of Windsor in the Mechanical, Automotive and Materials Engineering office.

An analysis of the uncertainty is given in Appendix VIII. The results of this analysis indicate the measurements were made with an uncertainty of ±0.29 m/s with a 95% level of confidence.
6.1 Velocity Magnitude

In this section, the velocity magnitude contours are compared and contrasted. The contour plots are grouped using three different criteria. In section 6.1.1, the contours are compared for a changing fan speed, while maintaining a constant flow rate. In this section, the contours for each fan are considered separately. In section 6.1.2, the contours are compared for a changing flow rate while maintaining a constant fan speed. As well, in this section, the contours for each fan are considered separately. In section 6.1.3, the effect of fan design is considered by comparing the velocity contours for a constant fan speed and flow rate, changing only the fan design. Velocity Magnitude contours for Fan1 are found in Figure 6.1 to Figure 6.6. Fan2 and Fan3 velocity magnitude contours are in Figure 6.25 to Figure 6.30 and Figure 6.49 to Figure 6.54 respectively.

6.1.1 Fan Speed

Each fan was tested at two different fan speeds, 2300 RPM and 2700 RPM. For each speed, three flow rates were used. The only flow rate that was common to both fan speeds, however, was the medium flow rate of 800 CFM. Table 6.1 summarizes the minimum and maximum velocity measured for a flow rate of 800 CFM for both fan speeds. The data for each fan is presented in this table.

<table>
<thead>
<tr>
<th></th>
<th>Fan Speed (RPM)</th>
<th>Minimum Velocity Magnitude (m/s)</th>
<th>Maximum Velocity Magnitude (m/s)</th>
<th>Velocity Magnitude Range (max - min) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan1</td>
<td>2300</td>
<td>2.38</td>
<td>7.18</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>2700</td>
<td>2.37</td>
<td>11.06</td>
<td>8.69</td>
</tr>
<tr>
<td>Fan2</td>
<td>2300</td>
<td>2.93</td>
<td>13.65</td>
<td>10.72</td>
</tr>
<tr>
<td></td>
<td>2700</td>
<td>1.65</td>
<td>14.96</td>
<td>13.31</td>
</tr>
<tr>
<td>Fan3</td>
<td>2300</td>
<td>2.87</td>
<td>10.47</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>2700</td>
<td>0.43</td>
<td>12.97</td>
<td>12.54</td>
</tr>
</tbody>
</table>

Table 6.1: Measured Velocity Magnitude for a Flow Rate of 800 CFM
The data in this table show a trend. First, for all fan designs and a constant flow rate, increasing the fan speed will reduce the minimum velocity magnitude. Also, increasing the fan speed will increase the maximum velocity magnitude. Since the highest velocity magnitude always appears at the fan tip, this trend is expected. These two trends lead to the third observation; increasing the fan speed will increase the range of velocity magnitudes measured.

6.1.2 Flow Rate

All three fans were tested at a speed of 2300 RPM and 2700 RPM. When the fan was run at 2300 RPM, the three flow rates tested were 635 CFM, 800 CFM and 1123 CFM. The three flow rates tested for a fan speed of 2700 RPM were 737 CFM, 800 CFM and 1327 CFM. The flow rates of 635 CFM and 737 CFM are the design flow rates for Fan1 at a fan speed of 2300 RPM and 2700 RPM respectively.

The pattern of the contour plot does not change significantly as the flow rate changes. For all flow rates, the low velocity region extends outward from the fan hub and has a shape similar to the fan blade. A high velocity region appears at the fan tip for all fan designs and is located between the regions of low velocity magnitude. This pattern is less noticeable in the contour plots for Fan2 and Fan3 since the inter-blade region is much smaller. Figure 6.6 shows this pattern quite clearly. At the highest flow rate for both speeds, a region of high velocity magnitude can also be seen close to the fan hub.

The minimum and maximum velocity magnitude measured for Fan1 is summarized in Table 6.2. The flow rates are arranged in ascending order. This table shows a pattern for the minimum and maximum velocity magnitudes. As the flow rate
increases from the design flow rate, the minimum velocity magnitude increases and the maximum velocity magnitude decreases. The velocity magnitude range, therefore, decreases.

<table>
<thead>
<tr>
<th>Fan Speed (RPM)</th>
<th>Flow Rate (CFM)</th>
<th>Minimum Velocity Magnitude (m/s)</th>
<th>Maximum Velocity Magnitude (m/s)</th>
<th>Velocity Magnitude Range (max - min) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2300</td>
<td>635</td>
<td>1.50</td>
<td>9.69</td>
<td>8.19</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>2.38</td>
<td>7.18</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td>1123</td>
<td>3.75</td>
<td>6.87</td>
<td>3.12</td>
</tr>
<tr>
<td>2700</td>
<td>737</td>
<td>0.38</td>
<td>11.65</td>
<td>11.27</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>2.37</td>
<td>11.06</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>1327</td>
<td>4.70</td>
<td>8.51</td>
<td>3.81</td>
</tr>
</tbody>
</table>

Table 6.2: Measured Velocity Magnitude for Fan1 Arranged by Flow Rate

Table 6.3 and Table 6.4 show the minimum and maximum velocity magnitude measured for Fan2 and Fan3 respectively. These tables do not show the same pattern demonstrated in Table 6.2. The probable reason for this difference is the fact that the low flow rates are not necessarily the design flow rates for Fan2 and Fan3. The relationship between the flow rates measured and the design flow rate for Fan2 and Fan3 is not known. The flow rates were chosen for these fans so the data could be used to compare with available CFD predictions.

<table>
<thead>
<tr>
<th>Fan Speed (RPM)</th>
<th>Flow Rate (CFM)</th>
<th>Minimum Velocity Magnitude (m/s)</th>
<th>Maximum Velocity Magnitude (m/s)</th>
<th>Velocity Magnitude Range (max - min) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2300</td>
<td>635</td>
<td>2.26</td>
<td>12.25</td>
<td>9.99</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>2.93</td>
<td>13.65</td>
<td>10.72</td>
</tr>
<tr>
<td></td>
<td>1123</td>
<td>4.22</td>
<td>10.08</td>
<td>5.86</td>
</tr>
<tr>
<td>2700</td>
<td>737</td>
<td>0.90</td>
<td>12.92</td>
<td>12.02</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>1.65</td>
<td>14.96</td>
<td>13.31</td>
</tr>
<tr>
<td></td>
<td>1327</td>
<td>4.92</td>
<td>12.08</td>
<td>7.16</td>
</tr>
</tbody>
</table>

Table 6.3: Measured Velocity Magnitude for Fan2 Arranged by Flow Rate
<table>
<thead>
<tr>
<th>Fan Speed (RPM)</th>
<th>Flow Rate (CFM)</th>
<th>Minimum Velocity Magnitude (m/s)</th>
<th>Maximum Velocity Magnitude (m/s)</th>
<th>Velocity Magnitude Range (max - min) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2300</td>
<td>635</td>
<td>0.28</td>
<td>10.87</td>
<td>10.59</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>2.87</td>
<td>10.47</td>
<td>7.60</td>
</tr>
<tr>
<td></td>
<td>1123</td>
<td>4.11</td>
<td>8.67</td>
<td>4.56</td>
</tr>
<tr>
<td>2700</td>
<td>737</td>
<td>0.55</td>
<td>12.57</td>
<td>12.02</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>0.43</td>
<td>12.97</td>
<td>12.54</td>
</tr>
<tr>
<td></td>
<td>1327</td>
<td>4.73</td>
<td>10.35</td>
<td>5.62</td>
</tr>
</tbody>
</table>

Table 6.4: Measured Velocity Magnitude for Fan3 Arranged by Flow Rate

6.1.3 Fan Design

The obvious and expected difference between the fan patterns is the number of repeated regions displayed in the contours for Fan1 compared with Fan2 and Fan3. Since Fan1 only has 5 blades, the contour plot only has 5 repeated regions. Fan2 and Fan3 have 9 blades and 9 repeated regions each. The datum point used to determine the location of the measurement plane was the bottom of the fan hub. The measurement plane was 30 mm upstream from the bottom of the hub. The distance between the measurement plane and the fan leading edge was not constant across radial locations or fan designs. The proximity of the blade to the leading edge would obviously affect the contour pattern.

The other noticeable difference is in the shape of the regions for each fan.

Looking at a typical contour plot for Fan1, such as Figure 6.2, one can notice the contour gradient is much steeper on the counter-clockwise side of the low velocity region than on the other. A contour plot of the same operating condition for Fan2 (Figure 6.26) and for Fan3 (Figure 6.50) the velocity gradient is more symmetrical. This difference between Fan1 and Fans 2 and 3 is most likely due to the fact that Fan1 has a much larger inter-blade region due to the fewer number of blades.
Another difference in the contour patterns can be noticed. Referring back to Figure 6.50, the low velocity region for Fan3 extends in a radial direction from the fan hub. The low velocity region for Fan2 (Figure 6.26), however, bends slightly counterclockwise as it extends from the fan hub. The contours for Fan1 (Figure 6.2) bend in the clockwise direction. This difference in pattern can be attributed to the difference in the blade shape for each fan. Recall, Fan3 is the only fan with a straight leading edge. The above observations can be made when comparing the patterns from each fan for any operating condition.

The value of the velocity magnitude for a selected operating condition can be compared for various fan designs. Table 6.5 summarizes the minimum and maximum velocity magnitudes measured for each operating condition and fan. The data is organized so that the minimum and maximum velocity magnitude for a given operating condition can be compared when a fan is changed. As well, the difference between the minimum and maximum values is given.
<table>
<thead>
<tr>
<th>Operating Condition (RPM / CFM)</th>
<th>Fan Label</th>
<th>Minimum Value Measured</th>
<th>Maximum Value Measured</th>
<th>Velocity Magnitude Range (max - min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (2300/800)</td>
<td>1</td>
<td>2.38</td>
<td>7.18</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.93</td>
<td>13.65</td>
<td>10.72</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.87</td>
<td>10.47</td>
<td>7.60</td>
</tr>
<tr>
<td>B (2300/635)</td>
<td>1</td>
<td>1.50</td>
<td>9.69</td>
<td>8.19</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.26</td>
<td>12.25</td>
<td>9.99</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.28</td>
<td>10.87</td>
<td>10.59</td>
</tr>
<tr>
<td>C (2300/1123)</td>
<td>1</td>
<td>3.75</td>
<td>6.87</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.22</td>
<td>10.08</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.11</td>
<td>8.67</td>
<td>4.56</td>
</tr>
<tr>
<td>D (2700/800)</td>
<td>1</td>
<td>2.37</td>
<td>11.06</td>
<td>8.69</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.65</td>
<td>14.96</td>
<td>13.31</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.43</td>
<td>12.97</td>
<td>12.54</td>
</tr>
<tr>
<td>E (2700/737)</td>
<td>1</td>
<td>0.38</td>
<td>11.65</td>
<td>11.27</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.90</td>
<td>12.92</td>
<td>12.02</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.55</td>
<td>12.57</td>
<td>12.02</td>
</tr>
<tr>
<td>F (2700/1327)</td>
<td>1</td>
<td>4.70</td>
<td>8.51</td>
<td>3.81</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.92</td>
<td>12.08</td>
<td>7.16</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.73</td>
<td>10.35</td>
<td>5.62</td>
</tr>
</tbody>
</table>

Table 6.5: Minimum and Maximum Velocity Magnitude Arranged by Fan Design

Table 6.6 is generated from the data in Table 6.5. For a given operating condition, the fan with the lowest minimum value and the fan with the highest minimum value are identified. The difference between these two values as a percentage of the highest value is also recorded. As well, the identification number of the fan with the lowest and the fan with the highest maximum value are given, as well as the percent difference.

The data in Table 6.6 for the maximum velocity shows a strong pattern. For every operating condition, Fan1 has the lowest maximum velocity magnitude. As well, for every operating condition, Fan2 has the highest maximum velocity magnitude. The difference between the maximum velocity magnitude for Fan1 and Fan2 is at least 10% and is as high as 47%. This large value indicates the difference is significant.
A similar pattern does not exist for the minimum velocity magnitude. While Fan2 generally generates the highest minimum velocity magnitude, Fan1 has a significantly higher velocity magnitude for operating condition D (as defined in Table 4.3). The lowest minimum velocity is evenly split between Fan1 and Fan3.

<table>
<thead>
<tr>
<th>Operating Condition (RPM/CFM)</th>
<th>MINIMUM VELOCITY MAGNITUDE</th>
<th>MAXIMUM VELOCITY MAGNITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FAN WITH LOWEST VELOCITY</td>
<td>FAN WITH HIGHEST VELOCITY</td>
</tr>
<tr>
<td>A (2300/800)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B (2300/635)</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>C (2300/1123)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>D (2700/800)</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>E (2700/737)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>F (2700/1327)</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.6: Velocity Magnitude Comparison Arranged by Fan Design

The maximum velocity magnitude will be in a region, relative to the fan blade, that is heavily influenced by the blade design. The minimum velocity magnitude, however, will be in a region that is not influenced by the blade. For this reason, it is expected that a relationship between the maximum velocity and blade design will exist. A similar relationship for the minimum velocity, however, will not develop.

6.2 Velocity Components

Axial velocity contours for Fan1 are in Figure 6.7 to Figure 6.12. The axial velocity contours for Fan2 and Fan3 are in Figure 6.31 to Figure 6.36 and Figure 6.55 to Figure 6.60 respectively. Notwithstanding the values represented by the contours, the
contour plots for the axial velocity are similar to the velocity magnitude contour plots. One significant difference is the low velocity regions in the axial velocity plots represent negative values indicating a region of re-circulation. The axial velocity pattern is also rotated slightly from the velocity magnitude contour plot. This apparent shift is due to the fact that the contours in the axial velocity plot pass through a value of zero as they move from a high positive value to a high negative value. The area where the contours represent zero will be the low value region on the velocity magnitude plot, since this plot shows absolute values.

The tangential velocity component contour plots for Fan1, Fan2 and Fan3 are found in Figure 6.13 to Figure 6.18, Figure 6.37 to Figure 6.42, and Figure 6.61 to Figure 6.66 respectively. The pattern for the tangential components also is indicative of the blade shape. At the outer edge, however, a large pocket of high velocity magnitude develops between the fan blades. This high velocity pocket extends further inward at higher flow rates. For Fan1, some of the contours are perpendicular to the inner most radius. For Fan2 and Fan3, however, regions of low or slightly negative contours develop close to the inner radius. The difference between these two patterns is due to the difference in the inner most radius measured. The height of the hub on Fan1 prevented measurements at the same radius as the hub. The closest measurement was taken at a radial distance of 4.8mm from the hub. For Fan2 and Fan3, however, measurements were taken at a position directly above the radius of the hub because the hub height did not interfere with the measuring volume. Directly above the fan hub, the velocity vectors were predominantly directed in the axial direction. This observation was made by witnessing the motion of the seed particles when the Fogger was directed toward the fan
hub. The velocity field measured for Fan1 is too far from the hub to be affected by the motion of the hub and show the pattern observed for Fan2 and Fan3.

The radial Velocity component contour plots for Fan1, Fan2 and Fan3 are found in Figure 6.19 to Figure 6.24, Figure 6.43 to Figure 6.48, and Figure 6.67 to Figure 6.72 respectively. The radial component of the velocity does not show the blade pattern as clearly as the other components. Instead, the radial component typically changes from a high negative (i.e. flowing away from the fan hub) value close to the hub to a high positive (i.e. flowing toward the fan hub) value close to the tip.
Figure 6.1: Velocity Magnitude Contour Plot for Fan1 at 800 CFM and 2300 rpm

Figure 6.2: Velocity Magnitude Contour Plot for Fan1 at 800 CFM and 2700 rpm
Figure 6.3: Velocity Magnitude Contour Plot for Fan1 at 635 CFM and 2300 rpm

Figure 6.4: Velocity Magnitude Contour Plot for Fan1 at 737 CFM and 2700 rpm
Figure 6.5: Velocity Magnitude Contour Plot for Fan1 at 1123 CFM and 2300 rpm

Figure 6.6: Velocity Magnitude Contour Plot for Fan1 at 1327 CFM and 2700 rpm
Figure 6.7: Axial Velocity Contour Plot for Fan1 at 800 CFM and 2300 rpm

Figure 6.8: Axial Velocity Contour Plot for Fan1 at 800 CFM and 2700 rpm
Figure 6.9: Axial Velocity Contour Plot for Fan1 at 635 CFM and 2300 rpm

Figure 6.10: Axial Velocity Contour Plot for Fan1 at 737 CFM and 2700 rpm
Figure 6.11: Axial Velocity Contour Plot for Fan1 at 1123 CFM and 2300 rpm

Figure 6.12: Axial Velocity Contour Plot for Fan1 at 1327 CFM and 2700 rpm
Figure 6.13: Tangential Velocity Contour Plot for Fan1 at 800 CFM and 2300 rpm

Figure 6.14: Tangential Velocity Contour Plot for Fan1 at 800 CFM and 2700 rpm
Figure 6.15: Tangential Velocity Contour Plot for Fan1 at 635 CFM and 2300 rpm

Figure 6.16: Tangential Velocity Contour Plot for Fan1 at 737 CFM and 2700 rpm
Figure 6.17: Tangential Velocity Contour Plot for Fan1 at 1123 CFM and 2300 rpm

Figure 6.18: Tangential Velocity Contour Plot for Fan1 at 1327 CFM and 2700 rpm
Figure 6.19: Radial Velocity Contour Plot for Fan1 at 800 CFM and 2300 rpm

Figure 6.20: Radial Velocity Contour Plot for Fan1 at 800 CFM and 2700 rpm
Figure 6.21: Radial Velocity Contour Plot for Fan 1 at 635 CFM and 2300 rpm

Figure 6.22: Radial Velocity Contour Plot for Fan 1 at 737 CFM and 2700 rpm
Figure 6.23: Radial Velocity Contour Plot for Fan1 at 1123 CFM and 2300 rpm

Figure 6.24: Radial Velocity Contour Plot for Fan1 at 1327 CFM and 2700 rpm
Figure 6.25: Velocity Magnitude Contour Plot for Fan2 at 800 CFM and 2300 rpm

Figure 6.26: Velocity Magnitude Contour Plot for Fan2 at 800 CFM and 2700 rpm
Figure 6.27: Velocity Magnitude Contour Plot for Fan2 at 635 CFM and 2300 rpm

Figure 6.28: Velocity Magnitude Contour Plot for Fan2 at 737 CFM and 2700 rpm
Figure 6.29: Velocity Magnitude Contour Plot for Fan2 at 1123 CFM and 2300 rpm

Figure 6.30: Velocity Magnitude Contour Plot for Fan2 at 1327 CFM and 2700 rpm
Figure 6.31: Axial Velocity Contour Plot for Fan2 at 800 CFM and 2300 rpm

Figure 6.32: Axial Velocity Contour Plot for Fan2 at 800 CFM and 2700 rpm
Figure 6.33: Axial Velocity Contour Plot for Fan2 at 635 CFM and 2300 rpm

Figure 6.34: Axial Velocity Contour Plot for Fan2 at 737 CFM and 2700 rpm
Figure 6.35: Axial Velocity Contour Plot for Fan2 at 1123 CFM and 2300 rpm

Figure 6.36: Axial Velocity Contour Plot for Fan2 at 1327 CFM and 2700 rpm
Figure 6.37: Tangential Velocity Contour Plot for Fan2 at 800 CFM and 2300 rpm

Figure 6.38: Tangential Velocity Contour Plot for Fan2 at 800 CFM and 2700 rpm
Figure 6.39: Tangential Velocity Contour Plot for Fan2 at 635 CFM and 2300 rpm

Figure 6.40: Tangential Velocity Contour Plot for Fan2 at 737 CFM and 2700 rpm
Figure 6.41: Tangential Velocity Contour Plot for Fan2 at 1123 CFM and 2300 rpm

Figure 6.42: Tangential Velocity Contour Plot for Fan2 at 1327 CFM and 2700 rpm
Figure 6.43: Radial Velocity Contour Plot for Fan2 at 800 CFM and 2300 rpm

Figure 6.44: Radial Velocity Contour Plot for Fan2 at 800 CFM and 2700 rpm
**Figure 6.45:** Radial Velocity Contour Plot for Fan2 at 635 CFM and 2300 rpm

**Figure 6.46:** Radial Velocity Contour Plot for Fan2 at 737 CFM and 2700 rpm
Figure 6.47: Radial Velocity Contour Plot for Fan2 at 1123 CFM and 2300 rpm

Figure 6.48: Radial Velocity Contour Plot for Fan2 at 1327 CFM and 2700 rpm
Figure 6.49: Velocity Magnitude Contour Plot for Fan3 at 800 CFM and 2300 rpm

Figure 6.50: Velocity Magnitude Contour Plot for Fan3 at 800 CFM and 2700 rpm
Figure 6.51: Velocity Magnitude Contour Plot for Fan3 at 635 CFM and 2300 rpm

Figure 6.52: Velocity Magnitude Contour Plot for Fan3 at 737 CFM and 2700 rpm
Figure 6.53: Velocity Magnitude Contour Plot for Fan3 at 1123 CFM and 2300 rpm

Figure 6.54: Velocity Magnitude Contour Plot for Fan3 at 1327 CFM and 2700 rpm
Figure 6.55: Axial Velocity Contour Plot for Fan3 at 800 CFM and 2300 rpm

Figure 6.56: Axial Velocity Contour Plot for Fan3 at 800 CFM and 2700 rpm
Figure 6.57: Axial Velocity Contour Plot for Fan3 at 635 CFM and 2300 rpm

Figure 6.58: Axial Velocity Contour Plot for Fan3 at 737 CFM and 2700 rpm
Figure 6.59: Axial Velocity Contour Plot for Fan3 at 1123 CFM and 2300 rpm

Figure 6.60: Axial Velocity Contour Plot for Fan3 at 1327 CFM and 2700 rpm
Figure 6.61: Tangential Velocity Contour Plot for Fan3 at 800 CFM and 2300 rpm

Figure 6.62: Tangential Velocity Contour Plot for Fan3 at 800 CFM and 2700 rpm
Figure 6.63: Tangential Velocity Contour Plot for Fan3 at 635 CFM and 2300 rpm

Figure 6.64: Tangential Velocity Contour Plot for Fan3 at 737 CFM and 2700 rpm
Figure 6.65: Tangential Velocity Contour Plot for Fan3 at 1123 CFM and 2300 rpm

Figure 6.66: Tangential Velocity Contour Plot for Fan3 at 1327 CFM and 2700 rpm
Figure 6.67: Radial Velocity Contour Plot for Fan3 at 800 CFM and 2300 rpm

Figure 6.68: Radial Velocity Contour Plot for Fan3 at 800 CFM and 2700 rpm
Figure 6.69: Radial Velocity Contour Plot for Fan3 at 635 CFM and 2300 rpm

Figure 6.70: Radial Velocity Contour Plot for Fan3 at 737 CFM and 2700 rpm
Figure 6.71: Radial Velocity Contour Plot for Fan3 at 1123 CFM and 2300 rpm

Figure 6.72: Radial Velocity Contour Plot for Fan3 at 1327 CFM and 2700 rpm
CHAPTER 7 - CONCLUSIONS AND RECOMMENDATIONS

Based on the objectives of this project as well as the results and discussion, the following conclusions and recommendations can be made.

7.1 Conclusions

1. A single component fibre optic, back-scatter laser Doppler anemometer can be utilized for measuring each of the three components of phase average velocity near an automotive cooling fan.

2. The design and construction of the probe fixture allowed for precise positioning and adjustment of the LDA probe. Within an acceptable tolerance of $\pm 1.1 \times 10^{-3}$ m, which is roughly the length of the measuring volume ($1.4 \times 10^{-3}$ m), the measuring volume location remains unchanged when the probe is moved so that all three components of average velocity can be measured. As well, the traverse mechanism used with the fixture and LDA probe functioned very well and could position the probe with an uncertainty of $\pm 10.6 \ \mu m$.

3. The results of the preliminary experiments show that the LDA and BSA were set up so that reliable phase average velocity measurements were taken with an uncertainty of $\pm 0.29 \ \text{m/s}$.

4. The contour plots created with FIELDVIEW have been formatted and are available for comparison with CFD predictions.

5. From the analysis of the experimental results, the following conclusions can be made:

   a) For a constant volume flowrate, increasing the fan speed increased the maximum measured velocity magnitude while decreasing the minimum
value measured, which had the effect of increasing the range of velocity magnitude measured.

b) For Fan1 with constant fan speed, increasing the flowrate above the design condition increased the minimum measured velocity magnitude while decreasing the maximum value measured, which had the effect of decreasing the velocity magnitude range. A similar analysis of Fan2 and Fan3 was not possible as the design conditions were not known.

c) For all operating conditions, Fan2 gave the highest value of maximum velocity magnitude while Fan1 gave the lowest value of maximum velocity magnitude.

d) Fan2 gave the highest minimum value of velocity magnitude for most of the operating conditions considered. However, no one fan was found to give the lowest minimum velocity magnitude in every operating condition considered.

e) Notwithstanding the differences in the magnitude of the velocity components, the contour plots for the axial and tangential velocity components exhibit similar patterns and are indicative of the fan design. The pattern for the radial component, however, is generally independent of the fan design.

f) The pattern for the tangential velocity component has a region of high velocity between the fan blades that extend further inward at higher flow rates.
g) The tangential velocity pattern shows a series of contours representing a low or slightly negative value which circle the hub for radial positions close to the hub. The contours for Fan1, however, are perpendicular to the fan hub as they approach the hub. The difference in pattern is due to the difference in the location of the inner most radial position measured. Because of the height of the fan hub, the measurements for Fan1 were further from the hub than the measurements for Fan2 and Fan3.

7.2 Recommendations

1. With increased funding, a multi-component LDA could be used for this experiment. The current equipment could not be used to acquire information such as Reynolds stresses or instantaneous velocity magnitude since these values are not steady. Simultaneous measurement of all three components is always more desirable since this method eliminates any extraneous variables that may result from a time lapse between measurements.

2. The preliminary experiments showed that the alignment, while sufficient for this experiment, could be off by as much as $1.1 \times 10^{-3}$ m, or roughly the measuring volume length ($1.4 \times 10^{-3}$ m). The alignment can be improved with the use of another device for focusing the measuring volume. Instead of using a cross-hair, a small pinhole can be machined and used. If the pinhole diameter is similar to the diameter of the measuring volume, the lasers will only pass through the pinhole when the measuring volume is focused on the pinhole.

3. The results of the preliminary experiments show that the LDA and BSA were set up so that reliable phase average velocity measurements were taken with an uncertainty
of ±0.29 m/s. The greatest contributing factor is the width of the angle bin.

Therefore, a reduction in the angle bin width is recommended. This is accomplished by increasing the number of angle bins in each revolution. The preliminary experiments will, of course, need to be repeated to determine the total count required to ensure that each of the new angle bins has at least 30 particles.

4. For further analysis of the fan design, Fan2 and Fan3 should be examined at their design conditions. For this study, the primary objective was to validate a CFD model. Therefore, the operating conditions measured were based on the operating conditions modeled so that the results could be compared with CFD predictions.

5. For further analysis of flow rate, different operating conditions should be chosen. Either operate the fans at the same flow rate for both fan speeds, or preferably, select the flow rates for each fan speed and design such that the non-dimensional flow coefficients remain constant.
REFERENCES


11. Menon, R.K., “Phase Averaged Measurements using a 3 Component LDV System”, Presented at the Tenth Symposium on Turbulence at the University of Missouri-Rolla, September, 1986.


18. Degroot, K., Interfacing the Serial Port, Co-op Work Term Project Report for the University of Windsor, September 1999.


APPENDIX I. MEASURING VOLUME CALCULATIONS

The calculations for the measuring volume were completed using Mathcad Plus Version 6.0. The following is a copy of the worksheet used for the calculations.

\[
F = 5 \times 10^{-3} \quad \text{Focal Length}
\]
\[
\lambda = 632.8 \times 10^{-9} \quad \text{Wave Length}
\]
\[
E = 1.0 \quad \text{Beam Expansion Ratio}
\]
\[
D_L = 0.27 \times 10^{-3} \quad \text{Beam Diameter}
\]
\[
d = 11 \times 10^{-3} \quad \text{Beam Spacing at Lens}
\]
\[
\theta = 2 \cdot \tan \left( \frac{d}{2 \cdot F} \right) \quad \theta = 0.219 \quad \text{radians}
\]
\[
\text{Change from Radians to Degrees} \quad \theta_{\text{deg}} = \theta \cdot \frac{180}{\pi}
\]
\[
\theta_{\text{deg}} = 12.555
\]

LENGTH \hspace{1cm} WIDTH \hspace{1cm} HEIGHT

\[
\delta_z = \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L \cdot \sin \left( \frac{\theta}{2} \right)}
\]
\[
\delta_y = \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L}
\]
\[
\delta_x = \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L \cdot \cos \left( \frac{\theta}{2} \right)}
\]
\[
\delta_z = 1.365 \times 10^{-3} \quad \delta_y = 1.492 \times 10^{-4} \quad \delta_x = 1.501 \times 10^{-4}
\]

Change dimensions to mm

\[
\delta_z = \delta_z \cdot 1000 \quad \delta_y = \delta_y \cdot 1000 \quad \delta_x = \delta_x \cdot 1000
\]
\[
\delta_z = 1.365 \quad \delta_y = 0.149 \quad \delta_x = 0.15
\]

FRINGE SPACING \hspace{5cm} NUMBER OF FRINGES

\[
\delta_f = \frac{\lambda}{2 \cdot \sin \left( \frac{\theta}{2} \right)}
\]
\[
N_f = 8 \cdot F \cdot \frac{\tan \left( \frac{\theta}{2} \right)}{\pi \cdot E \cdot D_L}
\]
\[
\delta_f = 2.894 \times 10^{-6} \quad N_f = 51.873
\]
APPENDIX II. DETAILS OF THE TRAVERSE COMPUTER AND SOFTWARE

The following is an excerpt from the Co-op Work Report of Mr. Keith DeGroot [18]. It is included here because it contains pertinent information to the operation of the facility used in this thesis that appeared in a document that is not readily available to the general public. The report was edited for this appendix to include only information pertinent to this study and to avoid repetition of information contained in the main body of this thesis.

INTRODUCTION

A study was undertaken at the University of Windsor to use a Laser Doppler Anemometer (LDA) to measure phase averaged velocity upstream of an automotive cooling fan. The fan was operated in a Fan Test Facility (described in the main body of this thesis). To obtain a velocity profile, measurements are made along a radial line passing through the axis of the fan.

The LDA signal was analyzed using a Burst Spectrum Analyzer (BSA), purchased from Dantec. The Dantec BSA Flow Software was used to control the measurement procedure and data analysis. This software has an integrated user-interface that enables the user to control the setup of all instrumentation in the LDA system as well as data acquisition and data analysis options. The software has the capability of operating a multi degree of freedom traverse so that a series of measurements can be made at different positions on a user-defined grid. The traverse used for this study was a single degree of freedom traverse intended to locate the probe at positions along a radial line upstream of the fan. The BSA can interface with a commercially available traverse controller available from Dantec, or a generic controller. For this study, a generic
controller was available. In order to interface with the generic controller, an auxiliary computer is necessary.

The BSA Flow Software and the auxiliary computer communicate via a serial port. The signal is interpreted by a program on the auxiliary computer, which was developed by the author (DeGroot) and is entitled “Tdriver”. The algorithm appears at the conclusion of this report. Once the auxiliary computer has interpreted the signal from the BSA, a signal is sent through a parallel port to the traverse controller, which actuates the stepper motor to turn the drive screw. The serial port, Tdriver program, and parallel port will each be considered in detail.

THE SERIAL PORT CONNECTION

A Serial/RS232 Port connection is used to facilitate the BSA Flow Software. When the software is configured to work with a generic traverse it sends information in the form of one of the following strings to the serial port:

<table>
<thead>
<tr>
<th>Command</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>#INIT:string&amp;</td>
<td>Used to let BSA Flow know traverse is present.</td>
</tr>
<tr>
<td>#MOVE:X,Y,</td>
<td>Gives co-ordinates of desired position.</td>
</tr>
<tr>
<td>#READ&amp;</td>
<td>Asks for the current position.</td>
</tr>
<tr>
<td>#STOP&amp;</td>
<td>Stops any moving.</td>
</tr>
<tr>
<td>#RESET&amp;</td>
<td>Resets current position as home</td>
</tr>
<tr>
<td>#HOME&amp;</td>
<td>Moves traverse into home position.</td>
</tr>
</tbody>
</table>

Table A: Command List

These strings are then received by the auxiliary computer and interpreted by the Tdriver program, which was created in the C programming language. The serial port connection can be made using either a DB 9 pin or DB 25 pin connection. For this project, a DB 9 pin connection was used. A null modem cable connects the two ports.
This cable crosses the Transmit Data and the Receive Data pins allowing the computers to communicate effectively.

THE PROGRAM

The "Tdriver" program is a translator between the BSA Flow Software and the traverse. Tdriver was developed using interrupts and buffers. When a character arrives at the serial port the program is interrupted. This allows it to store the character in a buffer. The interrupt will perform one of four possible functions depending on the character it receives. First, if the character is a pound symbol (#), the buffer will be reset with it at the beginning of the buffer. Second, if the character is a colon (:), a null character (/0) will be inserted in its place. Third, if the character is an ampersand (&), the interrupt will signal that a command has been sent. The fourth possibility is any other character. In this case, the character sent will be stored in the buffer.

The result of the interrupt is that when a command is sent the first part will be stored in one string, String 1, and the information coming with it in another, String2. The command can then be properly executed and the program will be allowed to continue.

When a command is received it is either directly handled by the interrupt or passed on to the main part of the program. In the case of the former, the commands handled include READ, RESET, and STOP. The commands MOVE and HOME are handled by the latter. MOVE and HOME perform the same actions with HOME setting the desired position to zero and MOVE extracting the desired position from the command string.

The main part of the program compares the current position of the traverse with the desired position. If the distance between the two is greater than the distance traveled
when the stepper motor moves a half of a step, the traverse will move one step in the
appropriate direction and record the new position. This loop continues until the current
position is within a half step of the desired position. The current position is then recorded
and the traverse stopped.

Each step taken either increments or decrements the current position by the step
size. The step size for the traverse setup has been calculated to be 21.1/6 μm, based on
the number of steps per revolution in the stepper motor (200) and the number of threads
per inch on the drive screw (6). The auxiliary computer and traverse controller
communicate through the parallel port.

THE PARALLEL PORT

The setup has pin 2 and pin 3 of the parallel port connected to STEP and FWD-
REV controls on the controller respectively. This is done with a parallel to co-ax cable
that was made at the University of Windsor. Setting pin 3 high will direct the traverse to
move forward and setting it low directs the traverse to move in reverse. To take a step,
pin 2 must be brought high and then back low.

The parallel port uses 5V as high and 0V as low. To control whether a pin is high
or low a hexadecimal number that represents an eight bit binary number is output to the
address of the parallel port. Pins 2 and 3 are controlled with the first and second bit of the
binary number. A high is represented by a binary one and a low by a binary zero. Table
B, below shows the values used to control the pins.
<table>
<thead>
<tr>
<th>Hexadecimal</th>
<th>Binary</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00</td>
<td>00000000</td>
<td>Pin 2 low &amp; Pin 3 low</td>
</tr>
<tr>
<td>0x01</td>
<td>00000001</td>
<td>Pin 2 high &amp; Pin 3 low</td>
</tr>
<tr>
<td>0x02</td>
<td>00000010</td>
<td>Pin 2 low &amp; Pin 3 high</td>
</tr>
<tr>
<td>0x03</td>
<td>00000011</td>
<td>Pin 2 high &amp; Pin3 high</td>
</tr>
</tbody>
</table>

Table B: Pin Control

PROGRAM AND TRAVERSE CONSIDERATIONS

The program has been tested and works well. By using mock test trials the program has been proven to be accurate in its positioning. With the use of a scale to measure the distance traveled and by setting the BSA Flow Software to move a particular distance, no discrepancy could be detected.

One source of uncertainty is the finite step size determined by the stepper motor. If the distance between the current position and the desired new position is not a multiple of the step size then it will be impossible to move the traverse to exactly the desired position. As previously mentioned, the greatest discrepancy between the desired position and an attainable position is a one-half of a step or about 10.5 μm. It is important to note, however, that the program records the attained position and uses that position as the starting point for the next move, not the previously desired position. Therefore, the previous error is not a consideration for the new position and the maximum uncertainty is ±10.5 μm.

Another positional error that may arise is a result of the C programming language. The BSA Software sends a numerical position to the program in the form of a string. The program then converts this string into a floating point number. The floating point number is used until the position needs to be returned to the BSA Flow Software. This floating point number must be converted to an integer before being converted to a string for
sending. The truncation that occurs to the floating point number as it is converted to an integer is a cause of uncertainty. The error arising from this conversion is less than a micrometer, however.

An extended length of the null modem cable will degrade the signal it carries. If this happens or if the signal degrades for any other reason, an error checking section could be added to Tdriver. There are error codes already explained in the BSA Flow Software Manual.

Another consideration is the time required to move the traverse. To send a step to the controller a high must be maintained for a short period of time. According to the electronic technologist (Patrick Seguin) in Mechanical, Automotive and Materials Engineering, the period could be approximately 50ms. This would give 20 steps per second which is much faster than the observed speed of the traverse. The delay function currently being used does not allow for a shorter period. Since the speed at which the traverse moves is not a significant factor in the time it will take to get the measurements it has been determined that no changes need to be made. If changes are made it should be noted that the stepper motor torque is reduced at high speeds.

The following general procedure must be followed when setting up the interface. First, the Tdriver program must be running before the BSA Flow Software is loaded. The BSA Flow software is then able to recognize the presence of the traverse. Second, if the BSA Flow Software has been closed and re-loaded it may not be able to connect to the port. The only solution found for this is to restart the computer and reopen the software. Finally, the traverse must be manually positioned into a pre-determined home position. A
stop on the traverse guide rail acts as the home position for this application. To identify
the home position, the BSA Flow must be "RESET".

**TDRIVER PROGRAM**

The following text is the algorithm used for the Tdriver program.

```
//Tdriver.c
//Traverse Driver
//July 28, 1999 Aug 20, 1999
//Keith DeGroot

//This program is used to translate between the traverse and the BSA
//@flow software. */

#include <stdio.h>
#include <bios.h>
#include <conio.h>
#include <dos.h>
#include <string.h>
#include <stdlib.h>
#include <time.h>

/**************************Constants used**************************/

#define LENGTH 256  //buffer array size
#define STEPSIZE 254/12  //step size in micrometers
#define DELAY 1       //step delay

/**************************For Serial Port**************************/

#define PORT1 0x3F8  /*Port Address com1*/

/* Defines Serial Ports Base Address */
/* COM1 0x3F8 */
/* COM2 0x2F8 */
/* COM3 0x3E8 */
/* COM4 0x2E8 */

#define INTVECT 0x0C /* Com Port's IRQ */
    /* Must also change the PIC setting */
    /* COM1 - 0x0C */
    /* COM2 - 0x0B */
```
/* COM3 - 0x0C */
/* COM4 - 0x0B */

 /***********************************************************************/

 /***********************************************************************/

 #define PORTADDRESS 0x378   //PARALLEL PORT BASE ADDRESS
 #define DATA PORTADDRESS  //Address for data out
 #define CONTROL PORTADDRESS+3

 /***********************************************************************/

 /***********************************************************************/

 int bufferin = 0;              //buffer index
 char *String1;                //pointer to first part of command
 char *String2;                //pointer to second part of command
 char Response1[LENGTH];     //first half of response to BSA
 char Response2[LENGTH];     //second half of response to BSA
 float DesiredPosition=0;
 long DPInt=0;
 float CurrentPosition=0;
 long CPInt=0;
 int JobComplete=1,MOVE=1,READ=1;  //condition indicators
 char ReadPosition[12]="0";   //Position to return to read command
 char *p;                    //used to convert position to ReadPosition
 char history[10000];       //used for debugging
 int history_count=0;       //used for debugging
 float STEP=STEPSIZE;

 /***********************************************************************/

 /***********************************************************************/

 void pause()
 {int x;for(x=0;x<10000;x++){};     //may be able to reduce 10000

 /***********************************************************************/

 /***********************************************************************/

 /****holdstep() : Used to hold parallel port high ***/***/

 //inline void holdstep()//inline doesn't work
 void holdstep()
 {
 float timediff=0,time1=0,time2=0;
 time1=clock();
void interrupt PORT1INT() /* ISR for PORT1 */
{
    int j;      // counter
    char* stopstring;   // used to extract numbers from string
    static int c;       // used to import
    static char buffer[LENGTH]; // buffer
    static int CommandSent=1;  // 1=not sent, zero=sent

    String1=buffer;        //set string one to beginning of buffer

    do {
        c = inp(PORT1 + 5);
        if (c & 1)
        {
            buffer[bufferin] = inp(PORT1);
            //history[history_count]=buffer[bufferin]; //for debugging
            if (buffer[bufferin]=='#')
            {
                bufferin=0;
                buffer[0]='#';
            }
            else if (buffer[bufferin]==':')
            {
                buffer[bufferin]='0';
                String2=&buffer[bufferin+1];
            }
            else if (buffer[bufferin]=='&')
            {
                buffer[bufferin]='0';
                CommandSent=0;
            }

            bufferin++;
            //history_count++;// for debugging
if (bufferin == LENGTH)
    bufferin = 0;

if (CommandSent == 0)
{
    if(strcmp(String1,"#INIT") == 0)
    {
        strcpy(Response1,String1);
        CommandSent=1;
        JobComplete=0;
    }
    else if (strcmp(String1,"#MOVE") == 0)
    {
        strcpy(Response1,String1);
        //p=ltoa(CPint,ReadPosition,10);
        DPint = strtol(String2,&stopstring,10);
        DesiredPosition=(float)DPint;
        CommandSent=1;
        MOVE=0;
    }
    else if (strcmp(String1,"#READ") == 0)
    {
        READ=0;
        CommandSent=1;
        p=ltoa(CPint,ReadPosition,10);
    }
}
else if (strcmp(String1,"#STOP") == 0)
{
    strcpy(Response1,String1);
    DesiredPosition=CurrentPosition;
    CommandSent=1;
    JobComplete=0;
}
else if (strcmp(String1,"#RESET") == 0)
{
    if (MOVE != 0)
    {
        strcpy(Response1,String1);
        CurrentPosition=0;
        CPint=(long)CurrentPosition;
        //p=ltoa(CurrentPosition,ReadPosition,10);
        CommandSent=1;
        JobComplete=0;
    }
else if (strcmp(String1, "#HOME") == 0)
{
    strcpy(Response1, String1);
    DesiredPosition=0;
    CommandSent=1;
    MOVE=0;
}
else
{
    CommandSent=1;
    JobComplete=0;
    //error
}
} //end of if (command==0)
} //END OF IF(C&1)

}while (c & 1);

outp(0x20, 0x20);

} //END OF ISR

/*****************************
***/

/*****************************/

//MAIN
****/*

void main(void)
{
    char CharSend; // used to exit program
    int j; // counter
    char noerror[4]=":0&"; // string for no error
    char ReadReply[6]=",0,0&"; // end of read reply to BSA
    char ReadResponse[9]="#READ:0;"; // start of read reply to BSA

/*****************************/

outp(PORT1 + 1, 0); /* Turn off interrupts - Port1 */

_dos_setvect(int vect, port1 int); /* Set Interrupt Vector Entry */
    /* COM1 - 0xC */
    /* COM2 - 0xB */
    /* COM3 - 0xC */
    /* COM4 - 0xB */
/* PORT 1 - COMMUNICATION SETTINGS */

outp(PORT1 + 3, 0x80);  /* Set DLAB On */

outp(PORT1 + 0, 0x0C);  /* Set Baud Rate - Divisor Latch Low Byte */  
/* 9,600 - 0x0C */

outp(PORT1 + 1, 0x00);  /* Set Baud Rate - Divisor Latch High Byte */
outp(PORT1 + 3, 0x03);  /* 8Bits, No Parity, 1 Stop Byte */
outp(PORT1 + 2, 0xC7);  /* FIFO Control Register */
outp(PORT1 + 4, 0x0B);  /* Turn on DTR, RTS, and OUT2 */

outp(0x21, (inp(0x21) & 0xEF));  /* Set Programmable Interrupt */
/* Controller */
/* COM1/3 (IRQ4) - 0xEF */
/* COM2/4 (IRQ3) - 0xF7 */

outp(PORT1 + 1, 0x01);  /* Interrupt when data recievied */

/***********************PARALLEL PORT SET-UP***************************/

outp(CONTROL, inp(CONTROL) & 0XDF); //Make sure port is in Forward Direction
outp(DATA, 0x00);  //All Low

/***************************Tdriver.exe******************************/

printf("\n***************Tdriver.exe***************\n\nPress ESC to quit \n");
do
{
    if (READ==0)
    {
        j=0;
do
        {
            outp(PORT1, ReadResponse[j]);
            j++;
pause();
        }while(ReadResponse[j]!="\0");
pause();
j=0;
do
    {

outp(PORT1,ReadPosition[j]);
pause();
j++;
}while(ReadPosition[j]!="0");
j=0;
do
{
    outp(PORT1,ReadReply[j]);
pause();
j++;
}while(ReadReply[j]!="0");
printf("nRead Return: ");
printf(ReadResponse);
printf(ReadPosition);
printf(ReadReply);
READ=1;
}//end of if (READ==0)

if (MOVE==0)
{
    if (CurrentPosition<=(DesiredPosition-(STEP/2)))
    {
        outp(DATA,0x03); //00000011 pin3:high pin2:high holdstep();
        outp(DATA,0x02); //00000010 pin3:high pin2:high
        CurrentPosition=CurrentPosition+STEP;
        CPint=(long)CurrentPosition;
        printf("Step forwards | Position: %li (um)n",CPint);
    }

    //p=itoa(CurrentPosition,ReadPosition,10);
    }
else if(CurrentPosition>(DesiredPosition+(STEP/2))
{
    outp(DATA,0x01); //00000001 pin3:low pin2:high holdstep();
    outp(DATA,0x00); //00000000 pin3:low pin2:low
    CurrentPosition=CurrentPosition-STEP;
    CPint=(long)CurrentPosition;
    //p=itoa(CurrentPosition,ReadPosition,10);
    printf("Step back | Position: %li(um)n",CPint);
    }
else //CurrentPosition == DesiredPosition
{
    printf("Now in Position: ");
    printf("%li(um)",CPint);
    printf("n");
//p=itoa(CurrentPosition,ReadPosition,10);
JobComplete=0;
MOVE=1;
//strcpy(Response2,noerror);
}
} //end of if(MOVE==0)

strcpy(Response2,noerror);
if (JobComplete==0)
{
  printf("\nResponse: ");
  printf(Response1);
  printf(Response2);
  /*********sending***********/
  j=0;
  do
  {
    outp(PORT1,Response1[j]);
    pause();
    j++;
  }while(Response1[j]!="\0");
  j=0;
  do
  {
    outp(PORT1,Response2[j]);
    pause();
    j++;
  }while(Response2[j]!="\0");
  /***********************
  JobComplete=1;
}

if (kbhit())  //needed to exit program
  CharSend=getch();

while(CharSend!=27);

printf("\n\n\nHave a nice day 
\n\n");

// Commented lines are used only for debugging.
// printf("\nString1: ");
// printf(String1);
// printf("\nString2: ");
// printf(String2);
// printf("\nDesired Position: ");
// printf("%ld",DesiredPosition);
// printf("\nResponse1: ");
// printf(Response1);
// printf("\n\n");
// printf("History:\n\n");
// for (j=0;j<1000;j++)
// {
// printf("%c",history[j]);
// }

/***********************Close Ports*************************/

outp(PORT1 + 1, 0); /* Turn off interrupts - Port1 */

outp(0x21,(inp(0x21) | 0x10)); /* MASK IRQ using PIC */
    /* COM1/3 (IRQ4) - 0x10 */
    /* COM2/4 (IRQ3) - 0x08 */

outp(DATA,0x00);       // all parallel pins low
}
### APPENDIX III. MEASURING VOLUME LOCATION EXPERIMENTAL DATA

**Table A-1 Redundant Measurements of a Velocity Component**

<table>
<thead>
<tr>
<th>Angle Bin</th>
<th>U1 Mean Velocity (m/s)</th>
<th>U4 Mean Velocity (m/s)</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.25</td>
<td>5.16</td>
<td>1.71%</td>
</tr>
<tr>
<td>1</td>
<td>5.19</td>
<td>5.05</td>
<td>2.70%</td>
</tr>
<tr>
<td>2</td>
<td>5.04</td>
<td>4.82</td>
<td>4.37%</td>
</tr>
<tr>
<td>3</td>
<td>4.85</td>
<td>4.62</td>
<td>4.74%</td>
</tr>
<tr>
<td>4</td>
<td>4.62</td>
<td>4.38</td>
<td>5.19%</td>
</tr>
<tr>
<td>5</td>
<td>4.31</td>
<td>4.1</td>
<td>4.87%</td>
</tr>
<tr>
<td>6</td>
<td>3.99</td>
<td>3.85</td>
<td>3.51%</td>
</tr>
<tr>
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<td>3.68</td>
<td>3.16%</td>
</tr>
<tr>
<td>8</td>
<td>3.73</td>
<td>3.71</td>
<td>0.54%</td>
</tr>
<tr>
<td>9</td>
<td>3.82</td>
<td>3.89</td>
<td>-1.83%</td>
</tr>
<tr>
<td>10</td>
<td>3.96</td>
<td>4.09</td>
<td>-3.28%</td>
</tr>
<tr>
<td>11</td>
<td>4.21</td>
<td>4.35</td>
<td>-3.33%</td>
</tr>
<tr>
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<td>4.46</td>
<td>4.62</td>
<td>-3.59%</td>
</tr>
<tr>
<td>13</td>
<td>4.68</td>
<td>4.85</td>
<td>-3.63%</td>
</tr>
<tr>
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<td>4.93</td>
<td>5.04</td>
<td>-2.23%</td>
</tr>
<tr>
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<td>5.06</td>
<td>5.17</td>
<td>-2.17%</td>
</tr>
<tr>
<td>16</td>
<td>5.21</td>
<td>5.28</td>
<td>-1.34%</td>
</tr>
<tr>
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<td>5.29</td>
<td>5.31</td>
<td>-0.38%</td>
</tr>
<tr>
<td>18</td>
<td>5.35</td>
<td>5.32</td>
<td>0.56%</td>
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<tr>
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<td>5.37</td>
<td>5.29</td>
<td>1.49%</td>
</tr>
<tr>
<td>20</td>
<td>5.3</td>
<td>5.2</td>
<td>1.89%</td>
</tr>
<tr>
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<td>5.22</td>
<td>5.1</td>
<td>2.30%</td>
</tr>
<tr>
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<td>5.07</td>
<td>4.91</td>
<td>3.16%</td>
</tr>
<tr>
<td>23</td>
<td>4.92</td>
<td>4.7</td>
<td>4.47%</td>
</tr>
<tr>
<td>24</td>
<td>4.67</td>
<td>4.41</td>
<td>5.57%</td>
</tr>
<tr>
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<td>4.35</td>
<td>4.17</td>
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<td>-2.49%</td>
</tr>
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<td>4.26</td>
<td>4.39</td>
<td>-3.05%</td>
</tr>
<tr>
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<td>4.66</td>
<td>-4.25%</td>
</tr>
<tr>
<td>33</td>
<td>4.73</td>
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<td>-3.59%</td>
</tr>
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<td>4.93</td>
<td>5.09</td>
<td>-3.25%</td>
</tr>
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<td>5.27</td>
<td>-3.13%</td>
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<td>5.35</td>
<td>-1.90%</td>
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<td>5.35</td>
<td>5.42</td>
<td>-1.31%</td>
</tr>
<tr>
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<td>5.41</td>
<td>5.41</td>
<td>0.00%</td>
</tr>
<tr>
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<td>5.39</td>
<td>5.35</td>
<td>0.74%</td>
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<td>45</td>
<td>4.46</td>
<td>4.2</td>
<td>5.83%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angle Bin</th>
<th>U1 Mean Velocity (m/s)</th>
<th>U4 Mean Velocity (m/s)</th>
<th>Percentage Difference</th>
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<tbody>
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<td>5.43</td>
<td>5.47</td>
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</tr>
<tr>
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### APPENDIX IV. AVERAGING TIME EXPERIMENTAL DATA

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### APPENDIX V. LDA OPERATING PARAMETERS

The following tables summarize the LDA parameters used in each experiment.

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APPENDIX VI. FIELDVIEW DATA ORGANIZATION ALGORITHM

The following text is the algorithm in FORTRAN for transforming the measurement data and organizing it appropriately for FIELDVIEW.

REAL DATAFILE(3, 181, 25)
    REAL TAN(181, 25), RAD (181, 25), AXIAL(181, 25), MAG(181, 25)
    REAL MAG1(181,25)

    CHARACTER CONDITION, FAN
    INTEGER NANGP, NRP, NVAR

    print*
    print*, 'ENSURE THE DATA IS IN THE FOLLOWING DIRECTORY'
    PRINT*,'C:\MCB\RAW LDA DATA'
    PRINT*

    PRINT*, 'INPUT THE NUMBER OF ANGLE BINS PER REVOLUTION'
    READ*, NANGP

    PRINT*, 'INPUT THE NUMBER OF RADIAL POSITIONS'
    READ*, NRP

    NVAR = 4

    CALL GETDATA (DATAFILE, CONDITION, FAN, NRP, NANGP)
    CALL TRANSFORMDATA (DATAFILE, TAN, RAD, AXIAL, MAG, MAG1,
    $ NRP, NANGP)
    CALL OUTPUTDATA (TAN, RAD, AXIAL, MAG, MAG1, CONDITION, FAN,
    $ NANGP, NRP, NVAR)

SUBROUTINE GETDATA (DATA, CONDITION, FAN, NRP, NANGP)

    CHARACTER DATAFILENAME*12'A1U1#001.1X1'/
    $, FILELOCATION*16'C:\MCB\RAWLDA-1V'/
    $, CONDITION, FAN, RADIUS*3, COMPONENT, DUMMYCHAR

    REAL DATA (3,181, 25), DUMMY2

    INTEGER U, R, THTA, DUMMY1, DUMMY3, NRP, NANGP

    RADIUS = '000'

    PRINT *, 'THE DATAFILENAME HAS THE FOLLOWING FORMAT'
    PRINT *, DATAFILENAME
    PRINT *, 'INPUT CONDITION SPECIFIER (A,B,C...)' 
    READ 100, CONDITION
    DATAFILENAME (1:1) = CONDITION

    PRINT *, 'INPUT FAN SPECIFIER (1,2,3...)'
READ 100, FAN
DATAFILENAME (2:2) = FAN

100 FORMAT (A)
110 FORMAT (I1)
120 FORMAT (I3,3)
DO U = 1,3

DO R = 1, NRP

WRITE (COMPONENT, 110) U
DATAFILENAME (4:4) = COMPONENT
WRITE (RADIUS, 120) R
DATAFILENAME (6:8) = RADIUS
OPEN (UNIT = 10, FILE = FILELOCATION//DATAFILENAME
$ STATUS = 'OLD' )
READ (10, 100) DUMMYCHAR
READ (10, 100) DUMMYCHAR

DO THETA = 1, NANGP
READ (10, *) DUMMY1, DUMMY2, DUMMY3, DATA (U, THETA, R)
END DO

CLOSE (10)
END DO

END DO

RETURN

SUBROUTINE TRANSFORMDATA (DATAIN, TAN, RAD, AXIAL, MAG,
$ MAGI, NRP, NANGP)

REAL DATAIN (3, 181, 25), U1 (181, 25), U2 (181, 25), U3 (181, 25)
REAL TAN (181, 25), RAD (181, 25), AXIAL (181, 25), MAG (181, 25)
REAL MAGI (181, 25)
INTEGER U, R, THETA

DO THETA = 1, NANGP
DO R = 1, NRP

U1 (THETA, R) = DATAIN (1, THETA, R)
U2 (THETA, R) = DATAIN (2, THETA, R)
U3 (THETA, R) = DATAIN (3, THETA, R)

END DO
END DO

130 FORMAT (F7.2)

DO THETA = 1, NANGP
DO R = 1, NRP

RAD (THETA, R) = -U1 (THETA, R) * SIN (RADIANS (15)) + U2 (THETA, R) *
$ COS (RADIANS (15)) * COS (RADIANS (45)) - U3 (THETA, R) * COS(RADIANS (15)) *
$ \cos(\text{Radian}(45.))$

END DO
END DO

DO THTA = 1, NANGP
DO R = 1, NRP

\[ \tan(\text{THTA}, R) = U_1(\text{THTA}, R) \times \cos(\text{Radian}(15.)) + U_2(\text{THTA}, R) \times \cos(\text{Radian}(45.)) - U_3(\text{THTA}, R) \times \sin(\text{Radian}(15.)) - \cos(\text{Radian}(45.)) \]

END DO
END DO

DO THTA = 1, NANGP
DO R = 1, NRP

\[ \text{AXIAL}(\text{THTA}, R) = U_2(\text{THTA}, R) \times \sin(\text{Radian}(45.)) + U_3(\text{THTA}, R) \times \sin(\text{Radian}(45.)) \]

END DO
END DO

DO THTA = 1, NANGP
DO R = 1, NRP

\[ \text{MAG}(\text{THTA}, R) = \text{RAD}(\text{THTA}, R) \times \text{RAD}(\text{THTA}, R) + \tan(\text{THTA}, R) \times \tan(\text{THTA}, R) + \text{AXIAL}(\text{THTA}, R) \times \text{AXIAL}(\text{THTA}, R) \]

\[ \text{MAG}(\text{THTA}, R) = \sqrt{\text{MAG}(\text{THTA}, R)} \]

END DO
END DO

DO THTA = 1, NANGP
DO R = 1, NRP

\[ \text{MAG1}(\text{THTA}, R) = U_1(\text{THTA}, R) \times U_1(\text{THTA}, R) + U_2(\text{THTA}, R) \times U_2(\text{THTA}, R) + U_3(\text{THTA}, R) \times U_3(\text{THTA}, R) \]

\[ \text{MAG1}(\text{THTA}, R) = \sqrt{\text{MAG1}(\text{THTA}, R)} \]

END DO
END DO

DO R = 1, NRP

\[ \text{AXIAL}(181, R) = \text{AXIAL}(1, R) \]
\[ \text{TAN}(181, R) = \text{TAN}(1, R) \]
\[ \text{RAD}(181, R) = \text{RAD}(1, R) \]
\[ \text{MAG}(181, R) = \text{MAG}(1, R) \]
\[ \text{MAG1}(181, R) = \text{MAG1}(1, R) \]

END DO
FUNCTION RADIAN (DEG)
  PI = 3.1416
  RADIANT = PI/180.*DEG
  RETURN
RETURN

SUBROUTINE OUTPUTDATA ( TAN, RAD, AXIAL, MAG, MAG1, $ CONDITION, FAN, NANGP, NRP, NVAR)

  REAL TAN(181, 25), RAD (181, 25), AXIAL(181, 25), MAG(181, 25)
  REAL MAG1 (181,25)
  REAL DATAOUT(181, 25, 4)
  CHARACTER CONDITION, FAN, OUTPUT*10 /'LDA_A1.FUN'/

  INTEGER NANGP, NRP, NVAR, R, THTA

  OUTPUT (5:5) = CONDITION
  OUTPUT (6:6) = FAN

  DO THTA = 1, NANGP+1
    DO R = 1, NRP

      DATAOUT (THTA, R, 1) = AXIAL (THTA, R)
      DATAOUT (THTA, R, 2) = TAN (THTA, R)
      DATAOUT (THTA, R, 3) = RAD (THTA, R)
      DATAOUT (THTA, R, 4) = MAG (THTA, R)

    END DO
  END DO

  100 FORMAT(5F8.2)

  PRINT*, 'THE OUTPUT FILE IS NAMED'
  PRINT*, OUTPUT
  OPEN (UNIT=10, FILE=OUTPUT)

  WRITE (10,*) NANGP+1, NRP, NVAR

  WRITE (10,100) (( DATAOUT(THTA,R, NVAR), THTA=1,NANGP+1), $ R=1,NRP), NVAR=1,4)

  CLOSE (10)
  RETURN
END
APPENDIX VII. FIELDVIEW GRID GENERATION ALGORITHM

The following text is the algorithm in FORTRAN for generating the grid used in FIELDVIEW to plot the data as organized using the algorithm in Appendix VI.

C THIS PROGRAM WAS DEVELOPED TO CREATE A GRID FILE FOR THE
C LDA DATA. THE INPUT FILE MUST BE AN ARRAY OF THE RADIAL LOCATIONS
C USED FOR MEASUREMENTS.

REAL  RPOINT(25), X(181,25), Y(181,25)
REAL  FT(13575), F1(4525), F2(4525), F3(4525)
REAL  THETA(181), F4(181,25,3)
REAL  HUB
INTEGER NRP, THTA, NVAR
CHARACTER*12 GRIDIN/'LDA_FAN1.TXT'/
CHARACTER*12 GRIDOUT/'LDA_FAN1.XYZ'/
CHARACTER DATAIN, DATAOUT, DUMMYCHAR

C NRP=20
THTA=180
NVAR=3
100 FORMAT(A)

PRINT *, 'INPUT THE NUMBER OF RADIAL POINTS'
READ *, NRP

PRINT *, 'INPUT GRID FILENAME (12 CHARACTERS MAX)' '
READ 100, GRIDIN

OPEN(UNIT=15, FILE=GRIDIN, STATUS='OLD')
READ(15, *) (RPOINT(I), I=1, NRP)
CLOSE(UNIT=15)

DO 15 I=1, THTA+1
   THETA(I)=2*(I-1)
15 CONTINUE

DO 30 J=1, THTA+1
   DO 20 J=1, NRP
      X(I,J)= RPOINT(J)*COS(3.1416*THETA(I)/180)
      Y(I,J)= RPOINT(J)*SIN(3.1416*THETA(I)/180)
20 CONTINUE
30 CONTINUE

GRIDOUT (1:8) = GRIDIN

PRINT*, 'THE OUTPUT GRID FILE IS ',GRIDOUT

OPEN(UNIT=35, FILE=GRIDOUT)
WRITE(35,*)THTA+1,NRP
WRITE(35,*)((X(I,J), I= 1,THTA+1),J=1,NRP),
& ((Y(I,J),I=1,THTA+1), J=1,NRP)
CLOSE(UNIT=35)

END
APPENDIX VIII. EXPERIMENTAL UNCERTAINTY

The experimental uncertainty from this experiment is derived from two sources: fan flow conditions and velocity data acquisition. The uncertainty in the operating conditions is explained by Nourse in [17]. The maximum uncertainty in the flow rate was found to be ±6% at the minimum flow rate of 0.3 m³/s (634 CFM) down to ±2.6% for a flow rate of 0.47 m³/s (994 CFM).

The uncertainty in the velocity magnitude is a function of the uncertainty in the measurement of each component. The uncertainty in velocity measurement is independent of the orientation of the LDA probe and therefore, the uncertainty will be the same for each component.

The uncertainty in the measurement component is a function of the following factors: spatial ambiguity in the measuring volume, phase angle of fan at the time of a measurement and the relocation of the measuring volume when the measured component is changed.

If a measuring volume is located in a steady one dimensional flow with a constant gradient, then particles will pass through the measuring volume with a range of velocities depending on the location of the particle’s path within the measuring volume. Since the arrival of a particle and it’s location is a random event, the readings from this measurement will show a distribution of velocities. This phenomenon is known as spatial ambiguity. Since the phase average velocity exhibits velocity gradients, spatial ambiguity is a cause of uncertainty for this study.

For each radial location, the measurement grid was divided into 180 bins of width 2°. Any particle that passed through the measuring volume within that 2° window was
measured and averaged with the rest of the sample. Particles passing through the measuring volume close to one end of the window, however, would have a different velocity than particles passing through the other. Decreasing the width of each window and increasing the number of angle bins for each revolution could reduce this uncertainty. The trade off is the decreased chance of a particle passing through any given window. An experiment with a smaller angle bin would have to use a much larger total count to ensure each angle bin had a statistically significant sample size.

The uncertainty can be estimated with the use of velocity data taken from a measurement at one radial location. With the use of the data collected during a preliminary experiment measuring 50,000 particles, (this sample size was determined in the preliminary experiments to yield a statistically significant sample size in each angle bin and to use a sufficiently long averaging time) the uncertainty can be estimated. Figure A.1 shows the average velocity measured, as well as the two-sigma standard deviation of the average velocity for each angle. The two-sigma standard deviation gives a 95% level of confidence. As well, the standard deviation as a percentage of the average velocity is plotted. This graph indicates that the standard deviation is constant within a narrow range. The average standard deviation is ±0.29 m/s, the maximum is ±0.40 m/s and the minimum is ±0.22 m/s. A constant uncertainty in absolute terms results in a varying uncertainty when converted into a percentage of the average velocity. As a percentage, the uncertainty varies between ±4%, when the velocity is at a maximum, and ±10%, for a minimum velocity. The average is ±6%.

The uncertainty due to probe location was investigated in section 4.1.1 and determined to be ±6%. The maximum uncertainty due to probe location occurs when the
absolute value of the gradient of the average velocity is at a maximum. When the
gradient is at zero (the maximum and minimum values of the velocity), the uncertainty
due to probe location is zero. In absolute terms, the maximum uncertainty was found to
be ±0.26 m/s.

Since the uncertainty due to spatial ambiguity and phase angle of the fan is greater
than the uncertainty due to probe location, a constant uncertainty of ±0.29 m/s can be
considered sufficient to account for all of the sources of uncertainty in data acquisition.

The uncertainty in data acquisition is carried through the data reduction. The data
was reduced in two ways. First, the measured components were transformed into axial,
tangential, and radial components. This transformation, of course, does not introduce any
new uncertainty. The components were also used to calculate the velocity magnitude.
The method used for estimating the uncertainty in the velocity magnitude is described by
Figliola and Beasley [22] and accepted by the American Society of Mechanical Engineers
(ASME) [23].

The velocity magnitude is calculated using equation (A.1).

\[ \text{Mag} = r^2 \cdot a^2 \cdot t^2 \]  \hspace{1cm} (A.1)

The precision uncertainty, \( P_{\text{Mag}} \), in the velocity magnitude is calculated using
equation (A.2). \( P_r, P_a, \) and \( P_t \), are the precision uncertainties in the radial, axial and
tangential velocity components respectively.

\[ P_{\text{Mag}} = \frac{\delta \text{Mag}}{\delta r} \cdot P_r^2 + \frac{\delta \text{Mag}}{\delta a} \cdot P_a^2 + \frac{\delta \text{Mag}}{\delta t} \cdot P_t^2 \]  \hspace{1cm} (A.2)

Inserting equation (A.1) into (A.2) and calculating the partial derivatives will
result in equation (A.3).
Equation (A.3) can be simplified to equation (A.4)

\[ P_{\text{Mag}} = \frac{r^2 - a^2 - t^2}{r^2} \cdot 2 \cdot r \cdot P_r - \frac{2 \cdot a \cdot P_a}{r^2} - \frac{2 \cdot t \cdot P_t}{a^2 - t^2} \]

Since the uncertainty in each component is not dependent on the orientation of the probe, the uncertainty was determined to be equal for all components. Therefore, the uncertainty in the radial component can be substituted for the uncertainty in the axial and tangential components. This substitution results in the simplification made in equation (A.5).

\[ P_{\text{Mag}} = \frac{r^2 - a^2 - t^2}{r^2} \cdot 2 \cdot a \cdot P_a - \frac{1}{r^2} \cdot \frac{1}{a^2 - t^2} \cdot t \cdot P_t \]

Further simplification results in equation (A.6)

\[ P_{\text{Mag}} = P_r \]

Since the uncertainty for each velocity component was found to be a constant value of ± 0.29 m/s, the uncertainty for the velocity magnitude is also ± 0.29 m/s.
Measurement Uncertainty

Figure A.1: Two Sigma Uncertainty
VITA AUCTORIS

1969  Born in Leamington Spa, England on November 06

1989  Completed high school at Walkerville Collegiate Institute, Windsor, Ontario, Canada in January

1993  Received Bachelor of Arts in Political Science at the University of Western Ontario, London, Ontario, Canada in June

1998  Received Bachelor of Applied Science in Mechanical Engineering at the University of Windsor, Windsor, Ontario, Canada in October.

2001  Currently a candidate for the Degree of Master of Applied Science in Mechanical Engineering at the University of Windsor, Windsor, Ontario, Canada