Development of an automotive fan test facility.

Philip John Nourse
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UMI®
Development of an Automotive Fan Test Facility

by

Philip J. Nourse

A THESIS

Submitted to the Faculty of Graduate Studies and Research Through 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

2000
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ABSTRACT

The University of Windsor/DaimlerChrysler Fan Test Facility is part of a study to develop a simplified numerical model for predicting the behaviour of automotive cooling fans. The facility could be used to validate computational fluid dynamic software. Three-dimensional velocity vector information is required on planes at specified axial locations downstream from the fan. The facility consists of a 3m x 3m x 3m test chamber, which contains a fan and shroud combination located in the ceiling. The fan is attached to a vertical rotating shaft, which is driven by a variable speed DC motor arrangement. An X-array hot-wire probe is positioned, consecutively, at two downstream locations to determine the 3 components of velocity over the plane. The “ram air” effect is simulated by drawing additional air through the fan using a blower on the exhaust from the test chamber. An orifice plate is used to determine the overall flow rate through the facility. The entire operation is automated using a microcomputer and a multi input/output card. Operating conditions allow for flow rates between 0.28 m³/s and 1.133 m³/s with pressure differences across the fan of less than 2500 Pa. This thesis outlines the development of the physical facility and the associated computer software used to gather data. Sample results are presented in the form of velocity components, velocity magnitude, and volume flow rate versus pressure performance characteristics.
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<tr>
<td>A</td>
<td>Coefficient used in Collis and Williams hot-wire anemometer calibration equation $(V^2)$</td>
<td>(3.1.2.2)</td>
</tr>
<tr>
<td>B</td>
<td>Coefficient used in Collis and Williams hot-wire anemometer calibration equation $(V^2/(m/s)^n)$</td>
<td>(3.1.2.2)</td>
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<tr>
<td>$C_d$</td>
<td>The discharge coefficient of the orifice plate</td>
<td>(3.4)</td>
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<tr>
<td>E</td>
<td>Voltage output from constant temperature hot-wire anemometer bridge $(V)$</td>
<td>(3.1.2.2)</td>
</tr>
<tr>
<td>$n$</td>
<td>Coefficient used in Collis and Williams hot-wire anemometer calibration equation</td>
<td>(3.1.2.2)</td>
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<td>$p$</td>
<td>Test chamber pressure $(Pa)$</td>
<td>(3.4)</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Difference between test chamber pressure and ambient pressure $(Pa)$</td>
<td>(3.4)</td>
</tr>
<tr>
<td>$P$</td>
<td>Ambient pressure $(Pa)$</td>
<td>(3.4)</td>
</tr>
<tr>
<td>$Q_F$</td>
<td>Flow rate through facility $(m^3/s)$</td>
<td>(3.4)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Flow velocity defined in speed-wire/angle-wire technique $(m/s)$</td>
<td>(3.1.2.2)</td>
</tr>
<tr>
<td>$Q_{eff}$</td>
<td>Effective velocity across one wire in an X-array probe defined as the velocity component perpendicular to the wire assuming the component parallel to the wire has no effect on voltage $(m/s)$</td>
<td>(3.1.2.2)</td>
</tr>
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</table>
\( R_c \)  
Resistance of hot-wire anemometer cable (\( \Omega \))  
(3.1.1)

\( R_e \)  
The Reynolds number of the flow through the orifice plate, based on the diameter of the outlet  
(3.4)

\( R_L \)  
Resistance of hot-wire anemometer leads (\( \Omega \))  
(3.1.1)

\( R_s \)  
Resistance of hot-wire anemometer assembly (\( \Omega \))  
(3.1.1)

\( R_w \)  
Resistance of hot-wire anemometer sensor wire (\( \Omega \))  
(3.1.1)

\( u \)  
The velocity component parallel to the probe axis when referred to in the speed-wire/angle-wire calibration technique (\( m/s \))  
(3.1.2.2)

\( u_t \)  
The radial velocity component of flow downstream from the cooling fan (\( m/s \))  
(3.6.1)

\( v \)  
The velocity component perpendicular to the probe axis when in reference to the speed-wire angle-wire calibration technique (3.1.2.2) (\( m/s \))

\( v_t \)  
The tangential velocity component of flow downstream from the cooling fan (\( m/s \))  
(3.6.1)

\( w_t \)  
The axial velocity component of flow downstream from the cooling fan (\( m/s \))  
(3.6.1)

\( V \)  
Volume of the test facility (\( m^3 \))  
(3.4)

\( \beta \)  
Angle of X-array wire with respect to the probe axis (degrees)  
(3.1.2.2)

\( \beta_D \)  
Diameter ratio of flow outlet tube to orifice plate  
(3.4)
Γ  The rotational angle of the Robotic Probe Aligner arm (degrees)  
(3.6.1)

γ  Flow velocity angle from probe axis (degrees)  
(3.1.2.2)

η  Normalized hot-wire anemometer voltage used in speed-wire/angle-wire technique  
(3.1.2.2)

θ  The rotational angle of the Robotic Probe Aligner base (degrees)  
(3.6.1)

ωₓ  Uncertainty of variable x  
(Appendix A)

Ω  Angular speed of the fan shaft (rotations per minute)  
(4.2)
CHAPTER 1  INTRODUCTION

1.1  General

The University of Windsor/DaimlerChrysler Fan Test Facility (UWDCFTF) is part of a collaborative project between the University of Windsor Fluid Dynamics Research Institute, Mechanical, Automotive and Materials Engineering, and DaimlerChrysler. The objective of this project is to develop a facility that can be used to validate numerical modeling techniques for cooling fans. Specifically, a larger study is currently underway to develop a simplified model of an automotive cooling fan. Such a model would take its input parameters from computational fluid dynamics calculations. The facility is being used to validate the computational fluid dynamics study, increasing the level of confidence in the parameters used to develop the simplified numerical fan model. The results also provide valuable information regarding the physics of the flow process associated with the fan. The specific information obtained in this validation is the pressure rise versus flow rate along with the three components of velocity on two planes downstream from the fan.

The facility described in this thesis is currently being used, by another student, to determine the three components of velocity on planes upstream from the fan using a laser Doppler anemometer. With minor modifications it could be used for studies of similar non-automotive fans.
1.2 Objectives

The object of this study is to design, construct, and verify an automotive fan test facility that can be used for determining all three velocity components on any plane from 25 mm to 100 mm downstream from the fan. The facility must be capable of providing pressure rise versus volume flow rate performance curves for the test fan. The range of variables associated with the fan must be typical of automotive cooling fans. The variables include the velocity components and magnitude, the volume flow rate and pressure rise, as well as the fan diameter and angular speed. Provision must also be made to simulate the “ram air effect” due to the passage of the automobile through the air.

In order to reduce the time and effort required to obtain the results, an additional objective is to provide a fully automated measurement process.
1.3 Literature Survey

Most experimental research performed on fans is concerned with the measurement of performance characteristics such as pressure rise versus volume flow rate or torque and power input. Very little work has been done to measure the velocity components or other local quantities across the face of a cooling fan. Of particular interest is a study done by Morris (1997) in which a facility was built to test an "aerodynamic shroud" device used to overcome the effects of large tip clearance on cooling fans in trucks. This study was also documented in a more recent paper (Morris et al., 1998). Morris measured flow rate using a non-traditional integral technique that involves the use of the force exerted by the flow on a turning vane. Velocity component measurements were accomplished using an X-array hot-wire anemometer with a technique similar to that used in this thesis. The method used to determine the position of the fan when velocity readings were taken was, however, based on the time it would take the shaft to rotate to a particular angle. In the current study, an optical encoder is used to indicate the angular position of the fan. This has the advantage of not relying on a constant fan speed for accuracy. Since the fan tip was of particular interest, flow visualization techniques involving wool tufts were used in order to predict the effects of the "aerodynamic shroud" on flow reversal in Morris' (1997) study. Morris (1997) pointed out the need for open air upstream and a large plenum downstream to adequately simulate cooling fan performance. This is standard in measuring cooling fan performance (Baranski, 1974). The techniques used by Morris (1997) for determining the three components of the velocity vector required that the X-
array probe be aligned with the flow. Although a more automated technique for pointing the hot-wire probe into the mean direction of the flow was used in the current study, no advances in hot-wire anemometry suitable for this study could be found to eliminate the need for alignment of the probe in the flow. Morris' (1997) technique was chosen as a model for the current facility because of the similarity in application. Other techniques, however, have been developed for determining flow fields, including one by Lofdahl et al. (1996) that involves the use of straight and slanted single hot-wire probes. While the use of a single wire probe improves the spatial resolution, a velocity cannot be determined from a single measurement but rather from combinations of measurements taken with the probe located at different angular positions. This means that voltages must be averaged rather than velocities. Since the velocity is not linearly related to the voltage, an additional error is introduced in the average.

Work has also been done on other types of turbomachinery using various measuring techniques. Vad and Ferenc (1998) used a three-component laser Doppler anemometer to measure the flow downstream of an axial fan. Their intent was to study the effects of radial velocity components on the performance of axial fans and provide this knowledge to fan designers. The use of a three-component laser Doppler anemometer was rejected in the current study primarily because of the cost of equipment. A disadvantage of this type of measurement technique is the inability of the laser Doppler anemometer to take a velocity reading on command. Velocity readings can only be taken when a seed particle is passing through the measuring volume of the anemometer. Phase averaged readings must rely on particles passing through the measuring volume during a specified
time window which corresponds to an angular position window. This angular position window is larger than that achieved using a hot-wire anemometer probe in conjunction with an encoder. This is especially important when the velocity gradients are high such as those found downstream of an automotive cooling fan. The use of a laser Doppler anemometer does, however, have an advantage over the use of a hot-wire anemometer probe in that the laser Doppler anemometer does not need to be aligned with the flow to obtain accurate results. Kuroumaru et al. (1982), and Hirsch and Kool (1977) used a single slanted hot-wire anemometer to measure the three components of flow downstream of an impeller, and an axial compressor stage respectively. The techniques used for determining the three components of velocity were similar to those proposed by Lofdahl (1996) with the same advantages and disadvantages as previously mentioned. Both researchers used a technique for determining the angular position of the fan similar to that used by Morris (1997).
CHAPTER 2   EXPERIMENTAL FACILITY

2.1 Flow Facility

This section begins with a description of the flow path through the facility along with a section dealing with design considerations. Specific equipment related to the facility are then detailed, including the probe positioning equipment, the optical encoder, the fan drive assembly, and the shroud section of the facility inlet.

2.1.1 Facility Flow Path

Figure 2.1.1 shows a perspective view of the facility with the plywood cladding removed. The test fan and shroud are located in the ceiling and the fan is attached to a vertical-rotating shaft. The shaft is driven by a variable speed DC motor. The numbers on Figure 2.1.1 indicate the flow path that is followed. The flow starts in the laboratory at a large distance from the fan (1) where velocity is assumed to be zero. The flow accelerates through the fan (2) and into the large upper section (3) of the facility. The downstream measurement equipment, fan shaft and, drive mechanisms are housed in this section. In order to ensure that the flow is reasonably symmetrical, grating (4) is placed in the four corners of the floor between the upper and lower (5) sections. A rectangular flow diffuser section (not shown) is placed in the center of the facility to draw air through all four corners of the floor separating the two sections. After exiting the reducer, the air flows through a damper that is intended to allow for lower flow rate control when partially closed. The flow exits the manifold through a connection in the side and enters the blower (6). After passing through the blower, the flow passes through an elbow (7) and then a long straight section. Finally, the air passes through the orifice plate (8) and back into the
laboratory. The blower serves to draw an additional amount of air through the test fan to simulated the "ram air" effect of an automobile travelling through still air.

2.1.2 Flow Facility Design

The flow facility is 3m x 3m x 3m in size. This size is required to allow sufficient room to place downstream measurement equipment so that it does not interfere with the flow.

The flow facility is located in a divided laboratory, relatively close to walls and the ceiling. The effects of these asymmetrical features were unknown. The influence of the floor in the facility on the incoming flow pattern also needed to be investigated.

A study was performed using a commercially available computational fluid dynamics software package, FLUENT, in order to estimate these effects. The computation was performed on an SGI Indy workstation with 64 MB of RAM. Figure 2.1.2 shows the simplified 3D geometry. A 39 x 37 x 39 grid was used. The fan opening was approximated as a square opening in the ceiling with the exhaust as a square opening on the floor of the facility. The boundary conditions used were constant velocity on the inlet and an outlet condition at the exit. The inlet flow area was located well away from the fan opening and was large enough to allow the assumption that specifying a velocity direction would not affect the direction of the flow entering the fan. The overall flow rate used in the simulation was 1.42 m$^3$/s. It was determined that the velocity is less than 1 m/s at points outside a radius of approximately 1 m of the fan. Any asymmetry of geometry in this low velocity region is not expected to affect the flow symmetry through the fan. The flow through the fan was found to be symmetrical about the two mid-planes of the square
opening in the model. Figure 2.1.3 shows the resulting symmetrical flow field through the fan entrance.

2.1.3 Probe Positioning Equipment

The probe positioning equipment consists of a DISA 9057 0112 three axis traverse, DISA 57 G10 controller, and a Robotic Probe Aligner (RPA) which was designed especially for this facility. The equipment is capable of positioning the probe tip at a specified position with an uncertainty estimated to be ± 1 mm. A complete uncertainty analysis is provided in Appendix A. Detailed CAD working drawings were produced using AutoCad and are stored on a CD and kept on file in the Mechanical, Automotive and Materials Engineering office at the University of Windsor. A number of parts for the RPA were fabricated at DaimlerChrysler Canada using their rapid prototyping facility while others were constructed in the University of Windsor machine shop. The arrangement of the components is shown in Figure 2.1.4. The three axis traverse was used to linearly position the probe under the fan and the controller was used to set up and control the traverse along with a DISA manual controller.

The RPA is a three degrees of freedom rotational device designed to increase the degrees of freedom of the overall traverse mechanism and is fixed to the three axis linear traverse. Figure 2.1.5 is a perspective drawing of the RPA. The three degrees of freedom are base rotation about axis (1), arm rotation about axis (2), and tip rotation about axis (3). The first two degrees of freedom of the RPA are intended to provide for alignment of the X-array probe with the general average direction of the flow. The base rotation allows the RPA to rotate in the horizontal plane. The arm rotation allows the
RPA to rotate from vertical. These two degrees of freedom define an essentially spherical coordinate system for the RPA. The final degree of freedom is the tip rotation. This allows flows to be measured in two planes without the need for repositioning of the traverse.

2.1.4 Optical Encoder

In order to accurately obtain data at each circumferential location, an optical encoder has been designed to provide a signal to the data acquisition card. The encoder is directly attached to the lower end of the drive shaft for the test fan. The encoder consists of a disk that has a slot located every two degrees. Extending from the disk is a tab that is used as a zero index. Figure 2.1.6 shows the optical encoder including the sensors and zero-index tab. Two optical sensors sense the position of the encoder, one for the zero-index, and one for the degree slots. Figure 2.1.7 shows a photograph of the encoder mounted on the drive shaft.

2.1.5 Motor and Shaft Assembly

The shaft was designed such that the natural frequency would be more than 100 Hz, corresponding to twice the rotational frequency. A further consideration for the design of the support equipment was that it did not interfere with the flow. Two bearings were used to support the shaft. The upper bearing (closest to the fan), which is located 500 mm from the fan, is supported by a truss system that is designed, with minimum material, to cause the least amount of flow interference. The second bearing, which also bears the vertical load of the shaft, is located 2 m from the fan and is supported by a substantial steel framework. A 1000 W (1.5 hp) motor is located on the frame and drives
the shaft via a belt system. Figure 2.1.8 illustrates the shaft, motor and frame arrangement. The frame is securely mounted to the concrete floor of the laboratory and the motor drive mechanism is located at the floor between the upper and lower chambers of the facility. The detailed CAD working drawings were also produced using AutoCad and included on the CD previously mentioned.

2.1.6 Removable Shroud Holder

In order to accommodate different sizes of fan, a replaceable shroud adapter was built and is illustrated in Figure 2.1.9. The current adapter fits into the ceiling of the facility and can accommodate shrouds of up to 380 mm in diameter.

2.2 Hot-wire Anemometer Equipment

A Dantec model 55P061 X-array constant temperature anemometer probe is used for velocity measurement. This probe is illustrated in Figure 2.2.1. This probe is capable of measuring two components of velocity in one plane. It is oriented in each of two planes, one after the other, at 90° to each other to resolve the three components of velocity. A DISA 56C17 CTA bridge is used to provide the current to maintain the wires at a constant temperature and to provide the voltage readouts for the probe. The bridge output voltage is recorded using the data acquisition equipment described in section 2.5.

2.3 Pressure Measurement Equipment

There are three pressure transducers used in the UWDCFTF. The first two are general purpose and are used to measure pressure within the facility during velocity measurements and to measure the dynamic pressure in conjunction with a Pitot-static tube during hot-wire calibration. The third is dedicated to measuring the pressure difference
across the orifice plate used to measure volumetric flow rate. Each pressure transducer is a Lucas model P3061 diaphragm type pressure gauge which uses a linear variable differential transformer to sense the diaphragm displacement. The first of the two general purpose pressure transducers measures pressures up to 497 Pa. The second measures pressures up to 1243 Pa. When used in conjunction with each other for calibrating the X-array probe, they are capable of measuring a wide speed range while still providing sensitivity for low speed flows. They are also used in conjunction with each other, one to read a positive and the other a negative static pressure condition in the facility should it exist. Figure 2.3.1 shows the valve system used to switch the pressure transducers between the appropriate pressure sources. Figure 2.3.2 is a photograph of the valve system.

When the pressure transducers are being calibrated, they are simultaneously connected to a constant pressure source and a micro-manometer, which was used as the standard.

The pressure transducer dedicated to the orifice plate for flow rate measurement measures pressures up to 4973 Pa. Pressure taps for this sensor are placed upstream at 1 diameter and downstream at ½ diameter from the orifice plate in accordance with standard practice (Miller, 1983).

All of the sensors are powered by a single 12 V power supply. The output signals from these pressure transducers are connected to data acquisition equipment described in section 2.5.
2.4 Flow Rate Measurement Equipment

Volumetric flow rate is measured using a square edged orifice plate near the end of the ductwork exiting the blower. The ducting leading to the orifice plate is 356 mm in diameter and the orifice plate diameter is 178 mm which gives a diameter ratio, $\beta$, of 0.5. Locations for the orifice plate, pressure tap, and flow exit to atmosphere where taken from the Flow Measurement Engineering Handbook (Miller, 1983). The handbook states that an accuracy of $\pm \, 2\%$ is achieved with this flow device.

2.5 Data Acquisition Equipment

A National Instruments MIO-16XE –10 general purpose multiple input-output card coupled with a National Instruments SC-2040 simultaneous sample and hold board in conjunction with a Pentium 100 computer is used for all data acquisition and control for the facility. The computer has 48 MB of RAM, of which, 24 MB is required to efficiently run the programs presented later in Chapter 3. The MIO-16XE –10 is a 16 bit card with 8 differential analog input channels, five digital input/output channels, two analog output channels, two general purpose counters, and several triggers including one analog trigger. The maximum sampling capability of the card is 100,000 samples/second/channel.

In order to ensure negligible time skew between the two hot-wire sensors in the X-array probe, the SC-2040 card is used to hold the analog signals while they are being read through the analog inputs.

The following data acquisition channels have been allocated for each pressure sensor:

Channel 5: P3061 – 5WD 1243 Pa Pressure Transducer
Channel 6: P3061 – 2WD 497 Pa Pressure Transducer

Channel 7: P3061 – 20WD 4973 Pa Pressure Transducer

The first analog output channel is used to control the speed of the test fan drive shaft. It provides a differential voltage through a custom built DC isolator for the motor controller and adjusts the 0-10 volt output of the MIO card to the required input for the motor controller. The resulting input into the motor controller controls the speed from 0 RPM to a maximum speed of 1750 RPM.

The second analog output channel is connected directly to the 0-10 volt input of the Allen Bradley variable frequency controller that controls the blower speed.

The A/D analog trigger is connected to the encoder zero pulse and is programmed to act like a Schmidt trigger in order to filter out accidental triggering due to noise. A digital trigger is connected to the encoder degree pulse. The digital trigger is sensitive to noise so a reliability indication system has been added to the data acquisition program to detect when a false pulse is received during any given cycle. The general purpose MIO card is capable of running more than one program at a time so the number of encoder wheel pulses per revolution can be counted at the same time the velocity data is being acquired. If the number of pulses exceeds the number of slots on the encoder wheel, the data is discarded. A readout indicating the percentage of data sets that are not discarded for this reason is displayed in the computer program.

One of the general purpose timers is required by the data acquisition card for the purpose of counting samples acquired. The other is used for counting clock pulses while measuring shaft speed and for counting encoder pulses as a way of detecting false pulses.
Only one digital input/output channel is used. It is used as a general purpose trigger for remote user input. A hand-held trigger is connected to this channel via a coaxial cable.

Figure 2.5.1 illustrates a schematic diagram of the data acquisition equipment.

2.6 Hot-wire Calibration Facility

The hot-wire calibration facility provides a uniform flow with nearly zero turbulence level and is shown schematically in Figure 2.6.1. A photograph of the facility is given in Figure 2.6.2. Air from the physical plant compressed air line is directed through pressure regulators, and a rotometer. The air then flows through a settling chamber which consists of a large cylinder containing flow straighteners, and finally through a small nozzle, 25.4 mm in diameter, on the other end of the cylinder. The resulting jet contains a uniform flow region (potential core) near the outlet (Islam, 1979). The probe is attached to a standard Dantec probe holder, which in turn is mounted on a standard Dantec extension tube. The entire assembly is mounted on a three-axis traverse with a single degree of freedom pivot to allow different settings of yaw angle. The pivot has an angular indicator with a vernier scale. The vernier scale has a resolution of 0.2 degrees. A Pitot-static tube is used, as a standard, to measure the flow velocity in the potential core. The two outputs from the Pitot-static tube are connected to the facility pressure sensor system so that the pressure differential can be determined by the data acquisition system. Using the three-axis traverse, the probe can be placed at any convenient location in the flow. In order to avoid interference, the Pitot-static tube and the probe are placed in diametrically opposite positions in the uniform flow region.
Figure 2.1.1  Perspective View of Fan Test Facility with Cladding Removed
Figure 2.1.2  Simplified 3D Model of Facility Used for Fluent Study

Figure 2.1.3  Calculated Flow Field Through Fan Entrance
Figure 2.1.4  Photograph of Traverse and Robotic Probe Aligner

Figure 2.1.5  Robotic Probe Aligner
Figure 2.1.6  Perspective Drawing of Optical Encoder Wheel Including Optical Sensors
Figure 2.1.7  Photograph of Encoder Wheel
Figure 2.1.8  Perspective Drawing of Shaft, Frame and Motor Assembly
Figure 2.1.9   Shroud Adapter
Figure 2.2.1 Sketch of X-array Hot-wire Anemometer
Figure 2.3.1  Pressure Sensor Valve System Schematic
Figure 2.3.2  Pressure Sensor Valve System Photograph
Figure 2.5.1  Data Acquisition System Schematic
Figure 2.6.1  Schematic of Calibration Flow Facility

Figure 2.6.2  Photograph of Calibration Facility
CHAPTER 3 EXPERIMENTAL PROCEDURES

A number of preliminary procedures were necessary before the final experimental procedure to acquire the velocity data could be achieved. This chapter contains an overview of each of these procedures. Details of the procedures can be found in Appendix B and, for convenience, are numbered in the same way as in this chapter.

3.1 CTA Calibration

The X-array constant temperature hot-wire probe requires frequent calibration in order to compensate for contamination and changes in room temperature. A program has been written to aid the operator in balancing the CTA bridge and in calibrating the probe. The program is called “CTA X-array Calibration” and outputs a file with the extension .CAL, which can be read by the “Fan Test Facility” program. The CTA X-array Calibration program is further described later in this section and in Appendix B.

3.1.1 Bridge Adjustment

In order to prepare the probe for calibration, the DISA 56C17 bridge must be adjusted to result in a probe resistance overheat ratio of approximately 0.8. This typically allows for a probe temperature less than the maximum allowable for the material. A feedback control loop is used to hold the wire at a constant resistance, and therefore a constant temperature. The basic procedure for balancing the DISA 56C17 bridge can be found in Hodge (1999). The resistance overheat ratio refers to the percentage of the initial wire resistance that was added in order to obtain a temperature well above room temperature. The total system resistance, $R_s$, can be written as:
\[ R_s = R_c + R_l + R_w \]  

(3-1-1)

where \( R_c \) is the cable resistance, \( R_l \) is the lead resistance, and \( R_w \) is the wire resistance. The lead (or prong) resistance is stated by the manufacturer. The cable resistance is determined by replacing the hot-wire probe with a short circuit probe and measuring the system resistance. Finally, the wire resistance is determined by solving for the cable resistance, knowing the lead resistance, and measuring the overall system resistance. The bridge is then set to have an overall system resistance such that the wire resistance is 1.8 times the room temperature wire resistance.

3.1.2 CTA X-array Calibration

The CTA X-array Calibration consists of two basic steps, collecting the calibration data, and performing the curve fits.

3.1.2.1 Calibration Data Collection

The program allows calibration data to be collected for any number of angles and any number of speeds. A matrix of 20 speeds by 13 angles was used for the calibration of the fan considered in this thesis. The speeds ranged from 7 m/s to 25 m/s and the angles ranged from \(-36^\circ\) to \(36^\circ\). A portion of the program enables the user to collect test data in order to validate the calibration. This must be done at the end of fan test data collection in order to ensure that a large amount of drift has not occurred in the calibration.

3.1.2.2 CTA Calibration

The CTA X-array Calibration is a modification of the "speed wire/angle wire" technique (Foss, et al. 1995) and is nearly identical to the technique used by Morris (1997). Morris denotes the velocity by \( Q \) and flow angle with respect to the probe by \( \gamma \).
These notations are used here as well. Figure 3.1.1 shows the relationship between the probe and this angle. The Collis and Williams equation (Collis and Williams, 1958)

\[ E^2 = A + BQ^2 \]  

(3-1-2)

is used to fit velocities for each calibration angle. The data is fit to this equation by applying a nonlinear fit developed by Swaminathan et al. (1983) and implemented by Hodge (1999) in a Fortran program that was translated into C for the purpose of this calibration. The voltages for a given velocity are normalized to the voltage where the angle is zero degrees. The variable \( \eta(\gamma) \) is defined for this purpose, and the equation

\[ \eta = \frac{E(Q,\gamma)}{E(Q,0)} - 1 \]  

(3-1-3)

is used to non-dimensionalize the voltage for each given speed in the calibration. \( \eta \) versus \( \gamma \) is then fit to a fifth order polynomial using a least squares method for each speed and for each wire. Figure 3.1.2 shows this curve fit taken directly from an actual calibration using the calibration program for one of these two wires.

In order to resolve the velocities from the wire voltages, an initial guess is made by applying a simple cosine law relationship. First, the angles of the wires with respect to the probe axis (\( \beta_1 \) for the first wire and \( \beta_2 \) for the second wire) are computed. The equation (Bohl, 1996) used to calculate \( \beta \) is

\[ \beta = \tan^{-1}\left( \frac{dE^2}{d\gamma}/(E^2 - A)n \right) \]  

(3-1-4)

for \( \gamma = 0 \). A central difference approximation is used to evaluate \( dE^2/d\gamma \). This differs from Morris (1997) who differentiated a second order polynomial fit. It is not necessary to calculate \( \beta \) for this procedure, however, because it is only used as an initial estimate of
velocity magnitude and angle. An angle of 45° could have been used instead. Making the estimate of $\beta$ more accurate increases the speed of convergence of the iterative procedure.

Next, the effective cooling velocity for each wire, i.e. the velocity component perpendicular to the wire assuming that the velocity component parallel to the wire has no effect on the output voltage, is calculated from

$$E^2 = A + B\left(\frac{Q_{\text{eff}}}{\cos(\beta)}\right)^n$$

(3-1-6)

evaluated at $\gamma = 0$. $Q_{\text{eff}}$ is solved for each wire and applied to the following system of equations, which is used to estimate the values for $u$ and $v$ based on the above assumed values:

$$Q_{\text{eff}(1)} = u \cos(\beta_1) + v \sin(\beta_1)$$

(3-1-7)

$$Q_{\text{eff}(2)} = u \cos(\beta_2) + v \sin(\beta_2)$$

(3-1-8)

The subscript 1 denotes wire 1 and the subscript 2 denotes wire 2. It should be noted that $u$ and $v$ represent the velocities parallel and perpendicular to the probe axis respectively and should not be confused with $u_1$ and $v_1$ used later, in this chapter, to define the radial and tangential velocities at points below the cooling fan. The initial estimates for speed and angle are then determined from $u$ and $v$ based on equations 3-1-7 and 3-1-8.

The wire that appears to be more perpendicular to the flow is the one with the largest effective velocity. From the initial guess, this is taken as the “speed wire” while the wire that appears to be more parallel to the flow is taken as the “angle wire”. This arrangement maximizes sensitivity for both speed and angle. A new estimate for $Q$ is made for the two angles closest to the guessed angle and the result is linearly interpolated to get
an improved guess for Q. This differs from Morris (1997) in that his technique used the nearest angle rather than an interpolation. The voltage at γ=0 for the new Q is then calculated using the Collis and Williams equation. The value of η for the voltage of the angle wire is then calculated for the two speeds closest to the new guess for Q. The new guess for γ is calculated by linearly interpolating between the values found from the two polynomial fits. This procedure is repeated using the newly guessed values for Q and γ until convergence is reached. Convergence is considered to be reached when Q varies by less than 0.01 m/s and γ varies by less than 0.1 degrees.

3.2 Pressure Transducer Calibration

All of the pressure transducers used in the facility are linear and are therefore easily calibrated. A micro-manometer (Meriam Model 34FB2) with an uncertainty of ± 0.25 Pa is used as the standard and calibration adjustments located directly on the pressure sensors are used to perform the calibration. Appendix B contains detailed instructions on how to calibrate the pressure sensors. Barometric pressure is recorded from a mercury manometer with an uncertainty of ± 0.5 mmHg located in the laboratory.

3.3 Probe Traverse and Positioning System Initialization

3.3.1 Robotic Probe Aligner (RPA) Setup

The Robotic Probe Aligner positions the probe so that it is approximately parallel to the flow. It must be approximately parallel for each set of velocity readings.

3.3.2 Traverse Setup

The traverse is controlled via the 57 G 10 Display/Controller. It can be alternatively controlled by a manual controller. A stationary point has been located on the
ceiling of the facility near the fan shroud. The traverse zero position is set based on that point.

3.4 Fan Flow Rate Measurement

Volumetric flow rate is determined by means of the orifice meter referred to in section 2.4. An equation which relates the discharge coefficient, \( C_d \), to the Reynolds number was derived from the tables in the Flow Measurement Engineering Handbook (Miller, 1983). This equation is:

\[
C_d = 0.619 + (0.6023 - 0.619) \left( \frac{Re^{-0.75} - 0.001}{0.01} \right) \tag{4-4-1}
\]

where \( Re \) is based on the diameter of the outlet tube.

The following equation is used to determine the volume flow rate, \( Q_f \):

\[
Q_f = \frac{1}{4} \pi d^2 C_d \sqrt{\frac{\Delta P}{\rho \left(1 - \beta_D^4\right)}} \tag{4-4-2}
\]

where \( \Delta P \) represents the pressure drop across the orifice plate, \( \rho \) represents the density of the air, \( \beta_D \) represents the diameter ratio of the orifice to the outlet tube, and \( d \) represents the orifice diameter.

Due to the fact that the volumetric flow rate is measured at the end of the outlet duct coming from the facility and the desired flow rate is that entering the facility, through the fan, any leakage of air into or out of the facility from the surrounding room needs to be eliminated or accounted for. Attempts to completely seal the facility were not successful and hence a technique for determining the leakage flow rate was developed. The outlet to the blower was sealed, the fan operated for some time and the fan opening
was suddenly sealed. The pressure decay was measured for the facility. An equation for the leakage flow rate was derived from this decay curve. Assuming a perfect gas and constant volume of the test chamber, the leakage volume flow rate into the chamber is given by:

\[ Q_L = \frac{V}{P} \frac{dP}{dt} \]  \hspace{1cm} (4-4-3)

where \( V \) is the facility volume, \( P \) is the ambient pressure, and \( \frac{dP}{dt} \) represents the facility pressure decay. This derivative was evaluated by first fitting the pressure vs. time to a third order polynomial, and then differentiating the polynomial. The values of \( Q_L \) and \( \Delta P \) were then used to determine a second order polynomial. The resulting formula for leakage flow rate is:

\[ Q_L = -1.10820 \times 10^{-4} \Delta P^2 + 2.27863 \times 10^{-1} \Delta P \]  \hspace{1cm} (4-4-4)

where \( Q_L \) is in m\(^3\)/s and \( \Delta P \) is in Pa.

This leakage flow is subtracted from the flow measured at the orifice plate to determine the overall flow rate. For the fan used in testing the facility, the maximum leakage flow rate for test conditions was 0.017 m\(^3\)/s for a fan flow rate of 0.283 m\(^3\)/s.

3.5 Facility Pressure Measurement

The measurement of pressure rise in the facility is accomplished with a pressure tap on a corner of the inlet wall, far from the actual inlet. It is assumed that the velocity at this location is zero. The pressure tap consists of a small hole, approximately 1 mm in diameter. An aluminum manifold is fastened over the hole in order to accommodate a \( \frac{1}{4} \) inch NPT nipple that is used to attach the pressure hose leading to the valve system. Since
the section of the fan curve of primary concern is the positive pressure section, the more sensitive 497 Pa pressure sensor is used to measure positive gauge pressures while a 1927 Pa pressure sensor is used to measure negative gauge pressures inside the facility.

3.6 Velocity Component Measurement

Three-component velocity measurements are taken at each angular position on the fan. The X-array hot-wire anemometer probe remains stationary and is pointed into the mean direction of the flow. The encoder wheel indicates to the data acquisition system when each angular position of the fan is over the X-array hot-wire anemometer probe. The remainder of this section describes the procedure for resolving the three components of velocity from the probe readings, aligning the probe with the mean flow direction, and gathering data at each angular position.

3.6.1 Measurement of the Components of Velocity Using a Two-component Probe

The three components of velocity are measured using the DANTEC X-array hot-wire probe described in section 3.2. Two components of flow are first taken in a plane parallel to the movement of the RPA arm, i.e. the Blue/Black plane, in Figure 3.6.1. This plane is the one in which the probe remains when it is rotated about axis 2 as shown in Figure 3.1.5. Two components of flow are then taken in a plane perpendicular to the movement of the RPA arm, i.e. the Red/Black plane, in Figure 3.6.1. In this case the probe is simply rotated 90° about axis 3 as shown in Figure 3.1.5. Measurements in both planes yield a magnitude and angle for the velocity. No attempt has been made to compensate for the bi-normal component of velocity (the component perpendicular to the measurement plane). This component leads to an error in calculating the true velocity.
magnitude. In order to reduce this effect, the velocity magnitude for the measurement plane that is more parallel to the flow is taken as being correct. The measurement plane that is more parallel to the flow is that one that has the largest flow angle. Figures 3.6.2 and 3.6.3 show histograms of the flow angles in the two planes and the correction that would be necessary to better align the probe with the flow. In this case, the speed would be taken from the measurement taken parallel to the direction of RPA movement because this plane is more aligned with the flow as it has the larger flow angle. Taking the flow angles in the two parallel planes, the velocity magnitude, and the angular position of the probe, the three components of velocity, \( u_1, v_1, \) and \( w_1 \) (radial, tangential, and axial) can be calculated. The following equations describe the transformation

\[
u_i = Q(\cos(\gamma_i) \sin(\gamma_2) \cos(\theta) + \sin(\gamma_i) \cos(\Gamma) \sin(\theta) + \cos(\gamma_i) \cos(\gamma_2) \sin(\Gamma) \sin(\theta)) \quad (4-6-1)
\]

\[
w_i = Q(\sin(\gamma_i) \sin(\Gamma) - \cos(\gamma_i) \cos(\gamma_2) \cos(\Gamma)) \quad (4-6-2)
\]

\[
v_i = Q(\cos(\gamma_i) \sin(\gamma_2) \sin(\theta) - \sin(\gamma_i) \cos(\Gamma) \cos(\theta) - \cos(\gamma_i) \cos(\gamma_2) \sin(\Gamma) \cos(\theta)) \quad (4-6-3)
\]

Figure 3.6.1 shows the coordinate system used and the definitions of the various angles.

3.6.2 Data Acquisition Timing

The data acquisition timing is accomplished as follows. An incremental optical encoder with a zero-index is used to generate the acquisition clock pulse. A simultaneous sample and hold (SSH) board is used to freeze the two voltage signals coming from the CTA probe. Finally, the MIO board retrieves the voltages from the sample and hold card,
and controls the hold mode on the sample and hold board. Figure 3.6.4 shows the actual sequence of signals used to acquire the data:

1. The MIO board is set to acquire data and simultaneously count the number of pulses in one revolution of the encoder wheel.
2. The clock or trigger signal from the encoder wheel forces the SSH into hold mode.
3. The index pulse from the encoder wheel goes low, causing the MIO board to be armed for both the data acquisition and the counting operation.
4. The first clock or trigger pulse from the encoder wheel causes the MIO board to take the first pair of voltage readings from the X-array probe. These readings are later discarded as there is no way to know which clock pulse caused the SSH board to go into hold mode.
5. Once the two voltages have been scanned into the card, the MIO board releases the SSH board from hold mode into track mode.
6. The next clock pulse from the encoder wheel forces the SSH board back into hold mode and triggers the MIO board to scan in the two voltages.
7. The MIO board releases the SSH board back into track mode.

The process is repeated until one revolution of the encoder wheel is completed.

3.6.3 Data Output and Results Display

In order to provide input to the Fan Test Facility program regarding what data points to use, a grid file has been devised. This file includes information on the number of equally spaced tangential points, the number of radial points, the distance from the fan hub, and the location of the radial points. Details on the format of this file can be found in
Appendix C. The program outputs two types of files. The first is a raw data file, which can only be read by the program itself. The second is a formatted data file, which contains information on the three components of velocity for each location. Details on the format for this file can also be found in Appendix C. A program written in Fortran has been developed to convert these files to a format compatible with Fieldview.

3.7 Data Collection

In order to validate the expected performance of the facility, a sample automotive cooling fan was installed and data was collected for flow rate versus pressure performance curves and velocity component colour plots.

3.7.1 Performance Curves

The fan shaft speed was set to 2700 RPM. Pressure differences were read for flow rates between 0.28 m³/s and 0.64 m³/s. The results were recorded and are presented in section 4.2.

3.7.2 Velocity Component Measurement

A calibration was performed on an X-array hot-wire probe. The facility was set up to take velocity measurements and the probe was set at 100 mm downstream of the base of the hub of the fan. The flow rate was set at 0.627 m³/s and the fan shaft speed at 2700 RPM. Measurements were taken at 20 equally spaced radial locations and 180 equally spaced circumferential locations. One thousand readings were taken at each location and an average of these readings was determined. Data was stored for later processing with Fieldview. The results of the post-processing in Fieldview are presented in section 4.2.
Probe Axis

Flow Direction

Figure 3.1.1  Definition of Flow Direction with Respect to Probe

Figure 3.1.2  Typical Curve Fit for Angle ($\gamma$) versus Normalized Velocity ($\eta$)
LEGEND

Radial direction: i
Circumferential direction: j
Axial direction: k
Blue/Black Plane: $\gamma_1$
Red/Black Plane: $\gamma_2$
Green Arrow: Probe orientation
Purple Arrow: Flow direction

Figure 3.6.1 Coordinate Systems
A less than -6° shift in the base angle will bring it more in line with the flow at this particular grid point.

A +18° shift in the arm angle will bring it more in line with the flow at this particular grid point.

Figure 3.6.2 Histogram of Angle Readings Perpendicular to the Direction of RPA Arm Movement

Figure 3.6.3 Histogram of Angle Readings Parallel to the Direction of RPA Arm Movement
Figure 3.6.4  Data Acquisition Timing
CHAPTER 4    RESULTS AND DISCUSSION

4.1 Performance Curve

The pressure versus flow rate performance curve that was obtained for the fan at a rated operating speed of 2700 RPM is shown in Figure 4.1.1. The curve is typical for fans of this type. Seventeen points are represented in this figure.

4.2 Velocity Component Measurements

The sample colour plots of axial, radial, and tangential velocity for the test fan are shown in Figures 4.2.1 through 4.2.3 respectively and a sample colour plot of velocity magnitude is also shown in Figure 4.2.4. The inner and outer boundaries of these plots represent the measurement limits for the experiment. The inner limit is 15 mm from the fan hub and the outer limit is at the fan tip. These measurements were taken at 100 mm downstream of the fan. There are sixteen colour levels used to obtain these plots.

The most noticeable feature is a general periodicity with angular position around the fan axis. It, however, is not an exact periodicity. This could be due to a number of reasons such as slight variations in the blade shapes, the fan not being perfectly round, or the fan not being perfectly centered in the shroud. Every plot gives a distinctive flow pattern. The pattern is generated by the number of blades in the fan. This can be seen very clearly in the axial and radial velocity plots, Figure 4.2.1 and Figure 4.2.2. Another noticeable feature is the five points of low radial velocity immediately adjacent to the hub, which also corresponds to points of high axial and tangential velocities. It should be mentioned that the negative values for the tangential velocity are due to the coordinate system that was chosen. Care should be taken when interpreting the pattern in Figure

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4.2.3 as a more negative value indicates a higher tangential velocity.

Other features are noticeable when changes are observed along the fan radius. In the case of each component, there is a low velocity region near the fan tip and a region of high velocity near the radial midpoint of the blades. Since the measurements are taken at a distance 100 mm downstream of the fan, this indicates that the flow tends to be confined within the cylinder defined by the fan diameter and that there is a strong migration of flow toward the radial midpoint of the blade.
Figure 4.1.1  Fan Performance Curve
Figure 4.2.1  Sample Colour Plot of Axial Velocity

\[ Q = 0.627 \text{ m}^3/\text{s}, \quad \Omega = 2700 \text{ RPM} \]
Figure 4.2.2  Sample Colour Plot of Radial Velocity
Figure 4.2.3  Sample Colour Plot of Tangential Velocity
\( Q = 0.627 \, \text{m}^3/\text{s}, \quad \Omega = 2700 \, \text{RPM} \)

Figure 4.2.4 Sample Colour Plot of Velocity Magnitude
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The University of Windsor/DaimlerChrysler Fan Test Facility has been designed, constructed and tested by obtaining results for a typical automotive cooling fan. Fan pressure versus flow rate performance characteristics as well as detailed three-component velocity measurements downstream from the fan were determined. The facility is capable of handling a wide range of test conditions and fan geometries. The facility inlet is interchangeable to accommodate fans with diameters up to 400 mm. Pressure differentials of up to 2500 Pa can be induced within the facility. Currently, pressures of up to 500 Pa can be measured to a measurement uncertainty ± 6.4 Pa. Flow rates between 0.28 m³/s and 1.133 m³/s can be studied with a measurement uncertainty of ± 6% for the lower range of flow and less than ± 2% for the upper range. Furthermore, shaft speeds of between 100 and 3000 RPM can be set with a precision of 1 RPM. The X-array CTA probe can be positioned automatically within a range that starts at 15 mm from the surface of the fan shaft and extends to 200 mm from the center of the fan shaft. The probe can also be positioned in the axial direction downstream within a range of 25 mm to 100 mm. These measurements are taken from the lowest point on the fan blade. The velocity range and uncertainty depend to a great extent on the calibration technique used for the hot-wire anemometers. The current calibration facility is capable of handling velocities in the range of 7 to 33 m/s.

The pressure versus flow rate performance characteristics that were found in the present study are typical of automotive fans. The sample velocity fields that were determined for the test fan demonstrated a reasonable degree of periodicity with angular
position on the plane perpendicular to the shaft axis.

In order to improve the performance of the facility for future studies, it is recommended that:

1. a flow nozzle be installed in place of the orifice plate to increase the flow rate measurement accuracy.

2. the hot-wire calibration technique be revised to allow for extrapolation to lower velocities than allowed for by the Pitot-static tube/pressure transducer arrangement.

3. a technique be devised for measuring total pressure at any point downstream of the fan.
REFERENCES


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Appendix A
Experimental Uncertainties
Stated Uncertainties in Equipment

Pressure Transducers:

All pressure transducers have an uncertainty of ± 0.5% of their rated pressure.

The following are the manufacturer’s stated uncertainties in Pa.

P3061 – 5WD 1243 Pa Pressure Transducer: ± 6.4 Pa
P3061 – 2WD 497 Pa Pressure Transducer ± 2.5 Pa
P3061 – 20WD 4973 Pa Pressure Transducer ± 24.9 Pa

Voltage:

The voltage measurement in the data acquisition board is stated to have an accuracy of ± 0.5 the least significant bit (LSB) and ± 0.6 LSB induced system noise. It has 16 bits of resolution. The following uncertainties apply to each piece of equipment:

<table>
<thead>
<tr>
<th>Device</th>
<th>Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Transducers:</td>
<td>-5 V to 5 V</td>
<td>± 0.17 mV</td>
</tr>
<tr>
<td>Hot-wire Anemometer Output:</td>
<td>0V to 5V</td>
<td>± 0.085 mV</td>
</tr>
</tbody>
</table>

Calculated Uncertainties

The uncertainty calculations were derived using classic relations found in Kline and McClintock (1953).

Facility Pressure:

The uncertainty in facility pressure includes a contribution from the data acquisition board and also from the pressure transducer and can therefore be given by:
\[ \omega_p = \sqrt{\left( \frac{P_R}{E_R} \frac{\omega_{E,\text{r}}}{E_R} \right)^2 + \omega_{p,\text{s}}^2} \]

where \( \omega_p \) represents the uncertainty in pressure measurement, \( P_R \) is the rated pressure of the transducer, \( E_R \) is the rated voltage of the transducer, \( \omega_{p,\text{s}} \) is the stated uncertainty of the pressure transducer, and \( \omega_{E,\text{r}} \) is the stated uncertainty of the voltage detected by the MIO board.

Calculation yields an insignificant contribution of voltage uncertainty to the overall uncertainty in pressure measurement. The facility pressure is therefore measured with an uncertainty of \( \pm 2.5 \) Pa for positive pressures and \( \pm 6.4 \) Pa for negative pressures.

Volume Flow Rate:

The expression for the uncertainty in volumetric flow rate is:

\[ \omega_Q = \sqrt{\left( \frac{\partial Q}{\partial d} \omega_d \right)^2 + \left( \frac{\partial Q}{\partial \rho} \omega_{\rho} \right)^2 + \left( \frac{\partial Q}{\partial D} \omega_D \right)^2 + \left( \frac{\partial Q}{\partial C_d} \omega_{C_d} \right)^2 + \left( \frac{\partial Q}{\partial \Delta P} \omega_{\Delta P} \right)^2} \]

where:

\[
\frac{\partial Q}{\partial C_d} = \frac{1}{4} \pi d^2 \sqrt{\frac{2 \cdot \Delta P}{\rho (1 - \beta_D^4)}}
\]

\[
\frac{\partial Q}{\partial d} = \frac{1}{2} \pi C_d d \sqrt{\frac{2 \Delta P}{\rho (1 - \beta_D^4)}} + \frac{1}{2} \frac{\pi C_d}{D^4} d^5 \sqrt{\frac{2 \Delta P}{\rho (1 - \beta_D^4)^3}}
\]

\[
\frac{\partial Q}{\partial D} = -\frac{1}{2} \frac{\pi C_d}{D^3} d^5 \sqrt{\frac{2 \Delta P}{\rho (1 - \beta_D^4)^3}}
\]

\[
\frac{\partial Q}{\partial \Delta P} = \frac{1}{8} C_d \pi d^2 \sqrt{\frac{2}{\Delta P \rho (1 - \beta_D^4)}}
\]

\[
\frac{\partial Q}{\partial \rho} = -\frac{1}{8} C_d \pi d^2 \sqrt{\frac{2 \Delta P}{\rho^3 (1 - \beta_D^4)}}
\]
$D$ represents the diameter of the outlet tube, and $d$ represents the diameter of the orifice.

$\omega_X$ represents the variable uncertainty where $X$ is $C_d$ for discharge coefficient, $d$ for orifice diameter, $D$ for outlet tube diameter, $\Delta P$ for pressure difference, and $\rho$ for air density.

With an uncertainty of 0.6% in $C_d$ (Miller, 1983), 5% in $\rho$, 0.1 mm in $d$, 1 mm in $D$, and 24.9 Pa in pressure, the uncertainty in flow rate is calculated to be as high as 6% at 0.3 m$^3$/s and drops to 2.6% at 0.47 m$^3$/s. The predominant uncertainty in calculating the leakage flow rate is the estimation of facility volume. This uncertainty is estimated to be ±10%. Applying this to the leakage flow rate of 0.017 m$^3$/s for a facility flow rate of 0.283 m$^3$/s, its contribution is 0.0017 m$^3$/s or 0.5%.

Velocities:

Comparison of the X-array velocities yielded by the calibration routine with velocities measured by a Pitot-static probe showed typical agreement within ±0.2 m/s and angles within ±0.5°.

Position:

An extremely accurate positioning is claimed by the manufacturer of the traverse mechanism. However, observation of the performance of the current setup indicates that the probe can be positioned to within ±1 mm.
Appendix B
Detailed Experimental Procedures

(Note that sections given in this appendix correspond to similarly numbered sections in the main body of the thesis)
B-3.1 CTA Calibration

B-3.1.1 Bridge Adjustment

Figure B-3.1.1 illustrates the bridge adjustment screen on which various numbers corresponding to the steps in this procedure are placed.

1) Open CTA Calibration program (CTA X-array Calibration.exe)

2) Enter the Bridge Adjustment portion of the program by clicking on the Bridge Adjust Button.

3) Enter the following data from the probe specifications into the probe info section:

<table>
<thead>
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<th>Probe ID</th>
<th>R @ 20°C</th>
<th>Lead R</th>
<th>Sensor TCR</th>
<th>T max</th>
</tr>
</thead>
</table>

Use the same data for both wires.

The probe should have an ID number on its case indicating which number it is. A particular number can be switched to by clicking on the left/right areas next to the probe number on the screen. If the probe number has already been entered, there will be no need to change its information.

4) Enter the current room temperature in the temperature text box.

Determine the Resistance of the Cables

In order to determine the resistance of the wire, the resistance of the entire system must first be determined. The resistance of the probe leads is given on the case and was entered in step 3. The resistance of the cable is yet to be determined.

5) Install the shorting probe (DISA Model 55H31)

6) Click on the “Find Cable Resistance” for the first wire.

7) Switch the knob on the left-hand bridge to standby.
8) Turn the “TEMP” screw until the bridge is zeroed. A centering of the red circle indicates the bridge is zeroed.

9) Install short circuit device with switch set to 5Ω. This device is blue and is labeled “CTA Bridge Adapter.” Plug the cable for wire one into the other end of the short circuit device.

10) Adjust the knob on the left-hand bridge to “TEMP”.

11) Balance the resistance by changing the “BRIDGE ADJ.” numbers until the red circle is roughly centered in the screen.

12) Continue adjusting using the “fine” screw until the red circle is centered.

13) Switch knob on the left-hand bridge to “STANDBY”.

14) Switch the short circuit device to short.

15) Switch knob on the left-hand bridge to “TEMP”.

16) Click on the “Find Cable Resistance” for the first wire again.

17) Switch knob on the left-hand bridge to “STANDBY”.

18) Remove short circuit device.

19) Repeat steps 6 through 18 for the second wire, using the right-hand bridge.

NOTE: The cable resistance for both cables should read between 0.6 and 0.75 Ω for a 5 m long cable.

_Determine Resistance in Wires_

The next step in calibrating the probe is to determine the resistances in the two wires.

Since the resistance of the cables is already known, as is the resistance of the probe leads, the wire resistance can be determined by subtracting the known resistances from the
resistance of the entire system.

20) Click on the “Find Wire Resistance” for the first wire.

21) Ensure that the knob on the left-hand bridge is set to “STANDBY”.

22) Install the X-array probe.

23) Set the knob on the left-hand bridge to “TEMP”.

24) Balance the resistance by changing the “BRIDGE ADJ.” numbers until the red circle is roughly centered in the screen.

25) Continue adjusting using the “FINE” screw until the red circle is centered.

26) Switch knob on the left-hand bridge to “STANDBY”.

27) Install the short circuit device with the switch set to “SHORT”.

28) Switch knob on the left-hand bridge to “TEMP”.

29) Click on the “Find Wire Resistance” for the first wire again.

30) Repeat steps 19 through 29 for the second wire using the right-hand bridge.

NOTE: The wire resistance for both wires should be between 2.5 and 4.0 Ω.

Set the Overheat Ratio

The final step in adjusting the bridge for the X-array probe is to set the overheat ratio. This ratio must be entered into the program before proceeding.

31) Click on “Set Overheat” for the first wire.

32) Set the knob on the left-hand bridge to “TEMP”.

33) Balance the resistance by changing the “BRIDGE ADJ.” numbers until the red circle is roughly centered in the screen.

34) Continue adjusting using the “FINE” screw until the red circle is centered.
35) Switch knob on the left-hand bridge to “STANDBY”.

36) Repeat steps 31 through 35 for the second wire.

Getting the Bridge Ready to Take Measurements

37) Remove the short circuit devices and plug the cables directly into the bridge.

38) Press OK to exit the Bridge Adjustment section of the program and save the current resistances.

B- 3.1.2 X-array CTA Calibration

Figure B-3.1.2 illustrates the X-array Calibration screen on which the numbers of various steps in this procedure are indicated.

1) Click on the Calibrate button to enter the Calibration portion of the X-array Calibration Program.

2) Ensure that all of the angles and speeds are set correctly. The minimum and maximum angles are typically set between −36 and 36 degrees. The minimum and maximum speeds are typically set between 7 and 25 m/s. If greater speeds are observed when taking velocity readings, the probe will have to be re-calibrated to include these speeds. Twenty speeds and 13 angles usually provide a good resolution.

3) Ensure that the channels and settings are correct for the pressure sensors.

4) Ensure that the pressure sensor power is on. (See Figure 3.3.2)

5) Ensure that the pressure sensor valves are correctly set. For this procedure, each valve knob should be vertical.

6) Ensure that the total and static pressure sensor tubes are correctly attached to the Pitot-static tube.
7) Set the probe up in the calibration unit so the single dot is facing upward.

8) Ensure that the probe is turned so that each set of two prongs is lined up vertically.

9) Run the Calibration portion of the X-array CTA Calibration Program.

10) Click the “Start Calibration” button.

11) Ensure that the probe is turned on (the switch on the bridge is set to flow). An X will appear through the angle portion of the screen if this is not the case.

12) Align the probe angle with the angle on the screen.

13) Ensure that the Pitot-static tube and X-array probe are both in the potential core of the calibration nozzle but well away from each other.

14) Adjust the compressed air for each velocity measurement so that the red ball aligns itself inside the central circle on the screen. The ball will jump when the next velocity is reached.

15) When the ball no longer moves and the angle changes on the screen, adjust the probe to the new angle.

16) Push the remote button to continue.

17) Repeat until the angle reads 360 degrees. The calibration is done.

18) Using the right mouse button, bring up the Pop Up Menu.

19) Choose “View Polynomial Fits”.

20) Click through the fits and ensure the fit is good on the left side of the graph. Figure 3.1.2 is an example of this screen.
21) If the fits are good, close the Polynomial Fit Dialog Box and type in the name (a date is usually best) of the Calibration in the current text box. Click on the Save Current button.

**B-3.1.3 Using the “Add Test Points Dialog Box”**

This dialog box is used to add points for testing the calibration. The following are the features that are labeled in Figure B-3.1.3.

1. **Angle:** Six possible angles can be used in the test.

2. **Speeds:** This list box contains all of the speeds currently being tested. Dropping the box down shows all of the speeds for that angle.

3. **Add:** Pressing this button removes whatever speed was just typed into the list box.

4. **Remove:** Pressing this button adds whatever speed is displayed in the list box.

5. **Use:** This checkbox tells whether or not to use the angle and associated speeds. Leaving this box blank when exiting the dialog box will cause a test angle and all of its associated speeds to be removed.

*Speed Point Generator:*

6. **Number of Speeds to Generate:** Tells how many equally spaced speeds to generate in each of the speed boxes for the selected angles.

7. **Lower, Upper Speed:** The range for the speeds to generate for testing.

8. **Apply to Angle:** Tells which angle to associate with the generate speeds.

9. **Apply:** Generate a set of speeds based on Number of Speeds, Upper, and Lower Speed, and place them under each angle in “Apply to Angle”.

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B-3.3 Probe Traverse and Positioning System Initialization

B-3.3.1 Robotic Probe Aligner (RPA) Setup

1) Place a level on the arm of the RPA.

2) Adjust the set screws so the arm is loose.

3) Adjust the arm so that it is level and retighten the set screws.

4) Run the Fan Test Facility Program.

5) From the Control menu, run the RPA controller.

6) Turn the RPA base until the arm is facing the back of the facility.

7) If the four screws on the base can be lined up with the four screws on the support, the RPA base is adjusted properly. If not, step the RPA base on the computer by clicking on the Zero Base control and stepping the base with the remote trigger until the screws can be lined up.

8) Once the RPA base is aligned, attach an elastic band in a way that the base will always have a slight counter-clockwise tension.

9) The picture on the RPA controller which is displayed on the computer screen should show the base at 0 degrees and the readout should indicate zero degrees. If not, entering 0 for the base angle and clicking Set, and then stepping the base forward and back will set the base to 0.

10) Insert the probe extension tube into the RPA arm so that it is 140 mm from the probe tip to the top of the sleeve. The tube is notched at 140 mm.

If the traverse has not been set up for proper location, skip steps 11,12,13.
11) Insert the probe holder into the extension tube and attach to the cables. Insert the probe into the holder.

12) Turn the probe until the single dot is to the East side of the facility and the prongs are lined up in the direction of the movement of the RPA arm.

13) Tape the probe holder to the extension tube with scotch tape to ensure the holder does not rotate in the tube. The probe is now ready for taking readings.

**B-3.3.2 Traverse Setup**

The traverse is controlled via the 57 G 10 Display/Controller. It is alternatively controlled by a manual controller.

1) Follow the Probe Aligner Setup to set up the Probe Aligner but, in place of the probe holder, insert the Traverse Indicating Tip.

2) Initialize all channels by typing each one into the Traverse Controller and pressing INIT.

3) Align the Traverse Indicating Tip with the reference point in the facility using the remote control.

4) Push the Channel 0 button, type the amount necessary to move from the reference point to the zero point for channel zero, and press start.

5) When Channel 0 (tangential direction) reaches the zero point, initialize Channel 0, press the Channel 0 button, type in the distance back to the reference point, and press start.

6) Repeat steps 4, 5 for Channel 1.
7) Push the Channel 2 button and press start. This will allow the controller to track the movement of Channel 2.

8) Using the manual controller, bring the Indicating Tip to a point underneath the fan so that an upward traverse will allow it to pass safely between the fan blades. Leave the manual controller on a channel.

9) For channels 0 and 1, type in the current position, and press start. This will tell the traverse that it should be at the current position. Turn the manual controller off.

10) Repeat Steps 4 and 5 for Channel 2.

11) Using the manual controller, move the RPA to a position that is safely away from the fan so that any alignments of the RPA will not result in the probe touching any part of the facility. Leave the manual controller on a channel.

12) Round off the positions for each channel and program the controller to move to the rounded off position.

13) Turn off the manual controller.

14) Proceed with steps 13, 14, 15 in section B-3.3.1

**B-3.6 Velocity Component Measurements**

**B-3.6.1 Loading the Calibration, Grid, and Data Files**

All files can be loaded from the file menu within the Fan Test Facility Program. While a Calibration file can be loaded or reloaded at any time, the Data Files (*.DFF) can only be loaded after the Grid File (*.GRD) has been loaded. Furthermore, the Data Files that are loaded must have been produced with the same size grid as is represented in the
Grid File.

The Grid File contains data about each radial location and the number of tangential locations to be used for taking velocity readings. The layout for the Grid File can be found in Appendix C. After the grid file is loaded, a number of circular icons representing each radial location appear on the lower right-hand corner of the screen. Each icon represents a radial location. The icons are coloured by status. A red icon contains no data, a green icon contains data, and a black icon may or may not contain data but it has been temporarily disabled for the purpose of outputting formatted velocity data.

The Calibration file contains the information from the calibration stored earlier. A Calibration file must be loaded before any velocity data can be taken. Without a Calibration file, raw voltages will be put in place of velocities and angles.

The Data File only needs to be loaded when a previous set of velocity readings is being continued or when outputting formatted velocity data. Ensure that the appropriate Grid File is loaded before loading the Data File.

**B-3.6.2 Powering Up**

The following items need to be powered up before continuing with the velocity readings.

1) The blower power is turned on by lifting the power lever beside the blower speed controller. Once this is done, the blower can be started by pushing the start button on the wall.

2) The shaft motor power is turned on by switching on the DC motor controller on the wall. Also, the power switch on the data acquisition connection box needs to be turned on in order to operate the DC isolator that connects the control voltage from
the computer to the DC motor controller.

3) If 180 tangential points have been chosen (recommended), the encoder degree switch on the data acquisition connection box needs to be switched to the ON position as well.

4) The pressure transducer power supply must be switched into the ON position in order to measure the facility pressure and provide flow rate feedback for the blower controller.

B-3.6.3 Setting the Probe Angle and Position

The Robotic Probe Aligner is initially set up so that decreasing the arm angle will align the probe with a more horizontal flow and increasing the base angle will align the probe with a more radial flow. While experience with a particular fan is the only way to determine an appropriate angle, a good initial guess is -30° for the arm angle and 30° for the base angle. Note that removing the tensioning band before rotating the RPA is recommended if an extreme change of the base angle is being performed or if a clockwise rotation of the base angle is being performed.

To enter the angle, and align and position the probe, the following procedure is used:

1) Choose a radial position and left click on it to bring it into focus.

2) Right click on the radial position to bring up the Pop-Up menu.

3) Choose the Enter Angle Manually from the Pop-Up menu.

4) Enter the initial guess for the alignment angle.

5) Choose the Align Probe for Optimal Angle option from the Pop-Up menu.

6) Ensure that the traverse is in the home position for safe rotation. If a clockwise
(negative angle) rotation is required, remove the tension band from the Robotic Probe Aligner.

7) Click on the View Scenario 1 button to ensure the current configuration will work without interfering with the fan shaft. If it doesn’t, click on the Scenario 2 button to switch to the reverse position. Check Scenario 2 in the same way as Scenario 1 was checked.

8) Choose GO from below the suggested angles. The Robotic Probe Aligner will align itself with the chosen angles.

9) Reattach the tension band to take out the backlash from the Robotic Probe Aligner base.

10) Click on the Go To Current Reading Position button and move the traverse to the indicated position, starting with channel 0 (tangential position), then moving channel 1 (radial position), and finally channel 2 (axial position).

**B-3.6.4 Setting the Appropriate Fan Speed and Flow Rate**

The fan speed and flow rate are set from within the Facility Controller dialog box. This dialog box can be activated from the Control Menu of the Fan Test Facility Program. For flow rates less than 0.47 m³/s (1000 CFM), the damper should be halfway open. For flow rates higher than 0.47 m³/s, the damper must be fully open.

1. Enter the Fan Speed in the appropriate text box and the Flow Rate in its text box.

2. Ensure that the power is on to the fan, blower, and pressure sensors. Also ensure that power is on to the data acquisition connection box, and the blower is started. The
blower is started when the display on the variable frequency drive reads a frequency (0.0 if the blower is at zero speed).

3. Press the GO button for Flow Rate and then the Go button for Shaft Speed. The blower and fan motor controllers will bring the facility up to the appropriate speed and flow rate.

**B-3.6.5 Taking the Velocity Readings**

This portion of the program is highly automated. The condition for actually taking velocity readings is a stable fan speed and flow rate.

1) Right click on the appropriate radial position to bring up the Pop-Up menu.

2) Click on Take Velocity Readings

When the fan speed and flow rate are stable, the computer will automatically begin to take readings. If, however the system is having trouble determining stability but the readings appear to actually be stable, the computer can be forced to take readings by bringing up the Adjust Speed Controller Sensitivity dialog box from the Control menu and Click on the Override and Take Readings button. The system will go through two sets of readings at 1000 revolutions of the encoder wheel each. During this time, the Facility Controller Dialog Box, the Save Data Dialog Box, and access to the data for the radial position being examined will be temporarily suspended. This access will be restored immediately after the last set of readings has been taken.

3) Right click on the radial position for which readings were just taken and click on Show Raw Outputs.

Histograms of results for each tangential point will be displayed. By changing the
Histogram List Box to Periodicity Chart (Figure B-3.6.1), a plot of the mean and standard deviation for all angles and speeds at that radial location can be displayed. Clicking on the right and left arrow keys will move a line to any tangential location. Changing the List Box back to Histogram will show the Histogram for that particular point. The other List Box gives the option of switching between the two probe planes. The first is the Arm Plane, which shows readings in the plane of the arm movement. The other is Tangential to Arm Plane, which shows readings in a plane rotated 90° about the probe axis.

4) If the means do not fall within ±12° or the spread is outside of the ±36° range for most points, the probe angle must be readjusted.

The new angles can be determined by determining how much shift is required to bring the mean back to zero and then by adjusting the base and arm angles. Note that if Scenario 2 is used, the angles are completely reversed and a positive shift becomes negative, and a negative shift becomes positive in this case. Figures 3.6.3 through 3.6.4 show how the angles will be shifted. Repeat procedure B-3.6.4 with the new guess and take the readings again using procedure B-3.6.5.
Figure B-3.1.1 Bridge Adjustment Screen
Figure B-3.1.2 X-array CTA Calibration Screen

Figure B-3.1.3 Add Test Points Dialog
Figure B-3.6.1 Map of Speeds and Angles Across the Face of the Fan.
### Appendix B Tables

<table>
<thead>
<tr>
<th>Table B-1</th>
<th>Valve Positions for Calibration</th>
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<th>Valve Positions for Taking Velocity Readings</th>
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Appendix C
File Formats
Grid and Data File Format

Grid File .GRD

Radial Points: [Number of Radial Points] [Point1 Location] ...[PointNLocation]
Tangential Points: [Number of Tangential Points]
Z Location: [Reading Distance From Hub]
Hub Diameter: [Diameter of Hub]

Data File .CTD

[Z Velocity 1] ... [Z Velocity N]
[R Velocity 1] ... [R Velocity N]
[O Velocity 1] ... [O Velocity N]

Sample Order for Z Velocities

Grid File:
Radial Points: 3 10.1 50.4 95.2
Tangential Points: 4
Z Location: 50
Hub Diameter: 117.5

Data File:
5 9 10 11 14 15 22 1 6 22 4 3
7 2 5 9 10 15 8 9 4 14 22

What the above means in terms of the grid

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