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The Design, Fabrication, and Evaluation of a Low-Speed, Low-Turbulence, Anechoic Wind Tunnel

Brian J. Kaplan

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THE DESIGN, FABRICATION, AND EVALUATION
OF A LOW-SPEED, LOW-TURBULENCE,
ANECHOIC WIND TUNNEL

by

Brian J. Kaplan

A Thesis Submitted to the
Graduate Studies Office
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Spring 1996
THE DESIGN, FABRICATION, AND TESTING OF A LOW-SPEED, LOW-TURBULENCE, ANECHOIC WIND TUNNEL

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Brian J. Kaplan

This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Howard Patrick, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Aerospace Engineering Department and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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I would like to express my thanks to my parents, Alan and Edith Kaplan, for their immeasurable support and guidance throughout this long journey. Without their guidance and love, I would not have been able to complete this project. I would also like to extend my sincere thanks to Professor H.V.L. Patrick for his advice throughout my years at Embry-Riddle. Dr. Patrick provided me with support, advice, and exhibited a tremendous amount of patience. As chairman of my thesis committee, Dr. Patrick made sure I got the most out of my research, while providing me with whatever I needed to complete my task.

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ABSTRACT

In order to provide a means for testing noise reduction techniques in propellers and fans, a low-speed, low-turbulence, anechoic wind tunnel was designed, fabricated and evaluated at Embry-Riddle Aeronautical University.

This open circuit wind tunnel was designed using several other existing wind tunnels as a guide and incorporated an open jet test section. The tunnel, which was built almost entirely out of wood and fiberglass, is powered by a 15 hp centrifugal fan.

Tufts of yarn, a pitot-static tube, and a hot film anemometer were used to determine the flow characteristics in the test section of this wind tunnel. From the hot film anemometer, values for velocity, standard deviation and turbulence intensity were determined for three different velocity settings; approximately 114 ft/s, 145 ft/s, and 215 ft/s respectively. For the 215 ft/s and 114 ft/s tests, the turbulence intensity ranged from 0.42% to 0.87% within a seven inch diameter about the centerline. This seven inch diameter was mapped out to simulate a seven inch diameter propeller. For the 145 ft/s test, the turbulence intensity became more erratic, and ranged between 0.67% and 1.5%. The velocity across the test section for all three tests varied by less than 2.0%, with 90% of the points varying by less than 1.0%.
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NOMENCLATURE

A - Local Area
A_j - Geometric Dependent Constant
A_2 - Geometric Dependent Constant
c - contraction Ratio
D - Local Tunnel Diameter
D_0 - Jet Diameter
K - Coefficient of Loss
K_o - Jet Coefficient of Loss
K.E. - Kinetic Energy
L - Distance
n - Frequency
p - Pressure
q - Dynamic Pressure
q_0 - Jet Dynamic Pressure
Re - Reynolds Number
s - Strouhal Number
S - X/L
U - Mean Velocity

u' - Root Mean Square Value of Longitudinal Component of Velocity

\(U_\infty\) - Freestream Velocity

V - Velocity

v' - Root Mean Square Value of Lateral Component of Velocity

W_1 - Width of Diffuser Entrance

X - Length

\(\theta\) - Diffuser Half Angle

\(\nu\) - Kinematic Viscosity
CHAPTER 1
INTRODUCTION

This chapter gives a brief overview of the project performed in this thesis. It also gives a historical background of the origins of this topic, and discusses previous research performed in this field which was useful as a guide for this project.

1.1 Identification of Problem

The problem of noise control and noise reduction is of interest to the Federal Aviation Administration as well as airlines and aircraft manufacturers. Several research projects are currently being conducted at Embry-Riddle Aeronautical University (ERAU), concentrating on active noise control of propellers, ducted fans, and cabin noise. There are also projects being conducted on designing quiet general aviation propellers. Some of these projects, as well as possible future projects, will require adequate testing facilities. At the current time, there is one wind tunnel, and three smoke tunnels at ERAU available for testing. Smoke tunnels are only useful for visualization of flow and are not appropriate for evaluating the aerodynamic performance and acoustic characteristics of propellers and fans. The available wind tunnel allows for several types of testing, however, it is not configured for anechoic tests. The need for performing propeller noise research prompted the need for an anechoic wind tunnel to be designed, fabricated and
evaluated. The space designated for this new wind tunnel is located in the experimental aerodynamics laboratory in the old engineering building at ERAU. The overall length of the room is approximately 40 feet, and the height is 21 feet. The desired test section size of 2 ft by 2 ft square is based on testing one-quarter scale general aviation aircraft propellers. The exterior shape and dimensions of the wind tunnel are designed around the length and height of the available room.

A scale model of this tunnel was developed and built, which was used to evaluate the proposed design and make modifications before building the full sized tunnel. The test section of the scale model needed to be large enough to test actual models, which meant that model propellers with at least a seven inch diameter needed to fit into the test section. The test section had to be at least eight inches by eight inches to fit a seven inch propeller without the blade tips experiencing disruption from the flow. This disruption avoidance will be discussed in a later chapter, and led to a scale of approximately 2.5:1.

A relatively small space was also provided to house the scale model. This space was actually smaller than required to maintain the 2.5:1 scale. Because of this small space, and due to the fact that the full size tunnel was being fit into a space that would make for a tight fit, maximization of space turned out to be a major consideration.

The preliminary design goals for this project were as follows:

1. Have a test section large enough to test seven inch diameter propellers.
2. Maximum velocity of approximately 0.2 Mach number.
3. Velocity of the test section should vary by less than one percent in any given
cross section of the test section.

4. Keep the turbulence intensity below 0.2% in the test section.

5. Anechoic to a lower cutoff frequency of 250 Hz.

1.2 Previous Research

There have been numerous wind tunnels designed and built in the twentieth century of which there are several different types and sizes. Wind tunnels can be either open or closed circuit. A closed circuit wind tunnel recirculates air through the tunnel in a continuous cycle while in an open circuit tunnel the air follows a straight path into the contraction through the tunnel and is exhausted into the atmosphere. Most wind tunnels have a contraction that accelerates the flow and a diffuser to decelerate the flow. Another important design attribute is the test section of the tunnel, which can be either open jet or enclosed. An open jet test section has no solid boundaries and the flow is open to surrounding quiescent air. A closed jet test section has the flow moving through a region with enclosed solid boundaries. Some of the other variables include power source, turbulence management, and whether the flow will be "pushed" or "sucked" through the tunnel (i.e. with the fan placed at the inlet or exhaust of an open circuit wind tunnel).

Some of the tunnel designs that are relevant to this project include Patrick[1], Nagel and Alaverdi[2], who designed an open circuit, non-anechoic wind tunnel at North Carolina State University. Also, Hanson[3] designed a low-noise, low-turbulence wind tunnel, which incorporated several concepts which are used in this project. Several other
papers, including Paterson, Vogt, and Foley[4], Tighe[5], and other studies, cited later in this paper, were used as reference for the design of this wind tunnel.
CHAPTER 2
BACKGROUND AND THEORY

2.1 Wind Tunnel Layout

All of the wind tunnels mentioned in the previous chapter used an open circuit design, and all have had some success. Because of this, and because it was easier to control the turbulence in an open circuit tunnel, this was the design chosen for this tunnel as well, as shown in Figure 1. Because of the size constraints, maximizing the space in which to install the finished tunnel was an important consideration in determining the overall layout of the tunnel.

The test section was a very important design criterion for maintaining noise control during testing. Patrick[1], and Hanson[3] both used an open jet test section surrounded by an anechoic chamber to perform low-noise tests. Both tunnels have the flow exiting the contraction and entering the diffuser via a collector used to capture the exit jet. A closed test section would not be beneficial in this situation because the test section has solid boundaries surrounding the flow. Acoustically absorbing material lining the test section would cause major air flow disturbances resulting in sound reverberation and
making acoustic measurements in the near-field difficult. For this reason, it is more beneficial to have an open jet test section surrounded by a large anechoic chamber.

There are seven main components in such an open circuit and open jet wind tunnel. As shown in Figure 1, these components are:

1. Turbulence Management Section
2. Contraction
3. Anechoic Chamber
4. Collector
5. Diffuser
6. Plenum Chamber
7. Fan/Motor Assembly

Because this is a suction type wind tunnel, the fan/motor assembly is at the end of the flow circuit.

Quiescent air from the surrounding room enters the turbulence management section at a velocity of approximately 15 ft/sec, before traveling through a honeycomb and then three screens, in which the turbulence is reduced, and the flow is straightened. The flow is then accelerated through the contraction cone to its maximum velocity of approximately 205 ft/s. The flow exiting the contraction into the test section region of the anechoic chamber is then captured by the collector. The collector delivers the flow into the diffuser and onward to the anechoic chamber. The contraction exit, test section, and collector are all located within the anechoic chamber. The anechoic chamber simulates a reverberant free acoustic environment. The flow is then decelerated through
Figure 1. Wind Tunnel Layout.
the diffuser before being conducted into the plenum chamber, where it enters the fan, and is subsequently exhausted into the laboratory at ambient atmospheric pressure.

2.2 Effects of Honeycomb on Free-Stream Turbulence

The primary reason for using honeycomb in the tunnel entrance is to straighten the flow, as well as reduce the radial component of large scale turbulence, i.e. vorticity.

There is a great deal of literature concerning the effects of damping screens on free-stream turbulence, but very little exists on the effects of honeycomb. Loehrke and Nagib[6] have reported the benefits and disadvantages of honeycomb as turbulence suppressors. Their work includes results of tests using soda straw honeycomb cells of different lengths and measuring the turbulence at various distances downstream of the straw cells. They found the honeycomb actually increased the turbulence level due to the "breakup of the mean profile emanating from the individual cells." By using honeycomb alone there is a drastic increase in the turbulence level just downstream of the honeycomb due to the mixing of the individual cell flows. However, when the turbulence is diffused a short distance downstream, the turbulence level was found to be lower than with no honeycomb.

These same investigators also showed that the addition of a single fine mesh screen placed across the downstream face of the straws creates a significant decrease in turbulence intensity as compared with that of honeycomb alone. There was also no peak in turbulence intensity immediately downstream of the honeycomb for this case in contrast to the case of honeycomb alone.
Figure 2. Comparison Between Downstream Axial Profiles of $u'/U$ for Free-Stream Conditions and for Honeycombs of Different Lengths (Reference 4).

This study also showed that there is little difference in turbulence reduction between varied lengths of straws, as can be seen in Figure 2, where the turbulence intensity $u'/U$ is
plotted as a function of downstream distance from the honeycomb exit. The free stream velocity is approximately 16.5 ft/sec, and the straw lengths are approximately 10, 3, and 1 inch in length respectively.

2.3 Turbulence Reduction Through a Contraction

Ramjee and Hussain[7] show that by passing flow through a contraction not only is the flow accelerated but the turbulence intensity level is decreased. Both the longitudinal and lateral components of turbulence are reduced through the contraction although the longitudinal component is reduced at a higher rate. The reduction in longitudinal turbulence is caused by a reduction in the vortex filaments that lie normal to the contraction axis. The lateral turbulence is decreased due to the stretching of the parallel vortex filaments. This turbulence reduction through the contraction is given as:

\[ \frac{u_e'}{u_i'} = \frac{1}{c}; \quad \frac{v_e'}{v_i'} = \sqrt{c} \]

Where \( e \) and \( i \) stand for the exit and inlet conditions, \( c \) is the contraction ratio, and \( u' \), and \( v' \) are the root mean square (rms) values of the longitudinal and lateral turbulence velocity fluctuations, respectively.

These equations show a clear relationship between the contraction ratio and the reduction of turbulence; or that an increase in \( c \) results in a decrease in turbulence intensity. This relationship holds true for contraction ratios up to about 45 after which there is little added turbulence reduction. It can be seen, therefore, that the area ratio of the contraction plays a major role in the design of a wind tunnel. It is beneficial for the
overall performance of the wind tunnel to have a contraction ratio as large as possible
while still maintaining useful turbulence reduction, yet not making it too large for the
available space in which to place the entire assembly.

2.4 Jet Mixing Regions

Because this is an open jet wind tunnel, a problem arises due to the flow exiting
the contraction into the open test section which is similar to that of an axially symmetric
jet being exhausted into a fluid at rest. This problem was resolved by Keuthe[8], whose
work is used here to determine the shape of the flow through the test section of the tunnel
designed. The flow exiting the mouth of the contraction “forms an annular ring enclosing
a core of potential flow in which the velocity is constant and equal to the outflow
velocity”[8] as illustrated in Figure 3. The potential flow core is of primary concern when
designing the test section, in order to insure the test model remains in a region void of
turbulent mixing. At some distance from the mouth of the contraction, the potential flow
core diffuses and all of the flow blends into the the turbulent mixing region.

Keuthe[8] predicts the shape of both the turbulent mixing region and the potential
flow core. Both the distance from the mouth, and the cone angle of the potential core are
plotted in Figure 3, as well as the turbulent mixing region. These data help determine the
location of the test section as well as the placement, size, and shape of the collector.
2.5 Pressure Drop Through The Tunnel

The operating curve of the fan/motor assembly, as shown in Figure 4, clearly shows that for the most efficient conditions for the fan occur at a volumetric flow rate of
12.2(10)^3 \text{ ft}^3/\text{min}, a pressure head of three inches of water, a 12 hp motor is required. The pressure drop through the tunnel is calculated to insure that the fan will operate at these tunnel conditions.

Relationships developed by Rae and Pope\[9\] are used to calculate the pressure drop through the tunnel. A loss of energy occurs in each section of the wind tunnel. This energy loss is written as a drop in static pressure, $\Delta p$, or as a loss coefficient, $K = \Delta p/q$, where $q$ is the dynamic pressure. These local losses are referenced to the jet dynamic pressure at the test section entrance, defining the coefficient of loss as:

$$K_0 = (\Delta p/q) \left( \frac{q}{q_0} \right) = K \left( \frac{q}{q_0} \right)$$

and since the dynamic head varies inversely as the fourth power of the tunnel diameter,

$$K_0 = KD_0^4/D^4$$

Where $D_0 = \text{jet diameter}$ and $D = \text{local tunnel diameter}$. The tunnel, however, does not have a circular cross section. The power coefficient equation, therefore, has to be related to the area of the test section as opposed to the diameter and is given as

$$K_0 = KA_0^2/A^2$$

After calculating $K_0$ for each component of the wind tunnel, the total value is determined by summing each and is used to determine the predicted pressure drop through the tunnel in inches of water. The pressure drop through the tunnel is calculated using the following equation:

$$\Delta p = (K_0)_{\text{TOTAL}}(q_0)$$
Operating Condition is Standard Air (70 deg F, Sea Level)

Figure 4. Fan Operating Curve.
The total pressure drop through the tunnel was calculated to be approximately six inches of water.

The pressure loss coefficient for each component are listed in Table 1:

### Table 1. Pressure Losses for the Tunnel.

<table>
<thead>
<tr>
<th>Section</th>
<th>$K_h$</th>
<th>Total Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb</td>
<td>0.0645</td>
<td>18</td>
</tr>
<tr>
<td>Screens</td>
<td>0.0215</td>
<td>6</td>
</tr>
<tr>
<td>Contraction</td>
<td>0.00876</td>
<td>2</td>
</tr>
<tr>
<td>Open Jet</td>
<td>0.13644</td>
<td>39</td>
</tr>
<tr>
<td>Collector</td>
<td>0.0061</td>
<td>2</td>
</tr>
<tr>
<td>Diffuser</td>
<td>0.00443</td>
<td>1</td>
</tr>
<tr>
<td>Plenum Chamber</td>
<td>0.11085</td>
<td>32</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>0.353</td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

The operating conditions of the fan are then determined as if operating at a pressure head of approximately seven inches of water. From Figure 4, the fan is capable of producing approximately 8200 cfm at this condition. At 8200 cfm, the test section velocity should be Mach 0.22, or 228 ft/s. The results obtained in Chapter 5 show that for full speed the average velocity was measured to be 213.6 ft/s. This measured value is 6.7% below the theoretical velocity obtained from the fan’s operating curve, and is within the uncertainty of measured values and expected fan/motor performance.
CHAPTER 3
TUNNEL DESIGN AND CONSTRUCTION

In order to construct an anechoic wind tunnel that can be used for the acoustic and aerodynamic evaluation of propellers, very low turbulence and constant velocity across the test section are required. In order to accomplish these goals, and maximize the space allotted for the tunnel an open circuit design was incorporated. The tunnel was originally scheduled to occupy a space sixteen feet in length, located in the experimental aerodynamics lab in the old engineering building at ERAU. The design consisted of seven major components. Each was designed separately and is discussed in more detail later in this chapter. These components, in order of flow direction starting at the entrance, are the turbulence management section, contraction, test section, collector, diffuser, plenum chamber, and fan/motor assembly.

3.1 Turbulence Management Section

There are several techniques that can be used to reduce turbulence of flow, including screens, honeycomb, perforated plates, and foam. The turbulence management section in this tunnel consists of honeycomb followed by a series of screens which are used to reduce the turbulence entering the contraction. There are several factors involved in the design of the settling chamber, such as the honeycomb material, the length, and the
diameter, as well as the screen mesh size, solidity, Reynolds number, and the quantity of screens. The turbulence management section of this tunnel is designed to attach to the contraction with an inlet dimension of 42.5 inch by 42.5 inch square. Figure 5 shows a side view of this turbulence management section. The screens and honeycomb are spaced six inches apart. The exterior is constructed of 1/2 inch thick plywood, with 2 inch x 4 inch wood supports. The walls are nailed together and a support structure is constructed that will be discussed later in this chapter. Another important feature of the turbulence management section design is accessibility for maintenance of the screens and honeycomb. In order to accomplish this, one side of the chamber is a removable panel and the chamber is designed so that the screens and honeycomb can be easily removed via a track system. The tracks are constructed of 1" x 2" and 1" x 6" pine boards, cut to length.

3.1.1 Screens

In order to determine the screens to be used, the characteristic Reynolds Number (Re) for the flow through a screen is calculated using the relationship:

\[ Re = \frac{Ud}{\nu} \]

where \( d \) is the wire diameter of the screen, \( U \) is the free stream velocity, and \( \nu \) is the kinematic viscosity of air.

This Reynolds number must be lower than the critical Reynolds number of the screen, which is defined as being the Reynolds number above which large scale eddies are formed. Schubauer[10] performed tests using various screens, based on the number of
Figure 5. Side View of Turbulence Management Section.
wires per inch of screen, also known as mesh size. These data are presented in Table 2, which gives a critical Reynolds number for various mesh sizes. This critical Reynolds Number, plotted as a function of solidity is presented in Figure 6, which is used to determine the percent open area of the screen, or solidity, which is the percent closed area of the screen. This figure plots critical Reynolds number as a function of solidity.

Table 2. Critical Reynolds Numbers and corresponding critical speeds.

<table>
<thead>
<tr>
<th>Screen designation</th>
<th>Wires per inch</th>
<th>Critical Reynolds numbers</th>
<th>Critical speed(^1) (fps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4</td>
<td>66</td>
<td>4.8</td>
</tr>
<tr>
<td>B</td>
<td>24</td>
<td>55</td>
<td>13.2</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
<td>32.5</td>
<td>3.4</td>
</tr>
<tr>
<td>D</td>
<td>40</td>
<td>46</td>
<td>11.9</td>
</tr>
<tr>
<td>E</td>
<td>50</td>
<td>46</td>
<td>15.1</td>
</tr>
<tr>
<td>F</td>
<td>54</td>
<td>44</td>
<td>14.4</td>
</tr>
</tbody>
</table>
Table 3. Screen Data.

<table>
<thead>
<tr>
<th>Screen Reynolds Number</th>
<th>43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Reynolds Number</td>
<td>44</td>
</tr>
<tr>
<td>Mesh Size</td>
<td>54</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>.0055 Inches</td>
</tr>
<tr>
<td>Solidity</td>
<td>50.</td>
</tr>
</tbody>
</table>

Any value to the right of the curve is representative of flow producing large scale eddies. With this information the screens chosen for the turbulence management section have the characteristics as shown in Table 3, and have been selected for their turbulence reducing effectiveness, and their market availability.

Data presented in Figure 7 was used to determine the distance between the screens. This figure shows the reduction of the longitudinal component of turbulence with respect to distance downstream of the screens. Curves are plotted for three different wind speeds, and the effects of the screen are given by the solid lines, while the dashed lines are representative of the flow if no screen were present. With a wind speed of 15 fps, and a Reynolds number of 44, this graph shows that there is little significant turbulence reduction with increased distance for the given circumstance. In a study conducted by Dryden and Shubauer[11], it was shown that the spacing between the screens has little

Figure 8. Axial Profiles of $u'/U_\infty$ for 3 and 7 Screens in Series.
Figure 6. Critical Reynolds Number Above Which Eddies are Produced, Showing Dependence on Solidity of Screen.
Figure 7. Longitudinal Component of Turbulence.
measurable effect on the reduction of turbulence. In this study they varied the distance between screens from six to twelve inches for most of the tests, but to study the effects of spacing they varied distance from two to twenty-eight inches. For the wind tunnel being designed here, in order to preserve space yet still achieve a lower turbulence, six inch spacing was chosen between the screens.

The Dryden and Shubauer[11] study also gives experimental numerical values for turbulence intensity for no screens, one, two, three and six screens in series. The results clearly show that using three screens in series, spaced six inches apart, results in a lower turbulence than for one or two screens. The experimental values are 0.020, 0.041, and 0.026 for three, one and two screens respectively. With six screens, however the turbulence level actually increases slightly, to a value of 0.021. The study uses 18-mesh screens for one, two and three screens, however, for the six screen study, different mesh screens are used, and they are not consistently spaced. From their study, it is evident that using three screens would be more beneficial than using one or two screens. Because the setup for six screens was not consistent with the rest of the study, the data can not be used to determine the turbulence reduction.

As a guide to determine the number of screens to be used, another study was also used. From Loehrke and Nagib[12], three screens were used in the turbulence management section. This quantity was chosen in order to save space by using as few screens as possible while still keeping the turbulence at a minimum. Figure 10 gives the turbulence intensity plotted as a function of downstream distance for 3 and 7 screens. As indicated, the added reduction in turbulence using seven screens as opposed to three was
not worth using an extra two feet of length. The figure also shows $u'/U_m$ as a function of distance downstream of the screens. In order to allow both curves to fit on one graph two vertical axes were used, with the curve for three screens corresponding to the axis on the left of the graph. Using seven screens as opposed to three would reduce the turbulence by 0.035 percent, which is not seen as a fair tradeoff for two feet of valuable space. For this application it was assumed that the turbulence level would decrease with four or five screens, although the degree of reduction was not known, so it was decided instead to use three screens. The screens were mounted on one inch by one inch wood frames and fastened to the frames with staples and wood tacks.

![Figure 8. Axial Profiles of $u'/U_m$ for 3 and 7 Screens in Series.](image-url)
3.1.2. Honeycomb

The purpose of the honeycomb in the turbulence management section is to reduce large scale turbulence by reducing the radial component of vorticity, or in a sense breaking up large scale eddies from the flow. The important considerations in the design of the honeycomb are cost, available space, and the pressure drop through the honeycomb. For cost considerations, soda straws are used as opposed to prefabricated honeycomb. Using straws with an outside diameter of 0.25 inches, due to availability, requires 41,000 straws to create the honeycomb block. Figure 9 plots turbulence intensity against distance downstream for different lengths of honeycomb with a screen immediately downstream as well as one for the honeycomb alone. This figure shows that there is a slight reduction in turbulence intensity when ten inch long straws are used as opposed to three inch. However, the pressure drop through the straws almost doubles when the length is increased from three to ten inches. Therefore, a compromise has been made between the maximum turbulence reduction and minimum pressure drop through the straws. Three inch length straws are chosen for the honeycomb. However, the only available length manufactured in quantity is 7.75 inch lengths. This requires manually cutting 41,000 soda straws from their original length to three inch lengths using a paper cutter.

Comparing the curves in Figure 9 for the 25 cm straws, with and without screens, clearly shows that the honeycomb with screens substantially reduces the downstream turbulence, and also reduces the decay rate of the flow through the straws. Two screens are used, one in front, and one behind the straws, not only to reduce the decay rate, but also as a means to hold the straws in place within the frame. Two one inch by two inch
boards are glued together to achieve the three inch length required for the honeycomb frame. The straws are then placed in the frame and the screens are stapled into place.

Figure 9. Comparison Between Downstream Axial Profiles of $u'/U$ for Honeycombs of Different Lengths Plus Screen.
3.2 Contraction

The principal goal of the contraction is to accelerate the flow while maintaining a steady, uniform exit flow. It is also important to avoid flow separation through the contraction. The contraction also serves as a turbulence reduction mechanism while also accomplishing the above goals.

The design of the contraction shape is based on a similar wind tunnel design, and is discussed in detail by Nagel[2]. The contour shape that is used in this tunnel is based on an equation developed by Nagel:

\[ Y = A_1 + A_2 \left[ S^4 \left( 15 - 24S + 10S^2 \right) \right] \]

where \( S = \frac{X}{L} \), and \( A_1 \) and \( A_2 \) are geometry dependent constants as shown in Figure 10.

![Figure 10. Contraction Contour Shape.](image-url)
The contraction ratio used in this tunnel is approximately twenty to one. Previous studies, mentioned in Section 2.2, show that the maximum contraction ratio for an effective contraction has been determined to be approximately forty-five to one.

The contraction is built using spruce one inch by two inch boards to construct an entrance and exit frame to support the numerous exterior ribs. Lap joints are used in the frames to provide extra strength as shown in Figure 11. The ribs are constructed of half inch thick plywood cut to the contour described above, with a height of 1.5 inches. Twelve full length ribs are built to give support to the entire structure, while eight half length and eight quarter length ribs are also required to add strength and stiffness to the larger inlet section of the contraction shown in Figure 12. Several cross members are also used to give additional support to the ribs. To fabricate the walls of the contraction equation [7] is used. However, a different length is entered into the equation to give a two dimensional projection of the curve. This curve is then plotted and traced onto an eighth inch thick hardboard wall.

Hardboard is selected for the walls for its flexibility, as well as its strength. The pressure in the exit of the contraction was calculated to be 0.96 Atmospheres. Brady and Clauser[13] shows hardboard to be very strong for its thickness and flexibility. The walls are attached to the frame using wood glue, countersunk wood screws, and filled with a polyester resin body filler. In order to provide added support to the contraction, the interior corners are fiberglass reinforced. Four layers of fiberglass are used with two layers on the inside and two layers on the outside of the contraction. This material gives
Figure 11. Contraction Frame with Lap Joints. Dimensions are in Inches.
Figure 12. Contraction Ribs. Dimensions are in Inches.
approximately an additional sixteenth of an inch of fiberglass to add to the strength of the contraction at the corners.

It is necessary to avoid vortices occurring in the corners. To prevent corner vortices from forming, the corners are rounded, using a two inch radius at the exit and tapered to a three inch radius at the entrance. The radii are fabricated using polyester filler to produce a smooth transition between the ends is achieved. The inside of the contraction is also painted with high gloss latex paint to insure a smooth surface and to reduce boundary layer growth through the contraction. The contraction is illustrated in Figure 13.

3.3 Test Section

In order for this tunnel to be useful for experimental work, a seven inch diameter model propeller must fit in the undisturbed flow occupying the test section. To insure adequate undisturbed flow, data reproduced by Keuthe[8] is used to determine the distance downstream of the contraction exit in which to place the test section. From Figure 3, with $u=1$, a distance of 1.5 diameters downstream provides ample space for such a seven inch diameter propeller to operate within the well defined flow. The precise dimensions of the test section at the contraction outlet are 8 inch by 8 inch. This gives a distance of 6 inches from the contraction exit to the propeller location in the test section. In the future, a test stand will be mounted at this location. Again, using Keuthe's[8] results, the dimensions of the jet mixing region of the exit flow are determined. Once these are obtained, the dimensions and location of a collector are determined.
Figure 13. Detailed Drawing of the Contraction. Dimensions are in Inches.
3.4 Collector

In order to deliver the flow from the test section into the diffuser with a minimal disturbance to the flow a collector is needed. The collector captures the flow from the jet mixing region and channels it into the diffuser. There is very little published information on optimum collector shapes and designs. However, Patrick[1] has had some experience with different shapes, and has reported significant reverse flow occurring at the entrance of the collector at all velocities. Because it is important to maintain low energy losses in the flow while trying to avoid separation, a new collector design is being incorporated into this design. A contraction contour equation has produced good results in previous tests with little separation, and is used to design the collector for this application. However, different dimensions are applied as appropriate for the tunnel being considered. It is important to note that the above shape has produced good results when used as a contraction, where the flow is well developed and the turbulence is low at the entrance. The flow in the collector for the present application is not well developed and the turbulence levels are expected to be extremely high because of the turbulent jet mixing occurring in the test section.

The overall length of the collector is 13.80 inches including inlet and exit frames as shown in Figure 14. The collector is fabricated using three layers of fiberglass, laid up over foam block templates. The structure is supported by ribs constructed of quarter inch thick plywood, cut to a 1.5 inch height. The ribs and collector are supported on the ends by one inch by two inch pine wood frames. A frame constructed of two inch by four inch
Figure 14. Detailed Drawing of the Collector. Dimensions are in Inches.
boards is attached to the exit of the collector to allow for a smooth transition to the diffuser. Like the contraction, the inside corners of the collector are filleted with a two inch radius to reduce the risk of corner vortices.

The entrance to the collector is located approximately two characteristic lengths, two times the width of the contraction exit downstream of the contraction exit. According to Keuthe[8], at u=0, at this distance will capture most of the jet mixture. The exit of the contraction, the test section and the collector are all located within the anechoic test chamber.

3.4 Anechoic Test Chamber

The anechoic test chamber is a large volume which serves several purposes in the wind tunnel's operation. First it prevents outside air from entering the test section and the diffuser. Any outside air entering the flow would be pumped into the diffuser, reducing the amount of flow from the contraction. By having a room surrounding the test section, steady flow will occur. In addition this anechoic volume provides sound proofing, and allows adequate room for making far-field acoustic measurements. The acoustic far field is defined as being the extent of the region where the acoustic pressure is in phase with the particle velocity all within a spherical sound surface.

The anechoic chamber as illustrated in Figure 15 is designed to withstand large forces occurring because of the low pressure caused by the flow as compared with the outside atmospheric pressure. This chamber is constructed of half inch thick plywood walls, supported by two inch by four inch wood boards. The walls are overlapped and
Figure 15. Anechoic Chamber Three View Drawing. Dimensions are in Inches.
nailed into the two inch by four inch boards, and the corners are sealed to prevent leakage. The internal structure provides support for the walls of the chamber, as well as providing a space for the installation of acoustic insulation. Two layers of insulation will be attached to the walls, starting with a layer of fiberglass insulation followed by a layer of Kraft paper next to the board wall, and then covered with a layer of one inch thick resilient, open-cell, polyurethane foam to absorb the noise being created by the flow. A 13 inch x 13 inch square appature is cut into the front face of the chamber and the exit of the contraction fits directly into this hole. Similarly a 15 inch x 15 inch square hole is cut in the rear face of the chamber to support the exit of the collector, which fits snugly into the hole and is nailed into place. The interface is sealed to prevent leakage. Each appature is reinforced with two by fours. One side of the chamber serves as a door, so that work may be performed in the test section. The entire side is used as a door instead of cutting a door into the wall, to allow sufficient maneuverability as well as to maintain structural integrity. Four large door hinges are used to attach the door to the frame, and five latches are used to secure the door when closed. The door is hinged upward, and is supported by a 61 inch support pole when open.

The center of the anechoic chamber and, therefore, the test section is positioned approximately six feet above ground level. It is necessary to have the test section located above ground level so that mechanisms can be installed later which will be used to drive propellers or fans mounted in the test section. The exact height of the tunnel centerline is fixed by the height of the fan/blower motor being used to power the tunnel. It is necessary to have the diffuser located at least a few inches above the fan to avoid contact with the
fan and therefore avoid any vibrational effects the fan may produce from interfering with
the diffuser operation.

Because of the height of the test section, a 25 inch high platform has been
constructed to ease access to the anechoic chamber. This platform was constructed of
half inch plywood with 2 inch x 4 inch wood supports, 4 inch x 4 inch wood legs and was
capable of supporting several hundred pounds.

3.5 Diffuser

The function of the diffuser is to decelerate the flow, by converting as large a
fraction as possible of the dynamic pressure into static pressure while maintaining steady,
symmetric flow. There are several diffuser types such as conical, two-dimensional straight
walled, and three-dimensional straight walled types. The configuration selected for this
tunnel is a three-dimensional straight walled type. This configuration is used to allow a
larger entrance/exit area ratio than in two dimensional diffusers with the same length.
Available space is again a consideration and there is a significant difference in length
between two-dimensional and three-dimensional diffusers given the same area ratio. A
conical diffuser would have been ideal. However, because of the rectangular to circular
transition needed, this would be extremely difficult to construct, therefore a straight
walled transition has been chosen as more appropriate.

The most important aspect in diffuser design is avoiding stall. When stall is
experienced, flow becomes erratic, and gross fluctuations appear in both the flow and
pressure resulting in erratic flow throughout the tunnel and large pressure losses across the diffuser. The geometric shape of the diffuser plays a major role in the development of the flow. The significant factors in the design include diffuser half angle $\theta$, area ratio and the non-dimensionalized length $L/W_1$, where $W_1$ is defined as the width of the diffuser entrance.

According to several studies, such as Kline, Abbott and Fox[14], the optimum effectiveness of a diffuser is achieved when the angle is approximately seven degrees. This optimum assures a maximum pressure recovery in the diffuser. However, the possibility of stall may still be present. At seven degrees, an $L/W_1$ of between 25 and 30 is necessary to prevent stall. Renault, Johnson, and Kline[15] shows that for two-dimensional diffusers, higher area ratios, up to about 5, exhibit high recovery but also experience some stall.

A compromise is made between high pressure recovery, minimal stall, and still maximizing the available space. From Kline[14] it can be seen that there are a number of different geometries that will result in no stall. Keeping the length constant at 64.6 inches to preserve space, the final values were determined to be:

<p>| | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$2\theta$</td>
<td>10.2 Deg.</td>
</tr>
<tr>
<td>$L/W_1$</td>
<td>5.6</td>
</tr>
<tr>
<td>AreaRatio</td>
<td>4.0</td>
</tr>
</tbody>
</table>

These values are in a region of no appreciable stall and still allow a high pressure recovery while maintaining a geometry that allows the diffuser to fit into the available space. These design parameters are based upon the assumption that a relatively thin turbulent boundary layer exists at the diffuser entrance.
Figure 16. Diffuser Layout Drawing.
The diffuser design data available is all premised upon thin turbulent boundary layers at the inlet. Unfortunately, the flow coming into the diffuser being reported is characterized by a flow composed of an open jet turbulent mixing region and a small potential core region near the centerline being accelerated through the collector. This flow is characterized by severe turbulent flow generated in the turbulent mixing region of the jet and a small potential flow core. The scale of the turbulence includes the very small scale generated at the intense shear layer next to the potential core to the very large scale which is on the order of the diffuser inlet.

No design data was located for such a diffuser with this turbulent flow. The design reported here is based upon the published design data and validated by experimental measurements to determine if the diffuser functions in an acceptable manner.

This diffuser is straight walled and, therefore, easier to construct than a conical diffuser. The walls are made of quarter inch plywood. They are supported by one inch by one inch cedar ribs spaced every twelve inches. The walls are overlapped and a 1 inch by 2 inch rib is used as a nailer to attach the walls. The length of the diffuser is 64.6 inches, while the inlet is 11 inch by 11 inch and the exit is 18 inch by 18 inch, as is shown in Figure 16.

Similar to the contraction, flow through the corners of the diffuser will create corner vortices which may cause separation. To prevent these vortices the same process was followed as in the contraction where the corners are filleted. However, the diffuser differs from the contraction in that a constant three inch radius is used throughout the length of the diffuser.
Extreme care was taken to have a smooth, large radius between the collector and the diffuser to minimize the intensity of the adverse pressure gradient in this transition region. It has been well established[13] that this transition was the most critical region to cause diffuser flow separation.

3.6 Plenum Chamber

This open circuit design employs a plenum chamber as a pressure and kinetic energy dump which is required because of the limited length available for the length of the tunnel. This design allows the energy and pressure of the flow to be dumped into the plenum chamber before entering the fan, resulting in a short but inefficient tunnel.

Unfortunately, this design results in a significant kinetic energy (K.E.) loss that could be avoided if sufficient tunnel length space were available. With sufficient tunnel length a long diffuser would significantly lower the flow speed into the fan and avoid the large K.E. loss experienced when using the plenum chamber.

The fan is located directly below the diffuser to provide for sufficient room for the diffuser in the limited space available. By placing the fan under the diffuser, the exit of the diffuser is directly above the entrance to the fan. This reduces the likelihood of waves propagating from the fan back down the diffuser into the anechoic chamber. With the two openings in the plenum chamber directly above one another any acoustic wave would have to reverberate off of the opposite wall in order to return down the diffuser. Sound
Figure 17. Plenum Chamber Layout. Dimensions are in Inches.
absorbing material in the plenum chamber will significantly reduce the magnitude of sound waves that do return to the anechoic chamber.

The design of the plenum chamber must allow easy access into the chamber for maintenance purposes. The chamber also must be strong enough to support the diffuser, and big enough for a person to enter. It is, therefore, made of 5/8 inch thick plywood walls with an interior support structure made of 2 inch by 4 inch wooden ribs. Similar to the anechoic chamber, a door to the plenum chamber is needed to allow for easy accessibility, however this door hinges on a horizontal axis. An entire wall is a door to ease fabrication.

The height of the plenum chamber is 89 inches, while the length and width are each 37 inches, as is shown in Figure 17. Additionally two inch by four inch boards are attached to the outside of the door to give increased strength, as well as to provide a surface for latches to be mounted. Three-eighths inch thick, foam weatherstripping is placed along the inside door frame to prevent air from leaking from the door joint.

3.7 Fan and Motor Assembly

It was decided early in the design that a suction fan would be more beneficial to this type of design because the turbulence management section would function better than if the fan was located at the tunnel entrance. In order for the tunnel to be useful for testing general aviation propellers, a test section velocity of about 0.2 Mach was determined as a reasonable value. To determine the size of the fan and motor needed to
power the tunnel, the flow rate through the test section and the energy losses through the entire tunnel had to be determined (refer to Ch. 2.5). Using the velocity and area of the contraction, the required flow rate was calculated as 11,300 cubic feet per minute (cfm).

After contacting several fan manufacturers, the best product available pricewise for this application was the Aerovent backward incline airfoil centrifugal fan. In this designation the blades have an airfoil shape and rotate backwards, forcing the air out the exhaust. The fan that is selected has an inlet diameter of 25 inches. The fan is powered by a 15 horsepower, 480 volt, 15 amp, three phase electric motor.

According to the fan’s operating curves, it provides 12,355 cfm at a static pressure rise of three inches of water. The pressure drop for the entire tunnel was calculated to be six inches of water. Again using the operating curves in Figure 4, at six inches of water, the fan would provide a flow rate of 9700 cfm at 15 hp. This flow rate corresponds to a maximum fan velocity of .25 Mach, or approximately 280 ft/s. This velocity is reasonable and the fan was chosen as an acceptable power source.

Because the fan operates at a constant power, an alternative method is needed to control the velocity of flow through the wind tunnel. Aerovent provided an alternative method with their inlet vane control which is attached to the fan inlet, and has seven settings, from fully open to fully closed, as shown in Figure 18. The flow speed is simply varied by hand operating a lever which varies the area of the opening. This controller produces a very nonlinear flow.
Figure 18. Inlet Vane Control.
3.8 Support Frames and Final Assembly

The fan and motor assembly sit on six rubber coated, one inch high legs that act as vibration dampeners. The plenum chamber sits on the floor, and needs no additional support frame. The diffuser, anechoic chamber, collector, contraction and turbulence management section are located a substantial distance above the ground and, therefore, do need a structure to support them.

Since the plenum chamber is in itself a support structure that sits level on the floor, the exit of the diffuser is supported by the plenum chamber. A 1 inch x 2 inch frame is built around the inside of the diffuser opening, and the diffuser is then bolted into place. Directly below the diffuser exit is the fan inlet. The fan inlet is bolted to the inlet vane control, which is bolted to a 27 inch ring frame. A sister frame is bolted to the plenum chamber, and the two frames are spaced two inches apart. The space between the two frames is filled with a role of vibration absorbing rubber. This assembly allows the vibration of the fan and motor to be isolated from the rest of the tunnel.

The test section centerline is 71 inches above ground level to match the diffuser inlet with the diffuser opening. A frame constructed of 4 inch x 4 inch boards and 2 inch x 4 inch boards is built to support the anechoic chamber, as show in Figure 19. A four inch thick square frame was built onto the end of the collector to allow it to fit into the diffuser opening on the anechoic chamber. The frame also gives an extra four inches of space between the collector and the diffuser. This space is necessary to provide a smooth transition between the collector and the diffuser. The collector is nailed into place in the anechoic chamber, and the diffuser was fastened into place on the collector frame using
Figure 19. Test Room Support.
wood screws. With the anechoic chamber supported, the contraction exit is slid into place in the chamber. The other end of the contraction is supported by a frame built to support both the contraction and the settling chamber, as seen in Figure 20. This frame is constructed of 2 inch x 4 inch wood boards and is nailed directly to the settling chamber. The contraction is attached to the frame connecting the two components using wood screws.

All connections between components are either sealed with weatherstripping or silicone caulk to prevent any air from leaking into or out of the tunnel. All corners of all of the components are also sealed with caulk. The components are either bolted or screwed into position. This fabrication technique allows for quick disassembling and, therefore, can be moved with minimal difficulty.
Figure 20. Turbulence Management Section Support.
CHAPTER 4
EXPERIMENTAL EVALUATION

To determine the flow performance of the wind tunnel, measurements were taken using a hot film anemometer, a pitot-static tube, a total pressure tube, and yarn tufts used for flow separation visualization. Using this equipment, the velocity distribution across the test section, as well as the turbulence intensity of the flow was determined. The following chapter gives a detailed description of the equipment used, and the procedure used to evaluate the wind tunnel performance.

4.1 Visualization

The first procedure in testing the wind tunnel was using tufts of yarn taped to the walls of the wind tunnel to determine if there was any separation occurring at various locations in the diffuser, collector, and contraction. Three inch lengths of yarn were taped to the walls of the diffuser at six positions downstream of the test section. Four or five pieces of yarn were placed per wall at each position, depending on the cross sectional area. The same procedure was followed for the collector and the contraction exit.

With the tunnel running at full speed, the motions of the yarn was observed, and was used to determine if separation was occurring in the diffuser or the contraction. The
yarn was also used to determine whether the collector was experiencing reverse flow, and if so, where such flow occurs.

4.2 Hot Film Anemometer

A hot film anemometer is used to determine the velocity, turbulence intensity, and temperature of a flow field. The system used to measure the wind tunnel flow is a TSI IFA 300 Constant Temperature Anemometer System. The system consists of several components, listed in Table 4.

Table 4. Anemometer Components.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16 Channel IFA 300 Anemometer System</td>
<td>183100</td>
</tr>
<tr>
<td>1</td>
<td>4-channel A/D Converter Board</td>
<td>962112</td>
</tr>
<tr>
<td>1</td>
<td>IFA 300 Software</td>
<td>1906132</td>
</tr>
<tr>
<td>1</td>
<td>Thermocouple</td>
<td>134100</td>
</tr>
<tr>
<td>1</td>
<td>Two Component Sensor</td>
<td>124000</td>
</tr>
<tr>
<td>1</td>
<td>One Component Sensor</td>
<td>121000</td>
</tr>
<tr>
<td>1</td>
<td>36&quot; Probe</td>
<td></td>
</tr>
<tr>
<td>Varied</td>
<td>Assorted Cables and Connectors</td>
<td>Varied</td>
</tr>
<tr>
<td>1</td>
<td>Flex 486 Computer</td>
<td>9328270</td>
</tr>
</tbody>
</table>
The system components are connected as shown in Figure 21.

With this system it is possible to immediately display mean velocity, turbulence intensity, and temperature, and spreadsheets with plots illustrating all four.
4.3 Probe Calibration

In order to obtain accurate values for velocity and turbulence intensity using the anemometer system, the probe must first be calibrated. A pitot-static tube is mounted in the center of the test section, and is connected to a u-tube manometer. With water as the fluid in the manometer, measurements are taken for five different velocity settings. Using Bernoulli’s equation, the measured pressure differences are converted into velocities for each of the fan settings, and these values are used to calibrate the probe with the one component sensor.

The calibration procedure is as follows:

Using the IFA 300 software, the probe calibration option is selected. Several options are available for the calibration, but for this experiment the velocity is manually entered, and the anemometer acquires the bridge voltage. The resistances of the cables and the probe, as well as values for offset and gain are entered into the program. Offset and gain values are used to clarify the signal and are obtained through trial and error. However, default settings are offered in the manual. The single sensor probe is attached to the 36 inch probe support, and is placed in the center of the test section, at the same location that the pitot tube was located. The tunnel is turned on, and a voltage is acquired for each setting. After acquiring a voltage for each velocity, the IFA 300 software then is used to construct a calibration curve, plotting voltage versus velocity.

This plot is used to determine future velocity readings. Once completed, the data is saved in the probe data file, and can be used at a later date to interpret acquired data.
4.4 Data Acquisition

The goal of the testing procedure is to determine the velocity profile across the test section of the wind tunnel, as well as the turbulence intensity level at several points. To accomplish this, a grid is defined in the test section as illustrated in Figure 22. This layout is chosen because it represents the area that will eventually be occupied by the propeller models.

A traversing mechanism is attached to the bottom of the anechoic chamber below the test section. The one component probe can be moved in both horizontal and vertical directions inside of the test section while the tunnel is in operation. This procedure allows
the testing to be performed at all locations without having to turn off the tunnel, and open
the anechoic chamber in order to move the probe.

The IFA 300 gives several options while acquiring data. Once the calibrated probe
is selected, sample rate, sample size, and sample time are chosen. The sample rate
determines how many samples will be taken per second. The sample size determines the
number of samples per channel, with each block containing 1024 samples. The time is
simply the sample size divided by the sample rate. For this testing, the sample rate is
chosen to be 1 kHz, and the sample size is chosen to be 1 block, or 1024 samples,
resulting in a sample time of 1.024 seconds.

A low pass filter selection is also available for the system and, for this test the auto
setting was selected which was 250 Hz. This option allows the computer to select the
optimum filter for the sample rate chosen.

The one component sensor is then used to acquire data for the twenty nine points
mapped out in the test section. Data is collected at three different velocities, ranging from
approximately 115 ft/s to 215 ft/s. Because of slight variations in the data, three data
points are collected for each location, and an average of these values is calculated for all
of the required information.

With the IFA 300 system, there are several post analysis selections that can
be chosen after the data has been collected. All data is saved in a data file, and is analyzed
by the system program, producing a table that gives mean velocity, standard deviation,
turbulence intensity, normal stress, skewness coefficient, and temperature for each data
point collected. Once this information is calculated, several plots can be obtained by the
software as well, including a spectrum analysis, which plots the power spectral density function (i.e. the energy distribution as a function of frequency, and the time history, which is a real time graph) and also plots velocity versus time for the signal.
CHAPTER 5
RESULTS

The velocity data was collected for the tunnel at three different velocities in order to give a good representation of the tunnel’s characteristics at different conditions. The velocities selected were approximately 114 ft/s, 143 ft/s, and 216 ft/s. Because of the mechanical mechanism used to control the flow through the tunnel, it was difficult to set the velocity to more equally spaced values. The six velocity settings on the inlet vane control were as follows:

<table>
<thead>
<tr>
<th>Setting</th>
<th>Velocity(ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>114</td>
</tr>
<tr>
<td>2</td>
<td>143</td>
</tr>
<tr>
<td>3</td>
<td>189</td>
</tr>
<tr>
<td>4</td>
<td>206</td>
</tr>
<tr>
<td>5</td>
<td>211</td>
</tr>
<tr>
<td>6</td>
<td>216</td>
</tr>
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</table>

It was, therefore, decided that the best representation of the velocity field would be the lowest speed, 114 ft/s, full speed, 216 ft/s, and the closest to the middle of the speed range that was available, 143 ft/s.

Data was gathered for each of the velocities, and the results are described in this chapter.
5.1 Visualization and Design Changes

As discussed in section 4.1, yarn was placed at several locations in the tunnel to determine if separation occurred. The yarn located on the exit of the contraction appeared steady and was representative of unseparated flow at all velocities tested. Therefore, it was decided that the flow through the contraction throat was not separating to any noticeable degree.

Yarn located in the entrance region of the collector exhibited quite different characteristics from that of the contraction throat. The collector was designed using very little published data as a guide. The collector shape was designed using the same characteristic equation that defines the shape of the curve for the contraction. It was evident by the behavior of the yarn located in the collector that there was reverse flow occurring along the line on all four sides as shown in Figure 23. Although this contraction shape worked well in keeping the flow attached to the contraction walls, the flow entering the contraction was well defined, low turbulence flow. The flow entering the collector was not as well behaved. As mentioned in Chapter 3, the flow coming through the collector is characterized by a flow composed of an open jet turbulent mixing region, and a small potential core, and was not able to be captured by the collector. It was clear, however, where the collector was functioning properly and recommendations on how to improve the design are made later.

To eliminate the reverse flow, the collector will be cropped off at the line shown in Figure 23. This will not only eliminate the reverse flow, but will allow the collector to be moved closer to the exit of the contraction. Moving the collector further upstream will increase the length of the diffuser, which should increase the overall performance of the tunnel.
Figure 23. Location of Reverse Flow on Collector.
The yarn was placed on the walls of the diffuser at six locations, equally spaced, downstream of the test section. Initial tests indicated that the flow was separating throughout the entire length of the diffuser. The first modification to correct this problem was to modify the transition region between the collector and the diffuser. It was observed that there were inconsistencies in the shape of the radius of the transition resulting in adverse pressure gradients which precipitated separation. Once the transition radius was smoothed, the separation in the throat disappeared, though there were regions of stall further downstream.

To determine if reducing the angle of the diffuser would eliminate the diffuser wall separation, new walls were constructed and installed in the diffuser. This reduced the diffuser angle from 10.5 degrees to 6.5 degrees. Once the corners were radiused there was a marked improvement in the flow. The flow was now attached throughout most of the diffuser, however it was obvious that the flow was entering the diffuser at a small angle off center. This could be seen as the yarn on the left and top walls was separating slightly, while the yarn on the other walls remained attached. The yarn located in the upper left corner was swirling, indicating the formation of vortices in the corner.

It was determined that during assembly, the contraction was installed at a small angle off center, forcing the flow to the lower left corner of the tunnel. This was corrected and the contraction was carefully aligned with the diffuser. The flow then appeared to be attached throughout the entire diffuser.

Using the yarn as a visualization tool, several modifications needed to be made to the tunnel, proving the importance of such a tool in aerodynamics experiments. It also showed the flow sensitivity to the geometric transitions between the contraction and the diffuser. Small
imperfections and inconsistencies in the construction caused large scale separation in the flow.

The importance of the positioning of the contraction was also made evident, as just one degree of alignment error caused the flow to separate, and vortices to form in the diffuser. The final angle of the diffuser was experimentally determined to be 6.5 degrees, which is interestingly close to the optimum diffuser angle of seven degrees for straight walled diffusers[14].

5.2 High Speed Results

The results of the testing for the highest speed on the wind tunnel were obtained by using a hot-film anemometer. Data is taken at the 29 location as shown in Figure 22 in chapter 4. The results for all three test runs are shown in Appendix A. The values of U, and u'/U are determined by the IFA 300 software by converting a bridge voltage measured by the anemometer.

The average mean velocity for the full speed testing was calculated to be 213.6 ft/s. The percent difference was defined as the difference between the average mean velocity and the mean velocity determined for each point. The standard deviation was defined as the amount the mean velocity varied during the 1.024 seconds that the data was being gathered.

The velocity profile is shown in Figure 24.

One of the initial goals for this tunnel was that the velocity not vary by more than one percent across the test section. For the most part this was achieved for the high speed data. There were four points on the grid that varied by more than one percent. Three of these points were located at the furthest distance from the center of the test section, and were bordering the edge of the potential core. Outside of the potential core, the flow exhibited high turbulence, as would be expected in the jet mixing region. The fourth point was also located in the upper right
Figure 24. High Speed Velocity Distribution. With Speed in ft/s.
Figure 25. High Speed Percent Turbulence Intensity Distribution.
Figure 26. High Speed Standard Deviation of Velocity Distribution.
corner of the test section, however not as far from center as the other points. Even these four points, while above one percent were still below two percent, and were therefore considered acceptable values in compromise of the original goal.

The turbulence intensity of the flow at full speed are somewhat higher than the initial goal of 0.2 percent. As can be seen in Figure 25, the turbulence levels along the inner circle average approximately 0.5 percent, while the values at the next level vary approximately between 0.52 and 0.62 percent. In the outer circle, turbulence intensity levels varied between approximately 0.65 to 1.0 percent. The highest levels of turbulence are at the farthest points from the center, as expected. Again this is because they lie on the border of the turbulent mixing region. While 0.2 percent was the initial goal for this tunnel, the values obtained here are still acceptable values for an anechoic tunnel. The standard deviation of the mean velocity for the high speed test is shown in Figure 26. There are also recommendations made later in this paper on ways to further reduce the turbulence level in the tunnel.

Figure 27 shows the spectrum analysis of the full speed run at the center location of the test section. The graph is plotted with both axes in the log mode in order to provide a clear picture. It can be seen that there are three peaks in the graph occurring in the very low frequency range. The first peak occurs at 1Hz, the second at 3 Hz, and the third at 6 Hz, and all three peaks are approximately $6 \times 10^{-5} \text{m/sec}^2/\text{Hz}$ in magnitude. It is theorized that these low frequency fluctuations are due to some small scale separation occurring at a very low frequency, probably due to some inconsistencies still present in the transition between the collector and the diffuser. This phenomenon can be observed by watching the probe in the flow. The probe vibrates at a very low frequency, however it does not vibrate with any regularity. A real time graph of the flow
Figure 27. High Speed Spectrum Analysis.

Figure 28. High Speed Real Time Display. With Speed in m/s, and Time in Seconds.
Figure 29. High Pass Spectrum Analysis.

Figure 30. High Pass Real Time Display. With Speed in m/s, and Time in Seconds.
speed at the center location of the test section for the high speed test is shown in Figure 28.

The Strouhal number for the probe support was calculated using Schichting[16] to determine if the vibration was due to vortex shedding. The following equation was used to calculate the frequency,

\[ S = \frac{nD}{v} \]

Where \( S \) is the Strouhal number, \( n \) is the frequency, \( D \) is the probe diameter, and \( V \) is the velocity in the test section. With an \( S \) of .21, velocity of 213.6 ft/s, and a 0.25 in probe diameter, the frequency was approximately 2100 Hz. This frequency was significantly higher than the visibly low frequency experienced by the probe.

5.2.1 High Pass Filter

A test run was conducted utilizing a High Pass filter set at 10 Hz. This setting simulated the results that would occur if the low frequency disturbance were not present. The results of this run showed the projected performance of the tunnel once the separation is reduced in the test section. When the High Pass filter was in use, the turbulence intensity was reduced from 0.48 to 0.285 at the center of the test section. The standard deviation for the mean flow was also significantly reduced when the filter was in place.

The spectrum analysis with the high pass filter is shown in Figure 29. While there are still small peaks present in the spectrum, the peaks in this figure are at least an order of magnitude lower than without the filter, and no peak occurs at one hertz, where the largest peak occurred without the filter. It is also evident from the real time display, as seen in Figure 30 that the flow appears more steady, and does not oscillate to the same degree that is present when the filter is
not used, as is also shown in the large decrease in the standard deviation.

5.3 Half Speed Results

The average velocity for the data taken at half speed is 143.0 ft/s. The velocity profile for the half speed test is shown in Figure 31. This data shows a significant increase in both turbulence intensity and standard deviation. The turbulence intensity at the center of the test section, as shown in Figure 32, increases from 0.48 at full speed to 0.795 at half speed, an increase of 66%. The turbulence intensity increases at every point mapped in the test section, as can be seen by comparing the values from Figure 32 to those of Figure 25.

The standard deviation of the mean velocity for the tunnel at half speed, the profile of which is shown in Figure 33, as well as the time history plot for the center location as shown in Figure 34 reveals the flow at half speed to be less well behaved than for the flow at full speed. The spectrum analysis, as seen in Figure 35, for this fan setting is similar to that of the full speed test in that there is a low frequency disturbance probably caused by separated flow. However, the energy level of the peak in this graph is an entire order of magnitude higher than in the full speed graph. Most of the disturbance in both graphs occurs below 15 Hz.

It is believed that at half speed, a tunnel structural vibration at a frequency that causes the flow properties of the tunnel to deteriorate more rapidly than for the tunnel at other speeds is occurring. This is evident by placing a hand on the walls of the tunnel, and feeling the vibrational effects at this half speed. While the flow characteristics worsen for the half speed test, they improve for the low speed test. The values collected for the low speed test are comparable to those gathered for the tunnel operating at full speed.
Figure 31. Half Speed Velocity Distribution. With Speed in ft/s.
Figure 32. Half Speed Percent Turbulence Intensity Distribution.
Figure 33. Half Speed Standard Deviation of Velocity Distribution.
Figure 34. Half Speed Spectrum Analysis.

Figure 35. Half Speed Real Time Display. With Speed in m/s, and Time in Seconds.
5.4 Low Speed Results

At the lowest speed setting, the velocity profile varied the least of the three settings. With an average velocity of 113.8 ft/s, the velocity never varied by more than 0.89%, a variation which is below the goal set at the beginning of the design of 1.0%. Even at the furthest radial points from the center of the test section the velocity never varied more than one percent. The velocity profile for this low speed case is shown in Figure 36.

The turbulence intensity values on the outer circle of the test section for this case, as seen in Figure 37, are all above 0.95, and six of the eight points exceed one percent. Again, this is expected due to the location of these points. These points all lie on or near the border separating the potential flow core from the higher turbulence jet mixing region. The nine inner points all have turbulence levels comparable to those at full speed, and in some cases the turbulence is actually less. The turbulence intensity at the low speed setting is lower than the values at half speed at every location on the grid. The standard deviation of the mean velocity is shown in Figure 38. Looking at the data for the first two runs, it would be expected that the flow properties would continue to deteriorate, however this is not the pattern that was followed. The data actually improved when compared to the half speed data. This further supports the hypothesis that the tunnel is experiencing some vibration at half speed due to a fan or motor frequency that excites the structure and causes boundary layer separation to occur at the middle speed.

The spectrum analysis in Figure 39 shows a similar curve to that of the full speed. The first peak occurs at one Hz, and has a magnitude of $1.6 \times 10^{-5} \text{ m}^2/\text{s}^2$. This is similar to that of the full speed spectrum analysis, although the peak is of higher magnitude on the full speed graph.
Figure 36. Low Speed Velocity Distribution. With Speed in ft/s.
Figure 37. Low Speed Percent Turbulence Intensity Distribution.
Figure 38. Low Speed Standard Deviation of Velocity Distribution.
Figure 39. Low Speed Spectrum Analysis.

Figure 40. Low Speed Real Time Display. With Speed in m/s, and Time in Seconds.
This suggests that the separation occurs even at the lowest fan setting. The real time plot shown in Figure 40 indicates that the velocity is not as steady as with the High Pass filter in place, however, the standard deviation is lower for the low speeds.

In all, the tunnel performed fairly well under the circumstances, and there are several factors that must be taken into consideration before proceeding with the full sized tunnel. These factors, as well as recommendations for improvements will be covered in the next chapter.
CHAPTER 6
CONCLUSIONS

6.1 Visualization

By observing the yarn tufts in the wind tunnel, some of the results of the design of this tunnel were obtained. These results led to the conclusions discussed in the sections that follow.

6.1.1 Diffuser

From the results collected during visualization, using yarn tufts it was clear that there were several aspects of the tunnel design and construction that need to be addressed at the preliminary stages. The first conclusion gathered from this visualization was that the angle of the diffuser was one of the most important aspects of the tunnels design. The original diffuser angle of 10.5 degrees was chosen based on experiments reported by Kline[12], which showed that no separation would occur at this angle for a given L/W₁. This angle was based on the entering flow, which consisted of a thin turbulent boundary layer. Because the flow entering the diffuser was characterized by turbulent jet mixing flow, the design data was not necessarily valid. The final diffuser angle of 6.5 degrees, resulted in no observable diffuser separation.
6.1.2 Collector

Visualization testing using yarn tufts also showed that the shape of the collector was less important to the overall tunnel performance than initially assumed. The original shape chosen for the collector had assumed a well behaved flow would be entering from the test section. As already discussed, the flow was not well behaved, and the collector experienced reverse flow, effectively making the first 6 inches of the collector useless. Another realization gained by visualization testing was the importance of the transition between the collector and the diffuser. This connection needs to be nearly flawless with respect to shape, smoothness and flatness, in order to prevent the flow from separating. Even very small imperfections, almost not visible to the eye, were enough to cause the flow to separate. Similarly, the corners of the diffuser, as well as the contraction needed to be rounded in order to prevent vortices from forming in the corners.

6.1.3 Contraction

Finally, sensitivity to precision flow alignment from component to component was revealed when it was determined that the contraction was placed into the anechoic chamber at an angle of 0.5 degrees off the axial centerline. This misalignment caused the flow to be “aimed” at one wall and, therefore, separated from the opposite wall.

6.2 Velocity Analysis

The results of the velocity testing led to the conclusions discussed in the following sections.
6.2.1 Mean Velocity

The velocity varied by less than one percent across the test section at all points in the low speed test. There were some points where the velocity variation rose above one percent for both the full speed and half speed tests, but only at the locations furthest from the center of the test section. This result was as expected as those locations are on the border between the potential core and the jet mixing region, a region which is characterized by small to large scale turbulent eddies. However, even at all points examined, the velocity never varied by more than two percent.

6.2.2 Turbulence Intensity

The initial goal for turbulence intensity was to be less than 0.2% turbulence throughout the test section. The actual values were greater than the design goal for all of the tests. The high and low speed tests produced the best results, with a turbulence intensity of 0.48%, and 0.42% respectively for the center location. The half speed turbulence intensity for the center of the test section was 0.8%. While the turbulence is significantly higher than the initial goal, the values obtained for the inner circle on the test section grid were all below 0.5 percent for the low and high speed tests. This represents the flow in the potential core, and these values were acceptable for the type of testing to be performed in this tunnel.

Some separation is still occurring in the wind tunnel due to the transition between the collector and the diffuser. The transition between the collector and the diffuser is not perfectly radiused and smooth, causing a small amount of random, low intensity separation and vortex shedding, resulting in large level low frequency fluctuations, not associated with free stream
turbulence. If this problem is corrected, it is believed that the turbulence intensity would be dramatically reduced. This is substantiated by the test performed using a high pass filter. The high pass filter provides a glimpse of the results that would be obtained if the low frequency disturbance were not present. The turbulence intensity was measured at 0.28% for this condition, which shows that if the separation were removed the turbulent intensity would decrease. If the time history of both the full speed test without the filter, and with the filter are compared, it is apparent that the flow is smoother, and there is a reduction in oscillation of the flow caused by the separation. The standard deviation of the mean flow when using the high pass filter present is also lower in magnitude, indicating a reduction in separation and turbulence.
7.1 Existing Tunnel Improvements

There are several recommendations for improvements to be made to the tunnel before the construction of the full scale tunnel is to be undertaken. Some of these recommendations are design changes, and some are construction or material changes. This chapter deals with these recommendations to improve the performance of this wind tunnel.

7.1.1 Diffuser Modification

Several recommendations can be made to improve the full sized tunnel. However, the existing problems with the scale model tunnel must first be corrected. The first and most obvious problem mentioned in previous chapters is the separated flow that is occurring in the diffuser and collector. Carefully smoothing the transition between the collector and diffuser and diffuser corner radii should significantly reduce any residual separation. This simple but time consuming modification will eliminate the apparently low frequency component of the free stream turbulence resulting in a much lower turbulent intensity. The first recommendation, therefore, is to rework this transition on the 1/4 scale model and determine to what degree the separation improves.
7.1.2 Acoustic Treatment

The next step needed to complete this tunnel would be to apply sound absorbing insulation throughout the tunnel, especially in the anechoic chamber and the plenum chamber. The insulation should be applied to the inside walls of these rooms, and testing performed to assure that the tunnel meets the goal of being anechoic to a lower cutoff frequency of 250 Hz.

7.2 Full Scale Recommendations

There are also several design changes recommended for the full size tunnel before construction is to begin. These recommendations follow.

7.2.1 Screens

Several changes should be made to the design of the full sized tunnel in order to improve the overall performance. The first recommendation is to use different screens in the turbulence management section. The current screens are effective and reduce the turbulence entering the contraction, however the full sized tunnel will experience higher free stream velocities and a less solid screen will help to reduce the turbulence to a higher degree than the screen used in the scale model tunnel. The reason for this is that the tunnel is scaled 2.6:1, but the fan and motor could not be scaled to the same ratio, and therefore the fan is on a larger scale than the one used on the small tunnel. Using screens with a larger mesh size, or more open area will allow a higher Reynold number flow to flow through the screens, and still reduce the turbulence. It is also recommended that two additional screens be added to help assure a turbulent intensity of 0.1%.
7.2.2 Assembly Procedure

It is evident from testing the scale model wind tunnel that the final assembly process is crucial to the performance of the tunnel. It is recommended that the separate components be assembled with extreme caution, and that each component is aligned as perfectly as possible.

7.2.3 Collector

The visual testing using yarn tufts showed that the collector experienced reverse flow near the entrance. It is recommended that the front half of the collector be eliminated at the point of reverse flow, and the collector/diffuser assembly be moved forward to the original test section location, which will reduce the distance from the jet exit to the collector.

7.2.4 Diffuser

Because the room in which the full scale tunnel is going to be located is larger than originally anticipated, there is sufficient room to enlarge certain areas of the tunnel in order to improve flow quality. The first change to be made is to lengthen the diffuser in order to return to the original length to throat width ratio, L/W₁. Maintaining an angle of 6.5 degrees and returning the L/W₁ to its original value of approximately 5.60 is recommended.

7.2.5 Plenum Chamber

It is also recommended that the plenum chamber be enlarged from its original dimensions. A larger plenum chamber reduces the chances of reverse flow due to large scale eddies, as well as
simplifying the construction of the room anechoic. If the flow is not behaving well in a larger plenum chamber, turning vanes can be used to eliminate any large scale eddies causing low frequency fluctuations in the mean flow velocity.
REFERENCES


APPENDIX A

VELOCITY TESTING RESULTS
<table>
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<th>Location</th>
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Table 5. High Speed Results.
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Table 7. Low Speed Results.