EXPERIMENTAL STUDY ON THE EFFECTS OF NOSE GEOMETRY ON DRAG
OVER AXISYMMETRIC BODIES IN SUPERSONIC FLOW

by

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A THESIS

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ABSTRACT

A new nose shape that was determined using the penetration mechanics to have the least penetration drag has been tested in the supersonic wind tunnel of The University of Alabama to determine the aerodynamic characteristics of this nose shape. The aerodynamic drag measured on the new nose shape and on four additional nose shapes are compared to each other. The results show that the new nose shape has the least aerodynamic drag. The measurements were made at Mach numbers ranging from 1.85 to 3.1. This study also required the maintenance of several components of the University of Alabama’s 6” by 6” supersonic wind tunnel and modification of the existing data acquisition programs. These repairs and modifications included the repair and recalibration of the supersonic wind tunnel, repair of the four-component force balance, and the modification of the tunnel’s control program.
# LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Nose Radius at the base (m)</td>
</tr>
<tr>
<td>$b$</td>
<td>Nose Length (m)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag Coefficient</td>
</tr>
<tr>
<td>$C_{PD}$</td>
<td>Penetration-Drag Coefficient</td>
</tr>
<tr>
<td>$C_P$</td>
<td>Coefficient of Pressure</td>
</tr>
<tr>
<td>$d_{max}$</td>
<td>Maximum Difference from Mean of Experimental Measurements</td>
</tr>
<tr>
<td>$D$</td>
<td>Aerodynamic Drag</td>
</tr>
<tr>
<td>$D_P$</td>
<td>Penetration Drag</td>
</tr>
<tr>
<td>$I_D$</td>
<td>Intermediate step in defining the nose factor</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach Number</td>
</tr>
<tr>
<td>$N$</td>
<td>Nose Factor</td>
</tr>
<tr>
<td>$N_F$</td>
<td>Normalized Force Coefficient</td>
</tr>
<tr>
<td>$P_0$</td>
<td>Stagnation Pressure in the Plenum Chamber</td>
</tr>
<tr>
<td>$P_\infty$</td>
<td>Static Pressure in the Test Section</td>
</tr>
<tr>
<td>$q_\infty$</td>
<td>Dynamic Pressure</td>
</tr>
<tr>
<td>$q_{\infty,p}$</td>
<td>Dynamic Pressure during penetration</td>
</tr>
<tr>
<td>$S$</td>
<td>Cross Sectional Area of Nose Shape Base</td>
</tr>
<tr>
<td>$x$</td>
<td>Nose Profile Abscissa (m)</td>
</tr>
<tr>
<td>$y$</td>
<td>Nose Profile Ordinate (m), Function describing nose geometry</td>
</tr>
<tr>
<td>$y'$</td>
<td>Local Slope of the nose shape</td>
</tr>
</tbody>
</table>
\(z\) Nose Geometry Non-dimensional Ordinate, \(z=y/a\)
\(z'\) Slope of the line segment between two adjacent points of the nose shape
\(\alpha\) Aspect ratio; Nose radius at the base/ nose length, \(\alpha=b/a\)
\(\gamma\) Specific Heat Ratio, 1.4 for air
\(\delta\) Surface Angle of the Body of Revolution with respect to the Symmetry Axis along the Direction of the Approach Flow.
\(\zeta\) Nose Geometry Non-dimensional Abscissa, \(\zeta=x/b\)
\(\sigma\) Standard Deviation or Uncertainty
ACKNOWLEDGMENTS

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CHAPTER 1
INTRODUCTION AND HISTORICAL BACKGROUND

1.1 Introduction

Supersonic travel poses many problems on missiles and rockets designed to produce maximum range and penetration into a target. In an effort to increase the efficiency of rocket designs a variety of nose shapes have been developed. This thesis will discuss the design of an optimized nose shape for minimum penetration drag. This design is tested using the University of Alabama’s supersonic wind tunnel and compared to shapes currently being utilized by the aerospace industry.

The effect of nose geometry on penetration performance has been studied for decades. A variety of analytical methods have been performed to attempt to optimize the nose shape for a penetrator. The new shape design was created by dividing the nose shape into line segments and searching through numerical space for the combination of line segment slopes that produced the nose geometry with the lowest nose shape factor. This nose shape factor is derived using penetration mechanics theory. The new design should provide an updated perspective on nose shape design.

The experimental data is collected in the 6” x 6” supersonic wind tunnel at Mach numbers between 2.5 and 3.6. This tunnel is a blowdown type supersonic tunnel that uses a 1000 cubic foot storage tank to hold pressurized air that is released into the plenum chamber of the supersonic tunnel. The pressure in the plenum chamber is maintained at a constant value in order to provide a constant static pressure in the test section of the wind tunnel. A tunnel program was developed
to automate the run of the supersonic tunnel by Daniel Lewis as part of his master’s thesis [Lewis, 2006]. This program controls the pneumatic valve that maintains a consistent running procedure.

A four component force balance is used to measure the drag on the nose shapes. The use of the force balance unit to collect the drag data required modifications to be made to the tunnel control program and to the force balance strain gage configuration. More details on these modifications can be found in Appendix A. In the current work, only the axial force gages and a temperature compensation gage were used. The temperature gage was used to ensure there was minimal effect on the strain readings due to the temperature changes from the total pressure loss during the tunnel run.

1.2 Historical Background of Nose Shape Design

Nose shape geometry has been a topic discussed for more than a century. Jean-Victor Poncelet introduced modern analytical penetration mechanics when he studied velocity dependent pressure action on a spherical cannon ball [Poncelet, 1829]. Variants of this work are still used today to estimate penetration depth of a projectile. The geometry of a nose is critical to an object’s penetration mechanics and its aerodynamic characteristics. As an employee of the Armament Research Department in the British army, Hill began researching the influence of “headshape” in penetration of thick armor [Hill, 1980]. This research culminated in a paper where he discussed a phenomenon he termed “cavitation” that was responsible for the degradation of a penetrators performance [Hill, 1980]. A few years later, Forrestal related the nose factor, $N$, with the performance of a rigid penetrator [Forrestal, 1986, 1991, 1992]. Here at the University of Alabama, Dr. Stanley Jones calculated the nose factor for several axisymmetric geometries and used calculus of variations to propose a simple approximate analytical geometry to minimize the nose factor
Yefremov and Takovitskii used the Euler equations to design nose shapes with specified dimensions and volumes and minimal aerodynamic wave drag [Yefremov, 2006]. At Mach numbers of 2 and 4 and with aspect ratios (AR= nose length divided by nose radius at the base), \( \frac{b}{a}=4 \) and \( \frac{b}{a}=8 \), the optimal shape of their nose are blunt with surfaces perpendicular to incoming flow. When removing the volume restriction, the resulting shape is very similar to the shape defined by Jones [Jones, 1998]. This is significant because the two methods differ from each other. The analysis made by Yefremov minimized aerodynamic drag while the analysis made by Jones was focused on minimizing penetration drag. The similarity is not surprising since both groups use Newton’s theory in describing the pressure distribution over the body; however, the resulting similarity of the shapes suggests a strong correlation between aerodynamic drag and the shapes penetration mechanics.

Takovitskii discussed another procedure for determining an optimal nose shape using a step-by-step construction of the segments of the shapes with minimum aerodynamic wave drag based on the locally extremal generatrix defined for different aspect ratio noses under different free-stream Mach number conditions. His results also show a seemingly blunt nose, where the first segment makes an angle of approximately 55° with respect to the nose centerline [Takovitskii, 2006a]. He also published a paper detailing an analytical method to minimize the aerodynamic wave drag with results that indicate an optimal shape that follows the two-thirds power law [Takovitskii, 2006b].

Foster and Dulikravich [1997] used two methods to compare and contrast their performance on optimization of nose shape geometry. The two methods were a hybrid gradient
optimization method and a hybrid genetic optimization method, and were used to evaluate optimal shapes of both a star shaped axisymmetric body and a three-dimensional lifting body at a zero degree angle-of-attack. The results for the star shaped axisymmetric nose optimized for minimum aerodynamic drag had a short, pointed nose section with a base diameter much smaller than the aft section diameter [Foster, 1997].

Taking into consideration the aerodynamic drag, heat transfer, and payload volume, Lee et al. [2006] obtained an optimal nose shape for a space launcher through the use of a multipoint response surface design method. They began with a baseline shape and focused on performance of three design criteria; maximum drag coefficient, maximum dynamic pressure, and first stage burnout. These design points correspond to Mach numbers of 1.2, 1.8, and 4.6 respectively. Their optimization yields a 24% improvement of drag performance of the launcher nose shape compared to the spherically rounded baseline nose (Korean three-staged rocket KSR-III nose). The nose shape achieved in the optimization was similar to the one proposed by Jones [1998], but had a more blunt nose [Lee, 2006]. Rangedda and Serra [2010] obtained similarly blunt shapes using a particle swarm optimization method.

Through the use of an evolutionary-algorithm optimization and ANSYS CFX computational fluid dynamics solver, Deepak et al. [2008] optimized the nose-cone shape of a hypersonic vehicle. For a baseline nose shape, the team used the HyShot experimental hypersonic flight vehicle, that has been tested jointly with the U.S. and Australian Defense Agencies. The optimized shape had a 2% drag reduction and utilized a spherically rounded tip followed by the shape proposed by Jones [1998] until a location of $\xi=0.2$, and a thicker aft section that followed a curve between the new optimal nose shape defined later in this thesis and the tangent ogive [Deepak, 2008].
The purpose of the current investigation is to define a new nose shape optimized by minimizing the nose factor, \( N \), using penetration mechanics theory, and compare the aerodynamic drag characteristics of this new shape to the drag characteristics of four other common shapes. For this purpose a new numerical method was introduced to minimize the nose factor, and was subsequently used to find an optimum nose shape. Next the aerodynamic drag forces for the five shapes were measured in a supersonic wind tunnel and the drag coefficient values calculated using the measured drag were compared to each other. The other four shapes in the study were: a three-quarter power series nose shape, Jones Approximate Minimal Nose Geometry (AMNG), a tangent ogive, and a conical nose. These four shapes were chosen since they are the commonly encountered nose shapes, both as penetrators and as aerodynamic bodies of revolution in previous research [Jones, 1998; Eggers, 1957; Forrestal, 2009]. Measurements made in earlier research at the University of Alabama by Lewis [2006] were inconclusive due to the marginal difference in drag coefficients between the nose shapes. In his study Lewis used long noses with an aspect ratio of \( b/a = 4 \) and four shapes: ogive, cone, three-quarter power series nose, and the AMNG. Despite the marginal differences it seemed as though the AMNG produced the least drag [Lewis, 2006]. In order to improve the accuracy of this new round of testing, the new shapes were manufactured with an aspect ratio of \( b/a = 2 \). The reason for manufacturing new nose shapes was to increase the drag for all of the shapes to help differentiating the drag values between different nose shapes.

As a note, this optimization approach was designed to maximize penetration depth. The process does not take into account any heat transfer effects which may influence the final nose geometry. The impact of heating on the effective application of the nose shape has not been considered either.
The following sections will detail the various procedures involved in testing the new nose shape. Chapter 2 discusses the optimization method for developing the new nose shapes and the penetration mechanics used to develop it. Chapter 3 explains the systems used to test the object, including the high speed wind tunnel, force balance, and schlieren system. Chapter 4 presents the results of the study, and includes a discussion of those results. Chapter 5 draws a close to the research and suggests modifications for further study and experimentation.
CHAPTER 2
NOSE SHAPE DESIGN PROCEDURE

The optimization of the nose required understanding of penetration mechanics and the development of a method to search for a shape that minimized the nose factor of a penetrator. In this chapter, details on the development of the new nose are presented.

2.1 Nose Factor

The nose factor, \( N \), is a parameter commonly used in penetration mechanics to quantify the penetration-drag characteristics of a nose geometry during penetration of hard targets. It is a non-dimensional quantity that is only dependent on the geometry of the nose shape. In penetration mechanics, it is common to approach the problem by ignoring the friction forces acting on a penetrator and assume the pressure forces are the primary source of penetration drag. Due to this assumption, the penetration-drag coefficient also becomes a function independent of everything except nose geometry. This also causes the nose factor and penetration-drag coefficient to differ by a constant multiplier. An analysis of the case for pressure-dependent friction has been given by Jones and Rule [2000], but will not be considered in this study.

The following equations detail the relationship between the nose factor, the penetration drag coefficient, and the coefficient of pressure, \( C_p \). The coefficient of pressure has been approximated, using an equation similar to Newton’s theory which applies to hypersonic flows [Anderson, 2007], to apply to a slender body during penetration. The expression for the \( C_p \) is as follows:
\[ C_p = 2 \sin^2 \delta = \frac{2y'^2}{1+y'^2} \]  \hfill (2.1.1)

Using this coefficient of pressure, and neglecting the viscous forces, the drag force can be found using:

\[ D_p = C_{PD} \cdot q_{\infty} \cdot \pi a^2 = 2\pi \cdot q_{\infty} \int_0^b C_p \cdot y \cdot y' \cdot dx \]  \hfill (2.1.2)

To lead to the definition of the nose factor, an intermediate step, \( I_D \) is defined as a function of the nose geometry:

\[ I_D = \frac{D_p}{2\pi q_{\infty}} = \int_0^b C_p \cdot y \cdot y' \cdot dx = \int_0^b \frac{2yy'^3}{1+y'^2} \, dx \]  \hfill (2.1.3)

To further simplify this expression the \( x \) and \( y \) coordinates are non-dimensionalized with the nose length, \( b \), and the nose base radius, \( a \), respectively, leading to a new expression for the \( I_D \):

\[ I_D = 2\alpha^2 a^2 \int_0^1 \frac{zz'^3}{1+a^2z'^2} \, d\xi \]  \hfill (2.1.4)

Finally the nose factor is defined as:

\[ N = \frac{C_{PD}}{2} = \frac{I_D}{a^2} = 2\alpha^2 \int_0^1 \frac{zz'^3}{1+a^2z'^2} \, d\xi \]  \hfill (2.1.5)

As was discussed earlier the expression for nose factor is solely dependent on the nose geometry. This allows the nose factor to be directly related to penetration-drag coefficient and means the minimum nose factor, \( N \), also corresponds to the nose that would experience the least resistance during penetration. Once again, it should be emphasized that this penetration-drag coefficient, \( C_{PD} \), is defined only using the form drag, drag due to the pressure related forces, without taking into account viscous effects. The penetration-drag coefficient used in penetration mechanics differs from the drag coefficient, \( C_D \), used in fluid mechanics. The aerodynamic drag coefficient of an object is dependent on Reynolds and Mach numbers [Anderson, 2007]. However, if Newton’s theory, the appropriate values for dynamic pressure, \( q \), and aerodynamic drag coefficient, \( C_D \), is applied, then equation 2.1.2, which describes penetration drag, \( D_P \), becomes the
equation for aerodynamic drag, $D$. This leads to the conclusion that minimizing nose factor will also minimize an object’s aerodynamic drag.

2.2 Calculation of the New Nose Shape

In this study to find a new nose shape for a rigid body penetrator, the nose factor was optimized. As discussed in section 2.1, a minimum nose factor will correspond to a nose shape with a minimum penetration-drag coefficient, which would result in a penetrator that would travel deepest when impacting a target. In order to find the optimum shape with the fewest assumptions, it was decided that a computer program would be used to solve for the shape using a step-by-step method. The computer program was designed to search through numerical space to find the nose shape with the lowest $N$ value by splitting the geometry of the nose into line segments. To accomplish this, the program first expressed the nose shape using line segments equally spaced along the longitudinal axis of the nose. This procedure is depicted in Figure 2.2.1. After the shape is split into line segments, the nose factor for each line segment was computed. The program minimizes the change in $N$ calculated as the sum of the nose factors for each line segment.

![Figure 2.2.1: Nose shape presented with line segments](image)

Using Figure 2.2.1, the slope, $z'$, of a line segment between two adjacent points can be expressed as:

$$z' = \frac{z_i - z_{i-1}}{\xi_i - \xi_{i-1}}$$  \hspace{1cm} (2.2.1)
An expression for a line between two adjacent points becomes:

\[ z = \frac{z_1 - z_{i-1}}{\xi_i - \xi_{i-1}} \xi_i + \frac{z_{i-1} \xi_i - z_i \xi_{i-1}}{\xi_i - \xi_{i-1}} \]  \hspace{1cm} (2.2.2)

Now the Nose factor can be calculated by applying equations 2.2.1 and 2.2.2 to equation 2.1.5:

\[ N_i = \frac{-2a^2(z_{i-1} - z_i)^3}{\xi_i - \xi_{i-1}} \left[ \xi_{i-1} z_i - \xi_i z_{i-1} + \frac{z_{i-1} - z_i}{2} (\xi_{i-1} + \xi_i) \right] \]  \hspace{1cm} (2.2.3)

The sum of the nose factors for individual segments gives the nose factor \( N = \sum N_i \), where index \( i \) changes between 1 to \( n+1 \), while \( \xi_1 = 0, z_1 = 0, \xi_{n+1} = 1, z_{n+1} = 1 \). This nose factor was then used to calculate the total derivative of \( N \):

\[ dN = \frac{\partial N}{\partial z_1} dz_1 + \frac{\partial N}{\partial z_2} dz_2 + \cdots + \frac{\partial N}{\partial z_n} dz_n = d \sum N_i \]  \hspace{1cm} (2.2.4)

The individual partial derivatives for each line segment was then calculated using:

\[ \frac{\partial N}{\partial z_i} = \frac{3(z_{i-1} - z_i)^2 \left[ \xi_{i-1} z_i - \xi_i z_{i-1} + \frac{z_{i-1} - z_i}{2} (\xi_{i-1} + \xi_i) \right]}{2(\xi_i - \xi_{i-1})^3 \left( \frac{(z_{i-1} - z_i)^2}{4(\xi_i - \xi_{i-1})^2} + 1 \right)} \]

\[ - \frac{3(z_{i-1} - z_{i+1})^2 \left[ \xi_i z_{i+1} - \xi_{i+1} z_i + \frac{z_i - z_{i+1}}{2} (\xi_i + \xi_{i+1}) \right]}{2(\xi_i - \xi_{i+1})^3 \left( \frac{(z_i - z_{i+1})^2}{4(\xi_i - \xi_{i+1})^2} + 1 \right)} \]

\[ - \frac{(\xi_{i-1} - \xi_i)^2 (z_{i-1} - z_i)^3}{2(\xi_i - \xi_{i-1})^3 \left( \frac{(z_{i-1} - z_i)^2}{4(\xi_i - \xi_{i-1})^2} + 1 \right)} - \frac{(\xi_i - \xi_{i+1})^3 (z_{i-1} - z_i)^3}{2(\xi_i - \xi_{i+1})^3 \left( \frac{(z_{i-1} - z_i)^2}{4(\xi_i - \xi_{i+1})^2} + 1 \right)} \]

\[ - \frac{2(z_{i-1} - z_i) (z_{i-1} - z_i)^3 \left[ \xi_{i-1} z_i - \xi_i z_{i-1} + \frac{z_{i-1} - z_i}{2} (\xi_{i-1} + \xi_i) \right]}{8(\xi_{i-1} - \xi_i)^3 \left( \frac{(z_{i-1} - z_i)^2}{4(\xi_{i-1} - \xi_i)^2} + 1 \right)} \]

\[ + \frac{2(z_i - z_{i+1}) (z_i - z_{i+1})^3 \left[ \xi_i z_{i+1} - \xi_{i+1} z_i + \frac{z_i - z_{i+1}}{2} (\xi_i + \xi_{i+1}) \right]}{8(\xi_i - \xi_{i+1})^5 \left( \frac{(z_i - z_{i+1})^2}{4(\xi_i - \xi_{i+1})^2} + 1 \right)} \]  \hspace{1cm} (2.2.5)
The new nose shape is defined by updating the \( z_i \) coordinates based on the \( \frac{\partial N}{\partial z_i} \) values since these partial derivatives also show the sensitivity of the \( N \) with respect to the \( z_i \) coordinates. Each \( \frac{\partial N}{\partial z_i} \) value is used to update the corresponding \( z_i \) value using:

\[
\begin{align*}
z_{i,j+1} &= z_{i,j} - C_1 \left( \frac{\partial N}{\partial z_i} \right)_j \\
&= z_{i,j} - C_1 \left( \frac{\partial N}{\partial z_i} \right)_j
\end{align*}
\] (2.2.6)

In this expression \( C_1 \) is just a constant equal to 0.0001, and indicates an iteration step. Each new \( z_i \) value was immediately used in the successive \( \frac{\partial N}{\partial z_i} \) calculation. The program was initialized with a circular cylindrical rod shaped nose. The length of the nose from 0 to 1 along the longitudinal domain was divided into 1000 equal segments. The number of segments required was investigated and it was determined that the solution was independent of iteration steps once more than 500 segments were used. The program had a specified end condition of \( \sum \frac{\partial N}{\partial z_i} < 1.1 \times 10^{-6} \).

This condition was set to ensure a converged solution was obtained. Once the solution converges, the largest change in the \( z_i \) values between the last two iterations is less than \( 10^{-10} \). These \( z_i \) values therefore define our new nose shape. The body shape has almost a flat nose with \( z_2 = 0.1211 \). The shape is similar to the one previously presented by Jones with a slightly more blunt tip [Jones, 1998]. When the program was ran with various aspect ratio values, it indicated that the nose shape does not change with \( \alpha \). The limiting value of the nose factor calculated for the first segment, \( \lim_{x_2 \to 0} N_{2} = z_{2}^{2} \) indicates a lower limit that can be achieved for the nose factor.

2.3 Description of Nose Geometries

The nose shapes tested in this study were a three-quarter power series nose, Approximate Minimal Nose Geometry, a standard cone, a tangent ogive, and the newly defined nose. Figure 2.3.1 shows a two-dimensional plot of the nose geometries for comparison.
The equations describing the five nose shapes are given in Table 2.3.1, along with the nose factor values for $\alpha = 0.5$.

<table>
<thead>
<tr>
<th>Nose Shape</th>
<th>Equation</th>
<th>Nose shape factor, $N$, for $\alpha = 0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4 Power Series</td>
<td>$z = \xi^{3/4}$</td>
<td>0.16907</td>
</tr>
<tr>
<td>AMNG</td>
<td>$z = \xi^{3/4} + \frac{9}{16} \alpha^2 (\xi^{1/4} - \xi^{3/4})$</td>
<td>0.163359</td>
</tr>
<tr>
<td>Cone</td>
<td>$z = \xi$</td>
<td>0.2</td>
</tr>
<tr>
<td>Tangent Ogive</td>
<td>$z = \frac{1}{4} \left( 1 + \frac{2}{\alpha^2} + \frac{1}{\alpha^4} \right) - \frac{1}{\alpha^2} \left( 1 - \xi \right)^2 - \frac{1}{2} \left( \frac{1}{\alpha^2} - 1 \right) \frac{1}{\alpha^2}$</td>
<td>0.24</td>
</tr>
<tr>
<td>New Shape</td>
<td>NA</td>
<td>0.16066</td>
</tr>
</tbody>
</table>

Table 2.3.1: Nose shape equations and $N$ values

The table shows that the new shape has the smallest nose factor when compared to the other given shapes. All of the noses in this study had an aspect ratio of 0.5. Previous work performed by Lewis involved testing the four shapes described here, but with an aspect ratio of 0.25 [Lewis, 2006]. Increase in the aspect ratio was required to increase the drag on all of the shapes and thus to decrease the uncertainty in the measured drag.
CHAPTER 3
EXPERIMENTAL SETUP

3.1 Supersonic Wind Tunnel

Objects designed for high speed applications require specialized testing in supersonic wind tunnels. These high speed tunnels are designed to generate a uniform flow within the test section that is faster than the local speed of sound. In order to achieve accurate data readings over the duration of a test, it is important to have accurate knowledge of the flow variables. Maintaining precise control of the plenum chamber pressure and throat area of the wind tunnel allows for accurate control of the Mach number and the static pressure within the test section.

Figure 3.1.1: Schematic of the supersonic wind tunnel lab [Lewis, 2006]

The supersonic tunnel that is used for this study is the University of Alabama’s large supersonic tunnel (Figure 3.1.1). The large supersonic wind tunnel is a 6” X 6” blow down facility with a Mach number range of 1.85 to 3.34. It is equipped with a sliding block nozzle to adjust the throat area and allow for the given range of Mach numbers. The system includes a 1,000 cubic
foot, high-pressure, air storage facility, two Ingersoll Rand compressors as well as an
Ingersoll Rand after-cooling/air-drying accessory. Plenum chamber pressure is controlled using
three pressure transducers together with a fuzzy logic controller for the butterfly valve [Lewis,
2006]. The parts used for pressure control are listed below and a schematic drawing of the
components is shown in Figure 3.1.2.

1. Bray Controls pneumatic-actuator-controlled butterfly valve
2. BLX V100 valve positioner
3. Keithley KPCI 1802-HC data acquisition board
4. Keithley STA 1800-HC I/O screw terminal board
5. Omega Engineering CCT signal conditioners.
6. Setra 205-2; 0-200 psia pressure transducers
7. Setra 24 V DC power supply for Setra pressure transducers
8. 135 psig Independent air supply
9. IBM PC and National Instruments LabVIEW 7.0

Figure 3.1.2: Mass Flow Rate Control Instrumentation and Data Acquisition Setup [Lewis, 2006]
The tunnel was last calibrated in 2006 when Lewis reworked the control program to automate the tunnel runs. The calibration was used to determine the relation between the counter number that is used to determine the location of the sliding bottom wall and the Mach number in the tunnel. The bottom wall of the tunnel is actuated using a motor/worm-gear mechanism. The calibration was performed using two methods. The first technique used to calculate the Mach number in the test section was to measure the shock angles on a two-dimensional wedge at several throat settings. The schlieren system was used to visualize the flow over the wedge which allowed the shock angles to be measured. Lewis determined that the lowest possible counter number setting of 0004 resulted in a Mach number of 1.75. The highest setting was a counter number of 2500 and resulted in a Mach number of 3.65 [Lewis, 2006]. While this method is a simple way to check the Mach number of the tunnel, it can be inaccurate due to difficulty in measuring the shock-wave angle using the schlieren pictures. In addition, asymmetric geometry of the tunnel wall results in non-symmetric boundary layer development on the bottom and the top walls of the tunnel making the Mach number distribution in the tunnel non-symmetric. A picture of the wedge being tested, for the current thesis, at a counter number of 1500 can be found in Figure 3.1.3.

Figure 3.1.3: Wedge at Counter Number 1500
In order to insure the accuracy of the wind tunnel calibration, Lewis also conducted a calibration based on normal shock relations. A pressure rake equipped with nine Pitot probes was designed and built for that purpose. The Pitot pressures and velocities were measured at a variety of throat settings, but the tunnel was unable to start at the extreme throat settings below 1500 and above 2250 due to the size and of the pressure rake inside the tunnel. The pressure rake showed a variance in Mach number near the walls of the tunnel, especially at the bottom wall, but confirmed that the center of the test section was at a uniform Mach number [Lewis, 2006]. This calibration is more accurate and insensitive to flow irregularity, but is more intensive and not functional for all throat settings.

During the current research it was found that the sliding block of the tunnel could no longer be moved to a location corresponding to a counter number setting below 0435. To ensure the counter had not shifted since the last calibration, the tunnel needed to be recalibrated. It was decided that a calibration using the two-dimensional wedge technique would be sufficient to confirm that calibration already made by Lewis was still valid or if the counter number had shifted. Since the tunnel has not been modified in any way since the last calibration this method was deemed sufficient in determining whether the counter has shifted or if the bottom sliding block was jammed preventing the tunnel to run at low Mach number settings. It was decided that if the counter had shifted then the calibration made by Lewis could still be used with new counter settings. The results of the Mach number calibration can be found in Figure 3.1.4.
Figure 3.1.4: Wind Tunnel Calibration

The results of the calibration show that the tunnels counter number has shifted slightly since the last calibration. By moving the old calibration up by 0300 on the counter setting the calibration realigns with the results of the new wedge calibration. The starting pressures were also recalculated using a similar method. To conduct the tests properly, both of the counter values corresponding to different tunnel Mach numbers and the corresponding starting plenum chamber pressure values need to be available when running the tunnel. A new sheet outlining the common run numbers was created for this purpose and can be found in Table 3.1.1.

<table>
<thead>
<tr>
<th>Counter Number</th>
<th>Mach Number</th>
<th>Starting Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.850</td>
<td>36.89</td>
</tr>
<tr>
<td>750</td>
<td>1.973</td>
<td>39.74</td>
</tr>
<tr>
<td>1000</td>
<td>2.114</td>
<td>43.95</td>
</tr>
<tr>
<td>1250</td>
<td>2.274</td>
<td>49.51</td>
</tr>
<tr>
<td>1500</td>
<td>2.451</td>
<td>56.42</td>
</tr>
<tr>
<td>1750</td>
<td>2.646</td>
<td>64.70</td>
</tr>
<tr>
<td>2000</td>
<td>2.860</td>
<td>74.33</td>
</tr>
<tr>
<td>2250</td>
<td>3.091</td>
<td>85.31</td>
</tr>
<tr>
<td>2500</td>
<td>3.341</td>
<td>97.65</td>
</tr>
</tbody>
</table>

Table 3.1.1: Calibration Results for tunnel with object in test section
3.2 Four Component Force Balance

Drag on the various nose shapes was measured using the four component force balance. The balance measures the pitch, roll, normal, and axial forces through the use of strain gages. These gages deform when force is applied to them causing a change in the electrical resistance which is then measured as a strain and used to determine the force on the object. For the current experiments the only force of interest was the axial force, as the balance was used to measure the drag forces only. The strain values in the gages were measured using a SCXI-1520, 8-Channel Universal Strain Gage Input Module equipped with a SCXI-1314 Front-Mounting Terminal Block. The input module and terminal block were mounted in a SCXI 1000 chassis and connected to the computer using a National Instruments DAQ-MX PCI-6052E card. Strain values were recorded in the Labview program used to control the tunnel. The balance is pictured in Figure 3.2.1.

Figure 3.2.1: University of Alabama Four-Component Force-Balance

Once the tunnel was ready to collect data the force balance was calibrated on a calibration stand to read force in the axial direction. The calibration stand consists of a mount, sleeve, weight hanger,
and pulleys to transfer the force from the vertical direction to the axial direction of the balance. Figure 3.2.2 shows the calibration data for the balance. The calibration mount is pictured in Figure 3.2.3.

![Graph showing Original Axial Strain Calibration](image)

Figure 3.2.2: Original Axial Strain Calibration

![Image of Force balance on calibration stand](image)

Figure 3.2.3: Force balance on calibration stand

### 3.3 Schlieren System

Schlieren systems are non-intrusive optical techniques used to visualize density gradients within a flow field. They use the relations between density and light refraction to create an image depicting the change in density, either through color shift or a simple monochromatic image. The setup used in the current thesis was a traditional schlieren system. A traditional schlieren system
collimates a light source to achieve parallel rays of light traveling through the flow field. The light is then focused to a point, or decollimated, where a knife edge blocks a portion of the light. In the experimental setup for this study, two parabolic mirrors are used to collimate and decollimate the light. The remaining light is projected onto an image plane to be viewed. When light is refracted it bends around or into the knife edge appearing on the image plane as either a bright or dark region in the image. The knife edge can be replaced by a color filter to quantitatively measure the deflections of light rays for determining the density gradients in the flow. Figure 3.3.1 depicts the basic schlieren setup.

![Schlieren Setup Diagram](image)

Figure 3.3.1: University of Alabama Schlieren System Setup [Lewis, 2006]

3.4 Manufactured Nose Shapes

Once the nose shapes were designed, they needed to be manufactured to test in the wind tunnel. The models were manufactured in the University of Alabama machine shop out of aluminum using a CNC machine. The shapes were made to screw onto the sting arm of the force balance and were manufactured at the same diameter, 1.225 inches, as the outer sleeve of the balance to prevent any flow irregularities at the base of the nose. The test models are pictured in Figure 3.4.1.
Figure 3.4.1: Models used in Drag Testing
CHAPTER 4
RESULTS AND DISCUSSION

In this chapter force balance measurements and the determination of the drag coefficients are described in detail. Calculated drag coefficient values for different nose shapes are compared to each other.

4.1 Drag Measurement Method

Measurements with the force-balance measurements require the calibration of the balance prior to the experiments. The balance calibration is determined by using the calibration stand described in Chapter 2. The balance was recalibrated any time a modification was made to the balance.

In the early stages of the experiments the balance was not able to read accurate results. The balance read erroneous results even though the calibration was very repeatable. A plot of the strain readings during a tunnel run at this stage can be found in Figure 4.1.1. The plenum pressure is also plotted alongside the axial strain to show that the plenum pressure and thus the static pressure in the test section were kept relatively constant.
To determine the drag, the strain needs to be constant during the run. Thus the variation in strain during the run made it impossible to select a region where drag could be measured. Also, the strain values varied in a fashion that indicated negative drag on the nose shapes after the tunnel started. This resulted in making several modification to the force-balance system and designing a new method to reduce the data. The changes made on the force-balance system are discussed in Appendix A section 2. Once the changes were incorporated, the axial strain measured during a run did not vary drastically. Figure 4.1.2 shows an example run after the alterations to the force-balance system were completed.
These new readings followed the expected variations for a strain during a run; however, the drag values calculated using the calibration curve shown in Figure 4.1.3 indicated that these values were too small to actually represent the drag on the object. For the data shown in Figure 4.1.2 the drag was measured at less than 1 lb while the expected value was about 6 lbs. At the low Mach numbers, the shapes that were expected to have low drag values even measured negative drag values during the run.
Every attempt was made to determine the cause of the low drag readings. The conclusion reached by examining the physics of the force-balance was that the force-balance operated correctly. It was then considered that the flow field generated in the tunnel may be the cause of the readings. One plausible explanation considered is the presence of “base drag” on the back of the balance due to the high static pressure observed in that region which could cause a decrease in the drag readings. The base drag is due to the static pressure difference between the pressure at the back end of the balance and the approach flow pressure. In the 6” x 6” tunnel, several reflections of the oblique shocks from the tunnel walls and from the cylindrical body of the model and the balance occur prior to the termination of the shock train with a normal shock somewhere along the length of the test section. Since the static pressure increases over each shock wave, the static pressure at the base of the force-balance becomes much larger than the approach flow static pressure resulting in a thrust on the model. It was also considered that since the nose shapes are not much different from each other, the shock structures forming over the objects would not be much different from each other, and that the base drag on the objects would be practically the same. The pressure rise associated with the base drag would be hard to estimate as there are no means to determine the number of shock waves occurring in the test section and there was no pressure tap in the rear portion of the test section to measure the pressure. Figure 4.1.4 details the principle discussed.

Figure: 4.1.4: Figure Describing Principle of Shock Waves Inside Tunnel
The low drag measurements observed required a new method to be devised to relatively compare the drag and the drag coefficients of different models. The method is described here. For this purpose, base drag values at different Mach numbers were determined using historical data on a cone; the base drag values were then used to augment the drag measured on different nose shapes. A similar procedure was used by Perkins when studying various axially symmetric nose shapes. The pressure at the base of the model was measured using pressure taps connected to a water manometer and was used to limit the drag reading to the “foredrag,” which consists only of the nose shape region [Perkins, 1958]. In that study, the forces generated by the base were subtracted from the force-balance readings; however, in the current study base drag could not be directly measured. Instead the historical drag coefficient data on a 25 degree cone was used to shift the drag readings up for the cone data so that one could obtain the historical data using the current load readings. The same load values were then used for all the other models. The drag coefficient measurements made by Owens [1965] were used to estimate the drag on a cone at each Mach number where drag was collected for this thesis. The base drag for each Mach number was calculated by subtracting the estimated actual drag by the calculated drag on a cone in this study. That base drag value was then added to all of the drag measurements at that particular Mach number. While this will not reveal accurate drag coefficients, it allows for the comparison of the shapes to each other.

4.2 Drag Coefficient Results

Once the force balance was ready, a series of tunnel runs was made. Since the cone shape was the shape with the most available historical data, it was chosen as the shape to determine the base drag. It was also used to determine the uncertainty in measurements between tunnel runs. This was achieved by running the tunnel three times at each Mach number while collecting drag
data for the cone. The other shapes were each run one time at the various Mach numbers.

Chauvenent’s Criterion was used to determine the uncertainty by calculating the standard deviation in the data sets taken during the three runs. Equation 4.2.1 shows the calculation for uncertainty using Chauvenent’s Criterion. The uncertainty is given as the standard deviation, $\sigma$, and the constant for three data points is 1.38. Table 4.2.1, 4.2.2, and 4.2.3 show the measurements made in the tunnel for the cone and the uncertainty values at each Mach number for different quantities.

$$\sigma = d_{\text{max}} * \frac{\sigma}{d_{\text{max}}}, \quad \frac{d_{\text{max}}}{\sigma} = 1.38 \quad (4.2.1)$$

<table>
<thead>
<tr>
<th>Mach</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>-0.000218</td>
<td>-0.000233</td>
<td>-0.000246</td>
<td>1.06771E-05</td>
</tr>
<tr>
<td>1.973</td>
<td>-0.000117</td>
<td>-0.000095</td>
<td>-0.000108</td>
<td>8.29805E-06</td>
</tr>
<tr>
<td>2.114</td>
<td>-0.000220</td>
<td>-0.000218</td>
<td>-0.000216</td>
<td>1.5172E-06</td>
</tr>
<tr>
<td>2.274</td>
<td>-0.000333</td>
<td>-0.000334</td>
<td>-0.000339</td>
<td>2.75533E-06</td>
</tr>
<tr>
<td>2.451</td>
<td>-0.000360</td>
<td>-0.000352</td>
<td>-0.000362</td>
<td>4.24763E-06</td>
</tr>
<tr>
<td>2.646</td>
<td>-0.000348</td>
<td>-0.000348</td>
<td>-0.000353</td>
<td>2.3784E-06</td>
</tr>
<tr>
<td>2.86</td>
<td>-0.000338</td>
<td>-0.000337</td>
<td>-0.000335</td>
<td>1.44438E-06</td>
</tr>
<tr>
<td>3.091</td>
<td>-0.000270</td>
<td>-0.000252</td>
<td>-0.000242</td>
<td>1.11381E-05</td>
</tr>
</tbody>
</table>

Table 4.2.1: Strain Measurements and Uncertainty on Cone Shape

<table>
<thead>
<tr>
<th>Mach</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>2.094957</td>
<td>2.246328</td>
<td>2.368147</td>
<td>0.102550779</td>
</tr>
<tr>
<td>1.973</td>
<td>1.128871</td>
<td>0.920846</td>
<td>1.042782</td>
<td>0.079700666</td>
</tr>
<tr>
<td>2.114</td>
<td>2.118995</td>
<td>2.097764</td>
<td>2.079895</td>
<td>0.014572367</td>
</tr>
<tr>
<td>2.274</td>
<td>3.200496</td>
<td>3.210694</td>
<td>3.260376</td>
<td>0.02646425</td>
</tr>
<tr>
<td>2.451</td>
<td>3.457897</td>
<td>3.387158</td>
<td>3.48532</td>
<td>0.04079744</td>
</tr>
<tr>
<td>2.646</td>
<td>3.34841</td>
<td>3.349463</td>
<td>3.396224</td>
<td>0.022843953</td>
</tr>
<tr>
<td>2.86</td>
<td>3.252594</td>
<td>3.246253</td>
<td>3.220706</td>
<td>0.013872927</td>
</tr>
<tr>
<td>3.091</td>
<td>2.599244</td>
<td>2.425674</td>
<td>2.32992</td>
<td>0.106979049</td>
</tr>
</tbody>
</table>

Table 4.2.2: Force Measurements and Uncertainty on Cone Shape
Table 4.2.3: Plenum Pressure Measurements and Uncertainty on Cone Shape

These measurements were used to calculate the drag coefficient at each Mach number. The drag coefficients were calculated using equations 4.2.2-4.2.5.

\[
\frac{p_0}{p_\infty} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}
\]

(4.2.2)

\[
p_e = p_0 \left(\frac{p_e}{p_0}\right)
\]

(4.2.3)

\[
q_\infty = \frac{1}{2} \gamma P_e M^2
\]

(4.2.4)

\[
C_D = \frac{D}{q_\infty S}
\]

(4.2.5)

Since the measured drag coefficients are too small, they were corrected by finding the base drag and applying that base drag to the other shapes. To accomplish this, historical data was plotted and a trend line was found to estimate the drag coefficient on a cone at the same Mach numbers the tests were made. Figure 4.2.1 shows the plot of historical data [Owens, 1965]. Once the historical values were found at the correct Mach numbers, the estimated drag was found using the plenum pressure, Mach number, and specific heat ratio. By subtracting the measured drag the estimated value for base drag could be found at each Mach number. Those values can be found in Table 4.2.4.
Once the base drag values were calculated they were added to the measured drag for all the other shapes to estimate the actual Cd at each Mach number in order to make a valid comparison of the nose shapes. The tables below show the measured strain, drag, plenum pressure and corrected drag coefficient for each shape.
<table>
<thead>
<tr>
<th>Mach</th>
<th>Strain</th>
<th>Drag</th>
<th>Plenum Pressure</th>
<th>Corrected Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>-0.00012</td>
<td>1.16388</td>
<td>38.1124</td>
<td>0.4365</td>
</tr>
<tr>
<td>1.973</td>
<td>-0.00015</td>
<td>1.469409</td>
<td>41.9060</td>
<td>0.5023</td>
</tr>
<tr>
<td>2.114</td>
<td>-0.0003</td>
<td>2.842935</td>
<td>45.9854</td>
<td>0.5100</td>
</tr>
<tr>
<td>2.274</td>
<td>-0.00037</td>
<td>3.58296</td>
<td>51.4611</td>
<td>0.4747</td>
</tr>
<tr>
<td>2.451</td>
<td>-0.00041</td>
<td>3.896181</td>
<td>59.0952</td>
<td>0.4645</td>
</tr>
<tr>
<td>2.646</td>
<td>-0.00038</td>
<td>3.665656</td>
<td>67.8159</td>
<td>0.4478</td>
</tr>
<tr>
<td>2.86</td>
<td>-0.00038</td>
<td>3.690591</td>
<td>78.6040</td>
<td>0.4468</td>
</tr>
<tr>
<td>3.091</td>
<td>-0.00032</td>
<td>3.048171</td>
<td>90.0954</td>
<td>0.4514</td>
</tr>
</tbody>
</table>

Table 4.2.5: Ogive Shape Experimental Values

<table>
<thead>
<tr>
<th>Mach</th>
<th>Strain</th>
<th>Drag</th>
<th>Plenum Pressure</th>
<th>Corrected Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>4.51E-05</td>
<td>-0.42815</td>
<td>38.2542</td>
<td>0.3439</td>
</tr>
<tr>
<td>1.973</td>
<td>7.56E-05</td>
<td>-0.72107</td>
<td>41.7763</td>
<td>0.3820</td>
</tr>
<tr>
<td>2.114</td>
<td>-5.9E-05</td>
<td>0.568393</td>
<td>45.9481</td>
<td>0.4058</td>
</tr>
<tr>
<td>2.274</td>
<td>-0.00018</td>
<td>1.739336</td>
<td>51.7061</td>
<td>0.3861</td>
</tr>
<tr>
<td>2.451</td>
<td>-0.00012</td>
<td>1.110188</td>
<td>59.2984</td>
<td>0.3726</td>
</tr>
<tr>
<td>2.646</td>
<td>-0.00012</td>
<td>1.195881</td>
<td>67.8692</td>
<td>0.3135</td>
</tr>
<tr>
<td>2.86</td>
<td>-0.00015</td>
<td>1.419354</td>
<td>78.6473</td>
<td>0.3201</td>
</tr>
<tr>
<td>3.091</td>
<td>-5.9E-05</td>
<td>0.575148</td>
<td>88.7413</td>
<td>0.3102</td>
</tr>
</tbody>
</table>

Table 4.2.6: 3/4 Power Shape Experimental Values

<table>
<thead>
<tr>
<th>Mach</th>
<th>Strain</th>
<th>Drag</th>
<th>Plenum Pressure</th>
<th>Corrected Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>-2.9E-05</td>
<td>0.285261</td>
<td>37.9751</td>
<td>0.3875</td>
</tr>
<tr>
<td>1.973</td>
<td>2.04E-05</td>
<td>-0.1914</td>
<td>41.9265</td>
<td>0.4100</td>
</tr>
<tr>
<td>2.114</td>
<td>-9.7E-05</td>
<td>0.938765</td>
<td>45.9481</td>
<td>0.4058</td>
</tr>
<tr>
<td>2.274</td>
<td>-0.00024</td>
<td>2.34709</td>
<td>51.6169</td>
<td>0.4062</td>
</tr>
<tr>
<td>2.451</td>
<td>-0.00019</td>
<td>1.785472</td>
<td>59.3492</td>
<td>0.3494</td>
</tr>
<tr>
<td>2.646</td>
<td>-0.00016</td>
<td>1.574644</td>
<td>68.0241</td>
<td>0.3329</td>
</tr>
<tr>
<td>2.86</td>
<td>-0.00021</td>
<td>1.985543</td>
<td>78.6031</td>
<td>0.3519</td>
</tr>
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<td>3.091</td>
<td>-0.00011</td>
<td>1.027532</td>
<td>89.7055</td>
<td>0.3337</td>
</tr>
</tbody>
</table>

Table 4.2.7: Jones’s Shape Experimental Values
After calculating the drag coefficient values for each shape, the values were plotted against the Mach number alongside the historical data for the cone shape. This is shown in Figure 4.2.2. This will show how the trend compares with the historical data. It was also of interest to plot the relative values to the cone and those values can be found in Figure 4.2.3.

Table 4.2.8: New Shape Experimental Values

<table>
<thead>
<tr>
<th>Mach</th>
<th>Strain</th>
<th>Drag</th>
<th>Plenum Pressure</th>
<th>Corrected Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>7.68E-05</td>
<td>-0.73262</td>
<td>37.9830</td>
<td>0.3289</td>
</tr>
<tr>
<td>1.973</td>
<td>7.52E-05</td>
<td>-0.71733</td>
<td>41.8120</td>
<td>0.3819</td>
</tr>
<tr>
<td>2.114</td>
<td>-4.8E-05</td>
<td>0.467603</td>
<td>45.9712</td>
<td>0.3798</td>
</tr>
<tr>
<td>2.274</td>
<td>-0.00011</td>
<td>1.103514</td>
<td>50.7528</td>
<td>0.3445</td>
</tr>
<tr>
<td>2.451</td>
<td>-9.6E-05</td>
<td>0.926785</td>
<td>59.2073</td>
<td>0.3042</td>
</tr>
<tr>
<td>2.646</td>
<td>-8.5E-05</td>
<td>0.819736</td>
<td>67.8803</td>
<td>0.2926</td>
</tr>
<tr>
<td>2.86</td>
<td>-0.00012</td>
<td>1.152559</td>
<td>78.5884</td>
<td>0.3054</td>
</tr>
<tr>
<td>3.091</td>
<td>-6.6E-05</td>
<td>0.634841</td>
<td>90.0916</td>
<td>0.3091</td>
</tr>
</tbody>
</table>

Figure 4.2.2: Corrected Drag Coefficient Values
It was also of interest to directly compare the drag readings without using the base drag. To accomplish this, the values for drag were subtracted from the drag on the cone at each Mach number and non-dimensionalized using base area and dynamic pressure. In Figure 4.2.4 the cone would be represented by the zero line. Larger numbers indicate a greater decrease in drag from the cone which would indicate less drag.

\[ N_F = \frac{D_{cone} - D}{q_\infty \cdot S} \]
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

The research presented in this thesis was aimed at understanding the effect of the nose shape on the aerodynamic drag generated by a circular cylinder axisymmetric body. The nose shapes tested in this study were a three-quarter power series nose, Approximate Minimal Nose Geometry, a standard cone, a tangent ogive, and the newly defined nose. All the noses had an aspect ratio of 1. The results indicate that the newly defined nose with the least nose factor that would result in most penetration also results in the least aerodynamic drag over a Mach number range $M=1.85 \,–\, 3.1$. The drag coefficient for the new nose shape in comparison to the drag coefficient of a cone was 20% (at $M=2.1$) to 35% (at $M=1.85$) less. The shape presented by Jones also worked well and proved to be the second most efficient shape with very small drag differences from the new nose shape. Despite the inability to accurately measure the drag coefficient for our setup, the procedure proved effective at comparing the nose geometries to one another.

The work undertaken during the thesis research also improved the usability and functionality of the University of Alabama’s 6-inch by 6-inch supersonic wind tunnel. It provided new insight on the operation and data collection during tunnel runs. The equipment and the programs associated with the tunnel run, such as the butterfly valve, tunnel run control and data acquisition program, and the force balance had to be thoroughly studied, repaired, and recalibrated. A calibration is made to redetermine the tunnel nozzle block location indicator versus the Mach number in the tunnel. The four component force balance proved to be the most difficult equipment
to work with and required extensive repairs and trouble shooting. An updated run procedure is also presented and should provide any operator with the knowledge they need to operate the tunnel effectively with minimal modifications to the control program or control equipment.

Future Work:

Further understanding of the effect of the nose shape on the drag of axisymmetric bodies requires more work to be done. One possible improvement on drag measurements procedures would be installing more pressure taps in the test section and on the back of the model. These pressure readings would then provide more information about the base drag and would be useful especially during small drag readings, such as the ones encountered during this study. It was also considered that a new force balance could be constructed to minimize the interaction of the air flowing over the force balance and the strain gages inside the force balance.

The tunnel operation could be improved by making additional changes. One change could be the addition of a heater to reduce the total temperature drop inside the storage tank during a tunnel run. This is a complicated procedure but would allow making more intricate testing possible within both high speed tunnels present in the high-bay area. A more accurate calibration should be considered to ensure the accuracy of the Mach numbers inside the test section of the large supersonic tunnel. One final addition could be the installation of a mist separator or a dryer on the pressure supply for the tunnel’s main valve actuator. Along with an accurate pressure regulator it would be easier to run the tunnel without worrying about water getting into the actuator.
REFERENCES


APPENDIX A
TUNNEL LAB MODIFICATIONS

A1 Tunnel Maintenance and Repairs

Prior to the research conducted for this thesis, the large supersonic tunnel was not used to collect data for over two years. This caused a few problems with the operation of the wind tunnel due to the necessity for highly accurate control of the plenum pressure for proper tunnel operation. When this research began, the tunnel’s pneumatically actuated valve was not functioning. It would not open to allow air to enter the plenum chamber. This necessitated a few maintenance procedures to improve the tunnel operations.

The first procedure involved removing the valve to remove the suspected rust built up in the valve’s interior. With the valve removed and cleaned, it began to function, but not as well as it did during the development of the tunnel’s fuzzy logic, PID control system [Lewis, 2006]. This led to severe issues with maintaining the control of the plenum pressure. After troubleshooting the control program and adjusting the gains in the PID controller, it was clear that the valve would need more work. After working with the tunnel to become familiar with its operation, it was noticed that when disconnecting the pneumatic actuator for the valve, a substantial amount of moisture would be released from the air connection. The actuator used a separate smaller, low pressure, air compressor without a dedicated dryer to prevent moisture build up in the tank. This was a known issue as part of the tunnel run procedure required the tank to be drained of moisture before running; however, the extended period of inactivity had caused moisture to build up within the actuator as well. To mitigate this issue, a new step was added to the tunnel run procedure which...
requires the user to disconnect the pneumatic actuator before leaving for the day, on the days the tunnel is used. It is also required that the secondary compressor be drained of any accumulated water before connecting it to the actuator. Once the actuator was drained of all water, the tunnel began to function well; and the additional changes made to the control program, discussed in Appendix A3, allowed for even more precise control of the tunnel run conditions.

A2 Force Balance Repairs and Modifications

Another problem arose when attempting to collect data using the decades old force balance. In the past, minor repairs had been made to the connections within the force balance to broken and frayed wires. These repairs were functional but required occasional maintenance and recalibration of the equipment. It was also determined that the drop in static temperature within the tunnel caused severe changes in strain readings through the course of a tunnel run. A variety of methods were attempted to correct this inaccuracy. One early attempt involved estimating the static temperature through the course of the tunnel run using Mach number relations and comparing that to strain reading to estimate a correction value for the tunnel runs. Another attempt was made by gluing a thermocouple into the force balance next to the axial strain gages. While this procedure seemed functional the necessary equipment to read the thermocouple alongside the data from the strain gages was not available. In order to overcome this obstacle it was determined that the best solution was to replace the old strain gages with the new ones, and install an additional gage in a new orientation that would be used for temperature compensation.

The procedure for installing the new gages was simple yet required accurate work in confined spaces. The new gages were placed in the same orientation as the old ones, but connected using a full Wheatstone bridge inside the balance. The old gages had individual sets of wires running out of the balance and connected in a bridge outside of the balance. There is limited space
in the conduit sections of the force balance for adding additional wires and the addition of an extra strain gage necessitated this change. A diagram of the force balance with the highlighted changes is pictured in Figure A2.1

![Diagram of the force balance with highlighted changes](image)

**Figure A2.1: Force Balance Strain Gage Locations and Modifications**

The old gages had to be removed before the new gages could be installed. Figure A2.2 shows an example of an old gage and the replacement gage. It required removing the old gage using a high speed rotary tool and sanding the locations well to prepare the area for the glue for the new gage. The wiring had to be reconnected and to simplify the connection of a Wheatstone Bridge.

![Comparison between old gage and newly installed gage](image)

**Figure A2.2: Comparison Between Old Gage and Newly Installed Gage**
bridge some solder points were glued to the balance inside the cavity. The wiring diagram used for the full Wheatstone bridge is pictured in Figure A2.3. Using a full Wheatstone bridge to increase accuracy requires R1 and R3 to be gages in compression and R4 and R2 to be in tension. The particular gages and their reaction to axial force can be found in Figure A2.4.

![Figure A2.3: Full Wheatstone Bridge Configuration](image1)

![Figure A2.4: Current gage configuration.](image2)
The new gage was placed in a quarter Wheatstone bridge with three 50 ohm resistors which is also the resistance of the newly installed temperature strain gage. The new gages worked well; however, temperature compensation proved ineffective for the data processing.

To limit interaction with the temperature, the gage region of the force balance was coated with a rubber insulation. This produced promising results though the coating peeled off on the rear of the balance during the first run. To help prevent this, an additional coat of polyurethane was applied to the rubber insulation to strengthen the insulation. To close any more gaps, a layer of aluminum tape was also added in regions where it would not restrict the motion of the sting arm and reduce readings made by the axial gage. Pictures of the insulation can be found in Figure A2.5.

![Figure A2.5: Insulation applied to the inside and outside of the force balance.](image)

While the insulation did help reduce temperature interaction it was only effective for the first couple seconds of the tunnel run. The last attempt at reducing this was to increase the interaction with axial force. There are two screws located inside the balance that limit the horizontal motion of the sting arm inside the force balance. Loosening both screws so they do not limit the sting at all, provided a better axial reading with minimal reaction to other forces or temperature. This has the downside of reducing the max force that can be safely applied to the balance; however, the estimated max force applied to these nose shapes was around 10 lbs, and the balance was tested to 40 lbs during calibration to ensure it would not break during a tunnel run.
A3 Tunnel Control Program Modifications

The program used to control the pneumatic valve was first written by Cameron Nott [2008], and then modified to provide more automation. Several modifications were made to the original program and this section details those changes made to the tunnel run program to make it more versatile and robust.

A) The program consisted of a single input and a PID controller to control the valve. It required the input for starting pressure, which is the pressure required to start the tunnel at various throat settings and is the pressure the program must maintain within the plenum chamber. While it was functional for a run, it was not very efficient and would often overshoot or undershoot the desired starting pressure forcing the data collection to take place after it leveled out. This is particularly difficult because it required longer run times and in turn, more time between runs to refill the tank. To limit tunnel run times an automated shut-off was added to close the valve when the storage pressure equals the required plenum pressure. An input was also added to allow further run time limitations by setting a “Cutoff Difference Pressure” which allows the user to increase the shut-off pressure to a setting higher than the desired plenum pressure.

B) To improve the accuracy of the controller at the beginning of the run, an additional input was added to control the “Initial Valve Setting” of the controller. This setting provides optimal starting conditions as the maximum plenum pressure for the initial valve setting is equal to the desired plenum pressure setting. This allowed for more accurate control at the beginning of a run but requires some experimentation to determine the value for the various counter setting. The setting changes depending on the storage tank pressure and also the pressure available for the valve’s pneumatic actuator. This is difficult to account for but to reduce effects it is best to pressurize the storage tank to a consistent pressure on every run, 170 psi is selected as it allows for
reasonable run times at the highest Mach numbers, and short refill times at the lower speed tunnel runs. To ensure the same pressure is available for the pneumatic actuator on every run the secondary compressor is drained until it restarts prior to every run. This ensures the secondary tank is also filled to its maximum pressure for every run. This new procedure improves upon the accuracy of the former system with the result of nearly identical tunnel runs at individual Mach numbers.

C) Prior to this research collecting data in the supersonic tunnel required the use of multiple programs running simultaneously. When attempting to correct for the temperature differential it became necessary to plot the strain readings alongside the tank pressures during a run. This wasn’t feasible with two separate programs as the data could not be lined up with the required accuracy. To solve this, the strain gage program was incorporated into the program used to control the tunnel. This allowed data from the tunnel run and the strain gages to be collected at the same time intervals and allowed for a better understanding of the tunnel run’s effect on the strain gage readings.
APPENDIX B

6-INCH X 6-INCH TUNNEL OPERATION

During research for this thesis it was found that previous user guides were inadequate when attempting to use the high speed wind tunnel. To help future tunnel operators, a new procedure was developed and is included in this appendix. Images are included to make the process easier as some of the explanations in previous guides proved difficult to understand.

B1 Filling the Storage Tank

Before use of the Wind Tunnel, the storage tank must be filled. To accomplish this there are two Ingersoll-Rand Compressors along with an I-R Dehumidifier.

1) Turn on power to the compressors. The switch is found in room 135A directly behind the large tank. It should be in the down switch position.

2) Press start on the control panel for both compressors.
3) Switch dehumidifier to the dryer on setting.

4) Open the blue outlet valve on the dehumidifier slightly until the rattling noise in the dryer stops (Turn clockwise to open, counterclockwise to close). This valve needs to be monitored during the filling process. Watch the digital gages on the compressors for pressure readings to see whether you need to open or close the valve slightly. It is recommended to maintain a pressure reading on the compressors of 150 to 160 pounds per square inch (psi) until the valve is fully open. Pressure readings on the compressors will rise as the tank fills.

5) The tank usually fills to a maximum of about 170 psi. It is best to run at the same storage pressure every run for optimum consistency. Switch off the compressors, turn off the
dryer, and close the valve. Occasionally, the dehumidifier will light up the High Humidity indicator. If this occurs, turn off and then back on the dehumidifier, close off the fill valve, but continue running the compressors. Let the dryer run through its cycle a few times. Each cycle takes about 4 minutes with the automatic settings. Once the High Humidity light goes off, start filling the tank by opening the valve.

B2 Pre-Run Checks

Once the tank is filled to a desired pressure, there are several factors that can change the run of the tunnel that need to be checked prior to starting the tunnel run. These are usually completed as the filling procedure is taking place.

1) Check the Main Valve.

To ensure proper valve operation drain the water from the small compressor used to operate the main valve. This valve has been very troublesome in the past. To maintain optimum performance capabilities unplug the air supply from the valve when not in use. This prevents water from entering the pneumatic valve which prevents it from opening. If this occurs there is a procedure to purge the valve found in the troubleshooting guide. In addition to draining the compressor each day before wind tunnel use, draining before each run ensures the same pressure is supplied to the valve each run. Be sure to reattach the supply to the valve after draining each run.

2) Check to make sure that the tunnel is shut before connecting the pneumatic valve’s pressure line and always before running the tunnel.

3) Check the rear floor of the test section.
Check bottom plate behind the test section. You should unscrew it, slide it forward hard until it hits the test section floor and then tighten the knob. Pictures of the knob are located in Figure B2.1.

![Figure B2.1: Tunnel region behind the test section and rear plate knob](image)

**B3 Program for Tunnel Operation**

On the control PC, there is a LabView Program called 2014 Controller w 4 comp FB & temp.vi. It requires certain inputs to run properly. Figure B2.2 shows a screenshot of the program. The inputs are described below.
1) Desired Plenum Pressure
   i) Pressure required in the Plenum Chamber to ensure supersonic velocity in test section.

2) Initial Valve Setting: the valve setting to start run
   i) This is dependent on a variety of conditions: storage pressure, valve supply pressure, counter number, test object size, etc. The object is to have the Initial Valve Setting’s max pressure equal to the Desired Plenum Pressure. It requires trial and error but usually ranges from 40 to 50 degrees, increasing as Mach number decreases.

3) Cut Off Pressure Difference (COPD): this is a setting used to limit tunnel run time.
   i) The program will normally shut off when storage pressure equals desired plenum pressure. To change that, you can increase this setting to shut off the tunnel earlier or later. For example, if the desired Plenum Pressure is 89 psi and the COPD is 20 psi the
valve will close when storage pressure reaches 109 psi. This decreases the time required to refill the tank after each run. It is recommended to have the Cut-Off Pressure Difference set so that the program will stop running when the pressure is 110 psi.

Once the inputs are entered, put on ear protection and sound the alarm, then the start button on the LabView program can be pressed. The program will pre-load the actuator with air then open the valve after three seconds. If undershoot or overshoot occurs press the large stop button and adjust the initial valve setting. Never use LabView’s built in stop button; this will not close the valve. If the tunnel runs smoothly the Stop button can be pressed and data can be saved.

B4 Troubleshooting

A troubleshooting guide has been made to assist with common problems. It is found in Table B4.1.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Possible Causes</th>
<th>Fixes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pneumatic valve won’t open</strong></td>
<td>Water is in the valve</td>
<td>Drain the water using the procedure detailed below</td>
</tr>
<tr>
<td></td>
<td>Computer or control modules aren’t functioning properly</td>
<td>Be sure all devices are plugged in and restart all systems. Shut off computer first then unplug all control devices for a few minutes then plug everything in and restart the computer. Check blue compressor for air pressure</td>
</tr>
<tr>
<td></td>
<td>Compressor for valve isn’t on or is broken</td>
<td></td>
</tr>
<tr>
<td><strong>Compressors will not turn on</strong></td>
<td>Main power switch is off or at the wrong setting</td>
<td>Check that the main power switch is switched down</td>
</tr>
<tr>
<td></td>
<td>Broken compressor</td>
<td>Call number on compressor for help</td>
</tr>
</tbody>
</table>
**Table B4.1: Tunnel Troubleshooting Guide**

<table>
<thead>
<tr>
<th>Issue</th>
<th>Possible Cause</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Humidity Light on Dryer</strong></td>
<td>Dryer is unable to remove enough water</td>
<td>Turn off and then back on the dehumidifier, close the fill valve, but continue running the compressors. Let the dryer run through its cycle a few times. Each cycle takes about 4 minutes with the automatic settings. Once the High Humidity light goes off, start filling the tank by opening the valve.</td>
</tr>
<tr>
<td><strong>Tunnel runs but there is no shock wave in schlieren images</strong></td>
<td>The test section floor isn’t touching the back section</td>
<td>Be sure the knob in Figure 6 has slid all the way till it hits the test section floor and is tightened well</td>
</tr>
<tr>
<td></td>
<td>Starting Pressure may be set too low</td>
<td>Check that the correct starting pressure at your counter setting</td>
</tr>
</tbody>
</table>

1) One common problem is the actuator will fill with water. A solution to the problem is listed below. Use this procedure if the valve fails to open or opens slower than expected. It should take no more than two seconds for the valve to fully open once its set to its max angle of 90 degrees. The first thing you must do is empty the large tank. You can do this using the “MoveValve.vi” sub vi program, shown in Figure B4.1, if the valve will partially open. If that will not open the valve, you must use a wrench on the actuator to open the valve. Figure B4.2 shows the location to use the wrench. Unplug the air supply and turn the valve clockwise until it opens. Remember: Sound the alarm and wear ear protection. You are basically running the tunnel.

2) Once the tunnel is empty you can begin the process of draining the valve. Drain the blue compressor first then reattach the air supply to the valve. The valve should be closed.

3) Use the sub vi “MoveValve.vi” to set the valve to an angle of 90 degrees. If there is water in the valve it may open slowly, only open partially, or may not open at all. Once the
computer is set to 90 degrees, you should be able to hear air hissing in the valve. This means it is trying to open. Unplug the air supply. The valve should return to 0 degrees if it opened at all. Now reattach the air supply. The valve should begin to open if it did not before. Repeat this process several times or until the valve returns to normal operation. You should be able to adjust the setting on the MoveValve.vi and see the valve open or close within 2 seconds.

4) To prevent this, always unplug the air supply when the tunnel is not being used.

Figure B4.1: MoveValve.vi

Figure B4.2: Manual Valve Operation Location
B5 Conclusion

This guide was developed to help future users operate the tunnel with a lesser learning curve. Many of the procedures outlined required trial and error to learn. It is expected that this guide will allow smoother tunnel operation so more time can be spent on performing research in the tunnel. It is expected that changes to the tunnel will be made over time and hopefully this guide will be updated as more operators use the tunnel.
APPENDIX C

TUNNEL RUN DATA

C1  Schlieren Images of tunnel runs

To ensure the tunnel had started, a traditional schlieren system was set up. The following pictures were taken using the system.

Figure C1.1: Calibration Wedge at Counter 500, 750, 1000, and 1250

Figure C1.2: Calibration Wedge at Counter 1500, 1750, 2000, and 2250

Figure C1.3: Calibration Wedge at Counter 2500

Figure C1.4: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 500
Figure C1.4: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 750

Figure C1.5: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 1000

Figure C1.6: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 1250

Figure C1.7: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 1500

Figure C1.8: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 1750

Figure C1.9: Cone, Ogive, ¾ Power, Jones, and New Shapes at Counter 2000
C2 Tunnel Run Data

Pictured below are plots of the tunnel runs that show the axial strain and the plenum pressure. The data was collected when both the axial strain and plenum pressure had settled to reasonably level readings.
Figure C2.3: Cone Run 3 at Counter 500

Figure C2.4: Ogive Run at Counter 500

Figure C2.5: ¾ Power Run at Counter 500
Figure C.2.6: Jones Run at Counter 500

Figure C.2.7: New Run at Counter 500

Figure C.2.8: Cone Run 1 at Counter 750
Figure C2.9: Cone Run 2 at Counter 750

Figure C2.10: Cone Run 3 at Counter 750

Figure C2.11: Ogive Run at Counter 750
Figure C.12: ¾ Power Run at Counter 750

Figure C.13: Jones Run at Counter 750

Figure C.14: New Run at Counter 750
Figure C.15: Cone Run 1 at Counter 1000

Figure C.16: Cone Run 2 at Counter 1000

Figure C.17: Cone Run 3 at Counter 1000
Figure C2.18: Ogive Run at Counter 1000

Figure C2.19: ¾ Power Run at Counter 1000

Figure C2.20: Jones Run at Counter 1000
Figure C.21: New Run at Counter 1000

Figure C.22: Cone Run 1 at Counter 1250

Figure C.23: Cone Run 2 at Counter 1250
Figure C2.24: Cone Run 3 at Counter 1250

Figure C2.25: Ogive Run at Counter 1250

Figure C2.26: ¾ Power Run at Counter 1250
Figure C2.27: Jones Run at Counter 1250

Figure C2.28: New Run at Counter 1250

Figure C2.29: Cone Run 1 at Counter 1500
Figure C.30: Cone Run 2 at Counter 1500

Figure C.31: Cone Run 3 at Counter 1500

Figure C.32: Ogive Run at Counter 1500
Figure C.2.33: ¾ Power Run at Counter 1500

Figure C.2.34: Jones Run at Counter 1500

Figure C.2.35: New Run at Counter 1500
Figure C2.36: Cone Run 1 at Counter 1750

Figure C2.37: Cone Run 2 at Counter 1750

Figure C2.38: Cone Run 3 at Counter 1750
Figure C2.39: Ogive Run at Counter 1750

Figure C2.40: ¾ Power Run at Counter 1750

Figure C2.41: Jones Run at Counter 1750
Figure C.42: New Run at Counter 1750

Figure C.43: Cone Run 1 at Counter 2000

Figure C.44: Cone Run 2 at Counter 2000
Figure C2.45: Cone Run 3 at Counter 2000

Figure C2.44: Ogive Run at Counter 2000

Figure C2.45: ¾ Power Run at Counter 2000
Figure C2.46: Jones Run at Counter 2000

Figure C2.47: New Run at Counter 2000

Figure C2.48: Cone Run 1 at Counter 2250
Figure C2.49: Cone Run 2 at Counter 2250

Figure C2.50: Cone Run 3 at Counter 2250

Figure C2.51: Ogive Run at Counter 2250
Figure C2.52: \(\frac{3}{4}\) Power Run at Counter 2250

Figure C2.53: Jones Run at Counter 2250

Figure C2.54: New Run at Counter 2250