INTERACTION BETWEEN A CONICAL SHOCK WAVE AND A PLANE COMPRESSIBLE TURBULENT BOUNDARY LAYER AT MACH 2.05

BY

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THESIS

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ABSTRACT

The interaction between an impinging conical shock wave with a plane compressible turbulent boundary layer has been studied at Mach 2.05. Surface oil flow and pressure-sensitive paint (PSP) data were obtained beneath the oncoming boundary layer, while schlieren and particle image velocimetry (PIV) data were obtained in the streamwise/wall-normal (x-y) plane. Oil flow data suggested that the interaction causes two-dimensional (2D) separation near the centerline, and outside of this region three-dimensional (3D) separation that propagates fluid away from the centerline toward the sidewall. PSP results showed relatively constant upstream-influence length across the inviscid shock trace. PSP also revealed significant spanwise and streamwise expansion just downstream of the shock trace, unlike the qualitatively similar two-dimensional, wedge-generated oblique shock/boundary-layer interaction. Schlieren data suggested that the flow through the interaction was unseparated, and that there is significant unsteadiness in interaction position away from the centerline due to variation in the incoming boundary layer. PIV data showed the convection of large-scale vortical structures at velocities on the order of the streamwise velocity at the vortex center. These structures were smoothed out in the interaction. The PIV data moreover confirmed the downstream expansion shown by the PSP as well as a mean lack of flow separation. However, PIV suggested that there were some cases of instantaneous separation. Overall, the interaction diverts fluid away from a low pressure zone a little way downstream of the shock. Ultimately, the geometric three-dimensionality of the problem manifests as a preferred three-dimensionality of fluid transport next to the wall, unlike the qualitatively similar, 2D oblique shock-wave/boundary-layer interaction.
ACKNOWLEDGEMENTS

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LIST OF VARIABLES

\[ a = \text{Sun-Childs parameter} \]
\[ A = \text{Sun-Childs parameter} \]
\[ A(T) = \text{pressure-sensitive-paint 0}\text{th order coefficient} \]
\[ B = \text{Sun-Childs parameter} \]
\[ B(T) = \text{pressure-sensitive-paint 1}\text{st order coefficient} \]
\[ c = \text{speed of sound} \]
\[ C(T) = \text{pressure-sensitive-paint 2}\text{nd order coefficient} \]
\[ C_f = \text{skin friction coefficient} \]
\[ c_p = \text{constant pressure specific heat} \]
\[ I = \text{pressure-sensitive-paint intensity} \]
\[ I_o = \text{intensity of PSP in zero-oxygen conditions} \]
\[ I_{ref} = \text{PSP reference intensity} \]
\[ K = \text{Gladstone-Dale constant} \]
\[ K_d = \text{PID controller derivative coefficient} \]
\[ k_{nr} = \text{PSP non-radiative rate constant} \]
\[ K_p = \text{PID controller proportional coefficient} \]
\[ k_q = \text{PSP quenching rate constant} \]
\[ k_r = \text{PSP radiative rate constant} \]
\[ M = \text{Mach number} \]
\[ n = \text{index of refraction} \]
\[ P = \text{pressure} \]
\[ P_{amb} = \text{ambient air pressure} \]
\[ P_o = \text{stagnation pressure} \]
\[ P_{peak} = \text{maximum stagnation pressure of wind tunnel under fixed current operation} \]
\[ P_{ramp} = \text{stagnation pressure at the end ramp, phase of wind tunnel operation} \]
\[ P_{tank} = \text{tank pressure} \]
\[ P_{target} = \text{stagnation pressure set point for wind tunnel} \]
\[ Pr = \text{Prandtl number} \]
\[ r = \text{recovery factor} \]
\[ R = \text{gas constant for air} \]
\[ Re = \text{Reynolds number} \]
\[ T = \text{temperature} \]
\[ t = \text{time} \]
\[ T_{aw} = \text{adiabatic wall temperature} \]
\[ T_e = \text{Temperature at the boundary layer edge} \]
\[ T_o = \text{stagnation temperature} \]
\[ T_{ref} = \text{reference temperature} \]
\[ T_w = \text{wall temperature} \]
\[ u = \text{streamwise velocity component} \]
\[ u_c = \text{convective velocity} \]
\[ u_e = \text{streamwise velocity at boundary layer edge (freestream velocity)} \]
\[ u_f = \text{friction velocity} \]
\[ v = \text{wall-normal velocity component} \]
\[ w = \text{spanwise velocity component} \]
\( x \) = streamwise coordinate  
\( y \) = wall-normal coordinate  
\( z \) = spanwise coordinate or path-length coordinate  
\( \alpha \) = light ray deflection angle  
\( \gamma \) = ratio of specific heats  
\( \delta \) = boundary layer thickness  
\( \delta_o \) = incoming boundary layer thickness  
\( \delta^* \) = boundary layer displacement thickness  
\( \delta_{99.5} \) = 99.5% boundary layer thickness, \( y \) where \( u/u_e = .995 \)  
\( \delta_{a \rightarrow \infty} \) = Sun-Childs modified wall-wake boundary layer thickness  
\( \Delta t \) = laser pulse spacing  
\( \eta \) = normalized wall-normal coordinate  
\( \theta \) = boundary layer momentum thickness  
\( \kappa \) = von Karman parameter  
\( \mu \) = dynamic viscosity  
\( \Pi \) = Coles wake parameter  
\( \rho \) = density  
\( \rho_e \) = density at boundary layer edge  
\( \rho_o \) = stagnation density  
\( \sigma \) = Sun-Childs parameter  
\( \tau \) = shear stress  
\( \tau_w \) = wall shear stress
PREFACE

Increasing the speed of flight has been a continuous goal since the invention of the airplane. Higher speed enables faster transport, more availability of destinations for people and cargo, and both strategic and tactical combat advantage. Increasing the speed of flight eventually requires vehicles to operate in the transonic and supersonic regimes. History has shown that this quest has been successful—large numbers of flight vehicles for commercial, military, and social purposes have been built that operate near and above Mach 1. While it is easy to laud these practical machines, we must not forget that applied technology is rooted in fundamental research, and high speed flight is no exception. Charles Yeager’s first recorded manned supersonic flight in 1947 is often called the breaking of the sound barrier. This was a notable achievement, especially in terms of the positive publicity it draws for us more keenly interested in supersonic flight than the average person. However, it must be remembered that the sound barrier was broken by scientists and engineers decades before it was ever broken by a fighter pilot by the likes of Mach, Meyer, and others. In the case of shock-wave/boundary-layer interactions, the subject of this thesis, evidence suggests that the first laboratory observation of the effect was in 1939 [1]. Let this be a reminder that if we are to advance in the field, we must advance in the laboratory first. To invest in technology is to invest in front end fundamental research. Do not shut the doors, even fiscal ones in times of uncertainty, on the opportunity of tomorrow.
CHAPTER 1: INTRODUCTION

1.1 Basic Physics of Interaction

The interactions between shock waves and boundary layers, so called shock-boundary layer interactions (SBLIs), are viscous, compressible, and often turbulent, flow phenomena. While shock waves are adequately described by inviscid theory, as a shock wave approaches a boundary layer, viscous effects introduced by the boundary layer dominate. Although the study of boundary layers is well-developed, the turbulence that dominates high speed boundary layers encountered in supersonic flow is not fully understood. Currently, there are several different numerical approaches to compute turbulent flows, and each approach can have highly varied results [2]. The interaction between these two phenomena adds another layer of complexity. As such, experimental work in SBLI is important for the understanding of basic flow physics, especially in light of the practical applications described in the previous section.

![Diagram of shock-boundary layer interaction](image1.png)

\textbf{Figure 1:} Two-dimensional diagrams of an oblique shock wave – boundary-layer interaction where the flow is a) attached or b) separated. Reprint of Figures 2.23 and 2.37 of [3]. Reprinted with the permission of Cambridge University Press and consent of author.
The current study is described by the interaction of a conical oblique shock wave and a plane compressible turbulent boundary layer at Mach 2. This puts the study in the class of three-dimensional (3D), steady, supersonic (as opposed to transonic or hypersonic), oblique shock/boundary-layer interactions. The basic physics of this type of SBLI can be described by the case of a two-dimensional (2D) oblique shock wave impinging on a flat plate, which is diagrammed in Fig. 1. Because there is a static pressure rise across a shock, the shock imposes an adverse pressure gradient in the boundary layer, causing the boundary layer to thicken. If the shock wave is strong enough, the generated adverse pressure gradient will cause the boundary layer to separate. In this case, a recirculation region forms. In 2D flow this is a separation bubble. In 3D flow, this may become a separation surface that rolls up into a vortex which may transport fluid crosswise out of the interaction region. Such fluid transport mechanisms are important for the study of such interactions, even ones labeled two-dimensional. In general, the thickening (or separation) of the boundary layer acts like a small “bump” on the wall, such that the flow is compressed as it goes over the front half of the “bump” and expanded over the back half. In separated flow, the flow can expand drastically enough such that the flow is turned sufficiently toward the wall, and upon impacting the wall, the wall acts as a ramp, generating an oblique “reattachment” shock, C5 in Fig. 1. This description is true for a cone-generated oblique shock, with some minor differences. For one, a cone has a 3D relief effect because it is axisymmetric instead of two dimensional; this effect causes the shock coming off the cone to be weaker than a wedge of the same vertex angle under the same flow conditions. Also, the shock trace of a cone is a hyperbola on a plane wall, not a straight line as in most basic 2D interactions [3]. For further details regarding basic physics of shock-boundary layer interactions, see Ref. [3]. For a general overview of plane compressible turbulent boundary layers, see Ref. [4].

1.2 Application Areas

Shock-wave/boundary-layer interactions are found in several situations, including the suction surface of transonic wings, inside supersonic inlets, and in multiple body interactions [5] [6]. In many cases the SBLIs are problematic. Normal SBLI cause wave drag over wings [3] and affect downstream subsonic air delivered to and internal inlet. Normal and oblique SBLIs in supersonic inlets can cause flow separation which leads to lower efficiency jet engines. In order to counteract this problem, systems to increase the boundary layer momentum, such as bleed
mechanisms and passive control devices, have been implemented or are being investigated [7]. SBLI occurs in turbine compressor blades [3]. Maximum pressure loads and heating often occur in regions of SBLI [1], which has far-reaching effects into other disciplines. Two problems with SBLI are control and development cost. Shock control remains an active area of research. Cost can be alleviated with the use of accurate, predictive computational modeling using computational fluid dynamics (CFD). However, uncertainty on the quality of turbulence modeling, and computational results that are far different from experiments, hinder the use of computational modeling. Two solutions to improving CFD are 1) “benchmark quality”, experimental data for CFD and 2) a better understanding of fluid physics fundamentals [1].

1.3 Purpose

The goal of this study is the observation of the interaction between a conical shock wave and plane turbulent boundary layer using modern measurement techniques. The purpose is to potentially deliver further insight into the physics of shock-boundary layer interactions, in particular information regarding the fundamental three-dimensionality. The experiment with a cone is useful because it is an experiment that has not been studied as much as other interactions. The studies of Gai et al. [8] and Panov [9] are the only ones to the author’s knowledge to study shock-wave/boundary-layer interaction between a conical shock and a plane flat surface. There have been axisymmetric studies undertaken, as referenced by Sun et al. in [10], but such studies do not have inherent geometrical three-dimensionality. There have also been studies between two cylindrical bodies, such as between a rocket and a booster, that are relevant to the current study [5] [6]. There has been work on three-dimensional SBLI, including sharp and blunt swept and unswept fins, semicones, double fin configurations, and swept compression ramps [3]. Of course, this work in no way completely encompasses the number of three-dimensional geometries available for study. It is useful to pick 3D geometries which are representative of geometries likely to show up in a flight vehicle or which are uniquely suited to garnering deeper understanding of underlying physics. A third class of geometries to study are those that are especially suited to validating computational fluid dynamics (CFD) codes and solvers. This last point is key to future experiment design because not all empirical results are immediately adaptable to validation of CFD [11]. The need for better understanding of the physics, both in
general and for the purpose of accurate modeling, was mentioned by Dolling in his famous review [1] as one goal to pursue in the study of SBLI going forward.

1.4 Review of Literature

Panov [9] and Gai et al. [6] both made separate measurements of a conical shock wave impinging on a plane compressible turbulent boundary layer at Mach 2. They made schlieren, oil flow, and pressure tap measurements. Gai et al. concluded that there was a horseshoe vortex that followed the shape of the shock wave, a zone of secondary separation within the primary separation, and that the strength of the interaction, including the probability of separation, is directly related to the height of the cone above the wall. They also developed a scaling law for upstream influence dependent on incoming boundary layer thickness, Mach number, and shock trace curvature [6]. Panov developed a scaling law between critical pressure ratio and the same parameters [9]. Other SBLI studies that are similar to the present interaction are the interaction between two conically-nosed cylindrical bodies, blunt fin interactions, and two-dimensional (2D) oblique SBLI. The interaction between two bodies is very similar to the interaction between the conical shock and plane turbulent boundary layer except for the fact that the boundary layer surface is curved. There are also interactions between a cone and an axisymmetric wall that are essentially a 2D interaction.

A large body of work exists on the aforementioned 2-D oblique shock interaction between a wedge and a plane boundary layer. This work gives insight into the general nature of impinging oblique SBLI, only lacking the same 3D mechanisms. Eagle lists much of the work in [11], including key test conditions and results. Current focus of the experimental work includes control [12], organization of and more basic experiments for RANS CFD validation [11], and the application of new, more advanced measurement techniques to gain deeper physical insight [Eagle] [11]. Numerically, there have been RANS studies that are useful for showing overall flow organization, but admittedly have problems modeling turbulence to an accuracy necessary for SBLI [13]. So far only one DNS study has been found, in which Pirozzoli studied the active unsteadiness of 2D SBLI, and suggested that this unsteadiness drives upstream acoustic waves [14]. As far as current experiments, Eagle et al. made stereo PIV measurements at Mach 2.75 on
a 6° wedge with the goal of understanding a rectangular inlet holistically, that is, to understand all 3-D aspects of the impinging oblique SBLI in a rectangular duct, including the corner flows, sidewall vortices, variation in the interaction in the spanwise coordinate [11]. Moreover, his experimental results sought to be especially conducive to CFD validation. Arguably the most advanced experimental study has been one by Humble et al., in which the authors made tomographic particle image velocimetry measurements of a Mach 2.1 interaction [15]. In it the authors discovered that ahead of the shock wave the flow is very spatially unsteady, with several independent vortex cores destabilizing the flow. The interaction then displays large local dependence on the local incoming boundary layer structures.
CHAPTER 2: FACILITY

2.1 Wind Tunnel Operation

All of the tests done in this study were done in the Large Rectangular Supersonic Tunnel (LRST) facility at the University of Illinois. It is a supersonic blow down tunnel that vents to atmosphere from plenum pressures that currently go up to 345 kPa (50 psia). However, this pressure maximum is a nominal safety cutoff that can be increased via changes in controller software.

The test section has a rectangular cross section of 12.7x12.7 cm\(^2\) (5x5 in\(^2\)), and is 23.9 cm (9.4 in) long, at which point there is a 6° angled ramp diffuser. The first 38.1 cm (15.0 in.) of the test section and diffuser have optical access on three sides. There are reconfigurable side windows with viewing areas of 25.4 cm x 17.8 cm (10 in. x 7 in.) each, and a bottom window of 31.8 cm x 2.5 cm (12.5 in. x 1 in.). There are two supersonic, converging-diverging nozzles available for the tunnel, a Mach 1.4 nozzle and a Mach 2.0 nozzle, nominally. Both nozzles were designed using the method of characteristics for higher Mach numbers, 1.5 and 2.15, respectively, in order to account for viscous losses. For the current tests, the Mach 2.0 nozzle was installed. For information about the construction of the tunnel itself, as well as performance specifications and basic tests with the Mach 1.4 nozzle installed, see [16]. The tunnel has probes for static pressure, stagnation pressure, and stagnation temperature. Before the current experiments, the Mach 2.0 nozzle had not been used; thus, a basic analysis of Mach 2.0 tunnel operation was undertaken here. The flow was assumed to be an ideal gas, and adiabatic and isentropic from the stagnation chamber through the test section. Thus, at stagnation, density was calculated from the temperature and pressure. Mach number was calculated from the measured stagnation-to-static pressure ratio using the isentropic relationship given in Eq. (1), and later confirmed from the Mach wave angle \(\mu\) measured in schlieren imaging using Eq. (2):

\[
M = \sqrt{\frac{2}{\gamma - 1} \left[ \left( \frac{p_o}{p} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (1)
\]

\[
M = \frac{1}{\sin(\mu)} \quad (2)
\]
Both of these calculations of Mach number agreed to hundredths level accuracy. Substituting the measured Mach number into the isentropic flow functions, the freestream values of temperature, density, and speed of sound were calculated. Sutherland’s law was used to calculate viscosity. These freestream values ahead of the shock are shown in Table 1:

<table>
<thead>
<tr>
<th>Table 1: Flow Properties ahead of shock, $\gamma = 1.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach number</td>
</tr>
<tr>
<td>Unit Reynolds number</td>
</tr>
<tr>
<td>Stagnation pressure</td>
</tr>
<tr>
<td>Stagnation temperature range</td>
</tr>
<tr>
<td>Nominal stagnation temperature</td>
</tr>
<tr>
<td>Stagnation density</td>
</tr>
<tr>
<td>Freestream pressure</td>
</tr>
<tr>
<td>Freestream temperature</td>
</tr>
<tr>
<td>Freestream density</td>
</tr>
<tr>
<td>Freestream viscosity</td>
</tr>
<tr>
<td>Freestream speed of sound</td>
</tr>
<tr>
<td>Freestream velocity</td>
</tr>
<tr>
<td>mass flow rate at 40 psia and 295 K</td>
</tr>
</tbody>
</table>

For the current experiments, a 25° half angle cone was mounted on a fixed sting and pointed into the flow. This model was originally designed for use in a Mach 4 facility; further details about its design can be found in Appendix C. The cone was placed in the tunnel such that the oblique shock-boundary layer interaction caused by the cone would be located on a removable plate 10.3 cm x 12.7 cm (4.07 in x 5 in) in size located on the ceiling of the test section that is easy to remove and modify. Henceforth the terms “plate” and “wall” will refer to this plate, as it is the region of interest on which the interaction occurs. A basic layout of the model and wind tunnel, along with an inviscid representation of the generated shock wave, are given in Fig. 2.
2.2 Wind Tunnel Control

The tunnel is controlled by a program in LabVIEW. There is a safety valve and pneumatic air supply that must be turned on manually, as well as a safety emergency shutoff, but otherwise the tunnel is controlled via computer. The valve can be manually controlled by the user specifying the valve how much to open, or it can be controlled automatically via a closed-loop controller. There was an original control algorithm for the Mach 1.4 nozzle, but that did not operate properly for the Mach 2.0 nozzle’s higher contraction ratio. So, a new control algorithm needed to be written to account for the changes in the physical system. Both control algorithms, implemented in LabVIEW, use current tank pressure and target stagnation pressure to determine the rate at which to open the automatic valve between the tank farm and the tunnel plenum. Because the tank farm rapidly decreases in pressure during operation due to the high tunnel mass flow rate, the control valve must be continually opened to maintain a constant stagnation pressure. The amount the valve is opened is directly controlled by the electric current to the
valve. Thus, any control law uses tank pressure, current stagnation pressure, and target stagnation pressure measurements as inputs to produce a current output to the valve. In order to minimize testing time lost while opening the valve, the valve must be rapidly opened initially, but then slowly opened afterward. In the original controller for the Mach 1.4 nozzle, a bicubic interpolation ramp function is used to initially open the valve quite rapidly. Next, a proportional controller (P-controller) takes over to maintain the tank pressure at the target stagnation pressure. After the Mach 2 nozzle was installed, the bicubic interpolation ramp plus P-controller formulation did not center the tunnel onto the desired stagnation pressure, so the system was changed. At first, the parameters of the bicubic interpolation function and the P-controller were varied in order to determine new parameters, but no working formulation was reached. Thus, a large volume of new data was obtained in order to determine new functions. The tunnel was started at a number of different constant valve current inputs and tank pressures, and then those data were correlated into a new control formulation. Ultimately, the bicubic ramp function was replaced by a function involving two 5th order, two-variable polynomial fits (i.e., \( z = A_1 x^5 + A_2 x^4 y + \cdots + A_n \)), where valve current was a function of target stagnation pressure and starting tank pressure. The P-controller portion was replaced with a proportional-derivative controller (PD-controller). The original LabVIEW controller is named Main_1_6_2.vi, and the new controller was named Main_1_6_2_M2_revD.vi. More detailed information can be found in Appendix B. For information about the original set up of the control law, see [16].
2.3 Incoming Boundary Layer

Information regarding the incoming boundary layer was determined from PIV data. Data used to calculate the incoming boundary layer profile were obtained at a location 19 mm upstream of the interaction region in order to avoid upstream influence. By avoiding upstream influence, these data are not limited to this experiment. Data were obtained on the lower wall of the test section only because the sting blocks the laser sheet from reaching the upper wall. Normalized and dimensional boundary layer profiles are shown in Fig. 3, and values of key parameters are shown in Table 2. The boundary layer thickness was defined to be the distance from the wall to the point having 99.5% of the freestream velocity.

Table 2: Key boundary layer parameters. $\delta, C_f,$ and $\Pi$ are taken from Sun-Childs where $a \to \infty$, and the other values were calculated from raw data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured boundary layer thickness</td>
<td>$\delta_{99.5}$</td>
<td>8.92 ± .19 mm</td>
</tr>
<tr>
<td>Sun-Childs boundary layer thickness</td>
<td>$\delta_a \to \infty$</td>
<td>9.377 mm</td>
</tr>
<tr>
<td>incompressible displacement thickness</td>
<td>$\delta^*$</td>
<td>1.26 mm</td>
</tr>
<tr>
<td>incompressible momentum thickness</td>
<td>$\theta$</td>
<td>0.944 mm</td>
</tr>
<tr>
<td>incompressible shape factor</td>
<td>$H$</td>
<td>1.33</td>
</tr>
<tr>
<td>skin friction coefficient</td>
<td>$C_f$</td>
<td>0.001526</td>
</tr>
<tr>
<td>Coles wake parameter</td>
<td>$\Pi$</td>
<td>0.83</td>
</tr>
</tbody>
</table>

The incompressible displacement thickness, momentum thickness, and shape factor were calculated using Eqs. (3)-(5).

$$\delta^* = \int_0^\infty \left(1 - \frac{u}{u_e}\right) dy$$

$$\theta = \int_0^\infty \frac{u}{u_e} \left(1 - \frac{u}{u_e}\right) dy$$

$$H = \frac{\delta^*}{\theta}$$

The Coles wake parameter was calculated in Eq. (6) as part of fitting the boundary layer velocity data to a profile given by Sun and Childs [10], as shown in Eq. (7), which is valid for turbulent compressible boundary layer profiles. The Coles wake parameter quantifies the deviation of the
wake region of the boundary layer from the log law. The Sun and Childs profile is a wall-wake profile for iso-energetic compressible boundary layers with a zero-velocity gradient at the boundary layer edge, built off of other work by Matthews and Coles [17] [18].

\[
\frac{\Pi}{\kappa} = \frac{1}{2} \left[ \frac{u_e^*}{u_e} - \frac{1}{\kappa} \ln \left( \frac{\delta u_e}{\nu_w} \right) - 5.2 + \frac{0.614}{a\kappa} \right] 
\]

\[
\frac{u}{u_e} = \frac{1}{\sqrt{\sigma}} \sin \left\{ \arcsin \sqrt{\sigma} \left( 1 + \frac{1}{\kappa} \frac{u_{\tau u}}{u_e^*} \left[ \ln \eta + \frac{2}{a} \sqrt{1 - \eta^a} - \frac{2}{a} \ln \left( 1 + \sqrt{1 - \eta^a} \right) \right] ight) 
- \frac{\Pi u_e}{\kappa u_e^*} \left[ 1 + \cos(\pi \eta) \right] \right\} 
\]

A nonlinear least-squares solver iterated Eq. (7) over \( \delta \) and \( C_f \), present in Eqs. (6), (12), and (13) until the best least-squares fit of the normalized velocity profile, from Eq. (7), matched the normalized boundary layer profile raw data. This is the method use to get \( \delta \) and \( C_f \). Equations used to calculate variables used in Eqs. (6) and (7) are given in Eqs. (8)-(13). These variables are functions of tunnel flow conditions and \( \delta \) and \( C_f \).

\[
\sigma = \frac{.5(y - 1)M^2}{1 + .5(y - 1)M^2} 
\]

\[
A = \sqrt{\frac{.5(y - 1)M^2}{T_w/T_e}} 
\]

\[
B = \frac{1 + .5(y - 1)M^2}{T_w/T_e} - 1 
\]

\[
u_e^* = \frac{u_e}{A} \arcsin \left( \frac{2A^2 - B}{\sqrt{B^2 + 4A^2}} \right) 
\]

\[
\frac{u_{\tau e}^*}{u_e^*} = \sqrt{\frac{C_f \sigma}{2(1 - \sigma)}} \arcsin(\sqrt{\sigma}) 
\]

\[
a = 1 \text{ or } \infty \quad \kappa = 0.41 \quad \eta = \frac{\gamma}{\delta} 
\]
Adiabatic wall temperature $T_{aw}$ was used for the wall temperature $T_w$ in Eqs. (9) and (10). $T_{aw}$ was calculated using Eq. (14), where $Pr^{1/3}$ is the recovery factor recommended for turbulent boundary layers [19]. This Prandtl number is calculated using flow conditions in the freestream. Sutherland’s law was used in order to calculated values for viscosity and thermal conductivity, and the constant-pressure specific heat value was calculated using a value of $7/2R$, predicted by classical kinetic theory.

$$T_{aw} = T_e \left( 1 + Pr^{1/3} \left( \frac{\gamma - 1}{2} \right) M^2 \right)$$  \hspace{1cm} (14)

Once $C_f$ is known from the Sun-Childs fit, the wall shear stress can be calculated using Eq. (15):

$$\tau_w = \frac{1}{2} \rho_e u_e^2 C_f$$  \hspace{1cm} (15)

Figure 3 shows the boundary layer profile fit with the Sun-Childs curve fit:
**Figure 3**: Sun-Childs curve fit of boundary layer. a) with units, b) non-dimensional.
CHAPTER 3: EXPERIMENTAL METHODS

3.1 Schlieren Background and Theory

The basics of schlieren imaging were put forward first by Robert Hooke in the 17th century, but the realization of its utility for supersonic aerodynamics did not come about until the schlieren imaging experiments of Ernst Mach and Peter Salcher in the late 19th century [20]. Schlieren and shadowgraph imaging are particularly useful in the imaging of supersonic flow due to their ability to image compressible flow phenomena. They are often used to image shock waves, shock-shock interactions, shock-boundary layer interactions, boundary layers, and turbulent structures in a flow at high contrast. The reason for their ability to capture compressible flow phenomena is because they are fundamentally optical techniques for visualizing phenomena in inhomogeneous media [20], i.e., media in which the index of refraction varies, in space, throughout the media [21]. The index of refraction of a gas varies with the density of the gas, as described by the Gladstone-Dale relationship:

\[
\frac{n - 1}{\rho} = K
\]  (16)

The Gladstone-Dale relationship is in reality a simplification of the Clausius-Mosotti relation that applies when the particles of a fluid are far apart [22]. The parameter \( K \) is a function of propagating light frequency, the particular gas mixture, dissociation, and polarizability, and has low temperature dependence [22] [23]. Because the present study is conducted solely with air at low temperature, the parameter \( K \) can be considered a constant, so it is safe to assume that index of refraction and density vary linearly with one another. In light of this relationship, schlieren and shadowgraph photography can be thought of as photography that magnifies small changes in the density. While they both image some of the same things, and the difference between the two is often just a knife edge, which is used in schlieren but removed in shadowgraph, the two methods are fundamentally different. A schlieren image is an actual image, whereas a shadowgraph is not. The features seen in a schlieren image are a direct representation, a 1:1 mapping, of the flow. As such, schlieren can image small gradients in index of refraction and is quantitatively accurate. Shadowgraph, on the other hand, images the Laplacian of the refracted light, thus is only sensitive to stronger refractive index gradients, and is not 1:1 accurate. This
lack of accuracy is because a shadowgraph does not require a focusing element (such as a lens or mirror); it is a shadow of features, not a focused representation of the features. However, it is possible to focus a shadowgraph setup, which will give greater quantitative accuracy [20].

One basic schlieren setup is the Z-type setup. In a basic Z-type setup, light issues from a light source, travels to one parabolic mirror (the collimating mirror), is reflected off of this mirror through the test section, reflects off of a second parabolic mirror (the focusing mirror), over a knife edge, into the camera. A diagram of this setup is given in Fig. 4. A ray trace of the setup is given in Fig. 5.

**Figure 4**: Diagram of schlieren setup

For taking shadowgrams, the knife edge is removed from the setup; all else remains the same. In reality, a shadowgram does not need this number of mirrors; since it is just imaging a shadow. The only thing needed for a shadowgram is a light source and a camera. In the setup used herein, a flat mirror was added between the light source and the collimating mirror, and between the focusing mirror and the camera, designated the 1st flat mirror and 2nd flat mirror, respectively, in Fig. 4. This choice was made in order that the light source would be vectorially parallel with the camera in order to diminish coma. The beam path length from the light source to the collimating
mirror is the focal length of the collimating mirror. The distance from the collimating mirror to the test section focal plane of interest, which plane is orthogonal to the beam vector, is also the focal length of this mirror. The distance from the test section to the focusing mirror is the focal length of the focusing mirror, as is the beam path length from the focusing mirror to the knife edge. Often the two parabolic mirrors are of the same focal length, so the distinction between the focal lengths of the two mirrors is unnecessary. The reason that the first mirror is called the collimating mirror, and the reason that parabolic mirrors are used, is because a foundational quality to schlieren imaging is that the light going through the test section be collimated, i.e., that all the individual light rays are parallel. This is the reason that the light source is placed at the focus of the collimating mirror. The camera is positioned behind the knife edge. Note that both of these figures are diagrams based on the setup used for the current experiments. The knife edge angle can be easily changed in order to enhance different effects of the flow in the image. Due to astigmatism in the optical setup, the knife edge needed to be repositioned forward or backward each time it was rotated by 90 degrees. When the knife edge is pointed vertically, such that the system measures density gradients in the streamwise direction, then the knife edge needs to be centered at the sagittal focus. When the knife edge is oriented horizontally, emphasizing transverse density gradients, the knife edge needs to be centered at the tangential focus.
Figure 5: Ray trace of schlieren setup. The rays change colors merely for clarity. Notice that the rays going through the test section are collimated.

Mathematically, schlieren can be described as an angle change in a ray of light going through a test section. The total angle of deflection of the light ray $\alpha$ over a distance $L$ in a test section may be written as Eq. (17), where $y$ represents the coordinate perpendicular to the knife edge [20].

$$\alpha = \frac{1}{n_{air}} \int_{0}^{L} \frac{\partial n}{\partial y} dz$$  \hspace{1cm} (17)

Schlieren creates a true image; what is seen is a 1:1 representation of what is being imaged. Shadowgraph, can be described as the displacement of, not the angular deflection of, of a light ray by the schlieren object. As a result, this “shadow” does not have the same 1:1 spatial accuracy of a schlieren image, so can rarely be used quantitatively [20]. The intensity of a schlieren image is proportional to $\frac{\partial n}{\partial y}$ whereas the intensity of a shadowgraph is proportional to $\frac{\partial^2 n}{\partial y^2}$. Because of its second derivative relationship, a shadowgram is more useful for delineating the most prominent flow details. On the other hand, schlieren is much more sensitive; it can detect very minor disturbances.
3.2 Schlieren Methods and Experimental Setup

For the different schlieren measurements, two pairs of parabolic mirrors were used in the Z-type setup, 8 inch diameter mirrors (only 7.5” was visible) from Edmund optics with a focal length of 64 inches, and 6 inch diameter mirrors with a focal length of 42 1/8 inches. The shorter focal length mirrors allow for greater magnification of the test section, while the longer focal length mirrors allow for a larger field of view. One disadvantage of the smaller mirrors is that their mounts are not as stable as the larger mirrors, so they require continuous adjustment. A high voltage spark was used as the light source and has a 20 ns pulse width. The spark was powered by a Xenon corporation model 473B Nanopulser. A 1600x1200 pixel resolution, PCO.1600 CCD camera with a manual focus, telephoto lens was used to record the images. The telephoto lens allows a greater magnification to be achieved than is possible with the mirrors alone. PCO-proprietary CamWare software was used to control the camera. CamWare can be configured to time the image capture itself, or to accept an external TTL trigger. The timing of image capture was directed by a Quantum Composers model 9518 pulse (delay) generator, which is able to produce TTL pulses at 10 ns resolution. It directed the timing of the camera and spark source. The exact timing of the setup is given in Fig. 6. The advantage of the spark source is that it has a very short duration and high intensity. Its main disadvantage is the intensity variation per image. Even though schlieren imaging can be done with a continuous light source, and using a continuously-on, very bright LED is often advantageous, the PCO.1600 camera displays vertical streaking when a continuous light source is used. Thus, a pulsed source was used. The main criterion that needs to be met is that the spark is pulsed on and off while the camera image sensor is exposed. Delays in the timing are due to signal travel delays in the electronics and software. The pulse generator has a delay of approximately 340 ns from firing until the actual spark.
For each test, a wind-on (i.e., "run") image set, a background image set, and a flatfield image set were obtained. All image sets are taken in the same ambient lighting conditions. Background image sets are taken when the light source is off and the flow is off. Flatfield image sets are taken when the light source is on and the flow off. Wind-on image sets are taken when the light source and tunnel are on. Each image set is stored as a stack of TIFF (tagged-image-file format) images. The background images were obtained in order to remove the effects of the camera and ambient conditions in post-processing, and the flatfield was obtained in order to remove undesirable artifacts of the optical setup, such as scratches. For the post-processing, the background and flatfield image sets were each averaged. The average background was subtracted from the run image set, and this difference was divided by the difference of the average background from the average flatfield to give a new stack of processed images. Note that the division operation is done element by element if processing it in a matrix calculation tool such as MATLAB or Octave. The entire operation is written in Eq. (18):

$$\text{Final Image} = \frac{\text{Run} - \text{mean}(\text{Background})}{\text{mean}(\text{Flatfield}) - \text{mean}(\text{Background})}$$

(18)

ImageJ and MATLAB software were used to do this image processing. An important thing to know about ImageJ is that the processed images are stored as single precision floating point values, whereas the original images are stored as unsigned (i.e., positive) 8-bit or 16-bit integer
values. This is important because other imaging software may expect 8-bit or 16-bit unsigned
values for images. So, the finally processed images must be multiplied, shifted to positive
values, and rounded in order to be format-readable by these other programs.

3.3 Surface Oil Flow Methods

In order to obtain surface oil measurements, DyeLite fluorescent dye was mixed into STP car
engine oil additive. This mixture was spread in a uniform film or applied as small dots with high
spatial resolution with a syringe. DyeLite is a dye that fluoresces yellow and green under
ultraviolet excitation. STP is a highly viscous oil. In a high-speed wind tunnel, the oil used for
visualization needs to be very viscous in order to withstand the high shear stresses of the flow. A
mixture of two drops of DyeLite in 50 mL of STP was found to work well. Images were taken
with a PCO.1600 camera with an 85 mm Nikon PC-E lens. Lighting was supplied by two
fluorescent blacklights stationed on either side of the tunnel. In order to test, first the camera
was set up in order to view the region of interest. Because the cone and sting were in the way of
the viewfinder, only one spanwise half of the plate was imaged, but this is acceptable because the
surface flow is symmetric about the centerline. After the camera was set up and the plane
brought into focus, the two blacklights were positioned. Positioning the lights is arguably the
most important part of setting up the test. They need to be placed so as to enhance fluorescence
while minimizing glare from the tunnel as well as from the oil. Before applying the oil, small
dots were painted on with a white-out correctional pen in order to give a scale for the images. In
order to apply a thin sheet of oil, the oil was dripped onto the plate and then smoothed out with a
wooden dowel. In order to apply dots onto the surface, a 20 mL medicinal syringe with a 26
gauge surgical needle was used. The sharp tip of the surgical needle was first cut away so that
the oil would exit from a round hole instead of an oblong cavity. The plate was then placed into
the tunnel. After running, the plate was removed so that still pictures could be taken. The oil
and white-out paint were removed with acetone before reapplication for another run.

3.4 PSP Background and Theory

The driving mechanism behind pressure-sensitive paint is oxygen quenching of the fluorescence
of the paint. As the concentration of oxygen increases, the number of molecular-level
fluorescing events in the paint decreases; thus, at the macro level, as oxygen concentration increases, intensity decreases. Because the concentration of a species is linearly related to its partial pressure in a mixed gas, and the partial pressure is a constant fraction of total pressure, the concentration of a specific species is directly proportional to the total pressure of the mixed gas. So, the paint can directly measure air pressure, even though the fluorescent intensity is really a function of oxygen concentration. Mathematically, the fluorescent intensity of the paint is given by Eq. (19), where \( I \) is the intensity, \( I_0 \) is the fluorescent intensity in a zero-oxygen environment, and \( k_r, k_{nr}, \) and \( k_q \) are temperature-dependent rate constants for radiative, non-radiative, and quenching processes, respectively, and \([O_2]\) is oxygen concentration. This equation is the Stern-Volmer relation.

\[
\frac{I_0}{I} = \frac{k_q}{k_r + k_{nr}} [O_2] \tag{19}
\]

After a few more steps, and relating the oxygen concentration to air pressure \( P \), we arrive at the more easily applied, and therefore more often used, version of the Stern-Volmer relation in Eqs. (20) and (21), where \( T \) is temperature, \( A \) and \( B \) are parameters, and the subscript “ref” stands for quantities taken at a reference condition:

\[
\frac{I_{\text{ref}}}{I} = A(T) + B(T) \frac{P}{P_{\text{ref}}} \tag{20}
\]

\[
A(T_{\text{ref}}) + B(T_{\text{ref}}) = 1 \tag{21}
\]

It is good news that this relationship is linear, especially because \( A \) and \( B \) are solely functions of the paint chosen and temperature. In fact, this leads to temperature being the greatest source of uncertainty in PSP measurements. In aerodynamic practice, what is done is to take two sets of images: one with the flow off, i.e., “wind-off”, the reference measurement, and these pixel values are used for \( I_{\text{ref}} \), and one with the flow on, i.e., “wind-on” for \( I \). Both measurements are accompanied by a few pressure tap measurements, which give \( P \) and \( P_{\text{ref}} \) values for calibration of the paint in all areas on the model. Note that this relationship is valid for conventional oxygen-quenched pressure-sensitive paints with a polymer binder. However, for paints that display a non-linear correlation of the Stern-Volmer relationship, using a higher-order polynomial.
relationship with temperature-dependent coefficients between intensity ratio and pressure ratio is found to be a reasonable approach, shown in Eq. (22): \[
\frac{I_{\text{ref}}}{I} = A(T) + B(T) \frac{P}{P_{\text{ref}}} + C(T) \left( \frac{P}{P_{\text{ref}}} \right)^2 + \ldots \quad (22)
\]

The information in this section was primarily taken from Ref. [24], and includes information from Ref. [25].

### 3.5 PSP Methods

For pressure measurements, ten pressure taps were drilled into the plate and UniFIB pressure-sensitive paint from Innovative Scientific Solutions [26] was applied over the whole surface. The pressure taps were used to calibrate the pressure-sensitive paint; the pressure tap farthest in the spanwise direction from the centerline went unused. The locations of these taps were chosen to meet the following general criteria: one centerline tap upstream of the shock, several close together in the SBLI region along the centerline in order to capture data in the separated flow region, three in the spanwise direction away from the centerline, one a moderate distance downstream of the shock along the centerline, and one far downstream of the shock. A picture and diagram of the plate are given in Fig. 7.
Figure 7: a) Picture of the plate with pressure tap holes (.040 in. diameter). The pink glow is the fluorescence emission in the visible red spectrum due to impinging ultraviolet light from the sun. b) Diagram of plate, dimensions are in mm.
The UniFIB paint has relatively low temperature sensitivity. It fluoresces in the visible red region of the spectrum, from 620 nm to 750 nm wavelength, under ultraviolet (UV) light, from 370 nm to 520 nm wavelength excitation. Detailed information, including intensity ratio versus pressure ratio data at different temperatures can be found in Ref. [26]. A silver-colored Sharpie® permanent marker pen was used to apply points to the paint with which to align the images in the post-processing in case of shift. The silver Sharpie® was chosen because it shows up very brightly in the PSP results images.

A NetScanner 98RK pressure acquisition system with a 9816 rack mount was used to gather data from the pressure taps. In order to operate, the NetScanner 98RK needs one or more 9816 pressure transducer rack mounts (it can host up to eight racks), a 9034 calibrator, a high-pressure (>80 psia) air supply (provided by pressurized N₂), a vacuum pump, and a computer, connected via Ethernet, to run the software. The transducers can be run with either the included NetScanner Unified Startup Software (NUSS) or LabVIEW. Each time the NetScanner is powered on, it must warm up for 45 minutes and then go through a re-zero calibration after the 45 minutes, before use. This function is in NUSS, and is different than a simple tare that can be done in LabVIEW. This re-zero calibration must also be performed every 5 hours while the system is in use. For detailed information regarding the setup, operation, and calibration of the NetScanner system, see Appendix F.

LabVIEW was used to control the wind tunnel and the pressure transducers. The LabVIEW program used was Main_1_6_3_M2.vi, and was modified from the original Mach 2.0 control program, Main_1_6_2_M2_revD.vi, by the addition of algorithms that recorded data from the pressure taps. There are sixteen pressure transducers on one 9816 rack mount. The transducers used for the current experiment each have a pressure range of 30 psi. Nine of these measured pressures in the tunnel; the tenth was used as an atmospheric reference, and the others are unused, but were functional should they be needed. A Setra model 370 absolute pressure barometer system was used to measure the true ambient pressure for each run.

A 1600x1200 (1.9 megapixel) resolution, 14-bit, CCD, PCO.1600 camera was used to obtain intensity measurements from the PSP. Proprietary CamWare software from PCO [27] was used
to control the camera and record the PSP data. The camera was filtered with a 610 nm long pass filter, an Andover 610FG07-50. The PSP-covered tunnel wall was illuminated with an ISSI LM2XX-DM 2-inch Water-Cooled LED lamp, fitted with an ultraviolet short-pass filter. The LED array was intermittent, with different numbers and sets of lights being active during each run. The light source was also fitted with an ISSI LM2X-10R40 parabolic LED Reflector, which acts as a light diffuser. Most of the measurements were obtained with 100 ms exposure time. At first, measurements were obtained with the light source continuously on, but greater dynamic range was experienced when the light source was phase locked with the camera. The phase locking was also done via the CamWare software. The lens used on the camera was a Nikon PC Micro Nikkor 85 mm f/2.8 lens. The PSP images were taken at an f/5.6 aperture setting. It is a tilt-shift macro lens, so the lens normal vector can be tilted in one plane from -8.3° to +8.3° in and away from the plane of the camera sensor, and can be shifted in the plane of the camera sensor fore and aft along the tilt axis from -10 mm to +10 mm as seen in Fig. 8.

![Figure 8: Tilt-shift motion of lens](image)

The shift capability allows the operator to shift the viewing field of the image in one direction without re-adjusting the focus. Because of the high level of magnification on the plate, this feature was used in order to quickly reposition the view in order to gather PSP data on the entire plate in two separate runs. More importantly, however, tilting the lens shifts the focal plane of the camera to no longer be parallel with the camera sensor. Because of the test setup, making the camera sensor parallel to the focal plane is impossible. When tilt is applied, the focal plane rotates, and the depth of field rotates as well, becoming an angular region such that closer to the camera, the depth of field is narrower than away from the camera. Because the focal region is now at an angle with respect to the camera, the entire plate can be in focus at once. These effects are diagrammed in Fig. 9.
One data set consisted of, in chronological order, photographing one background image set, one wind-off image set, a wind-on image set, a second wind-off image set, and a second background image set. The description for how these images sets are taken is described on page 19. The 50-100 images were taken for the background and wind-off image sets, and >200 images were taken for the wind-on image sets. During the wind-on image set, at each pressure tap, >200 measurements were obtained after the tunnel started. One baseline ambient pressure measurement was also recorded per run in order to get absolute pressure from the differential pressure recorded by the pressure taps. Post-processing followed. First, the first and second background image sets were averaged into one image, and the wind-off image sets were likewise averaged, all in ImageJ. Then, approximately 200 of the wind-on images after the paint intensity was fully developed (after the tunnel starts, the paint has a slow response time) were averaged into one image. OMSLite software, produced by ISSI, was used to align the averaged background, wind-off, and wind-on images using the alignment points applied with the silver Sharpie®. OMS Lite processed the aligned results according to Eq. (18) to arrive at a final intensity map for the run. In addition, the pressure tap measurements from the wind-on run were averaged so as to have one pressure value at each pressure tap for the run.
The final intensity data were correlated with the pressure tap data in MATLAB. First the intensity data were mean filtered over a 3x3 pixel area using OMS Lite. Secondly, in the intensity data image, >30 calibration points were placed close to and around each pressure tap using Tecplot, and one point was placed at the tap center. Lastly, the average of the intensities at each of these points was found, and weighted by each of their distances from the center of the pressure tap. This weighted average was the value for intensity ratio used in the calibration plots, Fig. 18 on page 45. In MATLAB, this weighted average intensity ratio was plotted against the pressure tap data and fitted with a linear least squares curve in order to acquire a Stern-Volmer relationship for that run. This curve was applied to the intensity map to get a pressure map over the entire plate surface.

Lastly, the perspective shift of the surface pressure map was removed mathematically. In a perspective transformation, all lines that are straight in reality are still straight in the transformed image, but parallel lines do not necessarily retain parallelism. First, the intensity data were transformed using the GNU Image Manipulation Tool (GIMP) in order to match a CAD model. MATLAB was then used to calculate the perspective transformation between the original intensity image and the transformed intensity. This transformation was then applied to the Stern-Volmer calculated pressure map.

3.6 PIV Theory

The goal of particle tracking methods, including particle tracking velocimetry (PTV) and particle image velocimetry (PIV) is to track a large number of particles suspended in a flow in order to obtain flow velocity field information. How the velocity field is obtained from the motion of these particles is described by basic kinematics. If a particle starts at location \((x,y,z)\), and over a short time difference \(\Delta t\) moves to location \((x',y',z')\), then the velocity components of the particle at its average location can be inferred by Eq. (23):

\[
(u, v, w) = \left( \frac{x' - x}{\Delta t}, \frac{y' - y}{\Delta t}, \frac{z' - z}{\Delta t} \right)
\]

(23)
For planar PIV, as done in this study, there are only two components, \((u,v)\). If we assume that each particle is light-weight, sufficiently small, and does not deform [28], it is reasonable to assume that the Lagrangian velocity of the particle at its location and the instant it is taken represents the Eulerian description of the fluid velocity field at that location. Extension of this concept to many particles calculates an entire velocity field. How the velocity is extracted depends heavily on post-processing techniques applied to the measurements. Measurement of particle locations is done by taking a double-exposure photograph of the particles. First, an image is taken at time \(t_0\), and then another is taken at time \(t_0 + \Delta t\). These two images together are called an image pair. In supersonic flows, the high velocities encountered require values for \(\Delta t\) that are very low, often less than 1 µs. So, two pictures need to be taken in rapid succession. In addition, the time that each image is exposed to light needs to be very short to diminish particle blur, and the particles must be strongly illuminated relative to the background. Two lasers fired \(\Delta t\) apart solve this problem. By syncing both lasers to the same, high-accuracy delay generator, a low, repeatable \(\Delta t\) is obtained. The camera exposure time is set very low in order to minimize non-laser light, ensuring that the effective exposure is the very small laser pulse-width. The region of interest is generated by forming a thin laser sheet parallel to the dominant flow direction, as seen in Fig. 10. If the laser sheet is not parallel with the dominant flow direction, then many particles illuminated by the laser sheet in the first image will have moved out of the plane of interest before the second image. A sheet that is too thick will image more particles than desired. The camera is usually placed perpendicular to this sheet. With respect to the camera, it is important that the polarization of the laser sheet also be perpendicular to the camera lens plane, as that will ensure greater particle illumination.
After data acquisition, the data are analyzed according to either PTV or PIV algorithms. In PTV, individual particles are identified and their motions are tracked. PTV is used when the number of particles is sparse. PIV algorithms are built around cross-correlation and are used when the seeding density is high. In cross-correlation, the software first selects a specific region in each image pair; these regions are called interrogation windows. Then, the software calculates a correlation map between the two images in an image pair in this interrogation window. The correlation map is, in essence, a statistical likelihood that a certain set of particles in the first image corresponds exactly to a set of particles in the second image of the pair. If this likelihood is significant, the software calculates one velocity vector in that interrogation window region with high certainty. Ultimately, the software draws one vector in each interrogation window in order to fill up the entire image resolution. There is a tradeoff here: more, smaller interrogation windows give a higher number of vectors in the final result, whereas fewer, larger interrogation windows have more particles to use, hence higher precision. For more discussion on PIV and PTV theory, including information on ensuring the proper spot size of particles on the camera and advanced data processing see [28].

3.7 PIV Methods

The current experiment used a Q-switched, frequency doubled, New Wave Research model Solo 200XT, two-head, Nd:YAG laser at 532 nm wavelength. The beam first went through a 750 mm focal length plano-convex lens, then into a 30 mm hemispherical lens, off of a 25 mm dichroic
laser line mirror inclined at 45°, and through the bottom window of the test section. The laser sheet was located 62 mm from the side window through which the camera viewed the sheet, a distance of 1.5 mm off of the tunnel centerline. The region of interest was approximately 84 mm by 41 mm. These distances were determined by placing a small ruler in the focal plane after the lens was focused and the data taken. The camera scaling at the focal plane is .041 mm/pixel in both the horizontal and vertical directions. The sheet was mutually parallel to the streamwise and vertical dimensions of the tunnel. Two distinct, Q-switched, laser pulses fired from the same head 606 ns apart for each image pair. The first pulse and second pulses had output energies of 105 mJ and 103 mJ, respectively. The laser is vertically polarized coming out of the head, as confirmed by experiment and [29]. A PCO.2000 CCD camera operating in “double shutter” mode captured each image pair. In double shutter mode, the first image was exposed for 2 µs, and the second exposure was open indefinitely. For more information on double shutter mode, see [30]. The image pair was 80 ms apart from each other. The timing of the two laser Q-switches, the 606 ns laser spacing, and the camera shutter were controlled with a Quantum Composers model 9518 delay generator with 10 ns precision. The camera had a Nikon AF Nikkor 85 mm f/1.4D lens. For the data displayed, images were taken with f/4 aperture setting. The lens was focused on the particles while the tunnel was running. At 531 m/s, the freestream speed of the PIV data, one particle will travel 0.322 mm (7.83 pixels) in 606 ns, the value of $\Delta t$. A diagram of the setup is shown in Fig. 11:

![Diagram of laser-camera system](image-url)
In order to seed the tunnel with particles, a ViCount compact 1300 artificial smoke generator was attached to the settling chamber in order to atomize the seed particles far upstream. The smoke generator produced a nominal particle size of 0.3 µm [31]. At first, a TSI model 9307 Laskin nozzle with nominal particles of 1 µm was used [32] with Bis(2-ethylhexyl) sebacate (DEHS) seeder, but this seeder did not produce enough particles for good quality PIV in the Mach 2 nozzle. However, for the Mach 1.4 nozzle the Laskin nozzle works well [7]. This smoke seeder was supplied with nitrogen at 345 kPa gauge pressure (50 psig), for a tunnel operating stagnation pressure of 276 kPa absolute pressure (40 psia), an absolute pressure difference of 168 kPa (24.4 psi).

Final processing was done using the LaVision DaVis 8.2.1 PIV processing package. A total of 1934 images pairs were taken. First, the 0.041 mm/pixel scaling was applied to the images so that the software would convert the pixel values to physical dimensions. A geometric mask was applied to unreliable regions in the image pairs, such as regions of high glare and camera sensor damage. The software processing underwent multiple passes of the data to arrive at velocity field information per image pair: there were first two passes with 64 pixel x 64 pixel size interrogation windows, followed by two passes with 32x32 size windows, followed by two passes with 16x16 size windows. There was 0% overlap between each interrogation window. Each pass was post-processed with a 3 window x 3 window mean smoothing and a median filter that removed and sometimes replaced vectors greater than 10 standard deviations away from the median. The number 10 was an arbitrary high number in order to not remove spurious vectors during this intermediate post-processing. In final post-processing, another post-processing filter that removed vectors with values greater than 5 standard deviations from the median and replaced them with different vectors with less than 3 standard deviations. The 3 standard deviations replace limit was chosen to ensure that turbulence was not removed. It also filtered to ensure that vectors remained within absolute bounds and that they had a peak ratio greater than 3. The velocity results at each final interrogation window were processed to yield averaged data and fluctuating velocity data (turbulence statistics). Error analysis for the PIV processing is presented in Appendix A.
The DaVis results were imported into MATLAB for further processing. The PIV data for the incoming boundary layer were fit to a modified wall-wake profile given by Sun Childs, as described in Eqs. (6) – (13). This profile iterates over the skin friction coefficient, $C_f$, and boundary layer thickness, $\delta$, in order to find a matching profile. MATLAB was also used to organize, visualize, and calculate derivative results.
CHAPTER 4: RESULTS

4.1 Inviscid Results

The hallmark study of compressible flow over a cone was conducted by G.I. Taylor and J.W. MacColl in 1933 [33]. The study was aimed at determining the streamlines and surface pressure on a cone moving at supersonic speeds for the inviscid case. One important result, predicted earlier, is that a cone causes a three-dimensional relief effect in the flow, where a cone will have a shock wave closer to the conical surface, and therefore will be weaker than a wedge of the same vertex angle. This result is due to the cone being a fundamentally three-dimensional flow field. The inviscid solution was shown to accurately predict wave angles and surface pressures under contemporary experiments. Besides the inviscid assumption, another shortfall is that it assumes a cone of infinite length. Nevertheless, it provides a strong approximation for the shock generated by the cone. For a cone with a 25° semivertex angle at Mach 2.05, the theory predicts a constant 42° shock angle [34]. The shock trace is described by the conic section intersection between a plane and a cone, which is a hyperbola. Since the wall is a distance of 6.35 cm from and parallel to the cone axis of rotation, the equation of the inviscid shock trace is given by Eq. (24), where $x$ is the streamwise coordinate and $z$ is the spanwise coordinate.

$$x^2 - \left(\frac{z}{\tan 42^\circ}\right)^2 = \left(\frac{6.35 \text{ cm}}{\tan 42^\circ}\right)^2$$ (24)
4.2 Oil Flow Results

Figure 12: Surface oil flow results over half of plate. Approximate streamlines in yellow, separation line in red, 2D attachment line in blue, 3D attachment line in green, and plate centerline in green dashes.

Figure 12 shows an oil flow image with approximate representative oil streaklines (yellow), 2D and 3D attachment lines (blue and green, respectively), and a separation line (red) over one half of the plate. The tunnel centerline is identified with a green dashed line. As the flow approaches the shock, it begins to diverge away from the plane of symmetry. The flow diverges ahead of the shock because of upstream influence in the boundary layer, as can be observed in the pressure-sensitive paint results. The red separation line matches the shape of the inviscid shock trace and approximates its location; however, the exact location of the inviscid shock trace cannot be determined here with a high degree of accuracy. The flow topology here looks much like that for a blunt fin or vertical cylinder [35] [36] [3]. This suggests that near the surface the conical SBLI behaves as if there is an obstacle in the flow. This will be referred to as a self-imposed shock
obstacle. Behind the shock, there is a region of separated, reverse flow that follows the shape of the shock. Nearest to the centerline, this separated flow is separated in a two-dimensional fashion, where all of the flow is oriented in the streamwise direction. Downstream of the separation line, the reattached flow continues to diverge away from the centerline. Ultimately however, this diverging flow re-orients itself and converges inward toward the centerline.

By watching a video of the surface oil flow as the wind tunnel starts and the flow develops, we may better observe the separated flow region, especially away from the centerline. Figure 13 contains four frames of this movie, and shows the development of the oil flow at different time instances. There is a region of predominant crossflow that is bounded by the separation line and an attachment line. This region is the one between the separation line and 3D attachment line indicated in Fig. 12. The yellow dots in Fig. 13 are indicative of scaling, and are spaced by 1.27 cm (0.5 in.) each in the horizontal (streamwise) and vertical (spanwise) directions in the picture. The yellow dot nearest to the bottom of the image lies along the tunnel centerline. Figure 13a displays the tunnel soon after startup, and the apparent motion of the film of oil shows in which direction that it is shearing. In this frame there is clearly a large volume of oil flow headed in the spanwise direction. Figure 13b is the same image at a later time, when the oil motion is still developing. Notice that in the upper part of the image a large volume of oil has moved toward the wall. Figure 13c is a snapshot after the flow has completely developed, and Fig. 13d is of a short time after c in order that the reader may observe the gradual changes in oil flow pattern after the main volume has been whisked away during the startup process.

![Figure 13](image.png)
Figure 13: Oil flow development over time. a) soon after tunnel start, b) oil position slightly developed, c) oil flow strongly developed, d) short time after c; notice motion of oil in separation region.

From these data we conclude that a separation bubble exists near the plane of symmetry; however, away from the plane of symmetry, a horseshoe-style vortex rolls up and off the surface over the separated region and transports fluid away from the centerline toward the side wall. Gai et al. also observed a horseshoe vortex from their oil flow results [8]. We do not see the secondary separation region that they did, however. While in the blunt fin case the reattachment line lies tangent to the blunt fin, in the current case the reattachment line neatly matches the profile of the separation line [37]. In both cases, there is a horseshoe vortex curving downstream. Because horseshoe vortices often occur in the presence of protrusions and other fixed obstacles in the flow, even passive flow control devices [7], it is again suggest that the conical shock acts similarly to a self-imposed, invisible, obstacle in the flow.

Figure 14 shows a still picture of the oil flow at the end of a test. From it we can see many of the features discussed above, especially the divergence of the streaklines just ahead of the shock, the 2D separation region near the centerline, and the far downstream convergence of the streaklines away along the centerline. We cannot see the strong 3D crossflow exhibited in the movie, though, which shows that surface flow visualizations, though often presented after the fact, are actually dynamic and contain added information when imaged as a motion picture.
Figure 14: Surface oil dot flow results over entire plate, taken in a dark chamber under blacklight illumination.
4.3 Schlieren Results

Figure 15 displays instantaneous schlieren images of the flow. The flow direction is from left to right and at a Mach number of 2.05, confirmed by measurements of Mach wave angles upstream. For flow measurement, the boundary layer thickness ahead of the shock-boundary layer interaction, $\delta_o$, as determined from particle image velocimetry measurements, is used as the length scale.

![Figures a) and b) with schlieren images and labels.]

Figure 15 (cont. on next page)
As seen in Fig. 15a, when the flow first reaches the cone, it forms an axisymmetric shock wave that comes off of the cone at a $42 \pm 0.5^\circ$ angle, the same as the angle predicted by Taylor-Maccoll theory [34]. Near the surface of the cone, Taylor-Maccoll theory predicts a Mach number of $1.46 \pm 0.1$. Assuming Mach 1.46 on the surface of the cone, the leading expansion wave will be a Mach wave with angle $43^\circ$ with respect to the cone surface, or $68^\circ$ with respect to the global freestream coordinate. This angle is confirmed in the schlieren in Fig. 15a and is seen where the relief transitions from light to dark. This expansion fan then asymptotically curves toward the impinging shock wave. The flow expands over the trailing edge of the cone into an expansion fan, indicated by the very dark relief in the region behind and downward with respect to the cone trailing edge. Downstream of the base, on the sting, there is a recompression shock that forms, the product of flow reattachment after shear layer separation over the recirculating base flow [38]. Upon close examination of the schlieren in Fig. 15c, the separated shear layer comes off of the trailing edge at a $15.6^\circ (+/-1^\circ)$ to the global streamwise direction, $40.6^\circ$ with respect to the cone surface. Using the Prandtl-Meyer function with $\theta = 40.6^\circ$, the Mach number coming off of the trailing edge, parallel to the separated shear layer, is 3.1 [39]. The presence of a second recompression shock on the sting, downstream of the first, is due to a small lip in the sting, a much smaller but identical situation as the first. The “window shock”, as labeled in Fig. 15a, is the footprint of the generated conical shock on the side windows.

The general structure of the shock-boundary layer interaction on the wall is best seen in Fig. 15. There is one set of shock waves emanating out of the boundary layer in the region $0.25\delta_o$ to $0.5\delta_o$ and another set of shock waves emanating out of the boundary layer from $\delta_o$ to $1.5\delta_o$. One possibility is that the first set of shock waves represents reflection shocks, and that the second set
of shock waves represents reattachment shocks, especially because the oil flow results suggest that the interaction is a separated interaction. There also seems to be evidence of a reattachment shock in Fig. 15a. However, the second set of shocks exists less than $2\delta_o$ downstream of the interaction, well in the range of possibility for the reflection shocks directly from the impinging conical shock wave. This evidence points against separation. Figure 15a shows a change from light to darker relief ahead of the triple point along the wall that could indicate a shock wave. However, Fig. 15b shows no shock wave. Thus, it is concluded that ahead of the interaction there is no leading shock wave, only compression waves, as in an unseparated interaction.

Moreover, the schlieren images do not display fully separated flow, such as that seen in Fig. 1 of [40]. So, other than the presence of bifurcation points above the wall and the oil flow results, the evidence points to no flow separation. All of this information together suggests that the flow is incipiently separated. This insipient separation result matches what Gai found, who did not report any fully separated flow in the interaction region for cone models at, and by extension above, 60 mm off of the surface of the wall of interest with half angles less than $46^o$ [8]. The current model is 63.5 mm off of the surface and has a half angle of $25^o$. These results confirm the 3D relief effect for a finite-length conical shock wave as compared to a wedge induced oblique shock as in [40]. Furthermore, the pressure sensitive paint results show that the pressure dramatically decreases after the conical shock, instead of staying constant after the interaction as it would for an oblique shock. Ultimately, this may suggest that a conical shock wave impinging on a plane wall as opposed to an axisymmetric wall is inherently better at entraining boundary layer momentum than a 2D shock. Moreover, because the conical shock has preferred three-dimensionality (i.e., the spanwise trace is always a downstream-concave hyperbola in the streamwise-spanwise plane), the flow follows a “preferred path”, especially for spanwise flows. This mitigates the spanwise instability found in a 2D wedge-induced shock. Further studies that need to be done are of the flow occurring near the corners. Although there is clearly less momentum loss in the center of the flow, this momentum loss may be confined toward the corners of the tunnel.

Downstream of the interaction, in Fig. 15b, there are several reflection shocks emanating from the wall. The presence of these reflection shocks is due to the curvature of the conical shock. As the shock contacts the boundary layer at different streamwise positions, the reflections are at
different streamwise positions. In addition, a video of the instantaneous schlieren images shows that these shocks are streamwise spatially unsteady. This unsteadiness is from variation in the turbulent boundary layer. In Fig. 15c, there is a dark patch along the wall, that remains small in size upstream of the interaction, but increases in size and lifts off from the wall approximately $1\delta_o$ downstream of the interaction. The schlieren suggests that this could be flow separation, however it occurs downstream of the likely separation region, and PIV results show that the flow is reattaching in this region. This patch also displays inherent unsteadiness downstream.

Because the knife edge is oriented horizontally for this photo, changes in this dark patch display changes in the wall-normal density gradient. This may be either expansion, as is confirmed in the PSP, or a temperature gradient. The unsteady changes in wall-normal density gradient downstream of the interaction indicate that after the interaction the boundary layer is no longer in equilibrium, thus analysis tools for isoenergetic boundary layers, such as the modified wall-wake method given in [10] may not be appropriate.
Figure 16: Focused instantaneous shadowgrams of the flow, showing several different structures.

Figure 16 shows several focused shadowgrams of the interaction. Using the shadowgram’s ability to observe more shockwaves, it can be seen that there are several lambda shocks, downstream of the most upstream lambda shock system that is indicative of the centerline interaction. For convention, the location of the triple point is used as the location of a particular lambda structure. Unfortunately, due to the multiplicity, faintness, and frame-by-frame variation of these structures, the exact locations were not quantified. These secondary and tertiary lambda shock systems are noticeable from 0 to $2\delta_o$ downstream of the initial lambda shock. These locations are in keeping with the conical shock curvature. If the conical shock footprint reached the side windows, which it will not due to interaction with the window boundary layers, it would contact the windows stretch downstream $3.03\delta_o$ from the initial interaction. Figure 15b shows that the window shocks begin to lose their general hyperbolic curvature approximately $1.5\delta_o$ away from the windows. Thus, after calculations, the farthest downstream from the initial lambda shock we can expect to see secondary lambda structures is $1.9\delta_o$, in line with the above observations. Furthermore, the triple-point locations vary in wall-normal height from 0 to $\delta_o$. 
when the initial interaction is only .7δ₀ above from the wall. This result suggests that the interaction may induce boundary layer thickening in the spanwise direction away from the centerline. This observation runs counter to the existence of other downstream lambda structures that are closer to the wall, which is in line with theory. Also, while Fig. 15a shows that the boundary layer does not appreciably change in size through the interaction, Fig. 16 shows that the structures in the boundary layer become less coarse and more pronounced downstream of the initial interaction. Moreover, in Fig. 16 it can be see that the size of flow structures downstream of the interaction is finer than the size of those upstream of the interaction, indicating that the interaction region “chops up” the smoother structures upstream, revealing that the boundary layer is no longer in equilibrium.
4.4 Pressure Tap Results

In order to calibrate the PSP data, pressure tap data were obtained along the plate centerline. These data were also used to characterize the best running conditions for the wind tunnel. Figure 17 shows pressure ratio $P/P_o$ versus position from the leading edge of the plate for various stagnation pressure values as measured by the pressure taps.

Figure 17: Pressure tap data at different total pressures. All taps are along centerline except tap closest to $x/\delta_0 = 5$, which is 0.13$\delta_0$ off of centerline.

All of the pressure taps are along the centerline of the tunnel, except the last one, which is located 1.27 cm (0.50 in) off of the centerline. The first tap is located ahead of the shock, so it shows the freestream pressure. At and above total pressures of 248 kPa (36 psia), the stagnation pressure has very little effect on the pressure distribution in the tunnel downstream of the shock. This result indicates that the tunnel has not completely started at the lower total pressures: the normal shock structure has not moved completely past the sting-model assembly. Above 234 kPa (34 psia) total pressure, the startup shock system has moved completely downstream. Thus, for this tunnel with the Mach 2 nozzle in place, it is best to take data above 248 kPa (36 psia) in order to avoid all effects of unstart. Schlieren images show an unsteady bow shock ahead of the
cone at 193 kPa (28 psia); thus a good rule of thumb is to never run the tunnel below 207 kPa (30 psia) in order to avoid possibility of unstart. Without the model, the tunnel will be easier to fully start; thus, these thresholds are conservative.

Because above 234 kPa the variation in downstream normalized pressure distribution is negligible, normalized PSP measurements are independent of stagnation pressure for these conditions. Thus, data were obtained at 276 kPa (40 psia). Upstream of the shock there is more variation, especially seen at the second pressure tap. This pressure tap corresponds with the upstream rise in pressure leading to the SBLI. The reason that the pressure upstream decreases with increasing total pressure is that at higher total pressures, the greater momentum of the flow suppresses the adverse pressure gradient caused by the interaction region, thus decreasing the upstream influence length. Thus, at higher total pressures, the shock-induced adverse pressure gradient acts over a shorter distance.

Figure 18: Pressure-intensity calibration of PSP a) front part of plate, b) aft portion of plate.

Figure 18 shows the calibration curves between the raw intensity data and the pressure tap data for the front and back sections of the plate. The pressure tap data are a differential pressure between the value measured at the tap and the outside ambient air pressure, $P_{amb}$, generally 99.3 kPa (14.4 psia). In order to capture the $P_{amb}$ dependence of the calibration, the pressure calibrated was a ratio of $P$ to $P_{amb}$. Two sets of data were obtained because the camera field of
view could not capture the entire plate section in its field of view. Both curves are strongly linear, in line with the prediction of the Stern-Volmer relationship.

4.5 Pressure-Sensitive Paint Results

Pressure-sensitive-paint data are especially useful in SBLI for determining upstream influence due to the ability for information to propagate upstream due to the presence of the subsonic sublayer next to the wall. Upstream influence is an important parameter for characterizing SBLI interactions [41] [42]. The upstream influence in some SBLIs is conically symmetric [42]. In this study, with a conical shock impinging on a flat plate and the associated SBLI, the flow is not conically symmetric. However, outside of the interaction region, the wall-normal pressure gradient is negligible, so the pressure data are reflective of freestream properties as well, especially in the incoming equilibrium boundary layer. Changes in slope in the reflection region can also predict flow separation [43].

Figure 22 shows the PSP data after calibration by the curves in Fig. 19. Qualitatively, we can observe the shape of the shock front, which is the same shape as seen in the oil flow results. As the flow moves downstream, along the centerline the pressure suddenly begins to rise at $x = -1\delta_o$, peaks at approximately $x = 0.5\delta_o$, and then decreases gradually to a minimum beyond $x = 6\delta_o$, in line with the pressure tap data presented in Fig. 17. Moving away from the centerline, the maximum pressure for each spanwise coordinate decreases to its minima at $z = -3\delta_o$ and $z = 2.5\delta_o$. Moving closer to the side wall causes an increase in the pressure again. This is probably due to sidewall influence. Although not seen, the sidewalls are located at $z = \pm 6.59\delta_o$ in this view. Downstream the isobars increase in curvature, indicating increased turning of the flow toward the centerline, predicted by the oil flow results. It appears that the sidewalls might be the cause of this increased curvature beyond $z = -3\delta_o$ and $z = 2.5\delta_o$. 
a)

Figure 19 (cont. on next page)
Figure 19: Pressure map over a) front half of plate, and b) back half of plate. The coordinate origin is along the plate spanwise centerline and at the inviscid shock footprint.

Further downstream the pressure decreases, indicating expansion in the flow, and it ultimately expands to a pressure even lower than the freestream. One possibility for this is temperature sensitivity of the paint; however, the same pressure trend is observed in the far downstream pressure tap of figure 1, demonstrating low temperature sensitivity of the PSP. The flow has probably not increased in velocity beyond the freestream velocity because of total pressure losses through the shock system and interaction region. Because of the shape of the isobars, we know that the flow turning and expansion downstream of a conical shock is inherently three-dimensional. Downstream of the shock and away from the centerline, the amount of flow turning is the greatest, indicated by the strong increase in curvature of the isobars. The increase in curvature has two inflection points, at about $z = -3\delta_o$ and $z = 2.5\delta_o$. Noticeably, these are the same locations where sidewall influence started to be felt upstream. So, while sidewall influence exerts a harsher adverse pressure gradient upstream, in the downstream region the sidewall influence exerts a stronger favorable pressure gradient. So, there are two regions of strong favorable pressure gradient: along the centerline due to the stronger shock on the plane of
symmetry, and near to the sidewalls. What would useful at this point would be to view pressure data near the sidewall.

![Pressure curves at different spanwise positions versus streamwise coordinate. The 0.155δ_o is the spanwise plane where PIV data was taken.](image)

**Figure 20:** Pressure curves at different spanwise positions versus streamwise coordinate. The 0.155δ_o is the spanwise plane where PIV data was taken.

Figure 20 shows streamwise plots of pressure at different spanwise coordinates. From the oil flow and schlieren results we have deduced that the flow is incipiently separated. The separation should show up in the pressure data as a double-plateau, in which the pressure linearly rises ahead of the shock and flattens out over the separated flow region. After the flow becomes reattached, the pressure should rise again into another plateau [43]. In the line plots, there is a negligible double-plateau effect. The pressure linearly rises, then decreases slope into another linearly rising section, and then flattens at the maximum pressure before immediately decreasing in the downstream region. If there is a separation region, it occurs at the small change in slope located at around $x/\delta_o = 0$. Similarly, Gai did not observe a pressure plateau in his pressure data [8], nor did he think that his data suggested any separation, probably because the pressure tap grid layout used by him does not have as high a spatial resolution as these PSP results. There is no second plateau due to the significant expansion behind a conically shaped shock, unlike a 2D separation region in which the pressure remains constant behind the shock.
Figure 21: Upstream influence normalized by boundary layer thickness.

Figure 21 is a plot of the upstream influence length in the streamwise direction normalized by boundary layer thickness versus spanwise distance from the centerline. The upstream influence is defined as the distance between the inviscid shock trace and the intersection between the initial pressure-rise slope and the constant incoming pressure [37]. From particle image velocimetry, the incoming boundary layer thickness is 8.92 mm (0.380 in). These results show that the upstream influence is on the order of the boundary layer thickness across the entire span. Moreover, although the upstream influence is predominantly constant across the span, it is at a minimum along the centerline, where the shock is strongest. This effect is weak, but it suggests that a stronger shock wave reaches deeper into the boundary layer, resulting in a thinner sublayer, ultimately weakening the upstream influence.
4.6 Particle Image Velocimetry Results

The raw image data were processed into instantaneous PIV velocity data, which were then post-processed into mean and turbulent velocity data, vorticity, and shear-stress data. Figure 22 presents the mean velocity data in streamwise and wall-normal directions over the whole data set. Figure 23 displays the mean velocity data in a region zoomed in on the interaction. The coordinate origin was defined by extrapolating the linear, upstream, far-above-the-wall part of the impinging shock wave in the field of view to the point that it hit the wall, as was done in [15]. This location is representative of the inviscid trace of the impinging shock wave.

**Figure 22:** Mean normalized velocity data in the a) streamwise and b) wall-normal directions.
a)

b)

**Figure 23:** Zoomed in on the interaction region, mean velocities in the a) streamwise and b) wall-normal directions. The white region in b. is a region of significantly low $v$-velocity, so it was colored white so as to maintain an appreciable color resolution in the interaction region.
Upstream of the impinging shock wave, the mean flow is almost completely in the streamwise direction, as is expected from inviscid theory. The wall-normal velocities are negligibly negative in this region, probably due to the PIV image plane being rotated 0.113° clockwise with respect to the tunnel plane. Also upstream of the interaction, the boundary layer is in equilibrium and remains at a relatively constant thickness. Outside of the boundary layer, when the flow impacts the impinging shock wave, the flow immediately turns downward, as expected. The flow that is farther from the wall appears to turn at a sharper angle through the impinging shock than the flow nearer to the wall. This is contradictory to theory, where the flow should turn at an identical angle at all locations along a shock, as is confirmed by PIV of 2D flows [44]. The cause of these angle differences is the interaction between the impinging shock and the expansion fan. Before the first expansion wave intersects the shock, the angle is predicted to be constant, and is, as seen in schlieren results. As the shock-tangential coordinate increases, the flow impacting the shock wave feels a smaller amount of the expansion after going through the shock wave. This effect indicates that the expansion is absorbed in the shock wave, and can be visualized by slight curvature in the streamwise direction by the shock wave. This expansion continues all the way to the interaction, but its effect is severely weakened by $y = 0.7\delta_o$ above the interaction. Part of this expansion can be attributed to particle lag because the PIV particles are not massless, so the shock in PIV measurements cannot be finely resolved. In the region between the impinging and reflecting shocks, the flow accelerates in the streamwise direction and increases from strongly negative to strongly positive in the wall-normal direction. If the base of the cone were flush with the sting, as would more likely occur in a physical system, then the expansion coming off of the sting would be weaker, but the leading Mach wave would be identical. After the flow decelerates through the reflecting shock, it again expands until contacting the reattachment shock from the cone base.

In the region above the boundary layer the flow clearly desires to continuously expand, being retarded only by shock waves. The first acceleration is due to the expansion fan off of the cone base, but the source of subsequent acceleration is unknown. In light of this information, it would be helpful to have PIV data of the field very far downstream. This analysis concurs with the both the PSP and schlieren results, the former of which suggests rapid expansion downstream of the interaction and the latter of which indicates expansion after the reflecting shock wave.
interaction. The physical mechanism underlying the expansion downstream of the interaction is not clearly understood, though it may be due to three-dimensional spanwise divergence of the streamlines away from the centerline caused by the shape of the shock. As the flow traverses the shock, the shock shape deflects the wall toward the side walls. It does not occur in a normal SBLI or 2D oblique impinging SBLI [45]. Gai noticed similar results in his pressure tap data but left it unexplained [8]. Since it occurs in the tunnel center region, then it is a product of the cone, and not of the sidewall interactions. This suggests that a conical shock has inherent expansion in the spanwise direction. Normally 3D relief for a cone is described by streamlines that curve toward the cone surface, but these results suggest that 3D relief extends to intersected surfaces. More interestingly, the expansion is nearest to the centerline, not on the outside.

As seen in Figs. 22a and 23a, the streamwise velocity of the fluid near the wall slows at $x = -1\delta_o$. This location coincides with the leading compression waves emanating ahead of the triple point, identifiable by a sharp increase in $v$ going from approximately $(-1.05\delta_o, 0)$ to $(-0.65\delta_o, 0.65\delta_o)$, as seen in Fig. 23b. This sudden increase in $v$ coincides with a slowing in $u$, further evidence that the flow has passed through the leading compression. $u$ reaches its lowest value at $x = -0.3\delta_o$, which coincides with an abrupt sign change in $v$, indicative of the flow passing through the trailing shock. After this point the boundary layer increases in speed as the flow heads back toward equilibrium.

In the mean velocity field there is little evidence of flow separation. There is no evidence of a reattachment shock, confirming that the possible reattachment shocks seen in the schlieren photos are, in fact, reflection shocks at far spanwise coordinates from the centerline. Furthermore, the PIV measurements show no recirculating flow. But the resolved PIV locations do not reach completely to the wind tunnel wall, and the interrogation windows are approximately $0.66$ mm x $0.66$ mm. There is a subsonic layer occurring from $-0.75\delta_o$ to $1.25\delta_o$ that has a maximum thickness of $0.17\delta_o$ at approximately $-0.3\delta_o$. This is also the streamwise location where $v$ changes sign.

Although there is no evidence of mean flow separation, there is some evidence of instantaneous flow separation, as is observed in [44]. In these cases we can induce that the flow probably is
separated because the values of $u$ at and next to the separated region are much smaller than the average values of $0.3u_e$ (158 m/s). Moreover, there is a smooth streamwise spatial gradient going into or away from these local separation regions. This data implies that there is unsteady incipient separation. This result concurs with [44] in describing the flowfield of an impinging shock as non-mean-flow dominated, i.e., there are significant aspects that cannot be observed in the mean flowfield.

Figure 24 presents the turbulence, measured as rms velocity fluctuations, in the streamwise and wall-normal directions. Figure 24a shows that streamwise turbulence intensity is concentrated next to the wall, under the interaction regions, and just behind the impinging shock far above the wall. The turbulence next to the shock indicates fluctuations in shock position, in agreement with the schlieren results. Interestingly, this shock-position fluctuation decreases along with the decrease in post-shock expansion discussed above, indicating that the level of shock fluctuations could be directly related to intersection with expansion fans. Figure 24a also reveals that all the turbulence of the incoming boundary layer is concentrated less than $0.8\delta_o$ from the wall in the wall-normal direction. The interaction increases the streamwise turbulence immediately after the interaction, but suggests that the recovering boundary layer has less turbulence than the incoming boundary layer. Along the whole domain, there is large turbulence next to wall in the boundary layer, as expected. Even though turbulence is stronger closer to the wall, this region is also prone to more error. The wall-normal turbulence shows the same basic trends as the streamwise turbulence: overall increases through the shocks and the interactions regions and concentrated areas just downstream of the various shock waves.
Figure 24: Velocity fluctuations in the a) streamwise and b) wall-normal directions.

Figure 25 shows swirling strength calculations and Figs. 26 and 27 show instantaneous streamline plots in various convective reference frames. Since separated flows are known to produce eddies that convect away from the separation due to a Kelvin-Hemholtz instability [46], the evidence of vortices coming out of the interaction region could indicate separation despite other data to the
Vortex identification was made using the vortex center identification algorithm in [47] and the swirling strength algorithm [48]. The first method did not show evidence of vortices caused by the interaction, and is not shown here. The swirling strength algorithm, implemented in DaVis, identified many vortex structures with no obvious correlation. Decreasing the sensitivity of the swirling strength did not reveal any clear features, either. It was found that making streamwise plots in DaVis made visualization of rotating structures very simple. It was found that for streamwise convective velocities $u_c \leq u_e$, there were convective structures.

Upstream of the interaction, it was found that the vortices remain at an approximately constant wall-normal displacement for a specific convective velocity. The vortices transported at higher convective velocities were located higher in the boundary layer, and including some structures traveling at $u_e$ at the edge of the boundary layer, seen in Fig. 26a. This information suggests that the structures in the incoming boundary layer convect at a rate proportional to the local value of $u$, independent of $u_e$. The presence of transporting structures over a range of convective velocities helps to explain why the swirling strength calculation had many large peaks. The swirling strength calculation is reference frame-independent, unlike a calculation of vorticity and other vortex identification algorithms; thus, it detects all of these rotating structures, not distinguishing by convection. Downstream of the interaction there are significantly fewer traveling eddies. This evidence confirms a lack of flow separation. The streamline plots suggest that the interaction decreases the amount of coherent rotation. However, the swirling strength calculations show roughly the same amount of rotation after the interaction as before, as indicated by the plot of swirl velocity standard deviations. One possibility is that the structures are too fine after the interaction for detection. Another possibility is that the interaction converts the angular momentum of the incoming fluid into the spanwise direction. This evidence is suggested by the presence of a large rotation under the interaction region at a convective speed of $0.6u_e$. These data confirm the existence of a horseshoe-style vortex seen in the oil flow results. If the upstream angular momentum is concentrated into the angular velocity of the vortex, and other energy is dissipated as disorganized turbulence downstream that would explain the lack of coherent rotational structures downstream.
Figure 25: Swirling strength calculations. All positive values indicate rotation; larger values indicate stronger rotation. a) Average calculation, b) Instantaneous calculation (frame 855)
a)

b)

c)  

Figure 26 (cont. on next page)
Figure 26: Instantaneous streamline plots of the flowfield upstream of the interaction at convective velocity ratios $u_c/u_e$ of a) 1.0, b) 0.9, c) 0.8, d) 0.7, e) 0.6.

Figure 27 (cont. on next page)
Overall, the PIV results show that the interaction is strongly dominated by expansion coming off of the base of the cone model, lacks mean separation but displays evidence of instantaneous separation as observed by Humble in [44], and destroys incoming organized rotation by possibly expelling the angular momentum in the spanwise direction. In order to confirm these conclusions, it would be ideal to take PIV data farther downstream and farther in the spanwise direction.
CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary

In the current study, several different measurement techniques were implemented. Schlieren imaging was used to image the significant flow features, including the shock wave generated by the cone, shock waves and structure in the SBLI region, expansion fans, and shock feet and shape on the side windows. The schlieren results were used quantitatively in order to determine locations for pressure taps for surface pressure measurements, used to calibrate high spatial resolution pressure sensitive paint measurements over the surface. Surface oil flow was used in order to understand three dimensional flow topology of the interaction. Lastly, particle image velocimetry was used in order to capture detail measurements of the entire velocity field for the incoming boundary layer, the interaction, and the boundary layer downstream of the interaction. The PIV data upstream is useful for other experiments for this facility, as this experiment is the first time that a Mach 2 nozzle has been used in the facility. Figure 28 shows the mean streamwise PIV and PSP results overlaid on top of a CAD model of the setup.

Figure 28: PIV and PSP measurements overlaid on CAD model of the experimental setup.
5.2 Conclusion
Ultimately, the interaction between a conical shock wave and plane turbulent boundary layer provided three main conclusions. First of all, the flow is strongly dominated by expansion that is concentrated toward the centerline, a.k.a. the plane of symmetry. This expansion manifests most noticeably as a strong pressure drop downstream along the surface and as increases in flow speeds in the freestream after the interaction. This suggests that 3D relief can be used to generate strong expansion in an incoming boundary layer, even overcoming the adverse pressure gradient associated with the SBLI. Secondly, this interaction is similar to a blunt fin interaction because there is a curved interaction, curved attachment-reattachment structure, and horseshoe vortex transporting fluid out of the interaction region toward the sidewall and downstream. The separation-reattachment structure and horseshoe vortex are also seen in subsonic regimes when flow strikes a vertical cylinder on a surface [49]. There is also upstream influence that has relatively constant distance ahead of the shock trace [37]. In light of these two experimental areas being topologically similar, one can easily compare and contrast them by thinking of a conical shock interaction as being akin to generating an “artificial” obstacle in the flow. This effect can be exploited in designs where flow redirection is required but a physical obstacle is impossible, such as in a low pressure exhaust. Thirdly, the interaction appears to smooth out and cancel larger-scale vortical structures in the incoming boundary layer. It is possible that the 0.66 mm × 0.66 mm size PIV interrogation windows are not fine enough, so that this angular momentum is in fact “chopped up”, but the presence of a large vortical structures convecting at 0.6Ue under the interaction suggests that angular momentum is transferred in a spanwise direction by the interaction. Indeed, both results are possible, but it remains to be seen to what extent.

5.3 Future Work
Future work that would be helpful includes the use of fully three-dimensional tomographic or stereo PIV on the interaction to fully characterize spanwise fluid transport. High speed, time-lapsed PIV would be useful for studying spanwise unsteadiness, in order to gauge the relative level of geometrically 3D interactions such as the one studied here as opposed to geometrically 2D interactions.
REFERENCES


APPENDIX A: PIV UNCERTAINTY

Error analysis was conducted according to the method outlined in [50]. This method outlines four sources of uncertainty, see in Figs. 29b-e: that due to equipment and setup, particle lag, sampling, and post-processing. The post-processing error was calculated using 20 synthetic images processed in the same fashion as the real images.

Figure 29 (cont. on next page)
Figure 29: Non-dimensional uncertainty plots: a) total uncertainty, b) equipment uncertainty, c) uncertainty from particle lag, d) sampling uncertainty, e) post-processing uncertainty.

As seen in Fig. 29a, the uncertainty is concentrated at the location of the impinging shock, and at the interaction of the reflecting shock and the sting reattachment shock. There is also a small band of uncertainty concentrated near the wall. Upon looking at the breakdown of individual uncertainties types, we can see that the uncertainty in shock location is largely due to particle lag, and also uncertainty arising from post-processing of the PIV data. These two uncertainties are coupled. As the flow rapidly slows through a shock, the inertia of the particles makes their deceleration slower than the flow. However, they still undergo a rapid deceleration, which is then more difficult for the PIV software to interrogate. Among the individual uncertainty types, uncertainty due to experimental equipment is the largest. The distribution of this uncertainty follows the same distribution as the net velocity because this uncertainty is represented by the speed (represented in pixel displacement per time) multiplied by a set of constant uncertainty terms, seen in Eq. 25, modified from Ref. [50].

\[
   w_u = \frac{\bar{u}}{L} \sqrt{w_L^2 + \left(\frac{\ell}{L}\right)^2 (w_{L1}^2 + w_{L2}^2) + \left(\frac{\ell}{\lambda} w_\lambda\right)^2 + \left(\frac{\ell}{\Delta t}\right)^2 (w_{\Delta t1}^2 + w_{\Delta t2}^2)} \quad (25)
\]

After uncertainty in the physical setup, processing error represents the next highest source of uncertainty, followed by particle lag uncertainty, and lastly by sampling uncertainty. Particle lag is concentrated where the flow goes through large accelerations/decelerations, hence it clearly denotes the shock locations. The post-processing uncertainty follows this same distribution because it is related to the lag, as was discussed a paragraph earlier. The sampling uncertainty is directly proportional to the turbulence, hence it matches the turbulence distribution seen in Figure 24. The sampling error is very small because it varies inversely with the number of images, and
1934 image pairs is large. Overall, the total average uncertainty in velocity measurement was 17.3 m/s, 3.28% of the freestream velocity of 526.3 m/s.
APPENDIX B: NEW LABVIEW CONTROL LAW AND GENERAL OVERVIEW

B.1 New Control Law

The wind tunnel is controlled by a program implemented in LabVIEW. The goal of the control law is to maintain the stagnation pressure, \( P_o \), at a constant target pressure, \( P_{\text{target}} \), by slowly opening a valve between the “tank farm” supply tanks and the lower pressure stagnation chamber. The inputs to the controller are tunnel stagnation pressure and feed tank pressure, \( P_{\text{tank}} \). Wind tunnel test section static pressure and stagnation temperature data are also available. The output signal from the controller is electrical current, \( I \), to send to the control valve. The more the valve opens, the higher the stagnation pressure. The lower the tank pressure, the lower the stagnation pressure. Because of the high mass flow out of the tanks, the supply pressure rapidly decreases during operation. Thus, the valve must be increasingly opened as time goes on. After operation ceases, the valve is closed and the air compressors slowly increase the tank pressure. Because the tank air supply is limited, the control law must be efficient in order to achieve runtime. Figure 30 demonstrates the layout of the operation:

Figure 30: Layout of the operation. Orange indicates mechanical devices; green indicates computerized equipment; dashed black lines indicate information flow; solid black and white arrows indicate direction of air flow; continuum of dark blue to light blue to white represents continuum from high pressure to atmospheric pressure of air flow.
In order to efficiently reach and maintain target pressure in the stagnation chamber (plenum), so that $P_o = P_{\text{target}}$, the control law was designed with two stages: the first stage rapidly opens the control valve to a target pressure, and the second stage is a closed-loop, PID (proportional-integral-derivative) feedback controller to maintain constant pressure. The reason that two stages are used instead of one closed-loop, PID stage is to alleviate the significant settling time that occurs if only a PID method is used. For the Mach 1.4 nozzle, the first stage is an open-loop bicubic interpolation function, and the second stage is a P-controller. For the Mach 2 nozzle, the first stage is represented by two 5th order polynomial surface functions, and the second stage is a PD-controller. The reason that a new control law needed to be developed was that the wind tunnel, the plant, changed, so that the Mach 1.4 controller, the original controller designed in line with [16], no longer was acceptable. It was found to be difficult to immediately adapt the control law from the Mach 1.4 nozzle to the Mach 2 nozzle by merely changing coefficients in the program. It was found to be time-consuming to develop a methodology to make a new control law, so the purpose of this document is to give direction of the methodology for the Mach 2 nozzle in order to ease the development of new control laws in the future, as all blow-down wind tunnels have a similar layout to what is shown in Fig. 30.

### B.1.1 Strategy to Make a New Control Law

The first step is to generate two functions with the form $I = f(P_{\text{target}}, P_{\text{tank}})$. In the current case a 5th order surface fit polynomial was chosen for both:

$$I = a_0 P_{\text{target}}^5 + a_1 P_{\text{target}}^4 P_{\text{tank}} + a_2 P_{\text{target}}^3 P_{\text{tank}}^2 + \cdots + a_{n-2} P_{\text{target}} P_{\text{tank}}^4 + a_{n-1} P_{\text{tank}}^5 + a_n$$  \hspace{1cm} (26)

In order to calculate the coefficients, 79 calibration runs were performed, the data of which were analyzed using a linear least-squares fit in MATLAB. A calibration run is one run under constant input current conditions. A sample calibration run is shown in Fig. 31.
The time before $t_i$ is an initial wait period. At $t_i$, the signal is first sent to the valve to open by supplying it with a constant current (13.7 mA in Fig. 31), the value used for $I$ in Eq. (26) for both polynomials. The value of $P_{\text{tank}}$ at $t_i$ is the value used in Eq. (26) for $P_{\text{tank}}$ in both polynomials.

After some delay in valve opening, the pressure initially rapidly rises, which is concluded at time $t_{\text{ramp}}$. The stagnation pressure at $t_{\text{ramp}}$ is $P_{\text{ramp}}$, and is the value used for $P_{\text{target}}$ in Eq. (26) for the first polynomial, also known as the “ramp law”. Then, the stagnation pressure begins a slow rise from $P_{\text{ramp}}$ to $P_{\text{peak}}$. $P_{\text{peak}}$ is the stagnation value at $t_{\text{peak}}$ as well as the value used for $P_{\text{target}}$ in Eq. (26) for the second polynomial, called the “peak law”. In order to vary the tank pressure, the tunnel must be run until the tank pressure dips below the desired tank pressure. After the tunnel is shut off below this desired pressure, the tank pressure will slowly rise. Once the tank pressure rises past the desired point, the user activates the tunnel. This procedure is necessary because the compressors cannot be paused at a specific tank pressure.

The end result of this initial stage is that the stagnation pressure rapidly rises, i.e., in a time much shorter than $t_{\text{peak}} - t_i$, to the target pressure. At this point the PID second stage takes over, already at its target pressure, thus minimizing overshoot and, more importantly, settling time. Overshoot is only undesirable if it takes the tunnel over a safety limit, such as the 50 psia.

Figure 31: Sample data set for one run.
software emergency shutoff switch. It should be noted that although the 5th order polynomial function used for the first stage is technically closed-loop, the control valve will fully open, causing an emergency shutoff. This negative behavior is attributable to the fact that the polynomial fit curves rapidly trend toward positive and negative infinity outside the main operating region.

B.1.2 Controller Tuning
The second stage of the control law is a modified PID controller. For the Mach 1.4 nozzle only the P-coefficient is used, and in the Mach 2 only the P and D coefficients are used. A PD-controller was chosen over a P-controller because the derivative component works to minimize overshoot and settling time [51]. The integral component was left out because the steady-state stability is more important than accuracy. Steady state error can be added or subtracted out manually. In order to select the proportional and derivative coefficients, $K_p$ and $K_d$, respectively, there are predictive tuning algorithms, such as the Ziegler-Nichols method [52], but manual fine tuning will always be required eventually. Make sure to first tune the order-of-magnitude. The Mach 2 nozzle coefficients were much lower than expected, $K_p = 2 \times 10^{-6}$ and $K_d = 10^{-5}$.

Reference [51] provides a freely available (online), handy “cheat-sheet” for tuning PID as well as a theoretical overview.

B.2 General Layout of LabVIEW Program
Figure 32 shows pictures of the program, and gives the logical sequence of the program as it is run.
Main front panel

*Automatic control inputs encircled in green*

Auto/Manual toggle switch

\[ P_{\text{target}} \]

Ramp time \( K_p \), \( K_d \), \( dt \)

a)

Main block diagram

Auto Control Rev D

\[ \text{True} \]

\[ \text{False} \]

b)

**Figure 32** (cont. on next page)
1. Polynomial Ramp Law

Poly Ramp Law (R1):
\[ z(x) = -4.42331274508631e-009 \times x^5 + 31.7528599611527e-009 \times x^4 + 86.0297321003539e-009 \times x^3 + 242.394524764919e-009 \times x^2 + 28.3214853095215e-009 \times x + 707.4089642241206e-009 \times y^4 + 1.4354726894869e-006 \times y^3 + 21.8206041931118e-006 \times y^2 - 61.31765943776e-006 \times y - 98.1922420007578e-006 \times y^2 + 116.1092767172914e-006 \times y^3 + 59.1380354400840e-006 \times y^4 + 5.6623295490816e-003 \times y^5 + 10.414134280874e-003 \times y^6 - 2.73714044081845e-003 \times y^7 + 69.6036110915693e-003 \times x^2 + 618.1838890425636e-003 \times y + 26.488992139748e-003 \times y^2 + 8.6419470953288e-003 \times y + 19.9967372709252 \times y,
\]
\[ y = 291.360461276351 \]

c)

2. Polynomial Peak Law

Peak Ramp Law (R2):
\[ z(x) = 25.680030746188e-009 \times x^5 + 283.882083685782e-009 \times x^4 + 847.537967434626e-009 \times x^3 + 2.10640823440183e-006 \times x^2 + 1.20672758732582e-009 \times y + 898.22795157764e-009 \times y^2 + 3.74576579406034e-006 \times y + 5.94090984409452e-006 \times y^2 + 1.42353503421725e-006 \times y^3 - 241.5259012040904e-006 \times y^4 + 126.39609430008e-006 \times y^5 + 226.736422326285e-006 \times y^6 + 3.60781902489508e-003 \times y^7 + 1.47983517576683e-003 \times y^8 - 2.15012917881551e-003 \times y^9 - 6.546289418512836e-003 \times x^2 - 243.712387259447e-003 \times x + 726.223115281793e-003 \times y^2 + 5.14390112070335 \times y + 19.3598941499179 \times y + 121.525909828159 \]
d)

Figure 32 (cont. on next page)
3. Control Algo Mach 2 PID

PID or PD-controller description

<table>
<thead>
<tr>
<th>Variable List</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cd</td>
<td>output current on current iteration</td>
</tr>
<tr>
<td>minim</td>
<td>output current for previous iteration</td>
</tr>
<tr>
<td>maxim</td>
<td>maximum allowed output current (0.021s device maximum)</td>
</tr>
<tr>
<td>sp</td>
<td>User Input Main front panel desired/target stagnation pressure, ( P_{target} )</td>
</tr>
<tr>
<td>pv</td>
<td>current stagnation pressure</td>
</tr>
<tr>
<td>err</td>
<td>( sp - pv )</td>
</tr>
<tr>
<td>err_old</td>
<td>( &quot;err&quot; ) on previous iteration</td>
</tr>
<tr>
<td>dt</td>
<td>User Input Main front panel derivative denominator</td>
</tr>
<tr>
<td>der</td>
<td>( (err - err_old)/dt ) approximate time derivative of error</td>
</tr>
<tr>
<td>p</td>
<td>User Input Main front panel ( K_p ) = proportional coefficient for PID control</td>
</tr>
<tr>
<td>d</td>
<td>User Input Main front panel ( K_d ) = derivative coefficient for PID control</td>
</tr>
<tr>
<td>tankP</td>
<td>current tank pressure</td>
</tr>
<tr>
<td>tankP_i</td>
<td>initial tank pressure [at start of run]</td>
</tr>
<tr>
<td>prop</td>
<td>temporary variable</td>
</tr>
<tr>
<td>&quot;004&quot;</td>
<td>lower limit on current output (analogous to maxim)</td>
</tr>
</tbody>
</table>

Figure 32: Control law sequence in LabVIEW diagrams. a) – f) are in logical order.
APPENDIX C: STING DESIGN

The sting used in the present study was originally designed to study flow control for boundary layers and shock waves in Mach 4 flow over a cone. The particular wind tunnel the sting was designed for has a test section cross sectional area of 5 in. x 5 in., and with the sting in, operates at Mach 4.03 with a flow speed of 670 m/s at working stagnation pressures under 300 psia. These intense flow conditions mandated that robustness be the driving design criterion. Furthermore, schlieren images taken without the sting in place, shown in Fig. 33, demonstrated a harsh startup process.

Figure 33: Harsh startup shock structure at Mach 4.

Because this startup structure was unquantified, the sting was designed to resist a pressure difference in the vertical direction of 370 psia (2.55 MPa), the working stagnation pressure limit of the tunnel. A finite element study was undertaken in order to determine the stresses experienced on the model. This study was completed considering both a 25° half-angle cone and a 15° half-angle cone. From this study, 150 ksi (1034 MPa) was determined to be the design stress criterion for the sting. Viscount 44 was chosen as the sting material because its yield strength is greater than 156 ksi, then sting dimensions were chosen based on the results. Although stresses on the sting are high, stresses on the cone model are not very high, so aluminum was used for the cone. The sting has since been used in that Mach 4 tunnel as well as the Mach 2 tunnel described in the main body of this thesis without incident. For the Mach 2 configuration, a small aluminum extension tube was added to make the sting longer. No extra finite element studies were done because the maximum pressure difference in the Mach 2 tunnel would be no higher than 50 psia (345 kPa), 86% smaller than the original perceived design load.
Figure 34 presents finite element results over the surface of the sting in Mach 4 configuration, demonstrating peak stresses at the corner of the sting and support. Drawings of the sting with relevant dimensions are shown in Fig. 35.
Figure 35 (cont. on next page)
c) **Figure 35**: Sting and model drawings: a) assembly blow-out, b) sting, c) 25° cone model, d) Mach 2 sting extension piece.
APPENDIX D: WIND TUNNEL SAFETY AND OPERATION

D.1 Safety

General safety procedures:

1. Always wear eye protection: safety or laser goggles
2. Always wear suitable laser goggles if laser is on
   a. Check optical density wavelength range to make sure that the goggles are suitable for the type(s) of laser(s) in use.
3. Always have someone else in lab during wind tunnel operation.
4. Lock doors.
5. Close and shutter windows in case of laser operation.
6. Turn on outside safety notification lights.
7. Wear hearing protection.
8. NEVER stand near windows during tunnel startup. Stand outside probably blast angle. If you must check the experiment, check AFTER the tunnel has started.

D.1.1 Potential hazards:

Overpressure: tunnel test section is pressurized beyond safe limits.

A. Causes
   a. tunnel exhaust is blocked and all valves between tank farm and wind tunnel are open.

B. Effects:
   a. window blowout
   b. potentially serious injury or death to persons

C. Directives
   a. NEVER stand near windows when tunnel starts. Stand outside blast angle.

D. Safety checks
   a. hard emergency shutoff switch.
   b. soft shutdown switch (LabVIEW “Stop” button).
c. automatic, software, maximum stagnation pressure limit (shuts off at stagnation pressure greater than 50 psia)

d. tunnel exhaust safety gate valve (green is open, red is closed)
   i. visual confirmation required to initiate LabVIEW program.

e. electrical gate valve interlock, described in [16].
   a. bottom access window designed to fail before side windows.

Premature tunnel operation (for example, while working in test section)

A. Causes:
   a. all valves are open between tank farm and wind tunnel

B. Effects:
   a. loose objects fly out of tunnel into lab
   b. loud noise
   c. potentially destroy experiment

C. Directives:
D. Safety Checks
   a. There are two valves between the tank farm and tunnel: the manual gate valve as well as electronic valve. Make sure gate valve is always closed except for right before a run

D.2 Operating Procedure

A. Small Compressor
B. Large Compressor
C. House air compressor
D. Basement entrance door
E. Elevator
F. Small compressor dryers
G. Large compressor dryers
H. Location of bypass valve when not using small compressor
I. Tank farm pressure gauge
J. Tank farm In Use switch
K. House air pressure gauge
L. Staircase

Figure 36: MEL basement map with pictures. Figure subheadings correspond to location on map.
D.2.1 Standard compressor startup procedure:

1. Get trained on how to use the compressors. Speak to the staff of the mechanical engineering machine shop.
   a. They can give you a key to the small compressor.
2. Get the basement key (accesses stairwell to basement as well as elevator) for the Mechanical Engineering Lab (MEL) from Professor Elliott. Basement map is shown in Fig. 36.
3. Go to basement of Mechanical Engineering Lab. Step 1 training will show you the compressor locations.
4. Turn on small compressor. See Fig. 37a.
   a. Make sure OnOff/Modulate dial is set to Modulate.
   b. Set Normal/No Load dial to No Load.
   c. Use key from machine shop to turn on compressor.
   d. Wait for small compressor to heat to 100 °F (can take several minutes).
   e. Turn Normal/No Load dial to Normal.
5. Wait for small compressor to pump tank farm up to 90 psi. See Fig. 37b.
6. Turn on large compressor. See Fig. 37c.
   a. Press start button.
   b. Wait about 10 seconds (can hear machine turn over). Press No Load button.
   c. Wait until coolant temperature reaches 150 °F (< 1 min).
      i. *Coolant temperature may not be shown on the home screen—cycle through using the up and down arrows. Because of the plastic covering over the keys, the buttons are difficult to reach. I used my long fingers; others have used a ball-point pen.
   d. Press Load button.
7. Turn tank farm switch to In Use. Fig. 37d.
D.2.2 One-compressor-down startup procedure:

If the small compressor is in maintenance, the tank farm can still be run using solely the large compressor using this modified procedure. If the large compressor is in maintenance, you can probably follow the standard procedure, but check with the MEL machine shop first.

Warning: If this modified procedure is not followed, the house air in MEL may fail, causing other’s problems. To check if the house air may fail, ensure that the house air pressure reading is above 90 psi, shown in Fig. 37f. If it’s dropping rapidly, turn the air
compressors back to no-load. DO NOT TURN THEM OFF. The reason that the house air may drop is because it partially powers the dryers for the large compressor.

1. – 3. Same as standard procedure.
4. Close the large dryer bypass valve, seen in Fig. 37e. The valve is located on the piping work behind the large compressor dryers.
5. Turn on the large compressor as specified in the standard procedure.
6. After pressure rises above 100 psi, open the valve closed in step 4.
7. Turn tank farm switch to In Use.
8. When operating under these conditions, ensure that the tank farm pressure does not go below 90 psi as observed in the lab.

D.2.3 Compressor shutdown procedure

1. Turn the tank farm switch to Not In Use.
2. Turn both compressors to No Load operation.
   a. Turn dial on small compressor to No Load.
   b. Press No Load button on large compressor.
3. Wait at least 10 minutes. Waiting ensures that the dryers can go through a final cycle.
4. Turn off compressors
   a. Press the red off button on the small compressor.
   b. Press the off button on the large compressor.
5. Record usage data on the log hanging on both compressors.
   a. Small compressors: total hours.
   b. Large compressor: total hours and run hours.
   c. Both compressors: any problems.
6. Note, a couple of times the large compressor has completely shutdown on its own before I arrived to shut them down and displayed an auto-shutdown notice without any warning indications.

D.2.4 Wind Tunnel Operation

1. Close Gate valve.
2. Ensure that wind tunnel is ready to run (pressure measurement lines attached, windows bolted on, camera and flow control equipment ready, seeder tank pressurized).

3. Turn on pressure and temperature measurement box.
   a. Temperature T1 is the stagnation chamber temperature. T1-T2 is the temperature recorded by the LabVIEW DAQ card.

4. Start LabVIEW control program.
   a. “Main_1_6_2_M2_revD.vi” for control at Mach 2
   b. “Main_1_6_3_M2.vi” for use with NetScanner pressure measurement system at Mach 2
   c. “Main_1_6_2.vi” for control at Mach 1.4

5. Open valve for house air (automatic valve is pneumatically powered).


7. Open the gate valve.

8. **Tunnel is ready to run**—make sure people are out of the way and proceed to start via LabVIEW.

9. [If conducting flow seeding, activate seeder after flow turns on and turn seeder off several seconds before tunnel shutdown.]

10. **Press red “stop” button in LabVIEW to turn off tunnel when desired (standard shutoff or emergency).**


12. Shut off house air.
APPENDIX E: PIV PROCESSING AND IMAGE FORMATTING

E.1 Processing in DaVis: Tips and Tricks

There are many different image processing options in DaVis. They are explained in detail in the FlowMaster manual. I haven’t done a whole lot with PIV, but I have tried to understand the manual and what the key differences are, rather than just shooting in the dark. I’m convinced you can get really good looking or really bad looking results from any data set if you fiddle with stuff. So, how do you get something that has the finest accuracy, instead of something that just looks good?

E.1.1 Scaling Problems

1) Sometimes scaling doesn’t work. Possible reasons are:
   a. If, after importing images, you apply the scaling to those images, then all the processing afterward should be scaled (this is the normal order of business). Sometimes, it is not.
   b. Some processing steps, when applied to scaled images, do not use the image scales, but revert back to pixels.
   c. If you have processed images before applying a scaling, then when the project is scaled those probably aren’t scaled (even though you tell DaVis to rescale all images).
   d. Add new images to a project after original scaling.

2) To fix this (by using a temporary project)
   a. Make a new project.
   b. Open that project in Windows explorer.
   c. In Windows explorer, copy the image and set files that you want to scale (but DaVis didn’t) from their current project folders into the new project folders. This is discussed in “Moving Files Around [and renaming via Windows” section.
   d. In DaVis, close and re-open the temporary project (so that it will recognize the new files).
e. Apply the scaling you desire. If you already know it, it is really easy to enter **using the following buttons** (circled in red):

![Scaling buttons](image)

f. Copy the scaled images from the temporary project back into the original project. Close and re-open the original project.

### E.1.2 Pre-Processing Images to Get Rid of Glare

There are several pre-processing techniques to remove glare:

1) **Butterworth filter** (only in version 8.2 and later).
   
   a. This subtracts out background intensity by using a set of \( n \) image pairs.
   
   According to the DaVis manual [53], the frequency of image capture divided by two is at least the number of images, \( n \), that you should use. So, for me, \( T = 80 \) ms between image pairs. \( f = 1/T = 12.5 \text{ Hz} \). \( n = f/2 = 12.5/2 = 6.25 \). So, at least 6.25 images. So, I used 7 images.

   b. This filter was recommended by a DaVis representative and is a time filter.
   
   Because it’s a time filter, this means that it processes a string of entire image pairs, rather than a spatial filter which generally acts over a local region of pixels in a single image pair.

   c. A Butterworth filter is essentially a highly-tunable bandpass filter. Other than the number of image pairs to use for the filter, \( n \), these tuning options are set automatically in DaVis, so are not available to the user.

2) Some of the other time-series filters I found to give bright spots at the mask edges (where I canceled out data).

3) Time-series filters will filter according to means, medians, etc., over several entire images, whereas spatial filters operate in one image around a local pixel.

4) Spatial filters are available to subtract relative background strength locally.

5) Some groups average all of the PIV images together and subtract this.

6) Some take a flatfield (no flow, no particles), and subtract this out.
E.1.3 PIV Processing

1) Pre-Processing
   a. This is a local background removal filter – there are more options discussed above

2) Masks
   a. **A mask does not delete vectors.** Rather, it will, per se, not take vectors into account, especially in subsequent operations on the PIV-processed data.
   b. So, use masks to cover parts of your images that you don’t want used. But, if you are really particular, crop the images before importing to DaVis as DaVis does not have a crop feature.

3) Vector Calculation Parameter
   a. Iterations
      i. The larger the interrogation window, the higher your correlations will be. The smaller the window, the greater spatial resolution. The trade-off is between these two options.
         1. Realistically, you will probably only be able to go down to 16x16, 24x24, or 32x32. Going smaller requires a really good setup.
         2. Note, when doing “Multi-pass (decreasing size)”, DaVis lowers resolution by a factor of two from the first pass to the last pass, except when the last pass is not a factor of two away (for example, specifying from 64x64 to 24x24 is possible, even though 64/2 = 32, and 32/2 = 16. In this case the 32x32 windows will go to 24x24 windows). So, assuming one pass at each window size, these are possibilities:

<table>
<thead>
<tr>
<th>1st pass</th>
<th>Final pass</th>
<th>Window passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>64x64</td>
<td>32x32</td>
<td>64x64, 32x32</td>
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<tr>
<td>128x128</td>
<td>32x32</td>
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<tr>
<td>64x64</td>
<td>16x16</td>
<td>64x64, 32x32, 16x16</td>
</tr>
<tr>
<td>96x96</td>
<td>24x24</td>
<td>96x96, 48x48, 24x24</td>
</tr>
<tr>
<td>64x64</td>
<td>24x24</td>
<td>64x64, 32x32, 24x24</td>
</tr>
<tr>
<td>96x96</td>
<td>16x16</td>
<td>96x96, 48x48, 24x24, 16x16</td>
</tr>
</tbody>
</table>
ii. **For greatest accuracy**: choose “Multi-pass (decreasing size)” and “Adaptive PIV weighting function”.
   1. Adaptive PIV weighting function is the most accurate and always requires at least two passes for each window size.
   2. For final processing of data, do only adaptive windows.

iii. For greatest speed: choose “No weighting function” (square windows).
   1. This is a good first step – choosing square windows with only a few passes could process 1000 of my images in less than 3 hours, even 1 hour. With adaptive windows it may take more than 30 hours. So, if you want same-day results, do this.

iv. **Do not go above 50% overlap.** Ideally use only 0% overlap. Greater overlap is basically spatial averaging.

b. Options:
   i. Turn on “High-accuracy for final passes”
      1. Use B-spline-6 if you are not sure what to do. This is the default and the newest available (only on version 8.2 and later). This uses bicubic interpolation.
      2. If you perform either the Lanczos or the Whittaker reconstruction, a higher value of $n$ is better. Both are filters based on the sinc function. The Whittaker reconstruction has no smoothing. See pages 73-75 of the DaVis manual, [54]. Also, see [55] for information on Lanczos reconstruction and [56] for information on Whittaker reconstruction.

4) Vector Calculation: GPU
   a. With NVIDIA CUDA you can do parallel processing on the Graphics Processing Unit (GPU) if properly configured [57].
   b. If CUDA is not available, then this window may still be used to view the individual processing steps (window sizes and iterations) that the application will go through.

5) Multi-pass options
   a. Initial Window shift: **not necessary with adaptive PIV**
i. This is the initial guess to the PIV speed. There are noticeable accuracy improvements if using square interrogation windows and a good guess. A reference vector field (e.g., a previous output) can also be used.

b. Correlation function: the standard correlation function is the default, and is faster. But the normalized correlation function is probably more accurate, so I suggest changing to this. The standard correlation has inherent weighting and bias that needs to be dealt with through proper pre-processing and decreasing window sizes.

c. Leave “deformed interrogation windows” as-is. Other option used in deformation processes. See pg. 82 of manual if curious.

6) Multi-pass post-processing: same options as in PIV Post-processing section below. This is post-processing done after each pass of a multi-pass. LaVision suggests that properly applying the strongly remove/iteratively replace median filter in this step along with multiple-pass, decreasing size, adaptive PIV can drastically improve accuracy. I was interested in spurious turbulence statistics, so I chose to do minimal processing here, i.e., choosing a high number (10) for the basic remove/replace median filter so that no vectors were removed.

7) Vector post-processing: do not check this box. You can do the same options as a second step. If you do it within the PIV step, the post-processing is permanent. If you save it until the next step, you can change it around.

E.1.4 PIV Post-Processing

When DaVis does a PIV calculation, it does not calculate just one vector per interrogation window; it calculates several and displays its top choice. If the correlations are especially poor, it may calculate 0-2 vectors per window, but it usually calculates several. What PIV post-processing does is to give DaVis guidelines on the decision of which of several vectors calculated in an image pair to keep. It can be instructed to completely remove a vector (use none of the calculated vectors) or replace the currently active vector with another one. These options are found in “Non-linear filter” → “Vector Post-processing” option.
1) **Vector range**: this sets an absolute limit on what vector values to allow. Anything outside the limit is not allowed (replaced or removed).

2) **Correlation value or Peak Ratio removal**: the user may choose to remove vectors with a peak ratio or correlation value lower that the specified number.
   a. The correlation value indicates how much two cross-correlated windows match. 1 (autocorrelation) indicates a perfect match, and 0 indicates no match.
   b. Peak ratio (Q-value) is the height ratio between two successive peaks in a correlation. A very strong peak generally indicates a good match.
   c. For highly conservative post-processing, only engage this function with either correlation values less than 0.7 or Peak Ratio (Q values) less than 3 as recommended by [54]. To filter out both values less than 3 as well as less than 0.7 apply the post-processing filter twice.

3) **Median filter**: according to [58], median filtering techniques are more accurate at producing the real value in a sample size than are mean filtering techniques. The median filter removes vectors far from the median. You can choose from 0 to 5 passes to perform this operation.
   a. **Remove/replace**: remove vectors greater than the **given number of standard deviations** (input argument) away from the median of the vectors in the current neighborhood and replace with one within the range.
      i. **Recommendation**: set to “1” if you don’t want to capture turbulence (will filter out more). Set to “3” if you want to capture turbulence. Setting to higher numbers will only leave out the most extreme results.
   b. **Strongly remove and iteratively replace**: An improvement on remove/replace. Once you find a good value for remove/replace, set this as the first argument. The first step removes vectors according to the standard remove/replace algorithm, and the second step proactively inserts other vectors according to this criterion.

4) **Remove groups with < [argument] vectors**
   a. **[argument]** is the number of vectors in the neighborhood. Increasing the value of **[argument]** increases the confidence of the results but deletes more vectors.

5) **Fill-up empty spaces** and **fill-up-all**: interpolation to fill up spaces where vectors were removed. Useful for derivative calculations.
6) **Smoothing**: spatial averaging

### E.2 Post-Processing in MATLAB

LaVision has a MATLAB add-in “readimx” for reading LaVision file types, which has changed significantly from version to version. However, DaVis can also output Tecplot-formatted *.dat text files as well, which are easily readable in any program. I have written a MATLAB script, DATtoDAT, which does the same things as IM7toDAT, without readimx. This is useful in Uncertainty calculations.

#### E.2.1 Formatting Images and Plots in MATLAB

Formatting of plots and images is difficult in MATLAB. It is difficult to easily change the font size, scaling, etc., to make it presentable. My recommendation is to sit down with someone for a day who knows it all and have them teach you. Useful included commands are: contour, surf, meshgrid, imagesc, imshow, colorbar, colormap, caxis, axis, set, get. Table 3 is a quick guide of custom scripts:

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>makecmap2</td>
<td>Makes custom colorbars, some pre-assigned (see help).</td>
<td>map = makecmap2(‘fav’)</td>
</tr>
<tr>
<td></td>
<td>Also makes new maps with RGB set points. Input RGB set points and the spacing</td>
<td>map = makecmap2(‘favblack’)</td>
</tr>
<tr>
<td></td>
<td>between them, and MATLAB interpolates a colormap. See help for examples of</td>
<td>map = makecmap2(</td>
</tr>
<tr>
<td></td>
<td>pre-sets.</td>
<td></td>
</tr>
<tr>
<td>figform1</td>
<td>Change font size of ALL text (title, legend, xyz axes labels, etc.)</td>
<td>map = figform1(gcf,16)</td>
</tr>
</tbody>
</table>

Table 3: MATLAB Custom Image Formatting Scripts
If you do not care about the background, skip to the *Image Import Options* section below. MATLAB and MS Office are not high school sweethearts! From my own classroom years as well as grading others’ homework as a TA, I have found that many don’t do this well. The plots may be very readable in MATLAB, but are not in MS Office. LaTeX is arguably the best option, but it is not quick to learn. This section gives a basic overview of the problem, and some solutions.

The basic problems is that MS Office has limited support for vector-rendered images. *.eps, *.emf, and *.wmf are the vector-rendered image file types that MS Office easily handles (In my experience, PowerPoint can handle *.pdf as well, but Word not so much even though it theoretically can.). Vector-rendered images are images that are mathematically-defined, such that they essentially have infinite resolution. They can be upscaled and down-scaled without losing quality; the user will never observe pixilation. The other image types, raster-rendered images, are just a matrix of individually-colored pixels (usually square in shape), and when zoomed in sufficiently, the pixilation is noticeable. High resolution raster images avoid this problem. Figure 38 compares vector and raster rendered images.

### E.2.2 Importing High-Quality Plots into Microsoft Products

<table>
<thead>
<tr>
<th>axes tick marks, colorbar labels.</th>
<th>Changes all font sizes in current figure to size 16.</th>
</tr>
</thead>
</table>


Figure 38: Difference between vector and raster images: b) is a zoomed in view of the yellow box in a), and d) is zoomed in on the nose of c).

E.2.3 Image import options

Here are a few options. There are also third-party add-ins to MATLAB that offer expanded capability, and some other office software, such as LibreOffice, includes better native support for vector graphics, but these steps only require MATLAB and MS Office.

1) Copy and paste MATLAB figure into Word (or other MS Office application, but we are assuming it is Word)
   a. In the MATLAB figure window, choose “Edit” → “Copy figure”, then paste (Ctrl + V) into Word.
   b. MATLAB copies and pastes in *.emf (enhanced metafile) format, which is vector rendered, and enables the user to re-size in Word.
c. In Word, if you want to save the figure, you can right click on the picture and choose “Save As Picture”. This will save it as an *.emf file that can be used independent of MATLAB.

2) Export from MATLAB while maintaining image transparency: if you want to make the image transparent (such that all blank spaces are transparent instead of the default white), then you must:
   a. Make the image transparent: `set(gca, 'color', 'none');`
   b. Copy figure into Word as in step #1a. If you want to save it, follow step #1c.
   c. MATLAB cannot save transparent images natively.

3) From the MATLAB figure window, choose “File” → “Save As”, and choose *.emf or *.eps (postscript file).
   a. Both of these file types are vector-rendered in MATLAB, but they look different. I prefer *.emf, but you may like the other better.
   b. Drag and drop into Word or select “Insert” → “Pictures”

4) Save the MATLAB figure as a high-resolution raster image (*.jpg, *.png, *.tif, *.bmp, etc.) and then downsize after importing into Word.
   a. To increase resolution, just resize the MATLAB figure with the mouse.
   b. If you want much larger resolution (beyond the size of the screen), change the figure position manually. For example, to increase resolution by arbitrary factor $k$ in both length and height:
      i. $A = \text{get(gcf,'pos')}$
      ii. $B = [A(1:2), k*A(3:4)]$
      iii. $\text{set(gcf, 'pos', B)}$
   c. Save the file using “saveas” command. For example:
      i. `saveas(gcf, 'data.png');`
APPENDIX F: SHORT AND EXTENDED NETSCANNER CALIBRATION PROCEDURE

F.1  Front Matter

F.1.1  Calibration Timeline

1. System needs to be zeroed (“zero calibration”/tare) at least once a day, ideally every 5 hours. The pressure transducers have a high zero drift.
2. After turning device on and waiting 45 min, zero device.
3. 98RK system needs to be calibrated once every six months.

F.1.2  Contacts

Author: Jason Hale, 949-241-7393, jason3.hale@gmail.com
NetScanner: Dan Ridenour – 757-766-4217, Chris LaRocque – 757-766-4218. I spoke with Dan and he was extremely courteous and helpful. Dan sent me an old version of the NetScanner Unified Startup Software (NUSS) manual because I could not locate one on the website. I have included that in a software package.

F.1.3  Websites and Downloads


F.1.4  Quick Calibration Directions

1. Hook up cables between 98RK (houses eight 9816 modules), 9034, and PC.
2. Turn on 98RK system
3. Wait 45 min for system to warm up. Do steps 4-7 while waiting.
4. Hook up hoses between 98RK, 9034 calibrator, vacuum pump, and N₂ tank.
5. Turn on NUSS.
6. Associate LRNs between 9034 and 9816 modules.
   a. Need one 9034 module for each pressure range you are calibrating at.
b. Cal to: “Cal”. End with: “Run” in 9816 windows

7. Set span or multi-point calibration points for the 9034 in NUSS software.

8. **If 45 min has not gone by, wait for this to complete.**

9. Turn on vacuum pump
   
   a. Remove red output plug, THEN turn on.

10. Make sure exhaust valve on N₂ tank and valves from N₂ tank to 9034 and 98RK are **closed**.

11. **Open N₂ tank** (tank to regulator).

12. Set regulator to **90 psig** on N₂ tank. **80 psig < N₂ PRESSURE < 110 psig**.
   
   a. **DO NOT EXCEED 110 psig**.
   
   b. **Won’t work under 80 psig (why I chose 90)**.

13. Re-zero the calibrator.

14. Do the multi-point scan calibration.
   
   a. **Only do once every 6 months for each transducer**.

15. Turn off the high pressure (N₂ tank). Bleed excess N₂. Close valves to 9034 and 98RK.

16. Turn off the vacuum pump.

17. Disconnect from modules in order to use in LabVIEW.

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**F.2 Extended Calibration Directions**

1. Hook up cables between 98RK (houses eight 9816 modules), 9034, and PC.
   
   a. Ethernet between PC and 98RK.
   
   b. Harness 9034 and 98RK.

2. Set IP address in PC to static IPs necessary for talking with Netscanner.
   
   a. **Start** ➔ **Control Panel** ➔ **Network Connections (Windows XP)**
   
   b. **Start** ➔ type “View Network Connections” in the search box and click on the program that pops up (**Windows 7**)
   
   c. **Right-click** ➔ **Properties** on the Ethernet connection that the 98RK box is connected to, probably **“Local Area Connection”**.
   
      i. *Some computers have multiple connections. If the following steps (c-i) do not work, then attempt them on a different connection.*
d. Under the **General** tab, click on **“Internet Protocol (TCP/IP)”** then click the **Properties** button.

   i. Click on **“Use the following IP address”**, not **“Obtain an IP address automatically”**. Change to the following : IP address: “200.xxx.xxx.xxx” (e.g. “200.1.1.1” or “200.200.200.1”)
   
   ii. **Subnet Mask:** “255.0.0.0”
   
   iii. **Default Gateway:** leave blank

   e. Click on **“Use the following DNS Server Addresses”** (it might be already clicked).

     i. **Preferred DNS server:** leave blank
   
     ii. **Alternate DNS server:** leave blank

   f. Click **“OK”** to be brought back to the **“Local Area Connection Properties”** window.

   g. Click **“OK”** to close out of it.

   **h. The IP address should now be changed. Wait 10 sec or so before checking.**

     i. Open Command Prompt and type in **“ipconfig”** and hit **enter**

        i. **Start→Run** OR {windows key}+R.

        ii. Type in **“cmd”** and click **OK**.

        iii. Type in **“ipconfig”** and hit **enter/return**.

        iv. This will display the IP addresses for the various connections. Make sure that they are the same that you input in step d.

3. Turn on 98RK system.

4. Wait 45 min for system to warm up. Do steps 5-11 while waiting.

5. Hook up hoses between 98RK, 9034 calibrator, vacuum pump, and N₂ tank.

   a. See Todd Reedy’s PhD dissertation [59] (can look it up at ideals.illinois.edu. A copy is probably on this or some other computer, and named Todd_Reedy.pdf)

   b. Calibration ports on the back of the 98RK depend on the pressure range of the individual transducer (see 98RK manual somewhere between pages 100-110). These are labeled “Cal 1”, “Cal 2”, “Cal 3”,…

   c. Which Cal port you use will be hooked up to the **“output”** port on the 9034.

   d. “125 psi” port on 98RK will be hooked up to **high pressure N₂ tank**.
6. Turn on **NetScanner Unified Startup Software, NUSS**.
   a. It will query the network automatically. If the different modules (9816s and the 9034s) that you have do not come up, then you have a problem.

7. Identify the modules that you would like to use.
   a. **Left click** on the module in order to get its information.
      i. *If left clicking doesn’t work (often it doesn’t), use the up and down arrow keys on the keyboard to move between them* (I believe that this is a bug).
   b. The “cluster/rack slot” variable is where it is mounted in the rack.
      i. *Currently they are in order left to right (viewed from the front) 1-8, with blue tape on the front of each module indicating its number.*
      ii. Module 1 is labeled “011”, module 2 “012”, module 3 “013”, … module 8 “018” – *this is ONLY for the current setup; I’m not sure if it changes if you swap out modules**.
   c. The **IP address** variable is the one that you need to use if you are accessing that module in LabVIEW.

8. **Connect** the 9816 module(s) that you want to calibrate.
   a. Select it (see 7a above about left-clicking).
   b. **Right click**, and select **Connect**.
      i. Note, right-click does right click for the highlighted module.
      ii. **Module symbol should turn yellow AND** when the “9816” parent tree symbol is highlighted, the module number should display “**connected**” next to it.
   c. Will need to **disconnect** before using in LabVIEW.
      i. Right-click as above, and select “disconnect”.

9. Connect the 9034 module by **right-clicking** “connect” as for the 9816 modules.

10. Assign LRNs for each 9034.
    a. **Left-click** (or arrow keys) to get the 9034 selected.
    b. **Go to the “NetScanner™ Unified Startup Software (NUSS)” window** (a separate window in Windows), **NOT the “Network Status” window** that we’ve done all this clicking around in.
c. Go to “Configure” → “Calibrators (NUSS)” (Configure is in the file bar).
d. There will be a column with each LRN (from 1-8).
e. For LRN #1, drop down the Calibrator list and select “9034-615” or whatever one is there, NOT “Extern.”
   i. LRN (Logical Range Number) actually doesn’t matter. LRN is just a variable name so that the software can associate a certain range of pressures (i.e., a certain number of transducers, all set for the same pressure) with a specific calibrator.
      1. NOTE that if you are using transducers rated for different pressures, then you need a different LRN per pressure range.
      ii. “Extern.” is a different way to calibrate things. I don’t know how to use it.
   f. The box just to the right will tell you the Calibrator’s range. This range is the range of pressure that the calibrator can supply to the 98RK. MAKE SURE THAT YOU DON’T OVERSUPPLY PRESSURE.
      i. IT’S OK to calibrate with a higher rated 9034 (for instance, calibrate 5 psid or 15 psid transducers with a 30 psi rated 9034, but read notes below on safety margins)
      ii. Pressure transducers have a margin at which they read voltage (i.e., a 15 psi transducer will stop reading around 18 psi, at which the voltage in the AD converter is saturated). It flatlines above this. The transducers are still accurate in this margin region, but not as accurate or guaranteed accurate outside of it.
      iii. Pressure transducers fail at 3X rated pressure (so 15 psi will fail at 45 psi)
   g. *I’m not sure how the Span Calibrate function works—this is what the “Zero-Only Set Point” and the “Span-Only Set Point” boxes are. The guy on the phone just told me to leave the first (Zero-only) set at “0” and the second one (span-only) set at “30”.
   h. Set the number of “Multi-Point Set Points” to at least “3”.
      i. What the multi-point calibration does is to calibrate at XX number of set points, and then draw a least-squares linear fit between the data points.
         1. 2 will get you a line, but isn’t that accurate.
2. 3 data points is probably good enough.
3. 5 is solid.
4. Do more if you want to be extra-persnickety. This doesn’t take vary long: I used 9 points and it took less than 5 minutes.

ii. The set points are in psi. **DO NOT HAVE A SET POINT ABOVE THE RANGE OF THE PRESSURE SCANNER.**

1. Anyway, for a ZZ psid rated pressure scanner, do from -12 psia to +ZZ for the multi-point set points.
   a. The -12 value is from Todd’s dissertation [59]. I don’t know how low of pressure the vacuum pump can hit. You may want to *cautiously* (find a manual or measure it) go lower. I think this number needs to be pretty accurate.
   b. For a 15 psid rated scanner do from -12 psia to +15 psia.
   c. For a 15 psid rated scanner do from -12 psia to +30 psia.

2. *I think that these set-points are differential reference pressures, but am not sure (i.e. if you are using a eight 5 psi transducers on rack module #4, and you are supplying a reference pressure of 500 psi [such as in a gas turbine experiment], which I believe you would supply to both the “Run Ref 4” and the “Cal Ref” ports on the back of the 98RK, but am not sure [need to check with them], then your multi point ranges would still go from -5 psi to +5 psi, even though the absolute pressures you were measuring would be say, from 495 psi to 505 psi.

   i. Click OK and exit out.

11. Associate LRNs for 9816 modules.
   a. **Left-click** (or arrow select) back in the “Network Status” window on the module that you want to calibrate.
   b. **Right-click**””Calibrate”””’Associate LRN(s)””.
   c. Set each transducer to the relevant LRN.
i. **Remember, each LRN corresponds to a different 9034** (this is necessary because some 9816 racks have different pressures on the same module).

ii. If you want to propagate values, there’s a check box at the bottom to facilitate this.

d. Set “**Cal to**” to “Cal” and “**End with**” to “Run”.

   i. “**Cal to**” sets which mode the calibration will be performed in.

   ii. “**End with**” sets which mode to move the manifold to after calibration.

   iii. The manifold switches between “calibrate” mode and “run” mode. There is a way to calibrate manually in “run” mode, but we will not do that here.

      1. Ask Phil (aka Dr. Ansell) about it.

   iv. Dan (on the phone) said that “**Cal to**” “Cal” and “**End with**” “Run” are the basic defaults, and **probably** what you should be using.

12. **If 45 min has not gone by, wait for the 45 min to complete.**

13. **The following is also discussed in Appendix C of Todd Reedy’s Dissertation [59].**

14. Turn on vacuum pump (same as #8 in Todd’s dissertation).

   a. Remove red output plug (plastic thing about .75” in diameter and 1” tall), THEN turn on.

15. Make sure valves are **CLOSED** on the N\textsubscript{2} tank.

   a. Main valve (tank to regulator)

   b. Exhaust valve

   c. [Blue] valve going from N\textsubscript{2} tank to the 98RK

   d. [Yellow] valve going from N\textsubscript{2} tank to the 9034 calibrator

16. Open N\textsubscript{2} tank **main valve.**

17. Set regulator to **90 psig** on N\textsubscript{2} tank. Limits: **80 psig < N\textsubscript{2} PRESSURE < 110 psig.**

   a. Pressure regulator **IS OPPOSITE** that of fasteners! I.E. **RIGHT-LOOSE,** **LEFT-TIGHT.**

      i. **TURN RIGHT (CLOCKWISE) == MORE PRESSURE!!**

   b. **DO NOT EXCEED 110 psig.**

   c. Won’t work under 80 psig (why I chose 90).

18. Open valves
a. Blue valve going from N2 tank to the 98RK
b. Yellow valve going from N2 tank to the 9034 calibrator

19. Readjust regulator pressure if needed.

20. Do a re-zero calibration.
   a. *Need to do this at least once a day, preferably every 5 hours.*
   b. Do this first thing after 98RK has warmed up for 45 minutes.
   c. Right-click module to be calibrated (make sure it’s connected)
      i. Select “Calibrate”→”Re-zero”.

21. Do the multi-point scan calibration.
   a. *ONLY need to do this once every 6 months for each pressure transducer.*
      However, it only takes about 2 minutes to do a 9-point calibration (tad overkill),
      probably15 minutes including turning the tanks on, etc., if you know what you’re
      doing, so if you don’t know last calibration date, do it.
   b. Right-click module to be calibrated (make sure it’s connected)
      i. Select “Calibrate”→”Multi-point”.

22. Turn off the high pressure. **Close N2 tank main valve.**

23. Release pressure. **Open exhaust valve.**

24. **CLOSE** valves.
   a. [Blue] valve going from N2 tank to the 98RK
   b. [Yellow] valve going from N2 tank to the 9034 calibrator
   c. Exhaust valve.

25. Turn off the vacuum pump.

26. Disconnect from 9034 and 9016s in the “Network Status” window in order to be able to
    use them in LabVIEW.