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Generating Low-Pressure Shock Waves for Calibrating High-Frequency Pressure Sensors

Dennis Charles Berridge

Purdue University

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By Dennis C. Berridge

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For the degree of Doctor of Philosophy

Is approved by the final examining committee:

Steven P. Schneider  Steven H. Collicott
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Shann J. Rufer

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Approved by Major Professor(s): Steven P. Schneider

 Approved by: Wayne Chen  11/24/2015
Head of the Departmental Graduate Program  Date
GENERATING LOW-PRESSURE SHOCK WAVES FOR CALIBRATING HIGH-FREQUENCY PRESSURE SENSORS

A Dissertation
Submitted to the Faculty
of
Purdue University
by
Dennis C. Berridge

In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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SYMBOLS

\( a \) speed of sound
\( f \) frequency (kHz)
\( M \) Mach number
\( P \) pressure (psi)
\( \Delta P \) pressure jump across shock \( (P_2 - P_1) \)
\( T \) temperature (K)
\( t \) time (seconds)
\( x \) axial coordinate (m)
\( \gamma \) specific heat ratio
\( \phi \) azimuthal coordinate (degrees)

Subscript

0 stagnation condition
1 undisturbed driven condition
2 condition behind shock
4 undisturbed driver condition
\( Avg, mean \) average (mean)
\( s \) shock condition
\( w \) wall condition

Abbreviations

AEDC Arnold Engineering Development Center
AIAA American Institute of Aeronautics and Astronautics
BAM6QT Boeing-AFOSR Mach-6 Quiet Tunnel
<table>
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<th>Abbreviation</th>
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<tr>
<td>DTIC</td>
<td>Defense Technical Information Center</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>LaRC</td>
<td>NASA Langley Research Center</td>
</tr>
<tr>
<td>LDI</td>
<td>Laser Differential Interferometer</td>
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<td>RMS</td>
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ABSTRACT

Berridge, Dennis C. PhD, Purdue University, December 2015. Generating Low-Pressure Shock Waves for Calibrating High-Frequency Pressure Sensors. Major Professor: Steven P. Schneider.

Measurements of hypersonic boundary-layer instabilities have recently been performed in a wide range of wind tunnels with fast-response pressure transducers. In order to achieve accurate amplitude measurements, the calibration and frequency response of the sensors must be understood. Hypersonic instabilities are high-frequency, low-amplitude waves, so relevant calibrations must use similar inputs. This is particularly important for the PCB-132 sensors which have been widely used to measure hypersonic boundary-layer instabilities despite the lack of low-amplitude calibrations or frequency response information.

This work demonstrates the creation of extremely low-amplitude shock waves in a shock tube, which can be used to calibrate sensors for instability measurements. The shocks are created using weak diaphragms and low driven pressures on the order of 1 millitorr. A method for automatically measuring the shock arrival time and amplitude was developed. The method uses a rising-edge detector, a minimum peak-width criterion, and a simple low-pass filter to detect small shock waves in traces with low signal-to-noise ratio.

Shock amplitudes as low as 0.001 psi are demonstrated. The flow is shown to agree with theoretical expectations within the existing uncertainties. Calibrations of PCB-132 sensors were performed between 0.001 and 1 psi. The sensors were found to have a linear calibration over the entire range within the sensor uncertainty.

Step responses were measured for PCB-132 and Kulite sensors. The PCB-132 step responses are complicated and vary between sensors, but they are repeatable. They
normalize well with the maximum peak voltage, demonstrating that the sensors are a linear system.
1. INTRODUCTION

Aerothermodynamic heating is a primary design concern for hypersonic vehicles. Since boundary-layer transition can increase heat transfer rates by more than a factor of three, the location of transition onset can be important. However, transition is a complex and poorly-understood phenomenon, which makes the prediction of transition onset difficult. No physical theory for predicting transition currently exists, so empirical correlations are typically used for design. The complexity of the transition process often restricts the range of applicability of these correlations and limits their accuracy. Due to the lack of information about when transition will occur, conservative assumptions must be made, increasing the mass of the thermal protection system and limiting vehicle performance. Improved transition prediction would decrease this performance penalty.

Improved transition predictions will require improved physical understanding of transition. In order to improve our understanding of the mechanisms of transition, they must be measured under a wide range of conditions. Conducting all fundamental research with flight tests is impractical and computations require some currently-unknown information about inputs, such as the disturbance environment. Because of these limitations, ground testing will necessarily play an important role in developing mechanism-based prediction methods. In order to explore the required range of conditions, experiments will need to be performed in many different wind tunnels. Since the wind tunnel environment (such as freestream noise levels) will affect the transition process, these effects must also be understood so that their influence can be separated from the influence of other parameters, such as Mach number.

It is well-known that freestream noise can have a large effect on the transition process. Noise affects the transition location and sometimes even parametric trends. This effect can make it difficult to interpret the results of wind tunnel tests, since
it is not clear how to compare results from different tunnels or flight. In order to aid this interpretation, both the effect of noise and the noise levels must be known. Measurements of freestream noise have often been missing, especially at the high frequencies which would be expected to have the greatest effect on the transition process. Boundary-layer instability measurements are also necessary to understand the effect of noise levels on transition, and these are also rare. Measurements of transition location are very common, and while these are useful for understanding the effect of noise and other parameters, they are insufficient for a physical understanding of the mechanisms.

Instability and freestream noise measurements are often not performed due to their difficulty. These measurements necessarily involve the use of equipment capable of measuring high-frequency, low-amplitude fluctuations. Such equipment often is not capable of surviving in hypersonic wind tunnels, especially in the more extreme environments present in large-scale production wind tunnels. Unfortunately, due to the important role these tunnels play in the development of flight vehicles, they are the ones in which such measurements would be the most useful.

Typically, the main measurement technique available for performing noise and instability measurements has been the hot wire. While hot wires are able to survive in some wind tunnels, the very high stagnation temperatures and pressures in the larger wind tunnels are often too high for a hot wire to survive if it is thin enough to provide a useful frequency response. In addition, hot wires often break even in hypersonic tunnels where they can be used, creating a significant amount of wasted effort. Since only one streamwise position can be measured at a time, and run times are often short, performing measurements in enough locations can require many runs. In many tunnels, the costs associated with such testing are too high to be practical.

New sensors are making instability measurements in large tunnels possible. PCB-132 piezoelectric pressure transducers are robust, highly sensitive sensors with a high frequency response able to measure instability waves with frequencies of hundreds of kilohertz. In addition, these sensors may be mounted flush with the surface of a model,
allowing multiple streamwise positions to be measured simultaneously. By providing a robust, unobtrusive measurement technique, these sensors eliminate some of the largest difficulties of using hot wires. Advancements in electronics manufacturing have made such high-frequency sensors easier to make, and it is likely that more will continue to be developed.

Unfortunately, while these sensors have been shown to be effective at measuring freestream noise and boundary-layer instabilities, they are not calibrated for these measurements. The sensors are actually time-of-arrival sensors, and the manufacturer performs only a very simple calibration. Both the calibration at low amplitudes and the frequency response of the sensors have been unknown. Both need to be identified in order to perform accurate quantitative instability measurements. Calibrations with input amplitudes in the range of the boundary-layer instabilities being measured are particularly needed for the PCB-132 sensors due to concerns that the sensors may have a nonlinear response. Additionally, as more sensors which can measure the instabilities are developed, the need to produce inputs similar to boundary-layer instabilities will continue.

This research uses a new shock tube to develop a method for performing the necessary calibrations. The shock tube has been designed to run at very low initial pressures. Combined with weak diaphragms, it is possible to create the small pressure rises necessary to calibrate the sensors for the low-amplitude fluctuations of interest. In addition, thin, fast shocks can be used as step inputs. The response of the sensors to these step inputs can be used to find the frequency response of the sensors, as in Rotea et al. [1].

Shock tubes have not been used to produce very low-amplitude pressure inputs in the past. The present research develops a new way of using shock tubes in order to produce these inputs. Shock tube techniques have typically concentrated on the production of large, strong shocks with high Mach numbers. Some research has also focused on creating weak shocks with low Mach numbers in order to study shock structure. In contrast, the present work focuses on creating low-amplitude shocks.
These shocks often have moderately high Mach numbers, from 3 to 3.5. These are not typically considered weak shocks. However, with the method in this research, these moderate Mach numbers are produced with weak diaphragms. The burst pressures are on the order of 1 psi.

This can be done because the Mach number of a shock depends primarily on the burst pressure ratio, while the amplitude depends largely on the burst pressure difference. By using low burst pressure differences and a low driven pressure, high pressure ratios can be achieved with low pressure differences. This produces a relatively thin, fast shock with a very low amplitude. These shocks can be used to produce low-amplitude, high-frequency inputs for many kinds of sensors.

In many cases, most aspects of a sensor’s response are known. For instance, diaphragm-based sensors typically follow a second-order underdamped model, and the sensing area is known to be the same as the diaphragm area. Much existing research is based on the calibration of sensors which have these properties. The methods of this research provide a new method for producing pressure inputs at the amplitudes of boundary-layer instabilities commonly encountered in hypersonic ground testing. It also provides a method for measuring the high-frequency response and sensing area of a sensor. Combined, these methods allow the characterization of a sensor in the absence of much prior knowledge about the sensor’s operation. This represents a new ability to calibrate sensors for hypersonic instability measurements.
2. REVIEW OF LITERATURE

This literature review covers the application of PCB-132 sensors to hypersonic transition experiments, shock tube experiments relevant to the current work, and an overview of alternate dynamic calibration techniques. The PCB-132 sensors are the sensor under test for the present work, but the focus of the work is the method used to calibrate them. The requirements for the calibration method are influenced by the hypersonic transition measurements being performed with the sensors, so an overview of this application is relevant.

Extensive shock tube literature exists, and a review of all shock tube work was not attempted. However, since shock tubes have been used so widely, some defense that the present work is actually new is warranted. Therefore, the review presented here summarizes the way shock tubes have generally been used, providing examples of many of the applications. Most work with shock tubes is not relevant to the present work, being concerned with phenomena at high Mach numbers and temperatures, and is only noted briefly.

The most relevant work is with sensor calibrations and low-pressure or low-density shock tubes. These areas are covered in more detail, but much of the work is again focused on very different operating conditions from the present research.

An extensive literature search was conducted to try to ensure that relevant work would not be missed. The author was able to search a very wide selection of literature, having access both to the databases provided by Purdue University as well as those provided by NASA Langley.
2.1 Measurements with PCB-132 Sensors

Fujii showed that PCB-132 pressure transducers could be used to measure second-mode waves [2]. Since then, the sensors have been used in many different tunnels and models. They have also been used in freestream measurements [3].

Experiments on a 7° cone at 6° angle of attack in the Hypersonic Ludwieg tube Braunschweig (HLB) were performed with ten PCB-132 sensors mounted in three groups, two of which were tightly clustered [4]. This is a cold-flow Mach 6 conventional wind tunnel. Both first and second-mode waves were likely detected, though stability calculations were not available to confirm the identification of the first-mode waves. The tight clustering of the sensors, as well as an ability to move an array of three sensors around the circumference, allowed for information about the spatial extent and wave angle to be determined.

Experiments were performed in HIEST with a 7° half-angle cone with small bluntness [5]. Since this is a free-piston shock tunnel, physical vibrations were a significant concern. Drop-hammer tests were performed with a plastic tip to examine the mechanical vibrations of the sensor, which were found to extend up to about 400 kHz, but not much beyond. Peaks due to mechanical vibration were observed in each run, and were found to be very repeatable. Despite these problems, second-mode waves were detected in a number of cases, and growth and breakdown were observed. Linear PSE computations were performed using STABL to compare to these measurements [6]. The computed frequencies for the second-mode waves compared reasonably well in the laminar regions of the flow. Computed $N$ factors at transition were found to be around 8. These calculations also suggested that increasing freestream stagnation enthalpy destabilizes the boundary layer. Further measurements in HIEST show possible observations of the first harmonic of the second-mode waves.

PCB-132 measurements were performed on a flared cone geometry at Purdue. This geometry was flared all the way to the nosetip, instead of incorporating a straight-cone section. This design leads to a cusp at the tip, which is difficult to
machine, so nosetip radii were larger than they would have been with a straight-cone section. The first nosetip radius used was 1 mm. The circular-flare profile was chosen by performing computations in STABL to determine the profile that gave the most unstable shape [7]. Large second-mode waves were measured, as well as harmonics at two and three times the fundamental second-mode frequency. Second-mode amplitudes were as large as 5% of the mean. Transition was not observed under quiet flow, but occurred quickly and at low pressure in noisy flow.

A sharper nosetip with radius 0.16 mm was constructed to try to increase the amplitude of the waves and observe transition under quiet flow [8]. PCB measurements under quiet flow with this nosetip showed large, nonlinear waves in some stage of breakdown, and eventually transition [9]. Temperature-sensitive paint measurements were performed to observe the transition front. Under quiet flow, a surprising pattern of hot streaks formed when the PCB measurements showed large, nonlinear second-mode waves. These streaks were oriented streamwise, with small cool regions at somewhat regular spanwise intervals. At the highest available quiet unit Reynolds numbers, the spanwise streaks appeared, cooled, and then appeared again at the back of the cone. Notably, no streaks were observed under noisy flow, possibly indicating some difference in the breakdown of the waves between noisy and quiet condition. Transition was observed to occur under quiet flow in the PCB spectra and the TSP near the second appearance of the streaks.

Measurements have now been performed in multiple shock tunnels, including the Tranzit-M tunnel at ITAM, the HEG tunnel in Göttingen, and the LENS-II facility at CUBRC [10–12]. The second-mode waves in spectra taken in shock tunnels usually do not appear as clearly as in cold-flow tunnels. However, it is clear that they can be measured, at least at large amplitudes. This would enable the measurement of breakdown amplitudes even in high-enthalpy facilities.

Freestream noise measurements have been performed in recent years in Tunnel 9, using Kulite sensors to measure noise between 0 and 50 kHz and PCB-132 sensors to measure higher frequencies [3, 13, 14]. Lafferty and Norris report measurements
with a Kulite XT-140A at Mach 8, 10, and 14. This sensor could measure frequencies between 0 and 20 kHz. The results agree well with existing data, and show the expected decrease in noise level with increasing unit Reynolds number. The noise levels are found to increase as the Mach number is increased, with levels starting at 2% at Mach 8, and 3.75% at Mach 14. Bounitch et al. performed similar measurements with PCB-132 sensors at Mach 10, and saw signal above the electronic noise out to 1 MHz, the highest measurable frequency for their experiments. The spectra reached an approximately constant value at about 600 kHz. The PCB calibration was adjusted to agree with the Kulites for frequencies both sensors could measure. The noise level was higher by 2% of the mean freestream pressure when the high-frequency data from the PCBs was included (25 kHz-1 MHz).

2.2 Shock Tube Designs & Physics

Shock tubes are one of the oldest and most widely-used tools in compressible aerodynamics. They have frequently been used for sensor calibrations and are generally considered the standard instrument for dynamic calibrations [15]. Shock tubes are used in a variety of other applications, including structural dynamics [16]. Shock tubes are often used in aerodynamics as a cost-effective method of examining high-enthalpy flows. Much of the work involves the investigation of chemical reaction rates and plasma effects, such as in Miller and Bengston [17].

2.2.1 Basic Principles of Shock Tube Operation

A shock wave is a very thin region in a fluid over which the flow properties change dramatically [18, p.507]. As a shock wave moves through a flow, it compresses, slows, and heats the fluid. Shock waves propagate through a flow at speeds greater than Mach 1.

Shock waves can form normal to a flow, or obliquely. Oblique waves are more common, but normal shock waves are simpler to analyze. A shock tube is a device
that creates normal shock waves of controlled strength. This provides a simple, well-understood flow which is useful for calibrations and other measurements. The planar normal shock is most commonly created by bursting a diaphragm. The portion of the tube behind the diaphragm is pressurized (the driver tube), while the rest of the tube (the driven tube) is left at a lower pressure. The diaphragm is then burst, either by “natural bursting”, wherein the pressure difference is increased until the diaphragm breaks, or through various means of controlling the burst pressure [19, pp.502-506]. The method of control used depends on the diaphragm thickness and material. Bursting methods include razor blades on which the diaphragm is cut as it deforms, scoring or scribing the diaphragm before it is installed, and electrical methods of weakening the diaphragm material.

After the diaphragm bursts, the region of high pressure (driver fluid) is in contact with the region of low pressure (driven fluid), and a shock wave forms and propagates into the region of low pressure. An expansion fan also forms, and propagates into the region of high pressure. At the same time, the driver gas begins to move down the shock tube, pushing the driven gas back. In the ideal case, the shock wave can be considered to form instantly when the diaphragm bursts, and the driver and driven gas can be assumed not to mix. This results in a “contact surface” moving down the shock tube. In this case, the shock tube can be divided into four different regions, illustrated in Figure 2.1:

1. Undisturbed driven fluid in front of the shock.
2. Driven fluid that has been compressed by the shock wave, before the arrival of the contact surface.
3. Driver fluid behind the contact surface which the expansion fan has passed through.
4. Undisturbed driver fluid which the expansion fan has not yet reached.

The shock moves more quickly than the contact surface, so regions 2 and 3 increase in size with time. Region 2 is typically the useful region of flow, since in this region
the flow has been affected by the shock wave and nothing else. Since the shock tube has a finite length, the shock wave and the expansion fan eventually reflect from the end walls of the tube. This means that there are three different ways for useful flow to end at a given location: when the contact surface, reflected shock, or reflected expansion wave arrive. Which boundary will be the limiting factor is determined by the driver and driven pressures and temperatures, the length of the driver and driven sections, and the distance of the given location from the end of the driven tube. A common method of examining the behavior of a shock tube is to plot the movement of these boundaries on an $x - t$ diagram (Figure 2.2). These diagrams show the position of the various regional boundaries on the horizontal axis, with time as the vertical axis.

The example in Figure 2.2 shows the positions up until the contact surface and the reflected shock collide. The slopes of the lines indicate the speed of the boundaries, with steeper lines indicating slower speeds. For values of $x$ greater than the position where the two meet, the reflected shock ends the period of useful flow, whereas for smaller values of $x$, the contact surface ends the useful flow period. The location at which the contact surface and the reflected shock intersect is the location which experiences the longest duration of useful flow. The expansion head refers to the front of the expansion wave, without indicating the thickness of the fan. The line for the
reflected expansion head is curved due to the constantly-changing flow properties as it collides with the rest of the expansion fan.

Figure 2.2. Example of an X-T diagram, created using code provided by Dr. Matthew Borg.

Calculating the properties of each of the regions is simple. The normal-shock relations can be used to find the properties across the shock, and isentropic relations can be used to find the properties across the expansion fan [19, pp. 63-69]. It is slightly more difficult to calculate the shock strength, simply because the shock Mach number ($M_s$) cannot be solved for explicitly. However, simple computer programs can be written to solve the equation quickly using methods such as interval bisection. The ratio of pressures in the driver and driven sections ($P_4$ and $P_1$) can be found in terms of the shock Mach number, speed of sound, and specific heat ratios [20]:

$$\frac{P_4}{P_1} = \frac{2\gamma_4 M_s^2 - (\gamma_4 - 1)}{\gamma_1 + 1} \left[ 1 - \frac{\gamma_4 - 1}{\gamma_1 + 1} a_4 \left( M_s - \frac{1}{M_s} \right) \right]^{-2\gamma_4/\gamma_4 - 1}$$

(2.1)

Reference 19 gives an essentially identical formulation on page 69, though the notation is somewhat less convenient. The subscripts indicate to which region the
property corresponds. In this formulation, the driver and driven gases are not assumed
to be the same, nor are their temperatures assumed to be the same, though they are
both assumed to be ideal gases. From Equation 2.1, several important aspects of
shock tube operation can be observed. The first is that the Mach number depends
on the pressure ratio between the driver and driven tubes. This means that stronger
shocks can be obtained both through pressurizing the driver section and through
evacuating the driven section. The presence of the ratio of the speeds of sound in the
driver and driven sections indicate that temperature differences, as well as molecular
mass differences, can also change the strength of the shock. If the driver gas is hotter
than the driven gas, a smaller pressure ratio will achieve the same Mach number. In
other words, heating the driver gas will create a stronger shock. Also, if the driver
gas is lighter than the driven gas, the shock will be stronger due to the higher speed
of sound in the driver section.

Another important property, especially for the calibration of pressure transducers,
is the pressure difference across the shock wave. This can be calculated by the normal
shock relation [18, p. 555]:

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma_1}{\gamma_1 + 1}(M_s^2 - 1)$$

There are two main influences on the pressure difference across the shock. The
first is the Mach number, with higher Mach numbers corresponding to higher pressure
differences, as would be expected. The other factor is the initial pressure in the
driven tube. Since the Mach number determines the pressure ratio, the size of the
pressure step can be determined by changing the driven pressure, but keeping the
ratio constant. A high Mach number does not necessarily guarantee a large pressure
difference, since the driven pressure could be kept low.

Also of interest is the behavior of the pressure rise if the pressure differential is
kept the same, but the driven pressure is reduced. Since diaphragms burst at a given
pressure differential, this situation mimics the control available with a shock tube. In
this case, the Mach number increases as the driven pressure is reduced, due to the increase in the ratio $P_2/P_1$.

Figure 2.3 shows the static pressure rises resulting from a 6.9-kPa pressure difference as the driven pressure is varied. The driver and driven gases are assumed to be air at 293 K. The figure shows that the static pressure rise decreases rapidly with decreasing driven pressure.

![Figure 2.3. Static pressure rise from a fixed pressure difference as driven pressure is varied.](image)

2.2.2 Shock Tube Designs and Techniques

Several extensive reports were written in the 1950s about shock tube design and flow physics. While the physical understanding of shock tubes and the state of shock tube instrumentation have both advanced significantly since the reports were written, they still provide much relevant information which can be hard to find elsewhere. Additionally, the reports contain many schlieren images which would take substantial effort to reproduce.
Glass and Hall provided an extensive overview covering perfect gas theory, real-gas effects, wave interactions, the effect of finite tube length, experimental observations, and boundary-layer effects [19]. The report includes a discussion of the design of shock tubes to create strong shock waves, including driver gas heating, cross-section area changes, alternatives to burst diaphragms, and the attenuation observed with strong shock waves. An overview of applications of the shock tube is also presented, most of which reflect the goal of creating strong shocks: the shock tube as a short-duration wind tunnel or as part of a shock tunnel, high-temperature gas experiments, and studies of combustion and chemical kinetics, as well as the calibration of sensors.

A relevant point for the present work is the coverage of different kinds of burst-control systems and diaphragm burst pressure ranges. The diaphragm burst pressures could be used to indicate the likelihood of low-amplitude shock research having occurred by the time of the report. For non-metallic diaphragms, the lowest burst pressure differential listed is 9 psi [19, p. 512]. A discussion of the bursting behaviors of different diaphragm materials is given, as well as the technique of layering several diaphragms to increase the burst pressure [19, pp. 502-503]. In the same location, information about the petalling behavior of metallic diaphragms is given, along with an equation for estimating the burst pressure of a diaphragm.

Burst control methods are discussed on page 506 of their report. The most common method is the use of a sharpened plunger to begin the burst process by piercing the diaphragm. It is stated that burst behavior is better if the diaphragm is loaded at a pressure difference close to the natural burst of the diaphragm. Double-diaphragm methods are also discussed for applications where two bursts were required at a precise time interval (such as for wave interaction studies). An electrical method is discussed which is similar in operation to the mechanical plunger. Rupture could be induced in thin metal diaphragms by using a spark discharge to burn a small hole in the center of the diaphragm.

An earlier study was given by Glass et al. [21]. The study discussed the theory of the shock tube in its basic operation before studying the paths of shock and expansion
waves during interactions, including the reflection of shock and expansion waves and the interactions between the contact surface and the shock wave. The production of strong shock waves was also discussed, along with shock tube design and the design of the particular shock tube used in the studies. Experimental observations and comparisons with theory were then presented and discussed, from the formation of the shock and flow conditions in the tube, to one-dimensional wave interaction studies.

Their wave-interaction tube was designed with extensive optical access, allowing thorough schlieren studies. It was designed with a 3 x 3-inch square driven tube to avoid optical distortions. They also used tourmaline gauges for the measurement of shock propagation. High-voltage spark gaps were used to initiate the diaphragm burst. They used a wave-speed camera, which gives a continuous distance-time record, essentially making an experimentally-measured x-t diagram.

Many high-quality schlieren images were included. They showed the development of the shock over a finite distance, the broadening of the contact surface, and transverse shock waves which formed between the primary shock and the contact surface. The shock was observed to form within a few cross-sectional widths downstream of the diaphragm. The transverse shock waves were created by the burst process of the shock tube, which was illustrated by a schlieren image on page 155 of their report, reproduced here as Figure 2.4. When the diaphragm burst, the initial shock wave formed was roughly a spherical section. The curved shock was reflected by the shock tube wall, creating curved reflected shocks directly behind the incident curved shock. The components of the reflected shocks which were more nearly normal were absorbed into the edges of the main shock, reducing its curvature. The more-steeply curved portions reflected off the other wall of the shock tube. Through repeated reflections, the absorbed portions of the reflected shocks made the main shock more planar, and the transverse shock fronts became more parallel to the main flow direction. The formation process and the creation of the transverse shock waves are often relevant when creating weak shock waves and when using low driven pressures.
A diagram of a similar process was shown on page 162 of their report. In this case, the shock diffracted into a wider channel. A transverse wave system was set up, similar to what was observed by Glass et al. and Persico et al., who also computed the flow [22].

A smaller report was produced by Lobb, who also used schlieren photography and a spark-gap burst-control method [23]. He observed relatively constant shock
velocities somewhat lower than that predicted by theory. He also studied the rupture of cellophane diaphragms and the formation of the shock wave. Cellophane diaphragms tended to shatter, rather than ripping along several axes like metal or mylar diaphragms. A diagram on page 34 of his report illustrated the shock formation process, including the reflected spherical shock waves creating a plane wave, and a non-uniform region between the shock and the contact region. The non-uniform region appeared to be caused by the transverse shock waves and the contact region, potentially reducing the useful test time. Schlieren images of the burst process were included on pages 60 and 61 of his report, one of which also appears in Glass et al. Lobb took many schlieren images of flow past a wedge. The Mach number was measured instantaneously by the angle of the bow shock on the wedge, which allowed further characterization of the non-uniform region. The contact surface appeared as turbulent fluctuations.

Sasoh et al. provided a unique design for a shock tube burst-control system using a laser [24]. They used a laser to weaken the diaphragm, starting the burst. However, they found that the laser could add significant energy to the process, resulting in additional fluctuations due to the ablation of the diaphragm. If the laser was not strong enough, the diaphragm did not open sufficiently, resulting in a smaller post-shock pressure. However, if the laser was too strong, the contaminating pressure fluctuations were generated. Because of these problems, the laser strength needed to be carefully set for the particular diaphragm material and thickness in use.

Garen et al. designed a pneumatic valve for the purpose of studying weak shock waves, which requires low pressure ratios [25]. Their valve allowed the use of arbitrarily low pressure differences. It consisted of a high pressure chamber with a flexible rubber sheet at one end and a vacuum chamber at the other, with a diaphragm sealing the high pressure chamber from the vacuum. The high pressure chamber was pressurized, which pushed the rubber sheet out in a spherical shape until it sealed against the driven tube. The driver chamber, also outside the rubber sheet, could be adjusted to any pressure. When the diaphragm was broken, the high pressure
chamber quickly evacuated into the vacuum chamber, pulling the rubber sheet away from the driven tube and starting the run. This method achieved opening times of 460 microseconds, similar to some opening time measurements with traditional diaphragms \[22, 26\], though much shorter opening times such as 70 microseconds are possible with diaphragms \[27\]. However, their shock tube was only about half the diameter of the shock tubes using traditional diaphragms, so a one-to-one comparison would probably result in slower opening times.

### 2.3 Piezoelectric Sensors in Shock Tubes

Piezoelectric sensors have been used in shock tubes for many years, with a report on their use published in 1946 \[28\]. The report discussed different designs of sensors, their sensitivities, and their shock responses. Several linear calibrations for different models of sensors were shown, along with descriptions of the design of the shock tube and the electronic data acquisition equipment used. The tests used cellophane diaphragms, a “knife” for burst control, and high shock pressures. No low-amplitude measurements were discussed.

The technical report by Janza gave a more in-depth look at the techniques and problems involved in using piezoelectric sensors, though the discussion was relevant to other sensor types \[29\]. He provided many images of oscilloscope data. Unfortunately, these are not well-preserved in the digital copy available on DTIC. The data included calibrations, documentation of temperature effects on piezoelectric gauges, and the effects of various experimental errors, including poor isolation of the sensor from the shock tube. He suggested the use of a pressure-tank calibrator which can create short-duration pressure pulses with a solenoid valve. He noted that linear sensors require only one measurement, but recommends more points be used unless the behavior of the sensor is well-understood. Noise from acceleration effects was discussed, and the use of blind sensors to determine the level of acceleration noise was recommended. No low-amplitude measurements were shown.
Gavrilenko and Nikolaev described the design of a piezoelectric pressure transducer which seems similar to the PCB-132 design [30]. Their sensor did not have a high-pass filter, and was able to measure the shock step, rather than a peak. They mounted the sensor in the side wall of the shock tube. Its rise time was 3 microseconds, rather than near 1 $\mu$s, but it’s unclear if this was because of the frequency response of the sensor, or if the shock required that long to pass over the sensor. However, the basic design was similar to a PCB-132: a wafer of piezoelectric ceramic covered with epoxy.

2.4 Low-Density Shock Tubes

While shock tubes have been a common research tool for many years, the design goal has typically been to create high Mach number shocks with large pressure and temperature steps. Since the present work seeks to create shocks with very small pressure rises, much of the shock-tube literature is not very applicable. However, several efforts have been made in the past to operate shock tubes at very low initial densities. While these shock tubes were also typically with high driver pressures and large shock pressure steps, certain phenomena unique to shock tubes at low densities were found.

Duff studied the operation of a small shock tube (1.125-inch I.D.) at moderately low pressures on the order of 1 torr with argon as the working fluid [31]. It was observed that at low driven pressures the useful flow time and the shock strength were reduced compared to results at higher driven pressures. The useful flow time is the time between the arrival of the shock and the arrival of the contact surface, seen as a density jump. In some situations, the useful flow time can be ended by the arrival of the reflected shock or the reflected expansion wave. The required diaphragm pressure ratio to produce a shock with a given Mach number increased dramatically as the driven pressure decreased. The duration of flow varied linearly with the driven pressure and decayed rapidly with increasing Mach number. The flow after the shock was found to have low uniformity. This was likely due to the boundary layer on the
driven tube wall behind the shock, which was expected to have a thickness of slightly more than half the tube radius.

Duff et al. studied the shape of the primary shock wave with piezoelectric sensors mounted in the end wall of the shock tube [32]. The speed of the shock was measured and assumed to be constant. Then, the arrival time at each sensor mounted in the end plate was measured, and the differences in the arrival times at each sensor were found. Using the speed of the shock, these time differences could be converted into distances, and used to find the curvature in the shock wave. The ideal shock would be a plane, but it was found that the shock more resembled a section of a sphere. Because the shock front is curved, the center of the shock front bulges out and is a certain distance downstream of the shock front along the tube wall. The bulge due to curvature was independent of shock strength, with a value about 3.5% of the tube diameter. Duff’s work after these results focused on chemical effects and explosively-driven shock tubes, so no further moderate-amplitude low-pressure work seems to have been done [33, 34].

A much larger shock tube with an inner diameter of 24 inches was designed explicitly for operation at low pressures of $10^{-4}$ torr by Lin et al. [35]. The driver section was only 5 inches in diameter to reduce the size of the contact layer, which was assumed to be related to the diaphragm diameter due to the vortex system created by the diaphragm burst. A transition section gradually increased the diameter to 24 inches. The available test time for shocks stronger than $M = 10$ was found to be about 30% of the ideal value. This value was relatively insensitive to the initial driven pressure, suggesting that the contact layer was the primary cause of the reduced test time, and not the boundary layer growth.

The thickness of the shock was measured using an ultraviolet absorption technique which used a beam that traversed the diameter of the shock tube. Thickness values were much higher than expected, and this was determined to be primarily due to shock curvature. The curvature was presumed to be due to the driven-wall boundary layer behind the shock. A good fit to the data could be found by assuming the
apparent thickness due to the curvature was equal to $\frac{1}{2}\sqrt{\ell R}$, where $\ell$ is the mean free path in front of the shock, and $R$ is the shock tube radius. Scatter in the apparent thickness was thought to be due to tilt in the shock. The rise time of the system used to measure the shock thickness was stated to be about 10 nanoseconds [36].

Liepmann et al. built a 17-inch shock tube for low-pressure studies, capable of reaching $10^{-5}$ torr, at the Graduate Aerodynamics Laboratory at Caltech (GAL-CIT) [37]. The shock tube incorporated a blade system for controlling the bursting of the diaphragm. The blades were found to reduce the opening time of the diaphragms, because cutting the diaphragm with the blades required less force than simply tearing the diaphragm with pressure. A shock tube based on the GALCIT design was built at the U.S. Air Force Academy, with the capability to reach pressures as low as $0.5 \times 10^{-6}$ torr [38]. It was also designed with the ability to use multiple test and driver gases. The intent, again, was to study real-gas effects in a shock tube, so large driver pressures were typically used in order to produce strong shocks up to Mach 10 with diaphragm pressure ratios up to 100 million.

Roshko also developed a theory for the influence of the boundary layer on the shock and contact surface behavior [39]. Mirels found that Roshko’s values for one parameter ($\beta$, which modified the boundary-layer thickness and depends on conditions outside the boundary layer) were much too low, except for very strong shocks [40]. He developed an alternate theory, which accounted for the variation in freestream quantities between the shock and the contact surface. It agrees with Roshko’s theory in most respects except for the $\beta$ values. The underestimation of $\beta$ leads to an overestimation of available test time. Mirels finds his own values closer, but still slightly low.

Anderson and Murthy performed numerical computations of the attenuation of the shock and the boundary-layer properties as the shock develops with downstream distance [41]. This method is qualitatively accurate, but cannot be used quantitatively due to effects not accounted for, such as the spreading of the contact mixing region,
the interaction between the boundary layer and the contact region, and real gas effects.

Sharma and Wilson performed time-accurate 2D computations including real-gas effects to investigate many of the same effects as Mirels [42]. Their values for test time agreed with Mirels, but their boundary-layer thicknesses tended to vary significantly from the predictions of Mirels, especially when nonuniformities that might arise in actual experiments were included in the computations. The Mirels values were valid if the shock was able to develop to the limiting case, but typical shock tubes are not long enough for this to occur, making more detailed measurements or computations necessary if the conditions are to be accurately known.

Badcock’s much-later computations mostly agree with the earlier results [43]. He found that the boundary layer acted like a converging-diverging nozzle, with a minimum cross-sectional area within the contact layer. The boundary layer thickness grew behind the shock, reaching a maximum inside the contact layer and then shrinking behind it. The flow accelerated through this “nozzle”, increasing the speed of the contact layer. He found that the shock decelerated quickly to a constant velocity after the flow was started. It then reached a nearly-constant velocity, which it maintained until the boundary layer grew to cover the entire cross-section of the tube. At this point, the shock began to decelerate again.

Additional computations were recently performed to model the mixing layer thickness [44]. The ideal theory models the contact region as a surface, with no mixing. However, in reality there is turbulent mixing, resulting in a mixing layer which can reduce the useful test time, since the contact layer will arrive earlier than it would if it had no thickness. A stochastic approach was used with some success. Comparisons to various experimental datasets are shown, including data from the 17-inch shock tube at GALCIT.
2.4.1 Moderately Low-Pressure Shock Tubes

Some work was also done with shock tubes that can only reach low or moderate vacuum. Peng and Liquornik used an electric shock tube operated at driven pressures from 1-10 torr to study flows at low energy densities [45]. They produced shocks from Mach 10 to 12. They do not report the pressure steps created by their shocks, but according to ideal theory, the minimum step pressure possible in this range of conditions is 3 psi.

Bander and Sanzone developed a laser schlieren technique to measure the shock velocity with a single detector [46]. They used a shock tube with the ability to reach driven pressures of 1 torr. They found that their technique could also detect the arrival of the contact surface, and compared their measured values to the theory of Mirels, with good agreement. Their values adhered more closely to Mirels’ predictions for turbulent flow than laminar flow.

Chung and Lu performed calibrations of fast-response Kulite pressure transducers with driven pressures from 3-50 torr [47]. Their shock tube used a double-diaphragm control method with 0.023-inch mylar diaphragms, with driver pressures of about 285 psi. They state that calculating the pressure step does not require very accurate measurements of the driver pressure, but is more accurately computed from the measured Mach number and the driven pressure. This method also has the benefit of not relying on the ideal theory to predict the Mach number. They measured the static pressure step by mounting sensors in the side wall of the tube, and prolonged their test time while preventing driver-tube overpressure by having the shock tube end in a large dump tank, which removes the reflected shock without requiring the driven tube to be at atmospheric pressure. They found the dynamic calibration to be only 1.6% larger than the static calibration. They note the importance of low-pass filtering to improve the signal-to-noise ratio when measuring pressure steps near the bottom of the sensor’s range.
2.5 Sensor Calibrations Performed With Shock Tubes

Shock tubes are frequently used for dynamic sensor calibrations. They are a simple, well-understood, and potentially low-cost apparatus that can easily produce inputs with frequency content above 1 MHz. Additionally, a shock tube produces an input not only in pressure, but also in density, temperature, and heat flux. For this reason, they are generally considered the standard dynamic-calibration instrument for many kinds of sensors.

Bean et al. proposed shock tubes as the basis for a NIST primary standard for the simultaneous measurement of dynamic pressure and temperature by using coherent anti-Stokes Raman spectroscopy (CARS) [48]. Their shock tube was designed for very high-pressure operation, with the driven tube even being able to withstand 20 MPa (2900 psia).

A typical example of shock-tube dynamic calibration of sensors was performed by Mersinligil et al [49]. They used a shock tube in conjunction with a static and aerodynamic calibration to test a fast-response cooled probe intended for measurements inside high-temperature gas turbines. Their primary interest in using a shock tube was to identify the resonance of the sensor, which was 60 kHz.

Stankevič and Šimkevičius used a shock tube to calibrate silicon micromachined piezoresistive pressure transducers [50]. They used pressure steps greater than 30 psi, and found differences of less than 2% between their measured pressure steps and theory. They measured the transfer functions for several pressure transducers, which showed few major departures from the expected transfer functions for frequencies up to 1 MHz. They observed substantially different frequency responses when the amplitude of the shock was big enough to force the sensing diaphragm into the bottom of the cavity.

Kobayashi et al. performed shock-tube experiments and theoretical analysis to identify the frequency response of sensors [51]. They obtained fairly clean measurements of the transfer function in the 0-25 kHz frequency range. They successfully
used a lumped-parameter analysis method to model the transfer function, which took the form of an underdamped second-order system.

Matthews et al. performed mathematical modeling for the dynamic calibration of sensors [52]. They examined both shock-tube and drop-test calibration methods and modeled the input as well as the sensor response. They found that shock tube testing has greater high-frequency content than drop testing. Several successful models of system responses were shown. They also showed one system with a noisy and/or complicated transfer function, for which the model incorrectly predicted no significant resonance and only followed the measured step response for a short time after the arrival of the step input.

Zelan et al. used a shock tube to calibrate a very-high-frequency fiber-optic sensor [53]. The sensor measured reflected light levels from a diaphragm, which changed when the diaphragm was deflected. They stated that no traceable standards for the primary dynamic calibration of pressure sensors exist. The fiber-optic sensor was designed for very high pressures, with a maximum measurement of 2 MPa. They used an unspecified piezoelectric reference sensor. They measured the frequency response of both the fiber-optic and piezoelectric sensors. The fiber-optic sensor exhibited a much faster rise time of less than half a microsecond, compared to slightly more than two microseconds for the piezoelectric transducer. However, it was unclear if the flat region of the frequency response for the fiber-optic sensor was much wider. The response of the fiber-optic sensor appeared to be inferior to the piezoelectric sensor at lower frequencies. The fiber-optic sensor response declined steadily with frequency below about 5 kHz, while the piezoelectric sensor response was flat in the same range. While the fiber-optic sensor exhibited no clear resonance, it had two large depressions in its response at 100 kHz and 300 kHz. The piezoelectric sensor showed only a resonance peak at 300 kHz. The depressions may be artifacts due to experimental errors, but this was not verified. The fiber-optic sensor was expected to have its lowest resonance at 5 MHz. It is unclear if this fiber-optic method could be adapted for low-pressure measurements.
Pastuhoff et al. used a shock tube to perform a dynamic calibration of pressure-sensitive paint (PSP) with pressure steps on the order of 10 psi [54]. They observed a ramp response with some instability from the paint, which is the expected response for a first-order system.

### 2.5.1 Low-Amplitude Calibration Attempts Using Shock Tubes

While there have been many calibrations performed with shock tubes, very few attempts have been made to calibrate sensors for small pressure inputs. In many cases, this has been because the sensors under calibration were intended for the measurement of large pressure fluctuations, as in the work of Zelan et al [53]. In other cases, the sensors were intended to measure low-frequency oscillations, for which other calibration methods are better (see Section 2.6). However, some shock tube work has focused on creating low-amplitude inputs. Recently, there has been a surge of interest in the low-amplitude calibrations due to their relevance to several applications. The first, the motivation for the present work, is boundary-layer instability measurements, especially at hypersonic speeds. The second is gas turbine experiments, for which measurements of unsteady pressures on the fan blades are especially important. Ainsworth et al. gave a summary of applications and requirements for these measurements, especially at frequencies above 100 kHz [55]. The third, which has generated the most relevant work, is ultrasonic structural diagnostics. Ultrasonic emitters and receivers are required in order to make measurements of defects in parts such as turbine fan blades. The detection of smaller defects requires increasing the required resolution of the ultrasonic measurements. In order to achieve a higher resolution, shorter wavelengths are required, which means the emitters must operate and be calibrated at higher frequencies.

These requirements, along with advancements in the manufacture of microelectromechanical systems (MEMS), have resulted in the construction of ultrasonic transducers with resonances as high as 2 MHz [56]. However, in order to make quantitative
measurements with these transducers, they must be calibrated at low amplitudes and high frequencies. Several methods have been proposed for this (See Section 2.6), but the shock tube has the advantages of a simple, well-understood input, and the easy attainment of signal at very high frequencies. Additionally, many of the other methods measure the emitted pressure waves from the transducer when it is subjected to an oscillatory voltage input, rather than sending a known pressure input and measuring the voltage returned. These methods may not be equivalent for all sensors of interest.

Revel et al. proposed to calibrate transducers with the incident wave in a shock tube [57]. Their stated intent was to generate a high-frequency input of at least 200 kHz, with desired amplitudes of 5-100 Pa (about 0.001-0.015 psi). They constructed a low-cost shock tube from plexiglas, which granted optical access for high-speed camera observations of the diaphragm burst process. The driven section was only about 5 feet long. This seems to have been too short, since shocks at lower pressures did not form properly within the shock tube. They used a needle as a burst control mechanism.

They decided not to target their intended amplitude range due to concerns about the high-frequency sensitivity of the reference pressure sensor they used, which was a PCB-102A18. This sensor is nearly identical to the most successful reference sensor used in the present work (PCB-102B18), so the cause of their concern is unclear. The frequency response of the PCB-102 sensor is sufficient to measure the shock within the available test time. It does not match the response of the sensor under test, but since the shock is being used as a step input, any sensor which can measure the amplitude of the step should be sufficient for the calibration. It should not need to measure accurately at the highest frequencies of interest, because the high-frequency content of a step input is known from theory.

Revel et al. provided useful data regarding diaphragm opening mechanics for their 0.012 mm (0.5-mil) latex diaphragms. They showed that at low pressure differences, the diaphragm split in half, or along one axis, resulting in a slower opening and a
weaker shock. Rothkopf and Low showed that longer opening times cause longer shock formation distances [58]. At higher pressures, they showed the diaphragm splitting along three axes, which gave an opening time quick enough to yield useful shocks within the length of their tube. They experienced difficulty generating shocks with sufficient high-frequency content. It appears that their sensor is mounted in the shock-tube wall, rather than in the end plate. This means that the step input is not completed until the shock has traversed the entire sensor face, which can drastically lower the frequency content of the input. They do not specify the sensor diameter, but it is likely that the shock traversal time was causing the difficulty, and a pitot mounting method would have solved the problem.

The shock tube appears to have had flow quality problems, as the calibrations were relatively low-quality ($R^2 = 0.72$) and their frequency-response measurements were noisy. Since they were unable to reach their targeted pressure regime, they used a reciprocal method to check the linearity of the sensors, and extrapolated from their measurements to the low amplitudes of interest. A reciprocal method uses three sensors of the same kind. One sensor is used as a transmitter, and another as a receiver. Each sensor is used as both a transmitter and a receiver with both of the other two sensors. The impedance of each sensor can be found by solving a system of simultaneous equations.

Persico et al. noted that incomplete diaphragm bursts resulted in a weaker shock, and installed an annular plate on the driven side of the diaphragm with inner diameters smaller than that of the shock tube [22]. This plate prevented the diaphragm from opening fully, creating a simple flow restriction. Similar to the results shown in Glass et al. [21, pp. 162-163], a flow restriction caused the shock to diffract toward the driver-tube wall, setting up a system of transverse shock waves. Persico et al. showed numerical results describing the process. The diffraction reduced the strength of the incident shock, but also created flow-quality problems. The following transverse shock waves dramatically reduced the usable test time. They also used a plexiglas section in order to take high-speed camera measurements of the diaphragm
opening process. They measured opening times of about 400 microseconds for a tube diameter of about 3.125 inches, with an opening diameter of about 2.25 inches.

Lienard et al. performed shock tube calibrations for high-pressure sound measurements [59]. They suggested the use of multiple calibration methods, since each method has different strengths and weaknesses. Although they performed testing for a high-pressure environment, their calibrations extended to some of the lowest amplitudes available in the literature. They were trying to use the shock tube as an acoustical calibration device, which required a thin diaphragm and a low pressure ratio. These testing conditions resulted in thick, slow-moving shocks, and their tests only examined frequency content from 20-2000 Hz. They were able to reach minimum pressure steps of 0.3 psi. They used two kinds of shock tubes: a linear tube and a helicoidal tube. The helicoidal tube followed a helical path in the same manner as a spiral staircase, rather than the usual linear path. They were able to achieve lower amplitudes in the helicoidal tube, since the shape allowed a longer tube length. The linear tube was limited to shocks with 1.45 psi pressure rises. Lower-amplitude shocks were unable to form within the tube due to the longer diaphragm opening times.

2.5.2 Calibrations of Non-Pressure Sensors with Shock Tubes

Shock tubes can be used to calibrate more than pressure sensors. Mohammed et al. used a shock tube to calibrate a fast response temperature sensor [60]. They used relatively low pressure ratios, from 10 to 100. They used high pressures in both driven and driver sections, since their aluminum diaphragms burst at 2 MPa. Their custom sensors had a rise time close to 1 microsecond.

Similar work was performed by Yang and Meng on thermocouple calibrations and frequency response analysis [61]. Calculations of heat flux showed a spike with a width of less than a microsecond, illustrating that a shock tube can be used to test the high-frequency response of heat-flux gauges, as well. This is further shown by the
work of Gul, who measured turbulent heat flux on a flat plate in a shock tube with thin-film gauges calibrated in a shock tube [62].

Shock tubes have typically not been used to calibrate hot wires, since hot wires are sensitive to density, velocity, and temperature changes, and a shock wave changes all three simultaneously. However, the work of Guy established methods for calibrating hot wires for use in a shock tube, as long as the temperature and pressure behind the shock wave can be measured or predicted [63]. Briassulis et al. also tested various hot-wire measurement techniques in shock tubes, including in-situ calibration using shocks of various strengths [64]. They experimented with analog and digital methods to correct for the frequency response of the hot wire, and performed measurements of grid-generated turbulent flow. Additional studies of turbulent flow in shock tubes using hot wires were performed by Duffy et al. [65].

2.6 Alternate Calibration Methods

While shock tube calibration has been the most commonly-used technique for dynamic calibration and frequency response measurement for pressure transducers, many other methods exist. The two basic kinds of dynamic calibration are impulsive and oscillatory. Impulsive methods use an impulse or step input to excite all response frequencies of the sensor under test, particularly the resonant frequency. Prominent examples include the shock tube test and the drop test, though Lienard et al. also discussed a ballistic method, which used the shock from a passing bullet as an acoustic impulse [59]. The frequency response must be computed from the Fourier transform of the experimentally-measured response, or from parameters that can be measured in the time response, such as the resonant frequency and the rise time. These parameters can be used in conjunction with a mathematical model for the frequency response to determine the response of a particular sensor.

Oscillatory methods measure the output of the sensor under test with inputs of known amplitude at a specific frequency. The output is then measured for a range
of input frequencies. The simplest methods use a sinusoidal input, which allows the frequency response to be measured directly. Other methods use square waves, wavebursts composed of multiple frequencies, or more complicated wave fields.

Willmarth provided an overview of different kinds of pressure transducers and how they work [66]. He noted that the resonant frequency and the sensitivity of a sensor are linked: higher sensitivities lead to lower resonant frequencies, and vice versa. He stated that higher frequency responses have generally been achieved through improvements in electronic amplifiers, which allow larger reductions in sensitivity. He also noted that there are two ways to handle frequency response requirements. The first is to make the response of the sensor fast enough that all of the frequencies of interest fall within the linear range of the sensor. The second is to compensate for the response of the sensor. This second technique is only possible for linear sensors, and requires knowledge of the properties of the sensor, as well as the medium. Examples of this technique were provided.

Compensating for the frequency response allows for the measurement of higher frequencies with any given transducer. Since the upper limit for the frequency range of interest is likely to continue increasing, the compensation technique will continue to be useful, even as transducers are developed with flat responses at ever-higher frequencies. The compensation technique requires accurate measurements of the sensor response at high frequencies. Work is therefore required to develop calibration techniques for these high frequencies.

Impulse methods generate very high-frequency inputs more easily than oscillatory methods. With a shock tube, it is difficult to create a shock that does not have content to at least 1 MHz, if the sensor is mounted so that it points into the flow.

Tkachenko et al. demonstrate a spring-based method for conducting drop-test calibrations of piezoelectric pressure transducers. They manage to apply the pressure load within $10^{-5}$ seconds [67]. Their inputs compare well with shock-tube results.

There are several advantages to the use of oscillatory methods. Hurst et al. describe many of the properties of a sensor that may have an effect on the frequency
response [15]. An important property of many sensors is the presence of a cavity above the sensing element, which has its own resonant frequency which is often lower than that of the sensing element. An impulse test will not drive this resonance, but oscillatory methods generally will.

Oscillatory tests can be more accurate than impulsive tests across the measured frequency range. Impulsive tests in shock tubes are not well-suited to measuring the response of a sensor at lower frequencies, since the test time is always limited by the arrival of the contact surface, reflected shock, or expansion wave. Also, impulsive tests often give poor results at some frequencies below the resonant frequency, as shown in Boerrigter and Charbonnier [68] and Hurst et al [15]. They often falsely indicate departures from a flat response earlier than the model or oscillatory methods. In most cases, the departures indicated experimentally are ignored, and the extent of the flat region is taken to be 20% of the resonant frequency, as it should be for a second-order underdamped system [15]. The reason for the inaccurate results is that impulsive tests suffer from a low signal-to-noise ratio outside the low-frequency and resonance regions. While step and impulse inputs have content at all frequencies, the magnitude of the content decreases rapidly with frequency. Near the resonance frequency, the measured signal is large due to the amplification by the sensor. However, away from the resonance frequency, both the input and output signals are low, and the measurements may be significantly distorted by electronic noise, vibration, and other non-ideal conditions. Oscillatory methods are more capable of accurately identifying the frequency response over the entire domain of interest.

For pressure measurements, many different methods may be chosen for frequencies below about 100 kHz, including pistonphones, solenoid valves, pulsating jets, sirens, and other speaker-type generators. Tables summarizing different methods, their frequency ranges, and their limitations are given by Gregory et al. [69] and Hurst et al. [15]. A very similar table to that in Hurst can be found in Zuckerwar et al. [70]. Oscillatory calibrations in air are difficult above 100 kHz. At high frequencies, the acoustic mismatch between air and the sensor causes low efficiency, and attenuation
becomes increasingly significant with increasing frequency [56]. Schindel et al. noted that for frequencies above about 500 kHz, the absorption of ultrasound increases with the square of the frequency and is proportional to pressure and the square root of temperature [71].

2.6.1 Examples of Low-Frequency Oscillatory Calibration Methods

Examples of lower-frequency calibrations are very common. Parrott et al designed a waveguide apparatus which sent convecting planar waves past a reference sensor and the sensor under test [72]. The waveguide was a rigid-walled duct, with a jet in a cylindrical chamber at one end that generated the acoustic waves, and the sensors under test at the other end. Planar waves were ensured in the frequency range of interest by designing the cross-section of the waveguide to be the appropriate width. For 30-40 kHz, the proper dimensions for the waveguide were 5 mm by 10 mm. The primary advantage of this method is the control of the spectrum shape and the relatively straightforward measurement of the transfer function. A very similar waveguide was used by Boerrigter and Charbonnier to calibrate up to 50 kHz [68]. Hurst et al. also calibrated a sensor up to 50 kHz using a waveguide which was driven by a speaker, rather than a jet [15].

Zuckerwar et al. demonstrated a substitution-based free-field calibration method for frequencies up to 80 kHz [70]. Substitution-based methods perform measurements with a reference sensor which is then removed and replaced with the sensor under test. A centrifugal fan was used as the noise source. Free-field calibrations have a relatively simple experimental setup, but various three-dimensional effects must be taken into account.

Beresh et al. used a similar method, but with wall-mounted sensors [73, 74]. An ultrasonic speaker reaching 45 kHz served as the acoustic source. They reported that the manufacturer claims the sensors have a flat response up to 300 kHz. They found that the PCB-132 sensors have a reasonably flat response in the tested frequency
range of 20-45 kHz. Higher frequencies could not be tested to due the limitations of the acoustic source.

Davis and Zasimowich demonstrated the use of a siren-type oscillator to create inputs up to 100 kHz [75]. This seems to be the highest frequency reached by simple pressure oscillators without using the MEMS techniques recently established (see Section 2.6.2).

Gregory et al. have used multiple methods in the dynamic calibration of pressure-sensitive paints (PSP) [69]. They used a fluidic oscillator which consisted of a jet that oscillated at 6.5 kHz, with frequency content up to 40 kHz. The PSP was calibrated using a high-speed camera, with a Kulite sensor for reference. A shock-tube method was compared to an acoustic resonance tube method for frequencies from 100 Hz to 10 kHz [76].

Kobata et al. used a rotating valve which approximated a square-wave input [77]. Their calibrations went only to 50 Hz. An advantage of this method was its ability to create low-amplitude inputs.

Jun et al. used a piston-in-cylinder device to generate low-frequency sinusoidal inputs in an airtight compartment [78]. Due to the contained nature of the measurements and the fairly simple physics involved, their calibrations were performed without a reference sensor, using only theoretical predictions for the input pressures. They generated inputs with amplitudes of about 1 psi at frequencies from 1-500 Hz. Their uncertainty was estimated to be within 2%.

Electrostatic actuators are often used for the dynamic calibration of sensors with accessible diaphragms. These are possible at low amplitudes and high frequencies, though Meyer and Houten provided a relatively low-frequency example up to 40 kHz [79]. While this technique is very flexible, it can only be used on a subset of sensors.

Swift et al. provided a demonstration of the reciprocity technique in calibrating a plane-wave resonator [80]. The sensor design was a silicon strain-gauge piezoresistive bridge. They used the technique to calibrate up to 400 Hz, and compared their
calibrations to static calibrations done with a mercury manometer. They agreed within 1%.

2.6.2 Examples of High-Frequency Oscillatory Calibrations

In air, the primary source for high-frequency oscillatory calibrations is the high-frequency ultrasonic transducers which have recently been constructed. While these transducers can easily create oscillations at high frequencies, calibrating the emitter is difficult. Almqvist et al. demonstrated the ability to characterize transducers up to 2 MHz with light diffraction tomography [56].

Schindel et al. demonstrated air-coupled capacitance transducers that were made with anisotropically-etched silicon backplates [71]. They achieved repeatable manufacturing of the transducers through a highly-uniform etching process. They showed measurements of the bandwidth of the transducers out to approximately 3 MHz using step or square-wave pulse voltage inputs. They demonstrated useful bandwidth from 100 kHz to 2.3 MHz. An estimate of detection sensitivity was provided using a laser interferometer.

Schindel also demonstrated ultrasonic measurements at 600 kHz in aluminum [81]. The frequency responses of the transducers used were shown to be flat, except near the resonance frequency. The technique was also demonstrated in polymers, wood, and other materials [82].

Anderson and Liu demonstrated the use of reciprocity techniques to characterize transducers up to 500 kHz [83]. They used three transducers in a free-field calibration technique, which required a mathematical model for the sensors. They were able to extend the reciprocity technique to high frequencies by accounting for attenuation and diffraction effects.

The radiation force technique was demonstrated for high frequencies by Swamy and Keil [84]. This method can create low-amplitude inputs, extending well below 0.001 psi. With this method, the transducer is placed in the wall of an anechoic
chamber filled with degassed water. A target is held facing the transducer, and connected to a microbalance. The force on the target is measured and provides a power measurement for the transducer. However, the method must be done in water, which will not be acceptable for all sensors. Additionally, the pressures measured in water may not correspond to the pressures that would be generated in air, due to the drastically different acoustic properties of the two mediums.

2.7 Spatial Resolution Effects

The measurement of high-frequency (and thus low-wavelength) fluctuations can frequently be complicated by the spatial resolution of the sensors used. If the sensor is small compared to the wavelength measured, then the output approximates a point measurement, and the full amplitude is measured. If the sensor diameter is significant compared to the wavelength, then the spatial resolution of the sensor becomes important. This is because the sensor does not measure at a point, but rather measures an average of all the values present on the active area of the sensor. This averaging reduces the measured amplitude.

If the wavelength and active area are known, it should be possible to account for this averaging. Various treatments are present in the literature, with Corcos providing probably the most well-known [85]. Corcos applied his analysis to the problem of measuring turbulent fluctuations in boundary layers. It is of interest to experimentally measure these fluctuations to as high a frequency as possible, but the fluctuation wavelengths extend to very small values, so spatial averaging is almost always a concern in these experiments.

Beresh et al. used the Corcos corrections in their measurements of turbulent fluctuations [73, 74]. They found that spatial resolution could explain much of the scatter in existing measurements. They also used PCB-132 sensors for high-frequency measurements, and attempted to apply the Corcos correction to those sensors, despite uncertainty about the shape and size of their sensing area. Their results indicated that
the sensing length (the length of the sensing area aligned with the direction of wave propagation) was closer to 1.6 mm than 0.762 mm, which was the size of the sensing element underneath the epoxy. They came to this conclusion because using the larger length with the Corcos correction yielded approximately the expected scaling with frequency, while the smaller length yielded no scaling.

White extended the work of Corcos for non-circular sensing areas and non-uniform sensitivities across the sensor face [86]. He calculated sensitivity reductions at various wavelengths for circular, square, rectangular, diamond, and elliptical sensing areas. He also investigated the effect of nonuniform sensitivity across the sensor face. He found that reduced sensitivity near the edges of the sensing area is equivalent to a uniform sensitivity with a smaller sensor. Enhanced sensitivity near the edges is equivalent to a larger uniform sensor. He cited experiments that used sensors with reduced and enhanced sensitivity near the edges [87, 88].
3. EXPERIMENTAL APPARATUS

3.1 3-Inch Shock Tube at Purdue

In order to create shocks at the low amplitudes of boundary-layer instabilities in wind tunnels, a new shock tube has been built with a design based on the 6-inch shock tube in the Graduate Aerospace Laboratories at Caltech (GALCIT) [89]. The new shock tube (Figure 3.1) has a 3.5-inch (15.2-cm) inner diameter, a 12-foot (3.6-m) driven section, and a four-foot (1.2-m) driver section. Anna Kerlo provided assistance in the design and drafting of many of the shock tube parts, as described in her course report at Purdue [90].
The driven section is able to reach minimum pressures of about 1 millitorr (100 Pa) using an Oerlikon TRIVAC D4B vacuum pump, with a minimum pressure below 1.5 millitorr and nominal pumping rate of 3.4 ft$^3$/min. The driver section is designed to withstand pressures as high as 1000 psia (6895 kPa). The targeted driven section pressures are in the region of moderate vacuum. High vacuum is usually considered to be pressures below $10^{-6}$ torr, and low vacuum is generally considered to be on the order of 1 torr. The design of the driven section incorporates parts which satisfy high-vacuum or ultra-high-vacuum requirements mixed with custom-designed parts whose performance is undetermined, and some standard parts which were not designed for vacuum seals. The use of vacuum grease was found to improve the performance of standard parts enough to achieve the moderate vacuum levels required.

The actual minimum pressure achievable depends on the configuration of the shock tube. If the shock tube is configured without the burst system and with no sensors installed, it is possible to reach pressures as low as 0.9 millitorr. Installing sensors increases the number of seals required, increasing the likelihood of leaks. Additionally, the seal between the sensor and insert is often formed solely by nail polish, which likely does not have the same vacuum performance as an o-ring with vacuum grease. With sensors installed, it is more common to reach minimum pressures of 1.5-3 millitorr.

With the electrical burst control system installed, vacuum performance is further degraded, though still sufficient to create very low-pressure shocks. The electrical burst system uses electrically-heated wires stretched across the interior of the shock tube in a cross pattern to cut a non-conductive diaphragm into four petals. The electrical power wires which pass through the shock tube wall are sealed using Conax fittings, which do not necessarily have high vacuum performance. With the electrical burst control system installed, minimum pressures are typically 8-20 millitorr. This performance is sufficient, since with the weakest diaphragms, runs below about 50 millitorr are not useful due to poor shock formation.

In addition to the effect of configuration changes, there is some run-to-run variation in the vacuum performance of the shock tube. The variation is likely due to
multiple factors. These include the diaphragm degassing, the varying levels of contaminants introduced when working inside the shock tube, and variation in the seal between the diaphragm and the driven transition section.

The current maximum pressure in the driver section is 140 psia, which is the supply pressure in the building. However, no diaphragms currently in use allow such high driver pressures. The present operational high-pressure limit for the driven section is ambient pressure. Higher pressure could certainly be applied, but an analysis to determine the maximum safe internal pressure has not been performed. The interior of the tube was honed, and the joints of the shock tube have been designed to be smooth. This was to avoid disturbing the flow and to create a clean planar shock wave with a following laminar boundary layer.

In order to use weak diaphragms at low driven pressures, it is necessary to reduce the driver section to pressures around 1 psia. To allow for this, the driver section is connected to the vacuum system. No high-vacuum parts were used in the driver section, and the minimum pressure that can be achieved in the driver section is on the order of 1 torr. Cut-off valves allow the driven section to continue to be pumped down after the driver section has reached the appropriate pressure, and also protect the vacuum system from the high pressures that will sometimes be present in the driver section.

The lowest static-pressure rise currently achievable with the shock tube is approximately 0.001 psi, which was the original performance goal. The minimum value observed was 0.0008 psi, but the uncertainty for this value is unknown. The lowest static pressure rises are only possible with the burst system installed. Without the burst system, the minimum rise measured was 0.008 psi. The difference is due to the improved shock formation behavior and lower minimum burst pressures (0.5 psid, compared to 2.5 psid) that can be achieved with the electrical burst system.
3.1.1 Shock Tube Construction

All tube sections, excluding the driver and driven transition sections, were manufactured from one long 304 stainless-steel pipe with a honed interior. The sections were cut from this pipe, with approximately 6 feet of pipe left over. Before the pipe was cut into sections, it was found to have an interior diameter of 3.523 inches at one end and 3.507 inches at the other, implying a variation of approximately 0.001 inch per foot. The shock tube sections are joined in the same order they had before the pipe was cut. This was done because the pipe interior diameter varied slightly over its length, and keeping the same order minimizes the interior step at each joint. In the future, the present arrangement of sections could be changed, particularly by manufacturing new sections to replace the existing ones. This interchangeable design maximizes the flexibility of the shock tube for other applications that may be of interest in the future.

No measurements of the interior step have been performed. The joints are faintly visible on the interior of the shock tube, but could not be adequately photographed, as seen in Figure 3.2. It is unlikely that the steps are larger than 0.001 in. There are open sensor mounts in the tube which appear on the walls. The joint is between the second and third sets of holes, going downstream. The second set of holes is highlighted in red, and the third set is highlighted in blue. When seen, the joints simply appear as a small line on the interior. It is believed that the steps are small enough that they create no significant disturbance. As can be seen in Figure 3.2, the use of a honed interior and the low-step joint design has resulted in a smooth interior surface.

The driver and driven transition sections, shown in Figure 3.3, were manufactured from carbon steel instead of stainless steel in order to reduce the machining time. The driven transition section is on the left, with the driver transition section and collar on the right. The clamp rings hang above the driven transition section. The collar is the piece that the hydraulic tubes connect to. The face of the driver transition section
is visible inside the collar. These sections connect the driver and driven tubes. The joint between these two sections is where the diaphragm is mounted. The electrical burst system is mounted in the driven transition section. An o-ring is mounted in the face of both sections to seal against the diaphragm. Vacuum grease was applied to the o-ring in the driven transition section in order to provide a vacuum seal.

The design of the joint is shown in Figure 3.4. A collar fits around the driver transition section, with hydraulic fluid in the gap between the two pieces. The collar and the driven transition section are held in place by clamp rings. The hydraulic fluid is then pressurized up to 1000 psi. This pressure forces the collar into the clamp rings, and the driver transition section into the driven transition section, which is also held in place by the clamp rings. The force from the hydraulic fluid is what clamps onto the diaphragm, holding it in place and providing the seal.
Figure 3.3. The transition section assembly.

Figure 3.4. Cross-section of the transition section joint when assembled. The region filled with high-pressure hydraulic fluid is shown in red.
3.1.2 Run Condition Measurements

The driver pressure was measured through multiple means. Instantaneous measurements were provided by a Kulite installed in the driver end plate. In most cases, a Paroscientific 740-30A quartz pressure transducer was used to take a manual measurement of the driver pressure before the run. The shock tube operator recorded the last value displayed before the run started. The estimated uncertainties for the manual measurements are listed in Table 3.1. Unfortunately, the Kulite sensor was unreliable. The wires broke frequently due to the significant flex in the wires when the shock tube was opened and closed. For this reason, the Kulite was not generally used as the reference measurement.

<table>
<thead>
<tr>
<th>Material</th>
<th>Driver Pressure (psi)</th>
<th>Uncertainty (psi)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31-mil polyethylene (burst)</td>
<td>0.5</td>
<td>.12</td>
<td>24</td>
</tr>
<tr>
<td>1.5-mil Mylar (burst)</td>
<td>6</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>2-mil Mylar (burst)</td>
<td>14</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>0.5-mil Al (natural)</td>
<td>2.5</td>
<td>.5</td>
<td>20</td>
</tr>
<tr>
<td>0.7-mil Al (natural)</td>
<td>3.5</td>
<td>.5</td>
<td>14</td>
</tr>
<tr>
<td>1.0-mil Acetate (natural)</td>
<td>20</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>
The Paroscientific gauge was also used for the static calibrations of the Kulites. In some cases, the Paroscientific gauge was removed due to the use of higher pressures which might damage the sensor.

The driven pressure was measured with an Oerlikon TTR 91 vacuum gauge. The TTR 91 was the only sensor used which was capable of measuring the low pressures used in the driven tube. The sensor is capable of measuring pressures across four orders of magnitude. In order to accommodate such a wide measurement range, the voltage output increases logarithmically with pressure. Because of this, it becomes increasingly inaccurate as the pressure increases. Comparisons with measurements from Kulite sensors and the Paroscientific gauge indicated that the errors become significant when the pressure exceeds about 2 psia. The quoted accuracy of the gauge is 15% of the reading between 0.7 millitorr and 75 torr. Outside of this range, the gauge is only accurate within 50%. The repeatability is quoted as 2%, and the resolution is 1% of the reading.

The driven pressure readings were also taken manually. Due to leaks and outgassing, the driven pressure was often changing up until the diaphragm burst. Because of this drift, the driven pressure readings also had limited accuracy. The estimated uncertainties due to the manual reading are given in Table 3.2 for a few commonly used pressures. For the total uncertainty at a given pressure, they must be combined with the 15% uncertainty of the gauge itself.

<table>
<thead>
<tr>
<th>Driven Pressure (torr)</th>
<th>Uncertainty (torr)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3.2. Estimated uncertainties for driven tube pressure measurements performed manually with the Paroscientific gauge.
3.1.3 Static Pressure Sensor Mounts

Sensors were mounted in the wall of the shock tube using half-inch diameter inserts with a static o-ring seal. Vacuum grease was applied to the o-rings to improve the seal for low driven pressures. Sensors were mounted in the inserts using nail polish. Extra nail polish was applied around the back of the sensor to try to ensure a good seal.

The sensor inserts are mostly interchangeable and can be mounted in any port in the shock tube. The exceptions are the three widened mounts which were made to accommodate the larger reference sensors. These large mounts have 0.75-in. diameters. The standard ports are 0.5 in. wide. All the sensor inserts and acrylic windows are made to be flush with the interior. The faces of the sensor inserts were contoured to match the curvature of the shock tube interior. Blank inserts should present negligible disturbance to the interior flow.

The sensor faces are flat, and can only be made approximately flush with the curved interior. The sensors were mounted so that they would be tangent to the interior surface, and thus present a small cavity, rather than flush with the sides of the sensor hole, thus presenting a small roughness in the middle. The difference between the two methods is shown in Figure 3.5. On the left, the sensor (yellow) is mounted to be tangent with the interior surface. The cavity between the sensor and the interior surface of the tube is clear. The plot on the right shows a sensor mounted to be flush with the sides of the insert. In this case, the sensor protrudes in the middle of the insert, creating a roughness. It was expected that cavities would disturb the flow less than a roughness of the same height.

Sensors were nearly always mounted in the wall, which is referred to as a static configuration because the sensors measure the static pressure. In some limited cases, sensors were also mounted in a pitot configuration. A pitot-mounted sensor is pointing into the flow, so that it measures the pitot pressure. Pitot sensors were mounted in thin chamfered tubes. The pitot measurements are discussed in Chapter 8.
Table 3.3 shows the locations of the existing static mounts. Downstream distance is measured from the diaphragm location. Angles are defined with $0^\circ$ at the top of the shock tube, increasing clockwise when looking downstream. The locations in Table 3.3 were the state of the tube at the end of this research. The initial layout of mounts was more sparse, without the windows or any of the larger sensor mounts. In the initial configuration, the mounts at 102 in., 138 in., and 144 in. did not exist, and only one mount at $0^\circ$ was present at 132 in. The initial layout was minimal so that the shock tube performance could be evaluated and the best layout could be determined. The sensor mounts may also continue to change in the future.

The driven section of the shock tube was built in three sections. These are connected with a joint design that minimizes the step on the interior and provides a vacuum seal with an o-ring.

### 3.2 Running with Natural Bursts

Thin aluminum foil diaphragms ordered from McMaster were used for most runs without the electrical burst system, with thicknesses of either 0.001 in., 0.0005 in., or 0.0007 in. These diaphragms typically had burst pressures between 2 and 3 psid.

<table>
<thead>
<tr>
<th>Downstream Location</th>
<th>Angular Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 in. (0.91 m)</td>
<td>0°</td>
</tr>
<tr>
<td>72 in. (1.83 m)</td>
<td>0°, 180°</td>
</tr>
<tr>
<td>96 in. (2.44 m)</td>
<td>0°, 90°, 180°, 270°</td>
</tr>
<tr>
<td>102 in. (2.59 m)</td>
<td>45°L, 225°</td>
</tr>
<tr>
<td>114 in. (2.90 m)</td>
<td>0°, 180°</td>
</tr>
<tr>
<td>132 in. (3.35 m)</td>
<td>0°, 90°W, 180°L, 270°W</td>
</tr>
<tr>
<td>138 in. (3.51 m)</td>
<td>45°L, 225°</td>
</tr>
<tr>
<td>144 in. (3.66 m)</td>
<td>0°</td>
</tr>
</tbody>
</table>

(14 and 21 kPa). Some acetate diaphragms were also occasionally used, which had a thickness of 0.001 in. and a burst pressure of about 20 psid. For some earlier runs, mylar of 0.001 in. thickness was used. These diaphragms had higher burst pressures of around 10 psid. The natural burst pressures for diaphragm materials used without the electrical burst system are shown in Table 3.4. For all materials, the standard deviation of the burst pressure was about 10%. Acetate has better natural bursting behavior than mylar because it is more brittle, and tends to quickly shatter into many pieces, whereas mylar diaphragms tend to tear and have a slower opening time.

Table 3.4. Burst pressures for diaphragm materials used with natural burst.

<table>
<thead>
<tr>
<th>Material</th>
<th>Burst Pressure (psid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-mil Aluminum Foil</td>
<td>2.5</td>
</tr>
<tr>
<td>0.7-mil Aluminum Foil</td>
<td>3.4</td>
</tr>
<tr>
<td>1.5-mil Mylar</td>
<td>20.6</td>
</tr>
<tr>
<td>1.0-mil Acetate</td>
<td>20.8</td>
</tr>
</tbody>
</table>
In most shock tubes using natural bursting, the diaphragm assumes a spherical shape, with maximum stress in the center. It then tears outward from the center, as can be observed in the pictures in Revel et al. [57].

However, in this shock tube, insert slots were cut into the driven transition section to allow for the installation of the electrical burst system. When the system is not installed, these slots are empty, as shown in Figure 3.6. During pressurization, the diaphragm is pressed into the slots, and stress concentrations are created at the corners of the slots. Instead of bursting in the middle, the diaphragm is initially punctured by one of the corners, and then rips around the interior edge of the shock tube until it begins to rip along a random path, usually after traversing more than 90°. Because of this tearing around the edge, the diaphragm tends to fly down the tube in 2-3 large pieces. The exception is for acetate diaphragms, which tend to shatter into a larger number of smaller pieces.

The diaphragm profiles were difficult to photograph clearly. An approximate outline has been drawn for Figure 3.7. The most obvious feature is the profile of the slot for the electrical burst system. By examining the plastic left over after the burst, it was clear that the bottom slot (at the 180° position) corresponded to the slot profile in the recovered diaphragm fragments. This seemed to indicate that the bottom slot was the one initiating burst.

This unique burst behavior had the effect of reducing the burst pressure, as tests with the burst system installed revealed. It is unknown what effect this behavior had on opening time or shock uniformity. It is also unknown to what extent this behavior applies to non-mylar diaphragms. The acetate diaphragms tended to shatter, making it difficult to determine what the contours of the burst were. Aluminum foil diaphragms were crumpled into balls as they flew down the tube, and could not be smoothed without significant damage. From a select few aluminum diaphragms which did not crumple much and examination of the material left at the transition section, it is believed that all diaphragms followed this burst behavior when natural burst was used.
Figure 3.6. The driven transition section with empty insert slots. The diaphragm is mounted on this face.

3.3 Electrical Burst Control System

An electrical burst control system was added to the shock tube in an effort to improve repeatability and reduce the minimum burst pressure differential. This burst control system improves repeatability through two mechanisms. The first is by allowing tighter control of the run conditions. Without a burst control system, the diaphragm ruptures whenever its natural strength is exceeded by the pressure load. Since different diaphragms will have different natural strengths due to normal manufacturing variations, each run will have slightly different conditions, with the deviation dependent on how the material was produced.

Additionally, since there is no independent control of the burst condition, the pressure in the driver section is constantly changing before the run. This unsteadiness
increases the chances of significant nonuniformity within the driver tube. It also makes accurately measuring the run conditions more challenging.

The second source of nonuniformity without a burst control system is natural variation in the burst process itself. Since the diaphragm ruptures when its natural strength is exceeded, it will also rupture along natural fracture paths, which will vary between diaphragms. The opening time of the diaphragm will depend on the fracture paths. Since the shock development length depends primarily on opening time, the development length will also vary [58].

A burst control system can reduce all of these variations. Since the burst conditions are controlled, they are more static before the run begins. If the burst control system controls the break pattern of the diaphragm, then variations in opening time and shock formation are also reduced. Methods that control the fracture path include
razor crossbars, diaphragm scoring, and electrical wires. Methods using a needle allow control over the burst conditions, but since they only begin the diaphragm rupture in the center, they do not necessarily reduce variation in opening time.

The electrical burst system installed in the 3-Inch Shock Tube was based on the system that had been used for the Mach-4 Quiet-Flow Ludwieg Tube at Purdue [91]. The system uses a large bank of capacitors with a total capacitance of about 1 Farad. These capacitors are charged to 36 V, and then discharged across 0.01 in. diameter Nichrome wires. The Nichrome wires are stretched across the shock-tube interior in a cross pattern nearly flush with the diaphragm, in order to maximize the length of contact with the diaphragm. As the pressure differential is applied to the diaphragm, it is pushed out into the driven section and against the wires, establishing a solid thermal contact. The leads connected to the parts inside the shock tube are disconnected from the capacitors until a switch is powered and then triggered. Additionally, the pressure of the wire should create a stress concentration in the diaphragm near the wire. Once triggered, the current heats the wires, melting the diaphragm and destroying the wires, resulting in a clean cut along the length of the wire.

A negative side-effect of this method is that small wire fragments fly down the shock tube, which could pose a risk to fragile sensors such as the Kulites. The risk may be small, since no sensors have yet been lost due to wire fragments. This disadvantage is offset by the fact that usually none of the diaphragm is broken off and sent downstream. When parts of the diaphragm do break off, they are generally much smaller than the pieces that break off without the burst system. Another limitation of this method is that it can only be used with non-conductive diaphragm materials.

Because the diaphragm is cut by heat from the wires, rather than allowed to tear naturally, the burst process becomes partially independent of the natural burst characteristics of the material. The burst process is still affected by the strength and weight of the material, but the tearing mechanics of the material become unimportant. This allows the use of materials that have undesirable or unusable natural bursting
mechanics. Many plastics stretch extensively before they tear, resulting in a slow and uneven burst. This slow burst process spreads out the pressure fluctuations, extending the shock formation distance.

Independence from natural burst characteristics is particularly useful when trying to create low-pressure shocks, because the plastics used to create very thin sheets tend to have poor natural burst characteristics. Diaphragms with poor natural burst characteristics actually work better with the electrical burst system. Since the diaphragm needs to press firmly into the wires without breaking, a flexible, ductile material works better than a stiff, brittle one.

Two kinds of material were primarily used with the electrical burst system, summarized in Table 3.5. The first was mylar in 1.5 and 2.0-mil thicknesses. These were used at pressure differentials of approximately 6 and 15 psi, respectively. 1.0-mil mylar was occasionally used in the testing phase, but it proved difficult to find the appropriate burst pressure difference and its use was discontinued. 1.0-mil acetate was also tested with the electrical burst system, but good cuts were difficult to achieve due to the brittle nature of the material.

The second diaphragm material used was 0.31-mil painter’s drop cloth. This plastic sheeting was the thinnest that could be found without making an impractically-large custom order from a manufacturer. The particular kind used was Blue Hawk painter’s sheeting. The actual material is not specified anywhere on the packaging. It was determined that the material is manufactured by Lowe’s, which supplied the Material Safety Data Sheet (MSDS) for the product. The MSDS says that the material is polyethylene, though there is some ambiguity about whether it is high- or low-density, and whether there may be other polymers in the blend.

The electrical burst system consists of several parts. The interior parts are shown in Figure 3.8. There are two power wires which pass through the wall of the shock tube, four brass inserts inside the wall of the shock tube, two steel crossbars, two brass bus bars, and two cutting wires. The power wires connect the internal circuit to the capacitor bank outside the shock tube. The brass inserts connect the cutting
Table 3.5. Burst pressures for diaphragm materials used with electrical burst system.

<table>
<thead>
<tr>
<th>Material</th>
<th>Burst Pressure (psid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31-mil Polyethylene</td>
<td>0.5</td>
</tr>
<tr>
<td>1.5-mil Mylar</td>
<td>6</td>
</tr>
<tr>
<td>2-mil Mylar</td>
<td>15</td>
</tr>
</tbody>
</table>

wires to the power system. They are mounted in slots in the wall of the shock tube and are flush with the interior of the shock tube, to minimize flow disturbance. The bus bars electrically connect pairs of inserts to eliminate the need for two additional power wires coming through the wall of the shock tube. Screws connect the bus bars and power wires to the downstream end of the inserts.

Two bus bars are used to ensure that two inserts are at the positive supply voltage, and the other two are connected to ground. Two crossbars support the brass inserts, keeping them from being blown down the tube. The crossbars are attached to the brass inserts using plastic dowel pins. A stronger material would be desirable for the dowel pins, but the crossbars must be electrically insulated from the brass inserts to prevent shorting the circuit. Brass was chosen for the electrical pieces due to its combination of good conductivity and machinability.

The internal pieces are insulated from the shock tube using 0.002-in. Kapton tape. Kapton tape was used because its thickness is well known, which allows for relatively tight fits to be used. The brass inserts are covered with this tape on all sides that contact the shock tube. A narrow strip is applied to the top of the insert to prevent electrical contact between the insert and the crossbar. Kapton tape is applied to the downstream ends of the crossbars to prevent electrical contact from being made directly with the power wires or bus bars. Standard electrical tape is used to insulate the bus bars from the shock tube. Kapton tape was originally used, but there are no
Figure 3.8. The internal pieces of the electrical burst system installed in the shock tube, without the cutting wires.

corns about ensuring a tight fit with the bus bars, and it was found that electrical tape was more durable.

The internal burst-control assembly creates an intrusion in the flow. However, the design attempted to minimize the level of intrusion. Also, the pieces are close enough to the diaphragm that it is believed the shock should still be largely unformed, and the disturbances caused by the electrical system should dissipate by the time the shock reaches the sensors in the second or third sections of the shock tube (5-11 feet from the diaphragm).

It had been hoped that the electrical burst system would make the burst pressure largely independent of the diaphragm material, but this did not turn out to be the
case. Instead, even with the burst system, only one nominal burst pressure differential is used for each diaphragm material and thickness. If the pressure differential is too low, the diaphragm is not pressed firmly enough into the wires to establish good thermal contact across the whole wire. Additionally, the stress in the diaphragm caused by the pressure difference may need to be above a certain level in order for the diaphragm to break quickly. Determining the usable ranges may be worthwhile in the future, but was not done here.

The actual cutting action of the electrical burst system is a complicated transient process. There are several mechanisms with potentially independent time limits which need to progress in a tightly-coupled way in order for a good cut to be achieved. This complexity causes the system to be sensitive to pressure differences and the quality of electrical contacts in the system, among other factors.

The first is the heating of the wires, which is dependent on the amount of current flowing through both wires. The two wires form two circuits which are connected in parallel at the pass-through power wires. The low resistance of the system (typically only about 2 Ω for each parallel circuit, and slightly more than 1 Ω for the whole circuit) and the short time scales involved mean that small differences in resistance between the two circuits, only 0.1-0.2 Ω, can prevent a good cut from being achieved. The wire with higher resistance draws less current, and thus heats more slowly and to a lower maximum temperature. The difference can be enough that the other wire cuts through the diaphragm before the higher-resistance wire has had a chance to weaken the diaphragm. In many cases, the higher-resistance wire is broken by the burst process, and the diaphragm is only cut along one axis. The poor cut results in a smeared-out region of compression waves, which require a much longer distance to form into a shock.

The low resistance differences required to cause this problem are usually created by degraded contact between the inserts and the bus bars. The most common reason is that the screws connecting the bus bars to the rest of the system are loosened
slightly during a run. Less commonly, insulating tape gets in between the bus bar and the brass insert, or corrosion in the same location degrades the contact.

The second process that limits the action of the electrical burst system is the tendency of the wires to burn or melt themselves. This process imposes a time limit for breaking the diaphragm, since if the wires destroy themselves before the diaphragm is weakened enough to burst, the wires fall, current stops flowing, and no run is achieved. This clearly places limitations on the thickness of diaphragm used, and potentially the loading of the diaphragm. The limitation on the loading comes from two factors. One is the need for good thermal contact across the entire diaphragm, which is achieved when the diaphragm has been pushed out into the wires. Sufficient deformation will require a certain load on the diaphragm. Additionally, if the diaphragm is strong enough, the wires may require more time than is available to cut through the material. In that case, the diaphragm can only be weakened by the wires, and the existing stress in the material due to the pressure difference must be high enough to complete the burst.

This consideration points to the third factor, which is the natural bursting behavior of the diaphragm material. In the present method, if the wires are not firmly pressed into the diaphragm, or if they generate heat too slowly, they may only initiate the natural burst process, which might outrun the cutting ability of the wires. Such behavior was occasionally observed. It was made evident by tears that did not follow the profile of the wires, but instead curved and followed other independent axes. When this occurs, it would be expected that the diaphragm opening time is increased, which increases the shock formation distance. This can be a critical factor at low densities, where the shock formation distance was already a significant portion of the tube. In that case, a longer opening time could make the shock formation distance longer than the driven tube, causing a failed run.

The present electrical burst system design may be unique in shock tubes. The majority of shock tubes that use burst control systems use a simple needle design, which breaks the diaphragm mechanically in the center, or scribed diaphragms. Scribed
diaphragms have a similar effect to the present system, in that they control both the burst pressure and the burst shape. However, scribing is generally only applied to relatively thick metallic diaphragms and high burst pressures. Alternative electrical burst-control systems seem to have been designed primarily with timing control in mind, and again only start the burst in the center. The 17-Inch GALCIT shock tube employed a razor system which has a similar effect to the scribing system. Liepmann et al. found that the razor system significantly reduced the opening time of their diaphragms, in addition to allowing control of the burst pressure [37]. However, this system gave somewhat ad-hoc control, since the pressure differential was used to force the diaphragm into the razors, with no independent way of controlling the burst. It would not allow for the precise control of the burst pressure that the present system has, and it may not allow for the low burst pressures of the present system.

The present system is merely an adaptation of the burst-control system developed for the Purdue Mach-4 Quiet-Flow Ludweig Tube (PQFLT). However, its application is significantly different. For the PQFLT, the system was only required to control the tunnel conditions. The manner in which the diaphragm was cut was unimportant, since the shock created went into the vacuum tank, and the startup process was long enough that the effects of an uneven cut would dissipate before they could significantly affect the run conditions. The present application required a substantially greater degree of control over the burst process, and the operation of the system had to be determined with a greater level of detail than was required for the PQFLT.

3.4 Instrumentation

3.4.1 PCB-132 Sensors

PCB-132 sensors are piezoelectric pressure transducers designed to measure the time of arrival of shock waves. They are high-pass filtered at 11 kHz, with a quoted resonant frequency above 1 MHz and a rise time of less than half a microsecond for reflected shocks (shocks measured with the sensor pointed into the flow, usually
referred to as pitot measurements in this document). The sensitivity of these sensors is quoted to be approximately 140 mV/psi, with a maximum measurement of 50 psi. The resolution is quoted at 1 mpsi. The sensors are not acceleration-compensated, and the measurements may be contaminated by vibrations. Their acceleration sensitivity has not been quantified.

The manufacturer performs an approximate calibration of the sensors in a shock tube, by running one shock with a pressure rise close to 1 psi past the sensor. The calibration is assumed to be linear, with a 0 V offset. The calibration is done this way because the sensors are not intended for accurate pressure measurements.

The manufacturer’s calibration is not necessarily relevant or sufficiently accurate for the purposes of instability measurements. The response for an input of 1 psi is not necessarily similar to the response for an instability wave, which has pressure fluctuations three orders of magnitude smaller. In addition, the frequency response for the sensor is not identified. Second-mode instabilities in wind tunnels typically have frequencies between 100 and 600 kHz, so the frequency response of the sensor may be important to determining the actual magnitude of the pressure fluctuations across this frequency range.

Figure 3.9. PCB-132 sensor with epoxy removed, showing the sensing element (brown square).
Another issue with PCB-132 sensors is their spatial resolution. The instability waves on models generally have wavelengths on the order of millimeters. The sensor is a cylinder 0.125 inches (3.2 mm) in diameter, which is often longer than the second-mode wavelength. However, the sensing element is only a 0.03 x 0.03-in square (0.762 x 0.762 mm), visible in Figure 3.9. While this is smaller, the size may still be significant when compared to the second-mode wavelength. If the sensor size is significant compared to the second-mode wavelength, there will be spatial averaging. This averaging must be taken into account to find accurate amplitudes, so it is necessary to know over what area the sensor is measuring.

The sizes of the cylinder and sensing element are known, but the area over which the sensor actually senses pressure, the active sensing area, is unknown. This is because the sensor face and sensing element are both covered with a conductive epoxy. Pressure is transmitted to the sensing element through the epoxy, but the manner in which this happens is not well-understood. Some of the epoxy not covering the sensing element might be transmitting pressure to it, increasing the effective sensor size. The sensing area may depend on the magnitude of the pressure fluctuation, as well as the actual thickness of the layer, which may vary between sensors. This makes it necessary to determine the sensing area of the sensors while calibrating them. As indicated in Figure 3.9, the sensing element is not precisely located on the sensor. The effective sensing area may depend on the location and orientation of the sensing element. The epoxy layer may also affect the sensitivity of the sensor. If the epoxy responds differently to inputs with different amplitudes, the sensor response may be nonlinear.

The response of PCB-132 sensors to shock waves is discussed in detail in Chapter 4. The details of the PCB-132 response were important to the way the shocks were detected and measured. Due to the length of the discussion, it is only included with the description of the shock detection code.
3.4.2 Kulite Sensors

Kulite XCQ-062-15A pressure transducers were one of the more successful reference sensors used. These are cylindrical piezoresistive sensors with a diameter of 0.67 in. (1.7 mm). The quoted resolution is infinitesimal. It is likely that the current measurements challenge the resolution of the Kulite sensors, but it is unclear what the decrease in accuracy at low amplitudes would be. No estimate has been made in this work due to the lack of available data. Since the XCQ sensors can perform static measurements, a static calibration can be performed and used to approximate the dynamic calibration. Chung and Lu performed dynamic and static calibrations on similar sensors from Kulite and found the dynamic calibration to be only 1.6% larger than the static calibration [47]. The uncertainty in the static calibrations performed is estimated as 1%, since there were slow pressure changes in the shock tube and it was possible that the pressure would vary slightly throughout the tube. Combined with the 1.6% figure from the measurements of Chung and Lu, the uncertainty for the Kulites is estimated as 2%.

Figure 3.10. The two kinds of Kulite used mounted in shock tube static inserts.

(a) An A-screen Kulite mounted in a shock tube static insert.  
(b) A B-screen Kulite mounted in a shock tube static insert.
Each diaphragm contains a four-arm Wheatstone bridge, which is used to detect the deflection of the diaphragm. The diaphragms are very sensitive and can be easily damaged when exposed. Because of this, the sensors use screens to protect the diaphragms. These limit the frequency response due to the introduction of a cavity over the sensor, which can resonate. In this work, A-screen and B-screen sensors were used as reference sensors for the shock amplitude. A-screens consist of a large central hole, while B-screens consist of an array of small holes, as shown in Figure 3.10. A-screens offer less protection, but a higher frequency response. A B-screen sensor was used to measure the driver pressure.

Kulites have a nearly flat frequency response from 0 to 50 kHz. The XCQ sensors can measure pressures between 0 and 15 psi, and are repeatable within 0.1% of the full scale value (0.015 psi). They are mechanically stopped to prevent damage to the diaphragm at higher pressures.

![Shock response for Kulite XCQ-062-15A with A-screen mounted in tube side-wall at 96 in. downstream, 0° position. Mach 1.11, $P_{\text{Driver}} = 1.5$ psia, $P_{\text{Driven}} = 49$ torr. Using electrical burst system with 0.31-mil plastic drop cloth.](image)
Because of the relatively low resonance frequency and very small diameter of these sensors, the resonance was always excited with every shock input. As shown in Figure 3.11, they have a high-amplitude resonance, and exhibit some instability early in the shock response. The oscillations decay slowly, but the average level of the sensor quickly reaches the steady-state value. Averaging can easily be used to find the step amplitude while the oscillations are still fairly large.

These sensors are among the most reliable for detecting shocks, meaning that they very frequently display a shock response that is detectable and allows the step amplitude to be measured. Their resonance, instability, and relatively slow rise make them less reliable for shock arrival time measurements than for amplitude measurements.

### 3.4.3 PCB-102 Sensors

Multiple models of the PCB-102 sensor exist. In this research, the PCB-102B18 model was used, and will simply be referred to as a PCB-102 or a 102. The sensor is shown mounted in a shock tube insert in Figure 3.12. This is a piezoelectric sensor intended for accurate dynamic pressure measurements. PCB provides a calibration for each sensor, which was 103.0 mV/psi for both sensors used in this research.

![Figure 3.12. A PCB-102B18 mounted in a shock tube static insert.](image)
PCB-102s have a 50 psi maximum measurement, with a resolution of 0.001 psi. The uncertainty is quoted as 1% of the measurement. The total uncertainty of the sensors has been estimated as 1% of the measurement plus the resolution. The resonance frequency for these sensors is quoted to be higher than 500 kHz, with a rise time of less than 1 microsecond. They have a good low-frequency response, with a minimum frequency of 0.5 Hz. This allows them to measure the shock as a step rather than a peak. Their acceleration sensitivity is quoted as less than 0.002 psi/g.

The resonance of these sensors was never observed in these experiments. The failure to observe resonance is likely due to the diameter of the sensors, which is 0.375 inches. A shock at Mach 3 should take about 0.01 ms to travel this distance, meaning the input contains frequency content only to 100 kHz. Since the fastest shocks created in this research had Mach numbers around 3 and these sensors were always static-mounted, it is unsurprising that the resonance was not observed.

These sensors do not match the PCB-132 frequency response, and the sensitivity and resolution are not quite high enough to securely meet the requirements of these calibrations. However, their frequency response is much higher than most of the other reference sensors, and their quoted sensitivity and resolution are comparable to those quoted for the PCB-132 sensors. This combination makes them a reasonable candidate for a reference sensor.

These sensors appear to be the most effective reference sensor of those tested, with the possible exception of the Kulites. They provide the cleanest and among the most reliable measurements of the shock amplitude. “Most reliable” is used to mean that they are able to measure shocks when other sensors may fail to detect them due to lower frequency response or sensitivity. In addition, the PCB-102s rarely indicate values that are unusually high or low when compared to the rest of the reference sensors and other runs at similar conditions.

A typical PCB-102 response is shown in Figure 3.13. Their response takes the form of a clean step, with no resonance and a fairly small amount of noise. This makes the measurement of the shock straightforward, since the rise is sharp and clear, without
resonance to distort the shock arrival time or the amplitude. There is sometimes some overshoot in the response. When present, this overshoot was excluded from the measurement.

Figure 3.13. Shock response for PCB-102B18 mounted in tube sidewall at 102 in. downstream, 225° position. Mach 1.11, $P_{Driver} = 1.5$ psia, $P_{Driven} = 49$ torr. Using electrical burst system with 0.31-mil plastic drop cloth.

3.4.4 PCB-106 Sensors

The PCB-106B52 is a piezoelectric sensor intended for accurate low-amplitude dynamic pressure measurements (shown in Figure 3.14). It is dynamically calibrated by PCB. The sensor has a maximum measurement of 1 psi, with a resolution of $2 \times 10^{-5}$ psi, far below the amplitude of the smallest shocks created in the 3-Inch Shock Tube. Its sensitivity is 5000 mV/psi, much higher than any other sensor used in this work. The uncertainty is quoted at 1% of the measurement, with a resolution of 0.02 mpsi. The acceleration sensitivity is quoted as less than 0.002 psi/g.
The disadvantages of the sensor are its large size, having a diameter of 0.618 inches, and its relatively low frequency response. The resonant frequency for this sensor is quoted to be at least 40 kHz, with a rise time of 12.5 microseconds. The lowest frequency measurable with the PCB-106 is 2.5 Hz. These sensors have a longer lead time when ordered than most, as they are not kept in stock and are only made when ordered.

The large size of the sensor makes it more difficult to mount. A larger sensor insert had to be designed specifically for this sensor, and larger mounts machined in the shock tube. Only three of these mounts were made, so the placement of the sensor was limited. However, the step created when the PCB-106 was mounted is large enough (about 1/32”) that it may have had some effect.

One further disadvantage of this sensor is its low maximum measurement. It cannot be used to measure pressure increases more than 1 psi, but the calibrations in this research generally do not extend above that value. However, the pressure in the shock tube continues to rise after the first incident shock, and the subsequent

![Figure 3.14. A PCB-106B52 mounted in a shock tube static insert. The step is visible at the bottom.](image-url)
pressure rises are larger than the initial rise. Because of this, the PCB-106 must be removed if any but the weakest diaphragms are installed in the tube.

Because of its low resonance frequency, this sensor always exhibited significant resonance, often even before the arrival of the shock. Due to the low frequency response and large sensing area of the PCB-106 its arrival time data were often excluded from shock speed calculations. The resonance can make it difficult to identify the arrival of the shock from the raw data, but this difficulty was largely overcome by the data processing techniques later developed (See Chapter 4).

![Shock response for PCB-106B52 mounted in tube sidewall at 132 in. downstream, 180° position. Mach 1.11, $P_{\text{Driver}} = 1.5 \text{ psia}, P_{\text{Driven}} = 49 \text{ torr}$. Using electrical burst system with 0.31-mil plastic drop cloth.](image)

**Figure 3.15.** Shock response for PCB-106B52 mounted in tube sidewall at 132 in. downstream, 180° position. Mach 1.11, $P_{\text{Driver}} = 1.5 \text{ psia}, P_{\text{Driven}} = 49 \text{ torr}$. Using electrical burst system with 0.31-mil plastic drop cloth.

### 3.4.5 PCB-103 Sensors

The PCB-103B11 is a calibrated dynamic pressure sensor intended for moderate-amplitude pressure measurements. It has a sensitivity near 500 mV/psi and a maximum measurement of 10 psi, with a $6 \times 10^{-4}$ psi resolution and an uncertainty of 1% of the measurement. It has an acceleration sensitivity of 0.0005 psi/g. This sensitivity
and resolution make it suitable for measuring the lowest-amplitude shocks produced in the 3-Inch Shock Tube.

The primary disadvantage of this sensor is its low frequency response. It has a resonant frequency of 13 kHz, far lower than any other sensor used here. Its rise time is 25 microseconds. It measures inputs as steps, not peaks, with a minimum frequency of 5 Hz.

The sensor is shown in Figure 3.16. This sensor, like the PCB-106, is too wide to be installed in the standard insert design, and must use the widened mounts. However, the size is due to the housing, not the sensing element. The sensor is designed somewhat like a rather large Kulite with an A-screen, as seen in Figure 3.16. The sensing element is in the cavity in the center.

![Figure 3.16. A PCB-103B11 mounted in a shock tube static insert.](image)

This sensor was not successful as a reference sensor. It was hoped that its high sensitivity would be useful, but the sensor is severely limited by its low frequency response. It frequently fails to detect shocks, even with more advanced shock detection methods. Its slow response also meant that test times were often too short for the PCB-103 to accurately measure the shock. Because of its slow rise, measurements
with this sensor were often lower than the other sensors. Due to these accuracy problems, results from this sensor were not used for quantitative measurements. Traces from this sensor are sometimes included, since they can be qualitatively useful. The PCB-103 is not recommended for continued use.

![Graph](image)

Figure 3.17. Shock response for PCB-103B11 mounted in tube sidewall at 102 in. downstream, 45° position. Mach 1.11, $P_{\text{Driver}} = 1.5$ psia, $P_{\text{Driven}} = 49$ torr. Using electrical burst system with 0.31-mil plastic drop cloth.

### 3.4.6 PCB-113 Sensors

The PCB-113B27 sensor was initially used because it was one of the few calibrated dynamic pressure sensors that were on hand when the present research began. It was found to be moderately effective as a reference sensor, but was less effective than the preceding sensors. It was primarily used at the beginning of the research, and was rarely installed after the other reference sensors were obtained.

The PCB-113B27 sensor is a piezoelectric sensor with a measurement range up to 100 psi. Its resolution is 0.001 psi, which is similar to the quoted value for the PCB-
132 sensors, and sufficient to measure most of the shocks created for these calibrations. It has a sensitivity near 50 mV/psi, which is low compared to the other sensors used in this research, including the PCB-132s.

The sensor has a resonant frequency greater than 500 kHz, and a rise time of less than one microsecond. It is able to measure frequencies down to 0.5 Hz. Its acceleration sensitivity is less than 0.002 psi/g. It is a relatively large sensor, with a sensing face 0.218 inches in diameter, as shown in Figure 3.18.

![PCB-113B27 mounted in a shock tube static insert. Vacuum grease is visible around the rim of the insert.](image)

Figure 3.18. A PCB-113B27 mounted in a shock tube static insert. Vacuum grease is visible around the rim of the insert.

The resonance of this sensor was generally not excited by shocks passing over the sensor face, so resonance was not a problem in measuring the shock amplitude. The signal-to-noise ratio for this sensor was not as good as some of the other reference sensors, but it was generally sufficient to detect and measure the shocks with reasonable accuracy. This sensor was not generally capable of detecting shocks at the very low end of the range producible in the 3-Inch Shock Tube.
Figure 3.19. Shock response for PCB-113B27 mounted in tube sidewall at 96 in. downstream, 270° position. Mach 2.15, $P_{\text{Driver}} = 3.5$ psia, $P_{\text{Driven}} = 5$ torr. Using natural burst with 0.7-mil aluminum.

### 3.4.7 PCB-105 Sensors

The PCB-105C02 sensor was initially used because it was one of the few dynamic reference pressure sensors that were on hand when the present research began. It was not found to be very effective, and was only used in the early stages of the research, before the other reference sensors were obtained.

The PCB-105 is a subminiature piezoelectric sensor, shown in Figure 3.20. The model used in the present research can measure a maximum of 100 psi, with a sensitivity near 50 mV/psi and a resolution of 0.005 psi. The resonant frequency is greater than 250 kHz, with a rise time less than two microseconds. The sensors have a small diameter of 0.099 in, as shown in Figure 3.20. Their acceleration sensitivity is less than 0.04 psi/g.

An example response from the PCB-105 is shown in Figure 3.21. The example was chosen so that the shock would be clearly visible. It is clear in the trace that
the PCB-105 has a lower signal-to-noise ratio than many of the other sensors. The noise level before the arrival of the shock is significant, despite the relatively large amplitude of the shock. Additionally, the sensor’s frequency response does not allow for a step measurement, but instead a peak is measured. The peak is narrow, which limits the amount of averaging that can be done to reduce the impact of noise on the measurement.

The combination of the high noise level, low sensitivity, and relatively quick roll-off for this sensor made it fairly inaccurate when compared to the other reference sensors. The same factors made it difficult to detect shocks with this sensor. Its measurements also tended to be inaccurate when it did measure a shock. Because of these difficulties, the measurements from this sensor were rarely used.

3.5 Data Acquisition System

Three models of Tektronix oscilloscopes were used to record the data: the DPO7054, TDS5304B, and MDO3014. A maximum of 4 oscilloscopes were used at a time, usually with two MDO3014s and one each of the other two kinds. All of these have 8-bit
resolution which can be increased as high as 11-bit when using Hi-Res mode, which was always used in this research. In Hi-Res mode, data is taken at the maximum sampling rate of the oscilloscope, averaged on the fly, and recorded at the lower specified sampling rate. The averaging improves the vertical resolution and reduces noise. The TDS5304B has a maximum sampling rate of 1.25 GS/s, the DPO7054 has a maximum sampling rate of 5 GS/s, and the MDO3014 has a maximum sampling rate of 100 MS/s. Each oscilloscope has four channels. Only three of the channels of the MDO3014 could be used for data collection, since it has no dedicated auxiliary input channel, and the triggering signal needed to be put on one of the regular channels. Sampling rates varied depending on the sensor and measurement types being used, but the minimum sampling rate was 500 kHz, and the maximum sampling rate was 1 GHz. The PCB-132 sensors were typically sampled at frequencies of at least 2 MHz to ensure good resolution of their signal.

Two kinds of signal conditioners were used with the PCB sensors. These were the 482A22 and the 482C05. Both are 4-channel signal conditioners with output from 0-10 V and frequency responses up to 1 MHz. The 482C05 is a newer model of
conditioner which has replaced the 482A22. The specific model used had no observed
effect on the data from the sensors. The Kulites were used with custom amplifiers
built at Purdue. These amplifiers use an INA103 instrumentation amplifier chip to
amplify the DC output of the sensor by a gain of 100.
4. SHOCK DETECTION AND MEASUREMENT

METHODS

Accurate calibrations require accurate and repeatable shock measurements. Additionally, the goal of this research is to establish a method for calibrating sensors for wind tunnel measurements. In order for the method to be practical, the calibrations must be performed quickly, which requires an efficient method for processing the data. These requirements point to the need for a code that reliably and accurately measures shock arrival times and amplitudes.

In order for the shock to be measured, it must first be located in the time trace. The location of the shock is unknown beforehand. The oscilloscopes are triggered by a rising edge signal from a Kulite mounted in the side-wall of the tube. The triggering Kulite was usually located far downstream to ensure a good signal, but its location varied. The trigger time is designated as \( t = 0 \) by the oscilloscopes. In many cases, the scopes are triggered when the shock arrives at the Kulite, which might allow the approximate shock arrival times at other locations to be predicted. However, the Kulites are susceptible to electronic noise, which sometimes creates short-duration voltage spikes. These spikes are a problem for runs with low-amplitude shocks. If the trigger level is set near the expected shock amplitude, the scopes will be triggered by electronic noise before the run is initiated. Because of this problem, the trigger level must be set far above the expected shock amplitude.

When the trigger level is high, the run is over by the time the oscilloscopes are triggered. The pressure continues to rise after the run, due to the reflected shocks or a large pressure ramp which is seen at lower driven pressures (shown in Figure 4.1). In these situations, the trigger time relative to the shock arrival is unpredictable. Because of this uncertainty, the oscilloscopes are set to record data well before the
trigger signal and for a time much longer than the run duration. The location of the shock within the trace becomes highly uncertain because of these settings.

![Figure 4.1. Trace from Kulite used to trigger the oscilloscopes, showing post-shock pressure ramp. Oscilloscopes triggered at $t = 0$. Sensor is 114 in. downstream, $\Delta P = 0.001$ psi, $P_{Driver} = 6.0$ psia, $P_{Driven} = 0.01$ torr. 1.5-mil mylar with burst system. Shock not clearly visible at this scale.](image)

Alternate triggering techniques were also tried. When the electrical burst system was installed, attempts were made to trigger the oscilloscopes using the drop in voltage across the capacitors in the burst system. However, the voltage decreased too slowly for the signal to serve as an accurate trigger. Triggering from the drop in driver pressure could also be attempted, but was not in this work due to the fact that the driver Kulite was not always installed.

### 4.1 Peak-Width Criterion for Shock Detection

Visually identifying the shock in the time trace is usually quite easy, but developing a shock-detection algorithm proved difficult. The simplest method is to use a rising-edge detector, like what is used to trigger the oscilloscopes. With such a method,
the shock is identified whenever the voltage exceeds some threshold value. However, this method suffers from the same problems encountered by the oscilloscopes, and frequently fails to detect the shock due to noise spikes crossing the detection threshold before the shock.

When the time trace is plotted, the shock signal is a particular geometric shape. This makes it easy to identify visually. However, writing a program to recognize a shape is complicated, especially when the size of the shape is unknown and the signal is noisy. The fact that noise spikes are the usual reason for failure when using a simple threshold method can be used to simplify the requirements. The code does not necessarily need to “know” what a shock looks like, it just needs to be able to distinguish between shocks and electronic noise spikes. This distinction can be made by adding a peak-width test to the threshold detector.

A typical high-amplitude PCB-132 shock response is shown in Figure 4.2. It is a relatively low-noise peak with a roll-off due to the high-pass filter. The full width at half-maximum (FWHM) is a typical measurement of peak width. For a time-domain peak, it is defined as the difference between the times when the peak crosses 50% of its maximum value in the rising and falling edges. For the peak in Figure 4.2, the 50% value is about 0.22 V, making the FWHM about 0.02 ms.

Two low-amplitude PCB-132 shock responses are shown in Figure 4.3. The first, in Figure 4.3(a), shows the PCB-132 step-type response to a low-amplitude shock. For these shocks, a sharp rise is observed, but the voltage trace does not return to the pre-shock level. The FWHM for this kind of response is essentially infinity, since the voltage never returns below 50% of the maximum value. The second kind of response is shown in Figure 4.3(b). This is the peak-type response, which is similar to the PCB-132 response for high-amplitude shocks. The primary difference is the low signal-to-noise ratio. For the response shown, the FWHM is about 0.04 ms, if noise is neglected. This result shows that low-amplitude shocks have peak widths of similar magnitude to high-amplitude shocks.
Figure 4.2. PCB-132 shock response to a high-amplitude shock. Sensor #6617 at 72 inches downstream without rubber insert, $\Delta P = 2.41$ psi, $P_{Driver} = 20.7$ psia, $P_{Driven} = 80.6$ torr. 1.0-mil acetate diaphragm with natural burst.
(a) PCB-132 step-type response for low-amplitude shock. Sensor #6707 at 144 in. downstream without rubber insert, \( \Delta P = 0.016 \) psi, \( P_{\text{Driver}} = 5.1 \) psia, \( P_{\text{Driven}} = 0.049 \) torr. 0.7-mil aluminum diaphragm with natural burst.

(b) PCB-132 peak-type response for low-amplitude shock. Sensor #6819 at 36 in. downstream with rubber insert, \( \Delta P = 0.05 \) psi, \( P_{\text{Driver}} = 0.57 \) psia, \( P_{\text{Driven}} = 1.01 \) torr. 0.31-mil polyethylene diaphragm with burst system.

Figure 4.3. Two kinds of PCB-132 responses to shocks at low amplitudes.
An electronic noise peak is shown in Figure 4.4. It consists of several very-high-frequency oscillations. Even at a sampling rate of 10 MHz, each oscillation occurs within a few samples. This much-smaller peak width allows for electronic noise peaks to be easily differentiated from shocks by using a peak-width criterion. The FWHM is simple to measure automatically. A small time window is established around the point where the voltage threshold is crossed. Within this window, the maximum voltage is found. The rising edge is found by finding where the trace crosses 50% of the maximum during the time in the interval before the maximum has been reached. The falling edge is found by finding where the trace crosses 50% of the maximum after the maximum has been reached. The difference is found as the FHWM and compared to some minimum value. If the peak width is smaller than that value, the peak is skipped. If the peak is wide enough, it is identified as a shock.
4.2 Moving Averages

Another way of reducing the effect of noise is to use a moving average as a low-pass filter. Two ways of applying averaging were considered. The first is the standard method of applying a moving average. In this method, the first averaged point \( j \) is found by averaging \( n \) points beginning with point \( i \) in the original data. The next point \( j + 1 \) is found by averaging \( n \) points beginning with point \( i + 1 \). Most points in the data are included in \( n \) averaged points, and the original sampling rate is preserved. Results found with this method are shown in Figure 4.5(a).

A second method, down-sampling, was also tried which is faster and reduces memory use. The first point is found in the same way as for the standard moving average. However, the second point \( j + 1 \) is found by averaging \( n \) points starting with point \( i + n + 1 \) in the original data. Results found with this method are shown in Figure 4.5(b). It is clear that the data are less smooth with this method.

Figure 4.5(b) shows that as the averaging is increased using down-sampling, the data quality decreases. At 100 kHz, only three points are found within the vicinity of the shock, with only one point during the rise. The higher sampling rates perform better, but the reduction in resolution is still significant, with only 1-2 points during the rise. This would result in substantial reduction in accuracy when identifying the shock arrival, since the arrival is generally found as the time at an individual data point. To improve accuracy, interpolation between data points would be necessary. Even with interpolation, this method would have reduced accuracy since the original response is very nonlinear.

However, averaging does significantly reduce noise. Before the arrival of the shock, the 500 kHz trace is nearly flat, rather than having the substantial fluctuations present in the original.

The data quality for the moving average is better, as is clear in Figure 4.5(a). The fact that the sampling rate is maintained means that resolution during the sensor rise is not lost. The low-pass filter does increase the rise time, but accurate measurements
Figure 4.5. Moving averages and down-sampling at several frequencies for the same original data. PCB-132 sensor #6773 at 36 in. downstream with rubber insert, $\Delta P = 0.014$ psi, $P_{Driver} = 0.59$ psia, $P_{Driven} = 0.21$ torr. 0.31-mil polyethylene diaphragm with burst system.
of the shock arrival are still possible, since all of the traces reach 50% of the rise at the same time. If the shock arrival is defined to be at 50% of the rise, the shock arrival time will be independent of averaging.

Significant smoothing of the data is achieved even with small amounts of averaging. With 1 MHz filter, the majority of the noise is eliminated, and the low-frequency noise that remains has a reduced amplitude. During the rise, the difference between the original trace and the 1 MHz trace is small. For 100 kHz, there is essentially no noise, though the rise has spread substantially.

4.3 Shock Detection Algorithm

Shock measurements using down-sampling are likely to be inaccurate due to the decreased resolution. However, using moving averages on the entire trace was slow, and memory tended to run out due to the amount of data involved. The primary problem is the creation of multiple versions of the trace, the batch processing of 12 sensors at once, and poor memory management in MATLAB. A two-step process was chosen which uses the advantages of both methods. Rate-reducing averaging is used for a coarsely filtered first pass using a large amount of averaging, which is used only to locate the shock in the time trace. A smaller interval surrounding the shock is then processed a second time using a higher-frequency moving average. This second pass is used to accurately measure the shock arrival time and amplitude.

First, the entire trace is processed using down-sampling with a relatively coarse filter (often 100 kHz). This nearly eliminates noise, though it also reduces the accuracy of the shock arrival-time measurement. However, the large amount of averaging allows the use of a low threshold voltage for identifying the shock.

Averaging reduces the number of noise peaks that cross the detection voltage threshold, which means fewer peaks need to be tested with the peak-width criterion. This is particularly important for traces with a large number of electronic noise peaks or low signal-to-noise ratios, since repeating the peak-width test a large number of
times greatly increases the processing time. The averaging also reduces the amplitude of noise, improving the signal-to-noise ratio. The shock is less affected due to its longer duration, though the sharp peaks in PCB-132 responses for large shocks can be attenuated by averaging. This attenuation is undesirable, since it reduces the measured peak magnitude. For these measurements, only very limited low-pass filtering can be used.

The reduction in noise amplitude also reduces the number of false negatives. If the fluctuations in the response cause the trace to cross the half-maximum point shortly after the rise, the FWHM may be below the minimum value, causing the algorithm to incorrectly skip the peak. A false negative could be triggered by resonance or other noise.

When a shock is identified with the coarse filter, a smaller portion of the trace is taken around the time of arrival. This smaller window is processed using a moving average and a higher-frequency filter. This can be done because of the smaller amount of data involved, and a higher-frequency filter can be used because of the reduced number of false positives within the smaller window.

The location of the shock is again found using the threshold/peak-width detector on the finely filtered data. The shock amplitude is then measured. A very small window of a few microseconds is established around the new shock-detection time. This window is used to find the time at 50% of the rise. A typical trace is processed in less than 2 seconds. Much of the processing time is devoted to creating the diagnostic plots which are discussed in the next section.

4.4 Amplitude Measurement

Determining the shock amplitude is complicated by the number of different shock response shapes. The two main shapes are step and peak responses. In general, a step response is measured as the difference in voltage between an average taken over a time interval after the shock arrival and the average of a time interval before the shock
arrival. A peak response is measured as the difference between the peak maximum and the average voltage of a time interval before the shock arrival.

However, there are many kinds of step responses due to the number of different sensors used. Each sensor has its own frequency response, so the time intervals will need to be changed. The run conditions and sensor position can also affect the time intervals used. For instance, it may be desirable to use a long post-shock time interval for a sensor with a slow response, but if the sensor is mounted near the end of the tube, the reflected shock may limit the usable measurement time. The arrival of the contact surface or a pressure ramp can also reduce the usable time.

Peak-response amplitude measurements have similar complications. For a low-noise peak, simply finding the maximum is sufficient. However, the search interval for the maximum needs to be defined, since the incident shock never creates the maximum in the entire trace, and is sometimes followed closely by an electronic noise peak, a reflected shock, or another disturbance. Additionally, some peaks have substantial noise, as was shown in Figure 4.3(b). Simply measuring the maximum or applying low-pass averaging may not be sufficient to yield an accurate answer. In these cases, an average over a short time period may be required. This period must be precisely located at the top of the peak.

The simplest solution is to allow the method to be customizable for every sensor and every run. However, some way of checking if the settings resulted in the correct answer is needed. For this reason, the shock detection code creates diagnostic plots for each sensor. These plots show the raw voltage and fine-filtered traces over the time of the smaller interval used for the second pass. They allow the user to determine if the averaging has reduced the shock amplitude or spread the shock rise unacceptably. They also show the beginning and end of the averaging intervals used to determine the voltage before and after the shock. The computed averages are shown as red lines crossing the entire fine-filtered window. A point is also plotted at the measured time-of-arrival of the shock and the voltage that was computed to be 50% of the rise.
If the time-of-arrival measurement was accurate, this point should fall on the time trace.

Sample diagnostic plots are shown in Figure 4.6. The red lines show that the shock amplitude is measured accurately when compared to the response in the raw data. A substantial amount of averaging was applied for the step measurement in Figure 4.6(a). Note that despite the significant spreading of the rise due to the averaging, the measured shock arrival point matches the rise in the raw data.

Figure 4.6(b) shows a peak-type measurement. The averaging interval after the rise is ignored, since the shock amplitude is calculated using the maximum of the filtered data. Even a small amount of filtering can reduce the noise in the data substantially. The light filtering in this example reduces the noise without significantly changing the response, even during the rise.

Figure 4.7 shows diagnostic plots for an extremely low-amplitude shock. This shock is among the weakest produced in the 3-Inch Shock Tube. These plots show the importance of averaging to the detection of shocks with low signal-to-noise ratios. In both cases, when looking only at the raw data, no shock is visible. Without averaging, the detector would not find the shock, even with the peak-width criterion. With a substantial amount of averaging, the shocks become visible, despite their low amplitude. The amplitudes and shock arrival times can be accurately measured. The arrival time measured by the PCB-132 in Figure 4.7(b) was confirmed by two other PCB-132 sensors mounted at the same location.
Figure 4.6. Diagnostic plots from the same run. $\Delta P = 0.81$ psi, $P_{Driver} = 6.0$ psia, $P_{Driven} = 9.82$ torr. 1.5-mil mylar diaphragm with burst system.
Figure 4.7. Diagnostic plots from the same run for an extremely low-amplitude shock. $\Delta P = 0.0013$ psi, $P_{Driver} = 0.59$ psia, $P_{Driven} = 0.0127$ torr. 0.31-mil polyethylene diaphragm with burst system.
4.5 Use of the Shock-Detection Code

Due to the need to adjust the detection and measurement variables for each sensor and verify the settings with the diagnostic plots, it is simplest to process a single run at a time. It is possible to process a batch of runs, and this can be done efficiently if the runs are at similar conditions. Batch processing can also be used for high-amplitude shocks, since the settings tend to be very consistent across different runs. This is partially because for large, well-defined shocks, a wide range of settings may be used without substantially affecting the results. However, when processing low-amplitude shocks, the data quality decreases and the range of usable settings is reduced. The results are still insensitive to the particular settings used as long as obviously unusable data is not included.

Settings which may be adjusted for each sensor include the frequencies of the coarse and fine filters, whether to use a peak or step measurement technique, the averaging intervals to use, the shock detection level, the minimum peak width, and the size of the finely-filtered data window. Adjusting these settings allows the shock to be detected and accurately measured using the code in 95-98% of cases. Pre-set values for a particular sensor type may also be applied to a range of channels. However, adjustments are often required for particular sensors, and using pre-set values was often less efficient.

Sometimes the shock is visible in the trace, but the automatic detection code fails to find it due to noise very close to the shock. Manual measurement becomes necessary in these cases. This is generally only necessary for the less-reliable reference sensors, such as the PCB-113 or PCB-103.

In some cases, it is necessary to apply averaging to the entire trace and locate the shock manually for at least one sensor in order to determine what settings are appropriate for the run. However, this is a simple procedure and is not as time-intensive as actually measuring the shock manually, especially since the other sensors can be measured automatically after this is done for a small number of sensors.
The use of this shock-detection code was a significant improvement over manual detection and a simple threshold technique. The simple threshold technique failed to accurately detect or measure the shock in about 50% of cases, requiring a substantial amount of manual processing. It had previously taken a week to process 360 records, which would be 30 runs when 12 sensors were in use. Using the peak-width criterion with averaging, the vast majority of cases could be processed automatically, and 30 runs might be processed in a single day. If the runs were all low-amplitude shocks and thus more difficult to measure, a more typical figure was 15-20 runs processed in a day.

Additionally, as shown in Figure 4.7, the current technique not only saves time, it allows the detection and measurement of shocks that would previously have gone undetected. This allows the measurement of smaller shock waves and reduces the number of traces which yield no useful data, raising the data-production efficiency of the shock tube. The automated nature of the process also allows much more repeatable shock measurements.
5. METHODS FOR IMPROVING THE SIGNAL-TO-NOISE RATIO FOR MEASUREMENTS OF SMALL SHOCK WAVES

The smallest shock waves measured with the 3-Inch Shock Tube have static pressure rises on the order of 0.001 psi. The PCB-132 sensitivities are typically around 100 mV/psi, which means that the smallest shocks measured in this research have signals of less than a millivolt. Achieving noise levels low enough to allow a reasonable signal-to-noise ratio with such small signals is difficult. Some techniques were developed in order to reduce the noise and improve the measurements.

5.1 Measurement Contamination from Vibration

Piezoelectric sensors are well-known to be sensitive to acceleration. These sensors generate an electric signal when the sensing element is deformed. The sensor may be deformed by external forces, such as pressure, or internal forces generated when the sensor is accelerated. Many accelerometers are piezoelectric for this reason.

Piezoelectric pressure transducers are often acceleration-compensated to reduce this noise source. A simple way of doing this is to add a piezoelectric element that is kept away from the flow. This element measures only the signal due to acceleration, and may be used to correct the flow sensor for acceleration effects. PCB-132 sensors are designed to be inexpensive and are not intended for accurate pressure measurements, so they are not acceleration-compensated.

It was initially expected that vibration would not be a problem in the 3-Inch Shock Tube, due to the very low burst pressures. When the tube runs, there is no perceptible vibration, and the run is barely audible. However, fluctuations before
the shock appeared frequently in the PCB-132 data. The fluctuations are shown in Figure 5.1. Raw voltage traces for the same sensor at the same location are shown for multiple conditions. The traces have been modified so that $t = 0$ at the shock arrival for each run. All of the runs were performed with 1.0-mil acetate diaphragms. All of the traces actually begin at 0 V, but offsets were added for clarity.

![Figure 5.1. Preceding fluctuations for a PCB-132 sensor at 114 in. downstream. 1.0-mil acetate with natural burst and no rubber sleeve. All traces actually centered at 0 V, offsets added for clarity.](image)

Far before the shock arrival, the noise level is fairly low. However, for most of the measurements, the fluctuation level increases noticeably starting about 1.5-2 ms before the shock arrival. The level of the elevated fluctuations does not change with the shock strength for most of the runs. The exception is for the highest-amplitude
shock, which shows no preceding fluctuations. As the driven pressure decreases, the arrival of the preceding fluctuations moves closer to the shock.

It was initially unclear what caused the fluctuations. Vibration was the most likely candidate, since the fluctuations arrived before the shock and vibration had been a significant problem for researchers attempting to use PCB-132 sensors in shock tunnels. However, it was surprising that such significant signal could be produced by what were presumed to be very small accelerations. Also, the fluctuation levels tended to decrease and eventually disappear as they moved downstream. It seemed likely that structural vibrations would extend through the whole shock tube.

Figure 5.2 shows the pressures measured by every sensor in the shock tube, with the exceptions of the driver Kulite and vacuum sensor. The legend entries for this kind of plot have to include a large amount of information, and to save space a code was adopted. To indicate that a trace is from a PCB-132 sensor, it begins with a “P”. For Kulites, the entry begins with a “K”. The other reference sensors are all made by PCB, and their legend entries begin with their model number. If the entry begins with a letter, the letter is immediately followed by the sensor distance from the diaphragm in inches. For entries beginning with a number, the distance is preceded by a dash to separate it from the model number. The distance is followed by a dash and three numbers which show the azimuthal location of the sensor in degrees, with zero at the top of the shock tube. If the sensor was a PCB-132 or a Kulite, the azimuthal location is followed by the serial number of the sensor in parentheses. If the manufacturer’s calibration was used for a PCB-132, the entry ends with “M”. Otherwise, a calibration found in the 3-Inch Shock Tube was used. For example, a PCB-132 at 96 inches and 0° with serial number 5396 using a calibration found in the shock tube would be denoted as “P96-000 (5396)”. If the manufacturer’s calibration was used, it would be “P96-000 (5396)M”. A PCB-102 located at 138 inches downstream and 225° would be denoted as “102-138-225”.

Each trace in Figure 5.2 shows the measured differential pressure. Offsets have been added to the data for clarity. Traces from sensors farther upstream are located
at the top of the plot. The order of the traces from top to bottom is the same as the order of the names in the legend.

Figure 5.2. Traces from every sensor for Run 103. No rubber inserts used. $\Delta P = 0.134$ psi, $P_{Driver} = 5.76$ psia, $P_{Driven} = 0.99$ torr. 0.7-mil aluminum with natural burst.

The size of the shock remains fairly constant as it travels downstream in Figure 5.2. However, the preceding fluctuations are nearly as large as the shock in the measurements at 36 and 72 inches. The amplitude of the fluctuations has decreased by 96 inches downstream. The preceding fluctuations have disappeared by 114 inches. Additionally, the preceding fluctuations appeared to sometimes be visible in the Kulite sensors and on the PCB-105, which were not expected to be sensitive to vibrations. This indicated that the fluctuations might be somehow present in the flow, though it was unclear what sort of flow feature might cause these fluctuations. It was thought that the diaphragm might have a slow opening process, with a rel-
atively long-duration, low-amplitude jet sending fluctuations downstream before the diaphragm opened enough for a shock to form.

There are several ways to test if the preceding fluctuations are vibrations. The most obvious is to create a “blind” sensor, meaning it is mounted in the shock tube but not exposed to the flow. This can be done by covering the sensor face to prevent pressure fluctuations from reaching the sensing element.

Initially, it was attempted to blind the PCB-132 sensors by applying electrical tape to the surface of a sensor mounted normally in a static insert. However, it was found that the sensor was still able to measure the shock in this configuration. The reason was that the pressure was transmitted through the tape into the epoxy, and then into the sensing element. There was no gap to prevent the transmission of pressure. This sort of taping method would work for a Kulite sensor due to the cavity between the screen and the sensing element. In order to create a cavity, a PCB-132 was mounted in a static insert as a recessed sensor. Instead of being flush with the insert face, the sensor was mounted with its face about 0.125 in. away from the insert face. Electrical tape was then placed over the hole in the insert to block the recessed sensor face from the flow. This method was successful in blocking any measurement of the shock wave, and thus any measurement of pressure waves.

The blind sensor was mounted in the same axial location as an exposed PCB-132 sensor. The shock and preceding fluctuations should arrive at approximately the same time for two sensors at the same axial location, allowing the direct comparison of the two traces. If the blind sensor shows the arrival of fluctuations at the same time as the flow sensor but does not show the arrival of the shock, the preceding fluctuations cannot be a flow feature. Instead, they must be vibrations traveling through the wall of the shock tube.

As shown in Figure 5.3, the arrival of fluctuations at the blind sensor match the arrival of the preceding fluctuations at the exposed sensor. Each plot shows traces taken simultaneously from an exposed flow sensor and a blind sensor mounted at the same axial location. Raw voltages are plotted with no modification. Results from four
runs with widely different conditions are shown. In each example, both sensors show a low level of noise, followed by a simultaneous increase. The flow sensor always clearly shows a shock, while the blind sensor never does. In Figures 5.3(a) and 5.3(b), an increase in fluctuations after the shock is visible on both sensors at about 4 ms. This increase may be caused by the shock reflecting off the end of the shock tube. This result shows conclusively that the preceding fluctuations were due to the acceleration sensitivity of the PCB-132 sensors and vibrations in the shock tube. Different sensors also appear to have different acceleration sensitivities, since the fluctuations on the blind sensor have a much higher amplitude than those on the flow sensor.

The identification of the preceding fluctuations as vibrations can be made even more certain by comparing the speed of the fluctuations with the expected speed of sound waves in the shock tube walls. The speed would not be expected to exactly match published sound speeds, due to the joints in the shock tube. However, an approximate match would be expected.

The speeds for various kinds of sound waves were found for similar materials in the CRC Handbook of Chemistry and Physics [92, p.14-48]. For steel, longitudinal waves tend to travel at about 5800-6000 m/s, while shear waves tend to travel at about 3100-3250 m/s. Extensional waves tend to travel at 5000-5180 m/s. With this information, it can be expected that the preceding fluctuations will travel through the tube in a range of speeds from 3000-6000 m/s.

Calculating the speed of the fluctuations in the shock tube is difficult, since they have no clearly-defined beginning. Instead of measuring the observed speed and comparing it to the range of expected speeds, a visual comparison was done, as shown in Figure 5.4. Each trace was normalized by its maximum voltage. Every sensor in the figure was a PCB-132 sensor, mounted directly in the metal insert. Two sensors were mounted in the pass-through inserts for the power wires for the electrical burst system. The power wires happened to have a diameter close to 0.125 inches, similar to the PCB-132 diameter. This allowed sensors to be mounted only 4.5 inches downstream from the diaphragm, enabling an attempt to measure the diaphragm
(a) $P_{Driver} = 20.6$ psia, $P_{Driven} = 0.11$ torr.

(b) $P_{Driver} = 16.8$ psia, $P_{Driven} = 0.13$ torr.

(c) $P_{Driver} = 20.3$ psia, $P_{Driven} = 50$ torr.

(d) $P_{Driver} = 21.3$ psia, $P_{Driven} = 100$ torr.

Figure 5.3. Comparisons of raw voltage for a blind and exposed PCB-132 at 96 in. downstream of the diaphragm. All runs performed with 1.5-mil mylar diaphragms and natural burst. Sensors are mounted directly in metal insert. Blind sensor was at 270°, exposed sensor was at 0°.
bursting behavior. The traces are again plotted with the most upstream sensors at the top of the plot. However, in this plot, the vertical offsets are proportional to the distance downstream, rather than being constant as in Figure 5.2. In this way, the vertical axis is a proxy for distance, while the horizontal axis is time. This means that a pressure wave traveling at a constant speed should track along a straight diagonal line, moving down and to the right as it appears in the different traces at the different locations in the shock tube.

The envelope of expected structural sound speeds can thus be superimposed on the plot as two straight lines with slopes corresponding to their speeds. The two lines are fixed at the same origin under the assumption that the sound waves would all be created at the same time. It was uncertain what origin should be used, so it was adjusted to give the best fit to the preceding fluctuations. In Figure 5.4, the origin point was chosen such that the beginning of the preceding fluctuations tends to fall on the line corresponding to the structural shear wave, which moves at 3000 m/s.

The sensors at 4.5 in. show signal nearly 1 ms before the times indicated by the structural vibration speeds. However, the vibration speeds converge at a point where the sensors at 4.5 in. show a large increase in fluctuations. It is possible that the earlier signal shows the beginning of the diaphragm burst, and the structural vibrations were mostly created when the burst process accelerated or was completed.

At 36 inches, the preceding fluctuations begin near the shear wave line. The beginning of the preceding fluctuations are near the shear wave line from 72 in. to 114 inches, which strongly indicates that the fluctuations are primarily composed of shear waves traveling through the shock tube wall. At 132 inches, the preceding fluctuations are not visible in the trace.

Whatever the cause of the earliest fluctuations very close to the diaphragm, the bulk of the data strongly indicate that the preceding fluctuations are structural waves. In order to reduce the effect of these waves and improve the signal-to-noise ratio for the PCB-132 sensors, it was necessary to find a way to reduce the vibrations or prevent them from reaching the sensors.
Figure 5.4. Structural sound speeds for steel compared to fluctuation speed in 3-Inch Shock Tube. $P_{Driver} = 20.9$ psia, $P_{Driven} = 25.2$ torr. 1.0-mil acetate with natural burst. All traces are from PCB-132 sensors mounted directly in metal insert.

5.2 Rubber Vibration-Damping Sleeves

The problem of vibration contamination of measurements with PCB-132 sensors was encountered by researchers attempting to use the sensors for instability measurements in shock tunnels [10–12]. When it was determined that the shock tube was also subject to vibration problems, the researchers at CUBRC were contacted for advice. Timothy Wadhams provided details of the vibration-dampening mount design used there. The design mounts the sensor inside a neoprene sleeve, which is then mounted in the metal insert. A PCB-132 mounted using this technique is shown in Figure 5.5. Similar designs have also been developed elsewhere.
Nail polish is used to glue the sensor to the rubber sleeve and the sleeve to the metal insert. No other adhesives were used, since the performance of the nail polish was sufficient. The hole in the center of the sleeve is slightly smaller than the PCB-132 sensor, and the outer diameter of the sleeve is wider than the hole in the metal insert. The interference fit ensures that the sleeve is compressed when installed. However, it also makes the sensor more difficult to install when sleeves are being used. In particular, the tight fit and the flexibility of the sleeve make it difficult to ensure that the entire sleeve is flush with both the sensor and the metal insert. There are often parts of the sleeve that stick out into the flow or form cavities around the sensor. These may interfere with the measurements, as discussed in Section 5.3.

The neoprene sleeves are very effective in reducing the noise from vibration. An example is shown in Figure 5.6. The traces show raw voltage from PCB-132 sensors mounted at 72 in. downstream at very similar conditions. The times are set so that the shock arrives at $t = 0$. For the sensor without a neoprene sleeve, the vibrations mostly drown out the shock. It is very faintly visible as a slight change in the mean.
level of the fluctuations. However, with the neoprene sleeve, hardly any vibrations are visible. The shock is plainly evident, with a constant low noise level. This is a large improvement in signal-to-noise ratio.

![Graph showing comparison of PCB-132 measurements with and without rubber sleeve. Sensor at 72 in. for both runs, using 0.5-mil aluminum with natural burst. $P_{\text{Driven}} = 5.3$ psia for both runs.]

While the vibrations are not always completely eliminated from the measurement, large reductions are observed. Substantial vibration noise can still be observed in some measurements, particularly for sensors far upstream at low driven pressures. Use of the rubber inserts makes it possible to measure shocks at 36 in. downstream of the diaphragm in most conditions. Without the rubber inserts, PCB-132 sensors mounted at 36 in. rarely detect shocks due to the large amount of vibration. An example of a measurement taken with a rubber insert at 36 inches is shown in Figure 5.7. The shock is clearly visible at $t = 0$ ms, though the signal-to-noise ratio is rather low. The
classic preceding fluctuations are visible beginning just before $t = -0.5$ ms, despite the use of a rubber sleeve. However, without a rubber sleeve, the fluctuations would typically be large enough that the shock would be indistinguishable.

Figure 5.7. PCB-132 measurements with rubber sleeve showing preceding fluctuations. Time is normalized so $t = 0$ when shock arrives. Sensor #6819 at 36 inches with rubber insert, using 1.5-mil mylar with electrical system. $\Delta P = 0.11$ psi, $P_{Driver} = 6.2$ psia, $P_{Driven} = 9.8$ torr.

Some unexplained low-frequency oscillations are visible near $t = -1$ ms. These oscillations are clearly different from the standard vibrations, since they contain primarily one relatively low frequency, compared to the broadband noise normally observed. These fluctuations are more similar to the first oscillations observed at 4.5 inches in Figure 5.2. They may also be caused by the earlier stages of the diaphragm burst. Farther downstream, they may either coincide with the rest of the fluctuations if there is a speed difference, or they may dampen more quickly.

Because of the large improvement, the neoprene sleeves were used for most PCB-132 measurements once they had been tested. However, one or two sensors were generally mounted directly in the metal inserts in order to continue evaluating the
method for any disadvantages. The sensors without sleeves were typically mounted at least 114 in. downstream, where the vibrations had generally attenuated enough that the contamination was not a large problem.

5.3 Creation of Pre-Shock Spikes Due to Rubber Sleeves

The rubber sleeves can occasionally introduce some new data-quality problems. The problems seem to be due to a failure to mount the sleeves flush with the sensor and insert faces. When the sleeve is not flush, a negative voltage spike is sometimes generated. A typical example of the negative preceding spike is shown in Figure 5.8.

![Figure 5.8. PCB-132 measurements with rubber sleeve showing negative preceding spike. Sensor # 6617 at 132 inches with rubber insert, using 0.5-mil aluminum with natural burst. $\Delta P = 0.74$ psi, $P_{Driver} = 3.4$ psia, $P_{Driven} = 51$ torr.](image)

The sensor in Figure 5.8 shows a flat response up until about 0.99 ms. At that point, the voltage decreases quickly before beginning the normal PCB-132 response.
These negative spikes are never observed without the rubber inserts, though they are not always observed with the rubber inserts. They are never present for very low-amplitude shocks. The preceding negative spikes change when the sensor is remounted, which indicates that the negative spikes are dependent on the mounting of the sensor.

Sometimes, spikes are observed after the shock arrival, as in Figure 5.9. This would seem to indicate that the surface nonuniformity was encountered after the shock reached the sensor, rather than before. Since the sensor is surrounded by rubber, this could easily occur if the obstruction was on the downstream side. One might expect to be able to create or eliminate this phenomenon by rotating the sensor mount 180°.

Some sensors which showed preceding negative spikes were rotated 180°. The entire metal insert was rotated, instead of re-mounting the sensor in a different orientation. This preserved the nonuniformities in the mounting. In Figure 5.9, the sensor shows a negative preceding spike in both orientations. The magnitude of the spike changed when the sensor was rotated. A spike after the shock arrival is shown only for one orientation. This shows the dependence of the response shape on the mounting of the sensor. It also shows that more than one nonuniformity may be affecting the measurement of the sensor. If only one nonuniformity existed, the spike would move from before the shock to after the shock when the sensor was rotated. Since a negative pre-shock spike exists in both orientations, it is likely that the spike is being created by the sensor sticking up past the rubber sleeve. The post-shock spike is likely due to a nonuniformity in the rubber, which was moved behind the sensor when the mounting was rotated.

An important question regarding the pre-shock spikes is whether or not they should be included in measurements of the peak height. Figure 5.9 indicates strongly that they should not. For two runs at the same conditions, the initial peak maximum is at the same voltage, despite the significant change in the pre-shock spike amplitude, and the changing presence of a post-shock spike. This indicates that the acceleration
Figure 5.9. PCB-132 measurements with rubber sleeve in two orientations, one showing post-shock spike. Sensor #5396 at 132 inches with rubber insert, using 0.31-mil polyethylene with electrical burst system. $\Delta P = 0.16$ psi, $P_{Driver} = 0.9$ psia, $P_{Driven} = 19.8$ torr.

which causes the pre-shock spike is of a very short duration, and does not affect the majority of the PCB-132 response. Therefore, the spike should be neglected when measuring the response of the PCB-132.

5.4 Amplification of Low-Amplitude Responses

The lowest-amplitude shocks produced in the 3-Inch Shock Tube are on the order of 0.001 psi. Since the PCB-132 sensitivities are on the order of 100 mV/psi, the response of a PCB-132 sensor to the lowest-amplitude shocks is only about 0.1 mV. This is also true for the PCB-102 reference sensors, which have similar sensitivities. It is difficult to measure this level of response with the oscilloscopes used in this research.
Each one has a maximum gain which displays 1 mV per vertical division. This means that the oscilloscopes have limited resolution when measuring the smallest shocks in the 3-Inch Shock Tube, which reduces the signal-to-noise ratio.

Since the signal-to-noise ratio is already limited for low shock amplitudes, reducing the noise due to limited oscilloscope resolution was of interest. If the oscilloscopes are a real contributor to the noise in the measurement, amplifying the sensor response should reduce the noise. Any noise which enters the measurement before the amplifier will also be amplified, so the use of an amplifier was expected to have only limited benefit. A Stanford Research Systems SR560 amplifier was connected to a PCB-132 sensor with a gain of 100 and AC coupling. A comparison of an amplified response to a non-amplified response for two runs at nearly identical conditions is shown in Figure 5.10.

![Figure 5.10. Effect of amplifier for low-amplitude PCB-132 response. Sensor # 6773 at 96 inches with rubber insert, 0.5-mil aluminum with natural burst.](image)
The results are shown in terms of pressure to give a more accurate sense of the signal-to-noise ratio. It is clear in the figure that there is less noise with the amplifier than without, though the difference does not make the shock much clearer visually. Without the amplifier, the RMS noise before the shock arrival was 0.00133 psi. With the amplifier, it was 0.000925 psi, 70% of the value without the amplifier. In both cases, the noise was computed from data between -0.5 and -0.1 ms in the plot. This is a significant decrease in the noise level. The noise level without amplification is similar to the smallest shock amplitudes, making noise reductions particularly important.

Only one amplifier was used for a handful of runs in the present work, to verify if the technique had any merit. It may be worth expanding the use of these amplifiers to the PCB-132 and PCB-102 sensors if cost-effective equipment can be found.
6. SHOCK TUBE FLOW QUALITY

In order to use the shock tube for sensor calibrations, the flow in the shock tube must be well-understood. A variety of measurements were performed in an attempt to understand the flow quality in the shock tube across its range of operation. This variation controls how accurate the calibrations can be. While the reference sensors used in this research were useful and give reasonable results, none of them are completely well-suited to performing these measurements. Additionally, it was unclear initially which sensors would be effective, and a substantial amount of work was necessary to evaluate their performance. Because of these limitations, the uncertainties in this work are larger than those required to provide truly useful quantitative calibrations for instability measurements. It may be possible to reduce these uncertainties by performing dynamic calibrations of the reference sensors and improving the degree of control over the conditions in the 3-Inch Shock Tube. However, these calibrations are outside of the scope of the present work, so the factory calibrations and uncertainties were used when available.

The goal of the present work was to establish that useful shock waves with pressure steps within the second-mode amplitude range could be created and measured. Several steps were taken to achieve this goal. A qualitative assessment of the flow is given first, to show the general behavior of the shock tube and the various sensors used. Then, the planarity of the shocks is quantified. Once the shocks are known to be planar, the shock speed can be measured by comparing the shock arrival time from sensor at different azimuthal positions. This allows a basic assessment of the axial uniformity of the flow, including the shock development length and the degree of shock attenuation, as well as repeatability. The repeatability of the shock pressure steps, defined as $P_2 - P_1$, between different runs at the same condition was also quan-
tified. The magnitude of the shock pressure step is also sometimes called the shock amplitude.

After these aspects have been quantified, it is possible to look at the uniformity in the shock pressure steps. This was assessed by comparing measurements performed with the same sensor in multiple locations for repeated run conditions, as well as using measurements from multiple sensors from the same run. By performing the analysis both ways, it is possible to determine how well the sensors agree with each other, as well as the variation in pressure inside the shock tube. These analyses were performed to examine variation with azimuthal position at the same axial location, as well as the variation between different axial locations.

Finally, the measured Mach numbers and shock pressure steps are compared to theoretical expectations. Since there was substantial uncertainty in the measured run conditions, the agreement was expected to be limited. However, if the measurements agree with theoretical expectations within the estimated uncertainty, then it can reasonably be concluded that the shock tube has good flow quality.

6.1 Qualitative Overview of Flow Characteristics

The flow in the shock tube can be assessed by plotting the pressure traces from every sensor in the shock tube. These plots show qualitatively how quickly the shock forms, the signal-to-noise ratio throughout the shock tube, and give an impression of shock development with axial position. If multiple sensors are present at the same position, the plots provide an impression of azimuthal uniformity. Some of these plots were shown and explained in Chapter 5.

Figure 6.1 shows all flow sensors for a run with a relatively high-pressure shock. The legend uses the same code that was explained in Chapter 5. Runs at these conditions typically have cleaner flows and more well-defined shocks. The average static pressure rise measured by the reference sensors was 0.79 psi for the run shown.
Calibrations found in the 3-Inch Shock Tube were used for every PCB-132 sensor, which were all mounted in rubber sleeves.

The shock was observed clearly at all stations. Most of the sensors exhibited very low noise throughout the entire trace. The Kulite at 96 inches shows the usual resonance after the shock arrival, which decays within about 1 ms. Preceding fluctuations were only visible on PCB-132 sensors up to 96 inches downstream, and the fluctuations were not particularly significant. The PCB-103 also exhibited vibration sensitivity. The amplitude of the shock does not appear to change much throughout the shock tube. There are also no perceptible differences in the arrival time of the shock for sensors at the same axial location. The low noise and apparently high axial and azimuthal uniformity show that the shock tube has good flow quality for runs at high pressure.

Figure 6.1. Traces from every sensor for Run 286. $\Delta P_{avg} = 0.79$ psi, $P_{Driver} = 14.4$ psia, $P_{Driven} = 10.6$ torr. 2-mil mylar with electrical system.

Figure 6.2 shows a similar plot for a run with a moderate shock amplitude. The same sensors are used in the same positions as for Figure 6.1, with the addition of
a PCB-106 at 132 inches. The average pressure rise for this run was 0.108 psi. The shock is again well-formed at most of the axial locations. However, at 36 inches, the shock is less clear. The amplitude of the vibration noise is similar to the shock amplitude. Again, the shock amplitude appears to be constant, and arrives at nearly the same time for all sensors at the same location.

Figure 6.2. Traces from every sensor for Run 296. $\Delta P_{avg} = 0.108$ psi, $P_{Driver} = 6.19$ psia, $P_{Driven} = 9.77$ torr. 1.5-mil mylar with electrical system.

Figure 6.3 shows a run with a moderately low shock amplitude. The average shock pressure rise measured by the useful reference sensors was 0.051 psi. The useful reference sensors are the Kulites, the PCB-102 sensors, and the PCB-106 sensor. The sensor layout is the same as in Figure 6.2, but with an additional PCB-132 sensor at 114 in. The shock appears clearly at every axial location, and again exhibits good uniformity. At 36 inches, there are small preceding fluctuations, but they disappear for all positions further downstream. The reflected shock is visible after the incident shock for the sensors at 132 and 144 inches.
Despite the decrease in shock amplitude, the shock in Figure 6.3 is clearer than in Figure 6.2. The reason is that the driver pressure has been greatly reduced, reducing the vibration noise due to the lower starting forces.

The largest second-mode waves observed in wind tunnels have had amplitudes on the order of 0.1 psi, and the shock in Figure 6.3 is about half that value. This shows that the 3-Inch Shock Tube is capable of creating high-quality shocks within the second-mode range. Shocks of this amplitude are already well below what has been demonstrated in most of the literature, as discussed in Chapter 2.

Figure 6.3. Traces from every sensor for Run 292. \( \Delta P_{avg} = 0.051 \) psi, \( P_{Driver} = 0.57 \) psia, \( P_{Driven} = 1.01 \) torr. 0.31-mil polyethylene with electrical system.

Figure 6.4 shows another full-run plot for a low-amplitude shock. The average measured pressure was 0.008 psi, making the shock an order of magnitude lower than the largest second-mode waves in wind tunnels. The sensor layout is the same as for Figure 6.3, but the data from the PCB-102 at 96 inches has been omitted. Improper
settings on the oscilloscope led to much of the data being clipped by the bottom of the oscilloscope window for that run.

Figure 6.4. Traces from every sensor for Run 293. $\Delta P_{avg} = 0.008$ psi, $P_{Driver} = 0.568$ psia, $P_{Driven} = 0.103$ torr. 0.31-mil polyethylene with electrical system.

The shock is still clearly visible at each station in Figure 6.4, but some flow and data quality problems are evident. First, the PCB-132 sensors at 36 and 72 inches indicated a larger amplitude than the rest of the sensors. The other sensors again appear consistent in their amplitudes and arrival times. The PCB-103 sensor at 102 inches appears to detect the shock slightly after the PCB-102 sensor at the same location, but this is due to the low frequency response of the PCB-103. This discrepancy demonstrates why the PCB-103 sensor was not used for quantitative assessments of the flow.
The vibration noise is significant at 36 inches, but negligible at distances farther downstream. The one exception is the PCB-103, which shows significant preceding fluctuations.

Most of the PCB-132 sensors have step-type response, rather than a peak response. The reason for the difference is unclear. Step-type responses only appear at low amplitudes. At higher amplitudes, many PCB-132 responses do not return to zero, but have a slight positive offset. The reason for the offset is also unclear, but the step-type responses may be caused by this tendency to develop an offset after the shock arrival.

Many of the PCB-132 sensors also exhibit a temporary rise after the shock arrival. PCB #6834 and #5396 show these temporary rises, though the shapes differ slightly on each sensor. The reason for this rise is also unclear, though it seems likely that it is not a flow feature, since it only appears on PCB-132 sensors. Sensor #6834 was mounted at 132 inches, 180° from a PCB-106. The PCB-106 shows no sign of any pressure rise or additional fluctuations after the shock arrival.

The reference sensors show a pressure rise that begins about 1 ms after the shock arrival. It is particularly evident on Kulite 355 at 96 inches and 270°, where it begins at about -2 ms. It is still present, though more subtle, on the PCB-106, beginning just after -1 ms. Following pressure rises often indicate that the shock has not yet completely formed, but in this case the delay seems too long for that to be the explanation, since it is a third of the total run time. The pressure rise may be due to gas in the contact region reaching the sensor, though Roshko’s theory predicts the arrival of the contact surface about 0.3 ms after the shock arrival at these conditions. While there are some data quality problems, it is clear that shocks of this amplitude can be measured.

Figure 6.5 shows pressure traces for a run with a shock at the extreme low end of the shock tube’s useful range. The average measured shock amplitude was 0.0022 psi, about two orders of magnitude smaller than the largest second-mode waves in wind
tunnels. The sensor layout is the same as for the previous plots, with all sensors included.

Figure 6.5. Traces from every sensor for Run 294. $\Delta P_{\text{avg}} = 0.0022$ psi, $P_{\text{Driver}} = 0.55$ psia, $P_{\text{Driven}} = 0.02$ torr. 0.31-mil polyethylene with electrical system.

It is difficult to create a full-run plot with scales that make the shocks plainly visible at such small amplitudes. Additionally, the shock is only visible on a few sensors. It is not detected by any sensors until it reaches 96 inches downstream. The sensors at 96 inches show the arrival of the shock at about -2 ms. It is visible as a small bump. The PCB-102 at 96 inches shows substantial noise. It is generally difficult to get useful measurements at 96 inches for shocks of this magnitude. The two Kulite sensors show rising pressures immediately following the jump for the shock. This following pressure ramp appears very similar to the one in Figure 6.4, and again the cause of it is unclear. It is expected that there will be little separation between the
shock and the contact region for runs at low driven pressures, since the low density reduces the Reynolds number of the flow, increasing the effect of the boundary layer behind the shock.

The shock is not clearly visible at 102 inches due to the low signal-to-noise ratio. The following pressure ramp is still visible at 102 inches. The shock can be more clearly seen in the PCB-132 sensors at 114 inches just before -1.5 ms. The sensors show step responses with a temporary pressure rise immediately behind the shock, similar to what was observed in Figure 6.4.

The same kind of shape is observed by PCB-132 #6834 at 132 inches just before -1 ms. The shock is also measured by the PCB-106 sensor at 132 inches, though it is difficult to see because the resonance of the sensor is significant both before and after the shock. Finally, the shock is fairly clearly visible for the PCB-132 sensor at 144 inches just after -1 ms. This shows that extremely low-amplitude shock waves can be produced in the 3-Inch Shock Tube.

Figure 6.6 shows selected traces from Figure 6.5 which have been low-pass filtered to 200 kHz using the standard moving average. The smaller number of sensors and low-pass filtering allows a clearer view of the shock.

While the noise remains significant for the PCB-102 at 102 inches, the low-pass filter shows the shock more clearly. The amplitude at 102 inches is similar to that measured by PCB #6617 at 114 inches. Sensor #6830 at 114 inches appears to measure a slightly smaller amplitude. The difference is about 0.0003 psi, nearly 20% of the total measurement, but smaller than the quoted resolution of the sensor. There is a small bump in the trace for PCB #6830 immediately before the shock arrival. The cause of this bump is unknown. It increases the average before the shock, reducing the measured shock amplitude. The amplitude at 132 inches appears to be similar to the amplitude at 144 and 102 inches.

The temporary pressure increase on the PCB-132 sensors begins immediately after the shock arrival in Figure 6.6. The shock amplitude was measured as only the increase during the sudden jump. However, since the temporary pressure increase
follows the shock so closely, distinguishing between the end of the shock and the beginning of the pressure increase can be difficult. Some of the pressure increase might be erroneously included in the measurement as part of the shock, or the end of the shock might be erroneously excluded. This difficulty would be expected to decrease the accuracy of these measurements, and thus their usefulness in calibrations.

Figure 6.7 shows all flow sensors for a run using natural burst. None of the PCB-132 sensors were mounted with a rubber insert. Because of this, the noise is substantial up to 72 inches downstream. Further downstream, the measurements have little noise.

Figure 6.8 shows all sensors for one of the weakest shocks created without the burst system. The shock has a pressure rise of 0.018 psi. The absolute lowest rise
Figure 6.7. Traces from all sensors for Run 103. $\Delta P_{avg} = 0.134$ psi, $P_{Driver} = 3.5$ psia, $P_{Driven} = 0.99$ torr. 0.7-mil aluminum with natural burst.

observed with a natural burst was 0.008 psi. The shock can be observed clearly even at 36 inches due to the use of rubber sleeves to reduce the vibration noise. Sensor #5396 at 96 inches showed a greater susceptibility to electronic noise than the other sensors. This is shown by the periodic bursts of noise spikes in the trace. The problem was caused by a bad electrical connection. The PCB-132 sensor at 144 inches shows the reflected shock just before 0.5 ms, along with some unsteadiness. The cause of the unsteadiness is unclear. The reflected shock is also visible on the PCB-103 at 138 inches just before 1 ms.

The same kinds of data quality problems are evident in Figure 6.8 which were noted earlier with the burst system. These include the following pressure ramp on the reference sensors and the temporary pressure rise following the shock on the PCB-132 sensors. The temporary rise is only visible for sensors mounted farther than
Figure 6.8. Traces from all sensors for Run 120. $\Delta P_{avg} = 0.018$ psi, $P_{Driver} = 2.5$ psia, $P_{Driven} = 0.0042$ torr. 0.5-mil aluminum with natural burst.

96 inches downstream. The reason for this is unknown. It is unclear if these problems are actual flow phenomena or are caused by the sensors.

6.2 Creation of Multiple Shocks

The preceding examples have all shown the expected behavior of a single incident shock. However, the burst system sometimes creates multiple incident shocks. This creates a more complicated flow system, which affects the flow quality for calibrations.

Figure 6.9 shows two sensors which measure multiple shocks. The fact that multiple incident shocks are present is shown most clearly when sensors at different positions are examined. Multiple shocks are expected in any measurement because of the reflected shocks. Incident shocks and reflected shocks can be distinguished by
their order of arrival at different sensors. Incident shocks arrive at upstream sensors first, while reflected shocks arrive at downstream sensors first.

In Figure 6.9, a small shock arrives at the Kulite sensor located at 114 inches at about $t = 7$ ms. The same small shock is detected by the PCB-102 sensor located at 138 inches at about $t = 9$ ms. Before anything else is detected by the PCB-102, a much larger shock arrives at the Kulite. Because the order of arrival has not been reversed, this shock must be an incident shock. Just after the second shock arrives at the Kulite, a second small shock arrives at the PCB-102. This shock was not detected by the Kulite. After the second small shock, the large incident shock arrives at the PCB-102 sensor. At about 15 ms, the reflected shock arrives at the PCB-102, and then at the Kulite about 2 ms later.

Figure 6.9. A double shock demonstrated on a Kulite and a PCB-102 at different positions. $\text{P}_{\text{Driver}} = 0.52$ psia, $\text{P}_{\text{Driven}} = 4.91$ torr. 0.31-mil polyethylene with electrical burst system.

Figure 6.10 shows a similar situation at different conditions. The primary difference is that the amplitude of the shocks is smaller than in Figure 6.9. Multi-shock systems were most often observed when the polyethylene diaphragms were used with the
electrical burst system. They were sometimes observed with the mylar diaphragms, as well. The cause of the preceding fluctuations was initially unclear, but it was suspected that a problem with the burst process was the cause. However, examination of the diaphragm after the run yielded no information about any problems with the burst process in these cases. If a double shock was observed, the diaphragms always showed the proper two-axis cut.

![Graph showing pressure vs. time for two types of shocks](image)

Figure 6.10. A double shock on a Kulite and multiple shocks on a PCB-102 sensor. \( P_{\text{Driver}} = 0.54 \text{ psia}, P_{\text{Driven}} = 14.2 \text{ torr} \). 0.31-mil polyethylene with electrical burst system.

Measurements of the resistances in the burst system circuit confirmed that the burst process was responsible. When the resistances were measured following a run with a double shock, differences were found between the circuit for the vertical and horizontal cutting wires. The differences were often on the order of 0.02 \( \Omega \). Sometimes, one of the wires would be an open circuit. Double shocks could only be created with an open circuit if the run used a 0.31-mil polyethylene diaphragm. For all other diaphragms, an open circuit resulted in one wire failing to cut the diaphragm, which created a single weak shock.
Resistance differences create a double shock because they create an imbalance in the heating of the cutting wires. The wire in the half of the circuit with higher resistance draws less current, and heats slower. This means that it cuts through the diaphragm after the lower-resistance wire. Because of this difference, for a brief period of time, the diaphragm has only been cut along one axis. This small opening creates a very weak shock wave. Shortly afterward, the other wire cuts along the other axis, and the diaphragm is able to open completely, creating a much stronger shock. Open circuits can create double shocks with polyethylene diaphragms because the diaphragms are weak enough that the force of the initial small-amplitude burst is sufficient to cut the diaphragm on the unheated wire. The other diaphragms are too strong for the second cut to happen without some heating of the wire.

The dependence of a double shock on the resistances in the burst system was confirmed by performing runs with the connection intentionally disrupted on one wire. This was accomplished by removing one of the bus bars. In this configuration, all runs produced multiple incident shocks. When the bus bar was reinstalled and ensured to have good electrical contact, a single incident shock was again produced.

Furthermore, in later runs a double shock was occasionally produced. When the electrical burst system was inspected after the run, differences in resistance were always found.

Multi-shock systems sometimes persisted throughout the entire shock tube. In other cases, the multi-shock system exists only in an upstream region. As the shocks move downstream, the smaller shocks are absorbed by the primary shock. An example of this is shown in Figure 6.11.

At 36 inches, the preceding shock arrives at about -4.5 ms, while the primary shock arrives at about -3.5 ms. For both sensors at 72 inches, the preceding shock is still visible, but it is now much closer to the primary shock. It is now less than 0.5 ms ahead of the primary shock. None of the sensors farther downstream show a multi-shock system. Since the preceding shock was weaker, it traveled at a lower
Mach number, and the primary shock caught up to the preceding shock and absorbed it somewhere between 72 and 96 inches downstream.

Runs with multi-shock patterns are not useful for calibrations, since the flow is clearly more complicated than the ideal situation. The preceding shock wave is created by poor burst mechanics, and the primary shock wave travels through the wake of the preceding shock. It is unclear if the data are useful once all the shock waves merge. This situation may be equivalent to a shock generated with more normal burst mechanics, or the wake may be more complicated due to the unusual formation process.
6.3 Shock Planarity

The vast majority of the data in this research were taken with sensors mounted in the side wall of the shock tube. While useful for investigating many questions about the flow quality in the shock tube, such methods can only measure at the edges of the shock wave. However, significant flow variation might be found throughout the rest of the shock wave. As Duff et al. showed, the shock may be curved in the middle [32]. Such a feature would not be found with sensors mounted in the side wall.

Duff performed his measurements with sensors mounted in the end plate of the shock tube. Assuming that all parts of the shock move at the same constant speed, it was possible to calculate axial differences in the position of the shock front. The differences between the shock arrival times for the sensors in the end plate were found and multiplied by the shock speed. This gives the distance traveled by the shock front in between the arrival times, which gives the axial difference in the shock position. By mounting many sensors in the end plate, it was possible to determine the approximate three-dimensional shape of the shock.

This method was also used in this research, with one modification. The sensors were mounted in pitot tubes that extended at least 5.5 inches past the end plate. This was done so that the sensors would simply measure the shock passage, rather than the reflection of the shock from the wall of the tube. A special end plate with mounts for sensors was designed and built for these experiments. The plate is shown in Figure 6.12.

The plate was designed with three radial rows of sensors at 120° intervals. This was so that the three-dimensional shape of the shock could be found with a lower number of sensors. The plate was designed with three sensor locations along each radial ray and a center-mounted sensor. Unfortunately, due to a design error, the mounts closest to the shock tube wall were unusable.

The sensors were mounted in a tube using nail polish. The end of the tube was chamfered to minimize the width of the obstruction encountered by the shock. The
tube fit through a Conax fitting which was mounted on the outer surface of the end plate. The nail polish provided the seal around the sensor, and the Conax fitting provided the seal around the tube. When a given mount was unused, the port was plugged with a normal NPT blank. The width of the Conax fittings was the limiting factor in how closely-spaced the sensor array could be.

It was important that the sensors were all mounted the same distance from the end plate. However, it was not very important what the distance from the end plate was. It was calculated that in order for the measurements to be completed before the shock reached the end plate, the tubes needed to extend at least 5.5 inches away from the surface of the end plate. In order to mount the sensors at the same distance, a mark was made at least 5.5 inches from the flat end of a tool. An ultra-fine-tip marker was used to make the mark, so the mark was 0.8 mm wide. The tool was placed immediately next to the pitot probe with the flat end against the end plate. The probe was then adjusted until the end of the probe was touching the mark. The Conax fitting was then tightened, locking the sensor in place, and the position was
checked again. Since the mark was 0.8 mm wide, this mounting technique should ensure that each sensor was the same distance from the end plate within 1 mm. This means that any measured differences in the shock arrival that are below 1 mm are insignificant.

The sensor layout used is shown in Figure 6.13. Two Kulites were installed to measure the pitot pressure step across the shock, but one was broken. Several PCB-132 sensors were installed at various points throughout the shock tube. These sensors were not switched because the installation of the sensors was quite time-consuming, and the pitot plate was not performing well enough to warrant extended experiments.

![Diagram showing the arrangement of sensors used when looking downstream.](image)

It was of particular interest to check the shock planarity at low driven pressures, since the boundary-layer effects induce the circular curvature found by Duff et al. Unfortunately, the nail polish was unable to provide a sufficient seal for the pressure to be reduced below 1 torr. This was not low enough to encounter the expected low-density effects. It was attempted to seal the interior of the tube by filling it with RTV, instead of only relying on the nail polish to provide the seal. However, this method did not improve the seal. The minimum pressure actually increased when this method was attempted.

Some measurements at higher driven pressures were still performed. Figure 6.14 shows raw time traces from the PCB-132 sensors installed in the pitot plate for a
relatively high driven pressure. The Kulite sensor was not used to assess planarity due to its lower frequency response. Each PCB-132 sensor shows a rise time of approximately 0.3 µs. The variation in the shock arrival time is approximately 0.5 µs. No particular correlation between sensor position and shock arrival time is evident. The center-mounted PCB-132, #6707, detects the shock last. The outer-most sensors, #6657 and #6772, detect the shock before and after sensor #5411, which was more centrally mounted. This indicates that the variations are due to the mounting uncertainty, which should not follow any particular pattern.

![Figure 6.14](image_url)

Figure 6.14. Time traces showing shock arrivals for PCB-132 sensors mounted in the pitot plate. 2-mil mylar with burst system, $P_{Driver} = 9.2$ psia, $P_{Driven} = 5$ torr, $P_{Ratio} = 95$.

Figure 6.15 shows shock arrivals at the pitot plate for a shock at lower driver and driven pressure. The results are similar. Again, the arrival times are all within 0.5 µs. The order of the arrivals is slightly different, with sensor #6772 now detecting the shock arrival nearly simultaneously with sensor #6707. Sensor #5411 now also detects the shock almost simultaneously with sensor #6657, instead of slightly after.
This indicates that the shock has arrived very slightly earlier at the more center-mounted sensors by about 0.1 µs.

Figure 6.15. Time traces showing shock arrivals for PCB-132 sensors mounted in the pitot plate. 0.31-mil polyethylene with burst system, \( P_{Driver} = 0.62 \) psia, \( P_{Driven} = 1.2 \) torr, \( P_{Ratio} = 28 \).

In order to quantify the differences in arrival time as a distance, it is necessary to measure the shock speed and the shock arrival time. The uncertainties in these measurements are included in the discussion of the Mach number in the shock tube later in this chapter. For planarity measurements, the uncertainties in sensor positioning are all that is necessary to explain the scatter in the data.

The average shock speed measured during the run was used to convert the time differences to distances. The planarity of the shock was measured over about 20 runs at driven pressures from 1-50 torr, with all three diaphragm types that are used with the electrical burst system. As discussed later, the uncertainty in the speed measurements is about 1.5%. Since sensor #6707 detected the shock last in nearly all cases and it was the central sensor, the differences for each sensor were calculated.
relative to the arrival at sensor #6707. All differences were found to be less than 1 mm, which is within the positioning uncertainty. The maximum difference was 0.5 mm for sensor #6657.

The average and standard deviation were computed for each sensor. Since none of the differences were significant, they were not separated by the run conditions. The results are shown in Table 6.1. It is clear from these results that no significant differences in shock arrival time are ever measured, indicating good planarity in the shock tube. Additionally, since the average offsets always indicate arrival times before the arrival at sensor #6707, every other pairing will indicate smaller offsets than those listed. Since four different sensors are used, it is unlikely that fortuitous error canceling has caused favorable results for each pairing.

Table 6.1. Shock arrival offsets in distance for pitot-mounted PCB-132 sensors.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Average (mm)</th>
<th>Standard Deviation (mm)</th>
<th>Standard Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6772</td>
<td>0.18</td>
<td>0.10</td>
<td>59</td>
</tr>
<tr>
<td>5411</td>
<td>0.24</td>
<td>0.032</td>
<td>13</td>
</tr>
<tr>
<td>6657</td>
<td>0.34</td>
<td>0.096</td>
<td>29</td>
</tr>
</tbody>
</table>

A limited number of pitot-mounted measurements were available. Additionally, with the pitot plate installed, driven pressures below 1 torr could not be tested. Since the shock is expected to be less planar at low driven pressures, it was desired to perform some analysis of shock planarity below 1 torr.

Shock planarity can also be measured using static-mounted sensors at the same axial location and different azimuthal positions. This will not measure shock curvature in the center of the tube, but it can measure tilt or other offsets around the wall of the shock tube. Additionally, since more data was available with static-mounted sensors, a sensor-switching analysis could be performed to control for the effect of sensor bias.
For static measurements, the rise time of the PCB-132 sensor increases to 1 \( \mu \text{s} \) because the shock must traverse the sensing area of the sensor. The positioning uncertainty is also larger for measurements in static configuration. Since the mounting position of the sensing element on a PCB-132 is uncertain, the effective position of the sensor may be anywhere on the sensor face. Therefore, the uncertainty is 1.6 mm, half the sensor diameter. When comparing measurements from two PCB-132 sensors, the expected uncertainty is 2.3 mm.

There were no available measurements where two sensors exchanged azimuthal positions. However, it was possible to compare one control sensor at a constant location to multiple sensors mounted 180\(^\circ\) across from the control sensor. In one case, PCB-132 #6830 was mounted at 114 inches and 180\(^\circ\). It was compared to PCB-132 #6617 and #6831 mounted at 114 inches and 0\(^\circ\).

Changing the sensor affected the measured difference slightly. For sensor #6617, the average difference was 0.12 mm, while the average was 0.58 mm for #6831. This shows that the sensor can have a small effect on the offset, but in neither case was the difference close to the expected positional uncertainty. This allows the conclusion that the shock is planar within 1 mm.

Measurements were also performed with 4 PCB-132 sensors mounted at 96 inches at 0\(^\circ\), 90\(^\circ\), 180\(^\circ\), and 270\(^\circ\). The shocks tested spanned from the minimum-amplitude shocks with pressure steps of 0.001 psi to shocks with pressure steps of 0.6 psi. All three diaphragm types used with the burst system were included.

Again, nearly every difference computed was less than 1 mm, and all were within the uncertainty. For each run, the difference was found between the first and last sensor to detect the shock. This gives the maximum difference within the set of four sensors. For the largest differences, the average was 1.2 mm, with a maximum of 1.8 mm. These are still well within the uncertainty of 2.3 mm.

These measurements allow the conclusion that the shocks produced in the 3-Inch Shock Tube are planar within the uncertainty of the measurements. The maximum
non-planarity in the shock tube is less than about 2 mm, which is only 2% of the tube diameter.

6.4 Repeatability

In order for the shock tube to be considered a reliable instrument, it must produce repeatable measurements. Repeatability would be expected to be worse for low-amplitude shocks, due to the lower signal, greater difficulty controlling the conditions, and greater expected influence of non-ideal effects which might be influenced by the burst process. However, accurate control of the conditions was limited across the range of the shock tube’s operation, which also limited repeatability.

This difficulty was primarily due to the fact that the conditions were recorded from manual readings, rather than read instantaneously from the oscilloscopes. Efforts were made to make instantaneous readings for both the driver and driven pressures, but these readings were found to be unreliable. This was largely because the electrical connections were fragile and broke frequently as the tube was opened between runs. Manual readings have inherently limited accuracy, since the pressures drift until the moment of the run. Efforts were made to stabilize the conditions and take readings as close to the beginning of the run as possible, but substantial uncertainty still remained. The uncertainties for the driver and driven pressures were listed in Chapter 3 in Tables 3.1 and 3.2.

Since the recorded conditions are uncertain, the repeatability of the results at conditions which are nominally the same is also limited. The condition uncertainties were used with ideal theory to calculate the expected uncertainties in the Mach number and shock pressure step when using the electrical burst system. Without the burst system, the estimated uncertainties for the aluminum diaphragms are similar to those for the polyethylene diaphragms. The uncertainties for acetate diaphragms are similar to those for 1.5-mil mylar run with the burst system. Without the burst system, the uncertainties are much larger at a given driver pressure than they would be with
the burst system, but the percentages are similar between the different diaphragm types. The uncertainties for Mach number are given in Table 6.2. The uncertainties for the shock pressure step are given in Table 6.3.

Table 6.2. Estimated uncertainties, in percent, for Mach numbers based on condition uncertainties. $P_4$ is driver pressure in psia.

<table>
<thead>
<tr>
<th>$P_{Driven}$ (torr)</th>
<th>$P_4 = 0.5$ (Polyethylene)</th>
<th>$P_4 = 6$ (1.5-mil)</th>
<th>$P_4 = 14$ (2-mil)</th>
<th>$P_4 = 2.5$ (Al)</th>
<th>$P_4 = 22$ (Acetate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{-2}$</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
<td>0.6</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6.3. Estimated uncertainties, in percent, for shock pressure steps based on condition uncertainties. $P_4$ is driver pressure in psia.

<table>
<thead>
<tr>
<th>$P_{Driven}$ (torr)</th>
<th>$P_4 = 0.5$ (Polyethylene)</th>
<th>$P_4 = 6$ (1.5-mil)</th>
<th>$P_4 = 14$ (2-mil)</th>
<th>$P_4 = 2.5$ (Al)</th>
<th>$P_4 = 22$ (Acetate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{-2}$</td>
<td>35</td>
<td>30</td>
<td>30</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>5</td>
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<tr>
<td>50</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

6.4.1 Repeatability With Electrical Burst System

Figures 6.16 and 6.17 show typical repeatability for very low amplitude shocks in the 3-Inch Shock Tube. The average measured amplitudes of the shocks were 1.12 mpsi for Run 263 and 1.13 mpsi for Run 264. Here, mpsi is used to mean one thousandth of a psi. This is a difference of less than 1%, despite the very small
amplitude. However, the measurements were inconsistent between runs. Only one reference sensor, the Kulite shown in Figure 6.16, detected the shock in both runs. For all the other reference sensors, the measurement quality was too low to record an amplitude in at least one of the runs. There were some PCB-132 sensors which detected the shock in both runs. The different measurement quality at most sensors suggests that the flow was not as repeatable at those sensors.

It is clear in Figure 6.16 that the amplitude measurement is similar between the two runs. However, the response shapes are different. The response for Run 263 shows a pressure ramp closely following the shock, which is either absent or of a much smaller magnitude in Run 264. The rise of the sensor is also much quicker in Run 263. The reasons for the differences are unclear. It is likely that they are caused by random differences in the burst process, such as the opening time.

Figure 6.16. Repeatability for Kulite sensor #355 at 114 in. Both runs with 0.31-mil polyethylene with electrical burst system. Traces low-pass filtered to 100 kHz for clarity.

Figure 6.17 shows measurements from a PCB-132 sensor mounted at 96 inches downstream in a rubber sleeve. The faster response of the PCB-132 sensors makes
them better able to measure shocks. A calibration performed with the 3-Inch Shock Tube was used to convert the voltage measurements into pressure. The method with which the calibration was found is discussed in Chapter 7.

The shock amplitude is repeatable within the sensor resolution between the two runs. Additionally, the rise for the sensor is nearly identical in the two runs. However, there is some variation in the shapes of the responses. For Run 263, the measured step is flat after the rise, but in Run 264, there is a small temporary rise shortly after the shock. This may represent an actual difference in amplitude, or be some artifact of the sensor response.

Figure 6.18 shows repeatability for one of the smallest shocks that can be created with mylar diaphragms. The shock is again located at $t = 0$, but it is harder to see than in Figure 6.16 due to the higher burst pressure. The higher driver pressures increase the vibration noise. Additionally, since lower driven pressures must be used to achieve the same amplitude, the shock development length is expected to be longer.
The shock has an amplitude of about 1 mpsi. The responses have the same shape in both runs. After the shock, the pressure remains constant for about 0.1 ms before a following pressure ramp arrives. This shows that despite the questionable look of the data in Figure 6.18, the shocks are repeatable at very low amplitudes. This makes them more likely to be useful for calibrations.

There were enough repeated runs for 0.31-mil polyethylene diaphragms into $5 \times 10^{-2}$ torr that the RMS variation for a given sensor at a given location could be computed. The RMS values are plotted in Figure 6.19. They were computed from measurements over 4-6 runs. The runs are the same for each sensor, but not every sensor was mounted in the same position for each run. The PCB-132 and PCB-106 sensors had data for at least five runs, while the PCB-102 sensors and Kulites only had data for four runs.
The variability is high, with values up to about 30%. However, this is consistent with the 35% uncertainty expected due to the run condition uncertainty. The RMS values decline slightly as the axial position increases. This is expected, since the shock wave would likely form over a significant portion of the length of the shock tube. Because the shock formation process is heavily dependent on the details of the burst and the conditions, it will be less repeatable, and increase the variation in the pressure step measurements.

Figure 6.19. RMS variations at different axial stations for very small shock pressure steps with amplitudes of about 4 mpsi.

RMS values could be computed for several conditions that produce moderate or large shocks. There were three additional conditions with the polyethylene diaphragms which had enough repeated runs to compute RMS values.
For driven pressures of 20 torr, 5-7 runs were available for each sensor. The PCB-132 sensors had data from 5-6 runs available, and all other sensors had 7. Again, each is computed from the same set of runs, though not each run was able to be used for each sensor due to configuration changes and occasional signal problems.

The RMS values are shown in Figure 6.20. They decrease substantially as the axial distance increases. At the most upstream station, the variation in the shock pressure steps is nearly 20%. By about 2.5 m, it has decreased to 5%. This behavior is explained by the finite shock formation distance. While the shock is forming, it will be less consistent between runs due to its dependence on the burst dynamics and other random factors. The different sensor types measure similar variation levels, indicating that the variation is due to changes in the flow, and not due to sensor problems.

![Figure 6.20. RMS variations at different axial stations for moderate pressure steps with amplitudes of about 0.17 psi. 0.31-mil polyethylene diaphragms into 20 torr.](image-url)
A large number of points were available for 0.31-mil polyethylene diaphragms and driven pressures of 15 torr. For each sensor, data from 15 runs were available. The RMS values are shown in Figure 6.21.

At the most upstream station, the RMS is about 15%. The levels become nearly constant at about 6% by 2 m. Again, the different sensor types measure approximately the same levels of variation between runs.

![Figure 6.21. RMS variations at different axial stations for moderate pressure steps with amplitudes of about 0.15 psi. 0.31-mil polyethylene diaphragms into 15 torr.](image)

There were not enough repeated runs performed with the 1.5-mil mylar diaphragms to warrant computing the RMS values. However, there was one condition with the 2-mil mylar diaphragms which had 6-7 repeated runs for each sensor. The computed RMS values are shown in Figure 6.22. No sensors were located at the most upstream position, so observations of shock development were not expected. Measurements
are available from 2.5 to 3.5 m. The variation is consistent throughout this region at about 3%. This level of variation agrees with the expected variation due to the uncertainty in the conditions.

![Figure 6.22. RMS variations at different axial stations for large pressure steps with amplitudes of about 1.5 psi. 2-mil mylar diaphragms into 30 torr.](image)

**6.4.2 Repeatability With Natural Burst**

Figure 6.23 shows repeatability for three runs performed with a natural burst. It is clear that both the amplitude and overall response shapes are very similar for all runs. This shows that good repeatability is possible without the burst system, as well. Note that the following pressure rise is present on all runs. It begins around 0.2 ms after the shock passage, though it does not show a well-defined beginning. This is similar to the performance found with the burst system when the ramp is
present. One difference between measurements with and without the burst system is the substantially higher noise levels observed with the burst system. These are partially due to the fact that the burst pressure differentials are higher without the burst system.

![Graph showing pressure vs. time with readings for different runs.]

*Figure 6.23. Repeatability for PCB-102 at 138 inches. All runs with 0.7-mil aluminum with natural burst. Traces low-pass filtered to 200 kHz for clarity.*

Figure 6.24 shows repeatability for high-amplitude runs performed using 1.0-mil acetate diaphragms and a natural burst. The sensor is a PCB-102 mounted 138 inches downstream. The measurements match within 1%.

Figure 6.25 shows Kulite measurements from the same runs shown in Figure 6.24. The Kulite is mounted further upstream at 96 in. While the measured amplitudes are similar in both figures, there is more variation at 96 in, at 9%. This is likely due to the development of the shock wave.
Figure 6.24. Repeatability for PCB-102 at 138 inches. Both runs with 1.0-mil acetate with natural burst. Traces low-pass filtered to 1 MHz for clarity.

Figure 6.25. Repeatability for Kulite #355 at 96 inches. Both runs with 1.0-mil acetate with natural burst. Traces low-pass filtered to 1 MHz for clarity.
Fewer runs were performed without the electrical burst system, since the performance with the system proved to be better due to the lower burst pressure differentials and better control over the run conditions. Because of this, there was only one condition without the electrical burst system with enough repeated runs to warrant computing RMS values. This was for 0.5-mil aluminum diaphragms with a driven pressure of 0.05 torr, which had four repeated runs. The RMS values are shown in Figure 6.26. The values are similar to those found with the electrical burst system using 0.31-mil polyethylene diaphragms with the same driven pressure. They range from approximately 10-30%, which is consistent with the expected variation due to the limited control over the run conditions. The fact that the ranges are similar indicates that the difficulty in controlling the driven pressure at the low end of the shock tube’s operating range is the controlling factor for the repeatability.

Figure 6.26. RMS variations at different axial stations for large pressure steps with amplitudes of about 0.01 psi. 0.5-mil aluminum diaphragms into $5 \times 10^{-2}$ torr.
6.5 Mach Number Measurements

It is expected that the shock strength and Mach number will vary with axial location. In some cases, the shock formation distance will be a significant percentage of the total driven tube length. The formation length depends on the driven pressure, shock Mach number, and diaphragm opening time. The Mach number would be expected to increase while the shock is forming. Once the shock has formed, the strength of the shock will begin decreasing. The decrease is due to the effect of the boundary layer behind the shock, which pulls fluid behind the contact surface, reducing the pressure behind the shock wave and moving the contact surface closer to the shock. The degree of the effect depends on the shock Mach number and the driven pressure.

Because of these different factors, the axial uniformity of the tube will vary depending on the run conditions, diaphragm material, and the burst method. Lower axial uniformity is expected for the low-amplitude shocks due to the potential for a longer formation distance and greater shock attenuation.

The Mach number was found by measuring the speed of the shock wave in the tube and dividing by the sound speed. No temperature measurement was taken inside the shock tube. The gas temperature was assumed to be the same as the room temperature, which was 294 K. This gives a sound speed of 343 m/s. The temperature in the room was controlled within 5 K, giving a 1% uncertainty in the Mach number.

Measurement of the shock speed was done by comparing time-of-arrival measurements from sensors at two locations. The location of the measurement was defined as the average of the locations of the two sensors used. Since the PCB-132 sensors are designed as time-of-arrival sensors, their measurements were used to calculate the Mach number. While the frequency response of the PCB-102 sensors is lower than that for the PCB-132 sensors, they have a similar rise time when mounted in static configuration. The rise time for both sensor types is 1 µs.
There are uncertainties in both the location and time-of-arrival. For the PCB-132 sensors, the location uncertainty is substantial. The sensing element may be mounted anywhere on the sensor face, so the uncertainty is the effective sensor location is equal to half the diameter of the sensor face, which is 1.6 mm. For the PCB-102 sensor, the uncertainty in the location of the sensor is smaller, since the construction of the sensor is more repeatable. In this case, the uncertainty is in the location of the sensor mount, which is estimated as 0.01 in, or 0.25 mm. The uncertainty in the time-of-arrival measurement is estimated as 50% of the rise time of the sensor. This incorporates uncertainty in the identification of the mid-point of the rise, as well as uncertainty due to the sensor’s frequency response.

Since the uncertainties are fixed times and lengths, the total uncertainty of a measurement depends on the distance between two sensors and the difference between the times of arrival. However, sensors are typically separated by about 12 inches (0.3 m) and the shock travel time over that distance is typically about 0.25 ms. For this representative case, the total uncertainty for the Mach number measurement is 1.4% for a pair of PCB-132 sensors, and 1.2% for a PCB-132 paired with a PCB-102.

Initially, only data from PCB-132 sensors was used to find the Mach number of the shock. This was done to eliminate any variation which might result from comparing two different sensors. An example is shown in Figure 6.27. This run is a relatively high-amplitude run, with a large burst pressure difference and a moderate downstream pressure. The Mach number is relatively high, with an average of 2.85. The shock speed decreases throughout the measured region of the shock tube. This indicates that the shock formation distance is short, which would be expected due to the higher driven pressure. The decrease in the Mach number is 7%. Two measurements are available at about 2.6 m because two PCB-132 sensors were mounted at the same location. The agreement between the two sensors is well within the uncertainty.
Mach numbers from two runs performed with a 1.5-mil mylar diaphragm and the electrical burst system are shown in Figure 6.28. The average Mach number for this condition is lower, at 2.4. A small amount of shock attenuation is evident, with the Mach number decreasing by 3.5%. The differences between the two runs fall within the measurement uncertainty.
Figure 6.28. Mach numbers computed with PCB-132 sensors. 1.5-mil mylar with electrical burst system.
Figure 6.29 shows Mach numbers measured from runs performed with 0.31-mil polyethylene diaphragms at a relatively high driven pressure. The Mach number produced is fairly low, with an average of 1.23 between the two runs shown. Attenuation is observed throughout the length of the shock tube, with the Mach number decreasing by 3%. The differences between the two runs are slightly outside the measurement uncertainty, but still within the variation expected due to differences in the run conditions.

![Mach Numbers](image)

Figure 6.29. Mach numbers computed with PCB-132 sensors. 0.31-mil polyethylene with electrical burst system.

Figure 6.30 shows Mach numbers measured for a run performed with a polyethylene diaphragm at a lower driven pressure. The Mach number is 1.96, with attenuation evident throughout the length of the shock tube. The total variation in the Mach number is 5%. Two measurements were available at about 2 m, which match almost exactly.
Figure 6.30. Mach numbers computed with PCB-132 sensors. 0.31-mil polyethylene with electrical burst system, $P_{\text{Driver}} = 0.5$ psia, $P_{\text{Driven}} = 0.7$ torr, $P_{\text{Ratio}} = 40$.

Figure 6.31 shows Mach number measurements for the minimum useful condition in the shock tube. When data are available before 2 m, an increase in the Mach number of 2% is visible. After 2 m, the Mach number decreases by 4%. This indicates that the formation distance for this low condition is approximately 2 m. The Mach numbers for different runs follow similar profiles, though the Mach numbers in Run 318 are 9% larger than those for Run 317. This variation is within the uncertainty due to the limited control over the run conditions. When multiple measurements are available at the same location, they agree well.

Some Mach number measurements were also performed without the burst system. An example for a large-amplitude shock is shown in Figure 6.32. In this case, a small amount of attenuation is observed throughout the shock tube. The Mach number decreases by 2%.
Figure 6.31. Mach numbers computed with PCB-132 sensors at the minimum useful condition. 0.31-mil polyethylene with electrical burst system.

Figure 6.32. Mach numbers computed with PCB-132 sensors. 1.0-mil acetate without electrical burst system, $P_{Driver} = 21$ psia, $P_{Driven} = 50$ torr, $P_{Ratio} = 20$. 
An example of a shock produced at a lower driven pressure without the burst system is shown in Figure 6.33. The Mach number is observed to increase up to 2 m, indicating a significant development length despite the driven pressure being relatively high at 10 torr. This indicates that the diaphragm opening time is longer without the burst system, increasing the distance over which the shock forms. The variation in the Mach number is 1%.

Figure 6.33. Mach numbers computed with PCB-132 sensors. 0.5-mil aluminum without electrical burst system, $P_{Driver} = 2.8$ psia, $P_{Driven} = 10$ torr, $P_{Ratio} = 15$.

Figure 6.34 shows Mach number measurements from two runs which used 0.7-mil aluminum diaphragms without the electrical burst system and driven pressures of $5 \times 10^{-2}$ torr. While repeatability is especially limited without the electrical burst system, the two runs shown happened to match closely. Every point matches within the uncertainty, and for the first three axial points the differences are much smaller than the uncertainty. The shock formation appears to be completed within 2.5 m,
but no measurements were available at 2 m to show if it ended earlier. The variation is about 3%.

Figure 6.34. Mach numbers computed with PCB-132 sensors. 0.7-mil aluminum without electrical burst system.

A limited number of PCB-102 sensors were used, making them less important for determining the axial variation in the shock Mach number. However, it was of interest to compare PCB-102 measurements with those of PCB-132 sensors to see if they were actually useful for measuring the speed of the shock wave. PCB-102 sensors were paired with the nearest PCB-132 sensors to calculate the shock speed. Speeds were not calculated using pairs of two PCB-102 sensors.

An example for a higher-amplitude shock is shown in Figure 6.35. The shock attenuates, as expected from the earlier results. The measurements using PCB-102 sensors match very closely with the measurements that use only PCB-132 sensors. The two sensor types disagree more farther downstream, but the differences are still within the uncertainty.
Another example for a shock created at the minimum condition is shown in Figure 6.36. Again the agreement between the two sensor types is very close. It increases to 1% downstream, but remains within the uncertainty. This shows that the PCB-102 sensors can also be used to measure the shock speed. However, switching back and forth between the measurements using only PCB-132 sensors and measurements which use both might sometimes obscure the trends, since the error is significant compared to the observed variation in the Mach number.

6.6 Azimuthal Uniformity

The azimuthal uniformity of the shock tube must also be checked. Comparing multiple measurements at the same axial location can reveal two things. The first is actual variations in pressure at different azimuthal positions at the same axial lo-
cation. Such differences would not be expected for a shock tube flow. The presence of differences would indicate poor flow quality. It would also make sensor calibrations difficult, since calibrations will necessarily involve comparing measurements at different azimuthal positions.

The second thing that can be revealed by such comparisons is systematic differences in measurements by different sensors. It is possible that calibration errors or the differing characteristics of the sensors could result in certain sensors reading significantly different values than others. If there are no differences in shock pressure step with azimuthal position, then the comparison of multiple measurements at the same axial position will reveal any sensor biases.

The available azimuthal positions in the 3-Inch Shock Tube are shown in Figure 6.37. There was no single axial location which had all of these positions available. At most locations, two azimuthal positions were available. The maximum number of
positions was at 96 inches, which had four sensor ports at 0°, 90°, 180°, and 270°. The positions at 45° and 225° were not used for checking azimuthal variations because one of the sensors was always a PCB-103, which did not give useful measurements.

![Diagram of available azimuthal locations in the shock tube. Positions are listed for an observer looking downstream.](image)

The azimuthal uniformity was investigated using the same sensor mounted in multiple locations during repeated runs, and by using multiple sensors in the same run. As shown previously, at conditions which are nominally the same, there can be substantial variation in the actual shock strength due to the limited control over the conditions. When a sensor is rotated through different positions, the actual shock amplitude may change. Additionally, since the calibrations of different sensors may not agree, comparing multiple sensors is uncertain.

In order to control for variation in the run conditions when moving a single sensor, measurements from a second sensor which did not move were also used. This control sensor was used to select which runs should be compared, and to check if apparent trends in the moving sensor could be explained by variations between runs. In general, runs were selected where the measurements of the control sensors matched within about 5%. A way of quantifying the amount of variation explained by the control
sensor is to divide the measurement of the moving sensor by the measurement of the control sensor. The amount that the ratio varies is the unexplained variation. Some unexplained variation is expected, since the shock is attenuating or developing as it moves downstream, and the control sensor was often at a different axial station which might have experienced a different level of variation. When these ratios are computed, the uncertainties of the two sensors were combined by taking the square root of the sum of the squares.

Traces from the same Kulite sensor in two different azimuthal positions are shown in Figure 6.38. A PCB-102 sensor at 132 inches indicated a 2% difference between the two runs. The Kulite sensor indicates no significant difference between the two measurements, indicating no dependence on azimuthal position.

Figure 6.38. Kulite 355 at two different azimuthal positions. \( x = 96 \) inches, 2-mil mylar diaphragms with electrical burst system, \( P_{\text{Driver}} = 14.4 \text{ psia}, P_{\text{Driven}} = 10 \text{ torr}, P_{\text{Ratio}} = 75. \)

Figure 6.39 shows the same Kulite sensor in the same two positions for different conditions. The driven pressure is the same, but a weaker diaphragm has been used resulting in a smaller shock pressure step. Again, there is no significant difference
in the shock pressure step between the two runs. A PCB-102 sensor at 132 inches downstream showed a difference of less than 1% between the same runs.

Figure 6.39. Kulite 355 at two different azimuthal positions. x = 96 inches, 1.5-mil mylar diaphragms with electrical burst system, \( P_{Driver} = 6.2 \) psia, \( P_{Driven} = 10 \) torr, \( P_{Ratio} = 32 \).

Figure 6.40 shows measurements from a PCB-132 sensor at a location further upstream. There is no significant difference in the amplitudes. However, the shapes of the responses are somewhat different because the sensor was re-mounted between the two runs. In both cases, the sensor was mounted in rubber. A PCB-132 sensor mounted at 96 inches for the same two runs shows a 7% difference in amplitude.
Figure 6.40. PCB-132 # 5396 at two different azimuthal positions. x = 72 inches, 0.5-mil aluminum diaphragms without electrical burst system, $P_{Driver} = 3.5$ psia, $P_{Driven} = 50$ torr, $P_{Ratio} = 1.8$. 
The ideal way to check flow uniformity is to switch the locations of two sensors for a repeated run. This is because each sensor can be used to control for variation due to both run conditions and position. Only one case like this was available.

Results from both sensors are shown in Figure 6.41. A PCB-102 sensor was switched with Kulite #355. For both sensors, the shock pressure step is significantly larger for one run than the other. However, the larger step is for Run 292 in both cases, shown in red. For both sensors, the pressure step for Run 292 is 1.28 times the step for Run 148. This shows that the shock strength was dependent on the run, and not on the sensor position.

Figure 6.42 shows a comparison for one of the weakest shocks which can be created in the shock tube. The Kulite sensor has been moved 180°, but there is no difference in the measured shock pressure step amplitude. A PCB-106 sensor at 132 inches measured amplitudes within 5% between the two runs. This shows that even at the lowest amplitudes, there is no significant dependence of shock pressure step amplitude on azimuthal position.
Figure 6.41. Two sensors at 96 inches exchanging positions for runs with 0.31-mil polyethylene with the electrical burst system. $P_{Driver} = 0.5$ psia, $P_{Driven} = 1$ torr, $P_{Ratio} = 13$. 
At one condition, a Kulite was rotated through three azimuthal positions at the same axial location. Another Kulite at 114 inches served as the control sensor for these measurements. However, the conditions were not repeated very closely. As a result, the measurements of the rotated sensor and the control sensor vary significantly. In this case, it is useful to compute the ratios of the pressure steps measured by the moving sensor to those measured by the control sensor.

The measured amplitudes for both sensors are shown in Figure 6.43(a). The measurements from the control sensor are shown at different azimuthal positions despite the fact that the control sensor did not move. The displayed azimuthal positions of the control sensor match the position of the rotated sensor in the same run. This allows a direct comparison of the variation in the two measurements.
(a) Shock pressure step amplitude measurements from rotated and control sensor.

(b) Ratios of amplitudes from rotated sensor to control sensor.

Figure 6.43. Kulite 355 at three azimuthal positions at 96 inches compared to Kulite 343 at 114 inches. 0.31-mil polyethylene with electrical burst system, $P_{Driver} = 0.7$ psia, $P_{Driven} = 10$ torr, $P_{Ratio} = 3.6$. 
The amplitudes of the rotated Kulite show a rise with increasing azimuthal position. However, the control sensor also shows this rise, indicating that most of the variation is due to different shock amplitudes in each run. Figure 6.43(b) shows the computed ratios of the rotated sensor and the control sensor. The ratios decrease slightly with increasing azimuthal position, but the differences are largely within the estimated uncertainty. The first point is not quite within the uncertainty, but the uncertainty may be underestimated. Additionally, since the two sensors are at different axial locations, the shock strength may not be changing by the same amount in each location. The data do not seem to indicate any significant dependence of shock strength on azimuthal position.

Measurements at multiple azimuthal stations during a single run were also performed. An example for a high-amplitude shock of 1.6 psi is shown in Figure 6.44. In this case, the measurements of all three sensors agree within the uncertainty. The PCB-102 measures a slightly higher value than the Kulites, but the difference is not significant.

![Figure 6.44](image_url)

Figure 6.44. Measurements from multiple azimuthal positions during a single run. x = 96 inches, 2-mil mylar diaphragms with electrical burst system, $P_{Driver} = 14.4$ psia, $P_{Driven} = 10$ torr, $P_{Ratio} = 75$. 
Figure 6.45. Measurements from multiple azimuthal positions during a single run. $x = 96$ inches, 0.31-mil polyethylene diaphragms with electrical burst system, $P_{Driver} = 0.57$ psia, $P_{Driven} = 1$ torr, $P_{Ratio} = 26$.

Figure 6.45 shows measurements for a lower-amplitude shock of 0.05 psi. In this case, the driven pressure is still relatively high, at 1 torr. While the difference between the PCB-102 and the Kulites is larger for this amplitude, it is still within the uncertainty. This indicates that again, there is no significant variation with azimuthal position, though there may be some sensor bias.

Measurements for an extremely low-amplitude shock of 0.002 psi are shown in Figure 6.46. At this location, the Kulite sensors continue to agree, but the PCB-102 measures a higher value at a level slightly beyond the uncertainty. However, the uncertainty shown for the Kulites is still only 2\% of the value, which is likely to be an underestimate at these low amplitudes.

These results do not indicate a significant variation in shock amplitude at different azimuthal stations. This indicates that the flow quality is good within the uncertainties. Additionally, measurements from different axial stations can be compared without controlling the azimuthal position. Measurements between different
Figure 6.46. Measurements from multiple azimuthal positions during a single run. $x = 96$ inches, 0.31-mil polyethylene diaphragms with electrical burst system, $P_{\text{Driver}} = 0.55$ psia, $P_{\text{Driven}} = 2 \times 10^{-2}$ torr, $P_{\text{Ratio}} = 1300$.

sensors tend to agree, though the PCB-102 sensors tend to read higher than the Kulites.

### 6.7 Axial Pressure Measurements

With the azimuthal uniformity of the shock tube established, it becomes much easier to examine the axial uniformity because the azimuthal position does not need to be controlled.

The analysis of the axial uniformity was performed in the same way as the analysis of the azimuthal uniformity. Single-sensor analyses were performed by placing a single sensor in multiple axial positions over multiple repeated runs and comparing to non-moving control sensors in order to control for variability between different runs. Then, multi-sensor analyses were performed for single runs.
PCB-102, PCB-106, and Kulite sensors were used for the multi-sensor analysis. PCB-132 sensors were not used for the multi-sensor analysis because of their uncertain calibration. However, it is valid to compare multiple measurements by the same PCB-132 sensor, so they were included in the single-sensor analysis.

An example of the raw data from a single-sensor analysis is shown in Figure 6.47. The data from the PCB-102 shows results from repeated runs as the sensor was moved downstream. The Kulite sensor was fixed at 96 inches, but is shown at the same axial position as the PCB-102 sensor for that run. The trends are somewhat obscure due to the changing measurements of the control sensor. However, the shock pressure step seems to decrease as the sensor is moved downstream. This would make sense, since in this range of conditions the Mach number of the shock was observed to decrease going downstream, indicating shock attenuation. The variation between the runs is within the uncertainty of the PCB-102 sensor, though the trend is clear and suggests a real difference. The control Kulite sensor indicates a rise in amplitude over the three runs which slightly exceeds the uncertainty.
Figure 6.47. Measurements from a PCB-102 sensor at multiple axial stations and a control Kulite at 96 in. $P_{Driver} = 1.5$ psia, $P_{Driven} = 50$ torr, $P_{Ratio} = 1.5$, 0.31-mil polyethylene with electrical burst system.

A clearer picture may be obtained by plotting the ratio of the PCB-102 measurement to the control Kulite measurement. These ratios are shown in Figure 6.48. The uncertainties shown incorporate the uncertainty of both sensors. When the ratios are shown, the downward trend is clearer. The shock pressure step amplitude measured by the PCB-102 decreases by 10% relative to the control sensor as it moves downstream.
Figure 6.48. Ratios of the shock pressure step from a PCB-102 sensor at multiple axial stations divided by measurements from a Kulite at 96 inches. $P_{\text{Driver}} = 1.5$ psia, $P_{\text{Driven}} = 50$ torr, $P_{\text{Ratio}} = 1.5$, 0.31-mil polyethylene with electrical burst system.

Pressure step ratios are also plotted for the same PCB-102 sensor for a higher-amplitude shock in Figure 6.49. Because the shocks were created with stronger 1.5-mil mylar diaphragms, the pressure steps are about 0.55 psi in amplitude, despite the lower driven pressure. Again, there is a decrease of 10% relative to the control sensor at 96 inches.

Figure 6.50 shows pressure step ratios for a PCB-132 sensor compared to a control Kulite at 96 inches. These measurements used the same driven pressure as was used in Figure 6.49, but with a weaker diaphragm. This creates a lower-amplitude shock at a lower Mach number. The average pressure step amplitude was 0.11 psi. The amplitudes for the PCB-132 sensor were calculated using a calibration curve found from measurements performed in the 3-Inch Shock Tube. The amplitudes
Figure 6.49. Ratios of the shock pressure step from a PCB-102 sensor at multiple axial stations divided by measurements from a Kulite at 96 inches. $P_{Driver} = 6.2$ psia, $P_{Driven} = 10$ torr, $P_{Ratio} = 32$, 1.5-mil mylar with electrical burst system.

were only found to keep the ratios reasonably close to 1, not to attempt an accurate measurement of the amplitude.

It is clear in Figure 6.50 that the trend for the shock pressure step to decrease moving downstream is continuing. However, while the decrease is still about 10%, it occurs mostly upstream of 3 m. Beyond 3 m, the amplitudes are consistent within the uncertainty, though the last point shows another decrease. Because of the lower Mach number, less attenuation might be expected than in the cases shown earlier.
Figure 6.50. Ratios of the shock pressure step from a PCB-132 sensor at multiple axial stations divided by measurements from a Kulite at 96 inches. $P_{\text{Driver}} = 0.7$ psia, $P_{\text{Driven}} = 10$ torr, $P_{\text{Ratio}} = 3.6$, 0.31-mil polyethylene with electrical burst system.

Figure 6.51 shows measurements from a PCB-102 sensor at multiple axial stations at a driven pressure of 1 torr. These conditions result in shocks with amplitudes of about 0.05 psi. At these conditions, the shock appears to strengthen as it travels downstream, rather than attenuating. This indicates that the shock formation length is much larger than it is at higher pressures, which could be explained by the lower density.

However, Mach number measurements at similar conditions show that the Mach number is decreasing as the shock travels downstream (see Figure 6.30). One would expect the shock pressure step to also decrease in this case. The reason for the discrepancy is not clear. The increase in shock pressure step and the decrease in Mach number are beyond the expected uncertainty, so they are not simply attributable to
measurement errors. The measured pressure step may be affected by the useful flow time, which should be increasing moving downstream. This would allow the sensor more time to respond to the shock, allowing it to reach a higher amplitude. The issue is worth further investigation.

![Graph showing normalized pressure step (P/P_{Control}) vs. x (m)](image)

**Figure 6.51.** Ratios of the shock pressure step from a PCB-102 sensor at multiple axial stations divided by measurements from a Kulite at 96 inches. $P_{Driver} = 0.5$ psia, $P_{Driven} = 1$ torr, $P_{Ratio} = 26$, 0.31-mil polyethylene with electrical burst system.

Figures 6.52 and 6.53 show shock pressure step ratios for measurements performed near the minimum useful condition in the 3-Inch Shock Tube. The average shock pressure step in these measurements is about 4 mpsi. In both cases, a PCB-106 sensor at 132 inches was used as the control sensor.

Figure 6.52 shows a pronounced increase in the shock pressure step compared to those measured by the control sensor, which remained fairly constant. This indicates that the shock is still forming as it travels down the tube. This is partially consistent with the Mach number results, except that the Mach number only increases until
about 2.5-3 m, and then shock attenuation is observed (see Figure 6.31). The lack of any attenuation in the pressure data is apparently a consistent problem at low densities.

![Figure 6.52](image.png)

Figure 6.52. Ratios of the shock pressure step from a PCB-102 sensor at multiple axial stations divided by measurements from a PCB-106 at 132 inches. $P_{Driver} = 0.5$ psia, $P_{Driven} = 5 \times 10^{-2}$ torr, $P_{Ratio} = 520$, 0.31-mil polyethylene with electrical burst system.

Figure 6.53 shows measurements from a Kulite sensor at multiple axial locations at the same run conditions as Figure 6.52. Again, the pressure steps increase as the sensor is moved downstream, but not by nearly as much as was observed with the PCB-102 sensor. The Kulite sensor has a much smaller diameter than the PCB-102 sensor, which may be affecting the measured amplitudes. It also has a lower frequency response, so that it may not be as responsive to the increase in useful flow time as the shock travels down the tube. The reason remains unclear.

One way of checking for sensor bias is to swap the positions of two sensors. Unfortunately, there was only one case where two sensors exactly swapped positions.
Figure 6.53. Ratios of the shock pressure step from a Kulite sensor at multiple axial stations divided by measurements from a PCB-106 at 132 inches. $P_{\text{Driver}} = 0.5 \text{ psia}$, $P_{\text{Driven}} = 5 \times 10^{-2} \text{ torr}$, $P_{\text{Ratio}} = 520$, 0.31-mil polyethylene with electrical burst system.

In this case, the conditions were not repeated closely. However, it is worth looking at the comparison to see if whatever sensor bias exists is able to alter the observed trends in the data.

The two PCB-102 sensors had the same quoted calibration. It was observed that the upstream sensor typically measured a higher shock amplitude, and so the two sensors were swapped to see if the calibration of one of the sensors was inaccurate. Unfortunately, some of the data was lost, and the repeated condition after the sensors were swapped was not available for comparison. This means that a quantitative estimate of any bias between the sensors cannot be attempted, but a qualitative assessment is possible.

The first arrangement is shown in Figure 6.54. The more upstream sensor measures a larger pressure step than the more downstream sensor, indicating shock at-
tennuation, as would be expected. The difference is slightly beyond the uncertainty in the measurement.

![Graph showing shock pressure step measurements from two PCB-102 sensors at different axial stations.](figure6.54)

Figure 6.54. Measurements from two PCB-102 sensors at different axial stations. $x = 96$ inches, 1.5-mil polyethylene diaphragms with electrical burst system, $P_{\text{Driver}} = 6.3$ psia, $P_{\text{Driven}} = 10$ torr, $P_{\text{Ratio}} = 32$.

Figure 6.55 shows the second arrangement. The measurement is taken with a lower driven pressure, decreasing the shock pressure step. The upstream sensor again measures a larger step than the downstream sensor, showing that any sensor bias is not able to overcome the differences that exist in the flow.

It is also possible to make comparisons of the pressure step amplitude measured by multiple sensors at different axial positions in the shock tube during a single run. In this case, the uncertain comparison between two different sensors becomes much more important.
An example of a multi-sensor measurement is shown in Figure 6.56. This is a shock with a relatively large pressure step, of approximately 0.55 psi. For this case, the measurements generally agree within the uncertainty. The exception is Kulite 355 at 3 m, which reads lower than Kulite 343 at 2.5 m. The reason for the discrepancy is unclear.

Another multi-sensor measurement for a shock with a smaller pressure step is shown in Figure 6.57. In this case, the sensors again agree within the uncertainty, but the uncertainty is greater as a percentage of the measurement, especially for the PCB-102 sensors. Additionally, there is no clear trend with axial position. While it is clear that the amplitude of the shock is between about 8 and 11 mpsi, the specific value is ambiguous within that range.

Multi-sensor measurements for one of the smallest pressure steps which can be produced in the 3-Inch Shock Tube are shown in Figure 6.58. In this case, a downward
Figure 6.56. Shock pressure step measurements from multiple sensors during a single run. $P_{Driver} = 6.2$ psia, $P_{Driven} = 10$ torr, $P_{Ratio} = 32$, 1.5-mil mylar with electrical burst system.

Figure 6.57. Shock pressure step measurements from multiple sensors during a single run. $P_{Driver} = 0.5$ psia, $P_{Driven} = 1$ torr, $P_{Ratio} = 26$, 0.31-mil polyethylene with electrical burst system.

trend in the amplitude appears to be evident. This partially contradicts the expected trend from the single-sensor analysis, as well as the Mach number analysis. However,
the decrease is well within the uncertainty of the PCB-102 sensors. It appears to be beyond the uncertainty of the Kulite sensors, but it is not clear that the 2% uncertainty estimate for the Kulites is valid for these low amplitudes. The shock amplitude seems to be approximately 3-5 mpsi, but the actual value is uncertain within this range.

![Graph](image)

Figure 6.58. Shock pressure step measurements from multiple sensors during a single run. \( P_{\text{Driver}} = 0.5 \) psia, \( P_{\text{Driven}} = 5 \times 10^{-2} \) torr, \( P_{\text{Ratio}} = 520 \), 0.31-mil polyethylene with electrical burst system.

Because the multi-sensor analysis does not reveal clear trends, it was not pursued in much detail. However, it illustrates the difficulty in accurately measuring such small shock pressure steps. Using off-the-shelf sensors with standard techniques does not seem to be sufficient to achieve highly-accurate measurements at low amplitudes. Independent dynamic calibrations will be required to verify that each sensor returns the same result for a given amplitude, so that problems like calibration drift are controlled. The actual uncertainties of these sensors must be characterized for the
unusually low pressure steps being measured in this work. Alternate sensing methods may also be required.

6.8 Comparisons to Theory

An important evaluation of flow quality is its comparison to theoretical expectations. Since theory is developed with assumptions of a relatively simple flow, adherence to theory indicates that the experimental flow is simple and has the expected characteristics. The shocks in the 3-Inch Shock Tube were expected to have limited adherence to theory. The low driven pressures lead to several non-ideal effects due to the increased influence of the following boundary layer. The low burst pressures decrease the driving force of the burst, which would likely increase opening times and shock-formation distances. Low densities increase the mean-free-path, which would also increase shock formation distances.

There are several ways to compare the measurements to theory. The Mach numbers and amplitudes are the primary quantities to be compared. The Mach numbers can be computed according to the ideal theory and with attenuation due to boundary-layer effects. Computing the ideal Mach number provides an expected upper limit on the measured Mach number. Other than measurement inaccuracies, there should be no way for the shock to exceed the ideal Mach number.

The shock attenuation can be estimated with several theories. Here, the method given by Roshko was used [39]. His theory predicts that the shock wave will eventually match the speed of the contact surface. This provides an expected lower estimate for the shock Mach number. It was not expected that the shocks would match these predictions, since the attenuation is expected to take place over a long distance. The curve showing the attenuated shock Mach number used a value with 90% of the maximum attenuation according to Roshko’s theory. This provides a conservative lower estimate for the expected range of Mach numbers.
Roshko’s theory was developed with strong shocks in mind, which have contact surface speeds faster than the speed of sound at the initial driven conditions. However, weak shocks have contact surfaces which move slower than the speed of sound. Since it makes no sense for the shock to attenuate to a subsonic speed, whenever the theory predicted a subsonic value, the result was changed to $M = 1$. The average Mach number measurement was used for these comparisons.

Figure 6.59 shows the comparison of the calculated Mach number envelope and the measured Mach numbers for runs performed with the electrical burst system. Runs were excluded from the plot if there was a noted problem with the burst, if there was a multi-shock pattern present, if no shock was observed, or if reliable measurements of the run conditions were unavailable. The pressure ratio used for the horizontal axis was the ratio of driver to driven pressures ($P_4/P_1$). Ideally, the Mach number is dependent only on the pressure ratio. However, in reality the Mach number also depends on the actual driven pressure value, because the density affects the attenuation due to boundary-layer growth. The data are separated by the diaphragm type used, which also separates them based on the actual driven pressure. This is because each diaphragm type used a fixed burst pressure difference, so the diaphragm type and burst pressure ratio determine the driven pressure. The uncertainties shown include both the measurement uncertainty and the uncertainty in the run conditions.

The measured values mostly cluster closely to the ideal values. The polyethylene diaphragms often produce Mach numbers that show about 25% of the calculated attenuation, though they often match the ideal value within the expected uncertainty. The other diaphragms produce Mach numbers that match the ideal value within the uncertainty. The greater attenuation with the polyethylene diaphragms may be due to the lower driven pressures used with those diaphragms. A small number of runs have measured Mach numbers slightly greater than those predicted by the ideal theory, but these differences are within the uncertainty.

There were not enough reliable runs without the burst system to warrant performing a similar comparison plot. This was partially because there were fewer runs
performed without the burst system, due to the improved results found when the system was used. However, it was also because there were fewer runs without the burst system where the run conditions were reliably known. This problem was caused because the driven pressure would often rise suddenly immediately before the run. This was observed either by seeing a rapid change on the vacuum gauge just before the run, or through disturbances recorded by the sensors in the shock tube, along with a shock pressure rise much larger than expected, as well as a lower Mach number. The apparent reason is that the diaphragm often cracks before ripping completely. The reason for this problem is unknown.

Figure 6.59. Comparison of theoretical Mach number envelope and experimentally measured Mach numbers with the electrical burst system.
It is also useful to compare the pressure step measurements to theoretical predictions. The pressure step tends to vary with axial location, so averages of the measurements were used for these comparisons.

Comparing theoretical pressure steps to the measured values is slightly more complicated than comparing the Mach numbers. While the Mach number only depends on the pressure ratio in ideal theory, the pressure step depends on both the shock Mach number and the driven pressure. Since it is expected that the Mach number will vary from ideal predictions, the ideal predictions for pressure steps are expected to be even less accurate. It can be difficult to separate differences in the Mach number from differences in the pressure measurement.

Because of this issue, it is also useful to calculate the static pressure rise using ideal theory, but with the measured Mach number as an input in order to eliminate the effect of Mach number differences. In these cases, only one pressure input is needed to get the step, since the pressure ratios are determined by the Mach number. The driven pressure was used to calculate the pressure step, as this method gives more accurate results in the literature [47]. The measured pressure was found as an average of the measurements of the PCB-102, Kulite, and PCB-106 sensors used during the run. Since the axial and azimuthal uniformity tests indicated few differences between the sensors beyond the uncertainty and no particular sensor could be chosen as more reliable than the others, an average seemed to be the best way to get a consistent measurement.

Given the multiple independent variables involved in the comparison, it was easiest to directly compare amplitudes from the computations and measurements. Figure 6.60 shows the comparisons for runs performed with 0.31-mil polyethylene diaphragms and the electrical burst system. Each run is plotted as a single point. The measured pressure step for the run determines its horizontal position, and the computed pressure step determines its vertical position. Perfect agreement between the two would result in a point somewhere on the line $y = x$, shown by the black line in the plot.
The agreement is better when the measured Mach number is used, as expected. Ideal theory generally predicts a larger pressure step than the measured Mach number indicates, probably due to the effect of attenuation resulting in lower Mach numbers. However, both methods tend to predict slightly larger pressure steps than are measured. It may be that the driven pressure is systematically underestimated, or that the measured pressure steps are erroneously high.

The agreement decreases below about 0.01 psi. This is largely attributable to the increased uncertainty, as evidenced by the fact that the uncertainty bars still reach close to 1:1 agreement. In some cases, the discrepancy is slightly beyond the uncertainty, but this may indicate that the uncertainty was underestimated.

Figure 6.60. Comparison of theoretical pressure step predictions with average measured steps for runs performed with 0.31-mil polyethylene diaphragms and the electrical burst system.
Figure 6.61 shows the same kind of plot, but for runs performed with 1.5-mil mylar diaphragms. These used a 6 psi burst pressure difference, resulting in larger shock amplitudes for the same driven pressure. The results are very similar for this diaphragm type. The computed shock pressure steps are generally higher than the measurements, and the ideal values are higher than those calculated using the measured Mach number. The results generally agree within the expected uncertainty.

![Comparison of theoretical pressure step predictions with average measured steps for runs performed with 1.5-mil mylar diaphragms and the electrical burst system.](image)

Figure 6.62 shows the same kind of plot for runs performed with 2-mil mylar diaphragms. Fewer runs were performed with this diaphragm type. The results are again similar, except that the measured pressure is often slightly higher than that computed using the measured Mach number. The reason for this change is
unclear. The vacuum gauge may read too low at higher pressures, and too high at low pressures. Again, there were insufficient numbers of reliable runs without the burst system to warrant making similar plots.

![Figure 6.62. Comparison of theoretical pressure step predictions with average measured steps for runs performed with 2-mil mylar diaphragms and the electrical burst system.](image)

Comparisons to theory indicate that the flow quality in the 3-Inch Shock Tube is fairly good. It is particularly important that the agreement at the low end of the range is good. This indicates that the measurements are useful for sensor calibrations.

### 6.9 Summary

The flow quality in the shock tube is generally good. The shock tube has been shown to generate shocks with amplitudes ranging from about 0.001-1 psi. Through-
out much of this range, the results agree reasonably well with theoretical predictions for Mach number and pressure rise. The pressure traces also appear nearly ideal over much of the range, showing a clearly-defined shock with quiescent flow following the shock for 0.2-1 ms. For shocks with amplitudes below about 0.05 psi, the data quality degrades. The signal-to-noise ratio decreases substantially, largely due to the small signals measured. Non-ideal features begin to appear in the pressure traces, such as pressure ramps closely following the shock wave.

Azimuthal and axial pressure measurements, as well as comparisons to theoretical predictions for the pressure rise, indicate that the shocks can be accurately measured even at the bottom of the shock tube range. There is agreement within the uncertainty for pressure measurements between different sensors during the same run. There is no evidence of azimuthal variation in either single-sensor or multi-sensor analyses. There is some evidence of axial variation in the shock pressure steps, though the actual level of variation is unclear due to the sensor uncertainties. The measurements are also repeatable within the control of the run conditions, which is currently limited by manual control and recording procedures.
7. LINEAR CALIBRATIONS OF PCB-132 SENSORS

It has been shown that the shock tube is capable of producing shocks with amplitudes down to 0.001 mpsi. The purpose for developing a method to create such shocks was to be able to calibrate sensors used in hypersonic instability measurements. The primary sensor of concern at the time of this research was the PCB-132 sensor.

These sensors are not calibrated thoroughly by the manufacturer, and there were concerns that the sensors might not be linear in the low amplitude range. These concerns were raised because of the poorly-defined behavior of the epoxy layer which covers the sensing element.

The calibrations were found by comparing the voltage amplitudes measured by PCB-132 sensors to the average of the pressure steps measured by the PCB-102, PCB-106, and Kulite sensors. This was done because the multi-sensor analyses shown in Chapter 6 showed that the reference sensors generally agreed within their uncertainty. The best practice would be to use at least one reference sensor at the same axial location as the PCB-132 being calibrated to measure the shock amplitude. However, a limited number of reference sensors were available, since they were still being evaluated. Therefore, averaging presented a way to control for random errors that might be present when using the measurement from a single reference pressure sensor, as well as bias errors introduced by using different reference sensors or sensors mounted at different axial locations in certain cases. Since the different reference sensors generally agreed within their uncertainty, averaging their measurements does not change the value beyond the existing uncertainty. A typical sensor calibration would normally involve about 10 points. The calibrations shown use a much higher number of points in order to give greater confidence in the result, as well as to verify the linearity of the sensor. Data from a given run were only omitted if the sensor failed to detect a shock or there was a known problem with the data or the run. Known
problems included the data being clipped due to improper oscilloscope settings and bad diaphragm bursts.

The resolution of the PCB-132 sensors is quoted by the manufacturer as 0.001 psi. Additionally, for each reference sensor used, the uncertainty was generally quoted as 1% of the measurement plus the resolution of the sensor. Therefore, a simple uncertainty estimate of 0.001 psi plus 1% of the measurement was used.

The data shown here were taken with the electrical burst system, since the flow without the burst system was not as well-characterized. Additionally, the electrical burst system allows the production of smaller shock pressure steps due to the lower burst pressure differentials. It also produces a shock with a given amplitude with lower noise. The lower noise is achieved because of lower vibration levels due to the lower burst pressure, as well as the higher driven pressures used to achieve a shock with a given amplitude. The method by which the shock is produced should not otherwise affect the calibration found, so the omission of data gathered without the electrical burst system does not affect the conclusions made here.

An example calibration is shown in Figure 7.1. Figure 7.1(a) shows the data on linear axes, while Figure 7.1(b) shows the data on logarithmic axes. The linear axes give a better impression of slope differences, while the logarithmic axes show the data more clearly over the entire amplitude range. The points are the measurements and the blue line is a linear fit calculated for the measured points. The fit was constrained to pass through the origin. The orange line is the calibration given by the manufacturer. The red line is the nominal threshold for the second-mode amplitude range.

In both plots, the points adhere closely to the best-fit line, strongly indicating that the sensor has linear behavior. Figure 7.1(b) shows that this behavior continues to the bottom of the range. The vast majority of the points fall on the best-fit line, within the uncertainty of the sensor. A few points fall close to the line, but slightly beyond the uncertainty. The measurements adhere better to the fit found in the shock tube than the manufacturer’s curve, but in this case the difference is not very
Figure 7.1. Calibration for PCB-132 #5411.
large. For this sensor, the manufacturer’s calibration was 100.4 mV/psi, while the calibration found in the shock tube was 91.0 mV/psi. This is a difference of 10%.

The scatter also appears to remain nearly constant down to the lowest amplitudes when plotted on logarithmic axes. This implies that the uncertainty in the measurements tends to be a percentage of the measurement, rather than a certain absolute value. For shocks with amplitudes greater than 0.1 psi, the average difference between the calibration prediction and the measured value for all calibrated sensors was 0.9%, with a standard deviation of 0.8% and a maximum of 4%. For shocks with amplitudes between 0.01-0.1 psi, the average difference was 1.7%, with a standard deviation of 2.3% and a maximum of 13%. For shocks with amplitudes below 0.01 psi, the average difference was 3.9%, with a standard deviation of 3.7% and a maximum of 18%. This shows that the scatter does increase as the amplitude decreases, but the average is always less than 5%. Since the measurements span three orders of magnitude, a factor of four increase in scatter is fairly low. The largest percentage differences correlate to measurement disparities that are within about 1 mV, which is within the sensor uncertainty.

Figure 7.2 shows the same kind of plots for another PCB-132 sensor. In this case, measurements were available to 0.001 psi. Again, the measurements are within the expected uncertainty of the best-fit line even at the smallest amplitudes.

Four additional examples of PCB-132 calibrations are shown on logarithmic axes in Figures 7.3 and 7.4. The error bars show the estimated uncertainty for the measurement. The sensors again show linearity down to the lowest amplitudes measured. In Figures 7.3 and 7.4 the calibrations extend to about 0.001 psi, two orders of magnitude below the second-mode amplitude threshold, or about $e^{4.5}$. This is a significant portion of the amplification which the largest second-mode waves experience, since typical amplification levels at transition are $e^5$-$e^9$. 
Figure 7.2. Calibration for PCB-132 #6617.
Figure 7.3. Calibrations for multiple PCB-132 sensors performed with the electrical burst system.
(a) Calibration for Sensor #6819 on logarithmic axes.

(b) Calibration for Sensor #6831 on logarithmic axes.

Figure 7.4. Calibrations for multiple PCB-132 sensors performed with the electrical burst system.
Table 7.1. Comparison of calibrations for PCB-132 sensors from PCB and found in the 3-Inch Shock Tube.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Manufacturer (V/psi)</th>
<th>Shock Tube (V/psi)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6830</td>
<td>0.174</td>
<td>0.169</td>
<td>3.0</td>
</tr>
<tr>
<td>6831</td>
<td>0.174</td>
<td>0.177</td>
<td>-1.7</td>
</tr>
<tr>
<td>6819</td>
<td>0.161</td>
<td>0.153</td>
<td>5.2</td>
</tr>
<tr>
<td>6657</td>
<td>0.137</td>
<td>0.154</td>
<td>-11</td>
</tr>
<tr>
<td>6773</td>
<td>0.112</td>
<td>0.137</td>
<td>-18</td>
</tr>
<tr>
<td>5411</td>
<td>0.100</td>
<td>0.091</td>
<td>11</td>
</tr>
<tr>
<td>6707</td>
<td>0.141</td>
<td>0.152</td>
<td>-7.2</td>
</tr>
<tr>
<td>5396</td>
<td>0.112</td>
<td>0.076</td>
<td>47</td>
</tr>
<tr>
<td>6772</td>
<td>0.170</td>
<td>0.178</td>
<td>-4.7</td>
</tr>
<tr>
<td>6617</td>
<td>0.143</td>
<td>0.173</td>
<td>-17</td>
</tr>
</tbody>
</table>

The differences between the calibrations found in the shock tube and the manufacturer’s calibrations are listed in Table 7.1. Table 7.1 shows the calibration sensitivities from both the manufacturer’s calibration sheet and those found in the 3-Inch Shock Tube in V/psi. The percentage differences are calculated by subtracting the shock-tube number from the manufacturer’s, and dividing by the shock-tube number. Positive differences indicate that the shock-tube sensitivity is lower than the manufacturer’s.

The smallest difference was 1.7%, and the largest was 47%. The average difference was 15%. The calibrations found in the shock tube show no trend towards being either smaller or larger than the manufacturer’s calibrations. This is also true when the calibrations show large differences. It appears that the differences are due to random error, rather than systematic bias.

It is promising that the sensors have a linear response at low amplitudes. This suggests that shock tubes that are not capable of creating such low amplitudes could be used to find accurate calibrations for PCB-132 sensors. The high-amplitude cali-
ibration can be extrapolated to low amplitudes with fairly high confidence. This was confirmed by finding the best-fit line with the low-amplitude points omitted. Doing so had no effect on the equation for the line within three significant digits.

The lack of effect may have been partially due to the fact that the higher amplitudes tend to dominate with a linear best-fit technique. For these calibrations, the low-amplitude data is as important as the high-amplitude data, but the large difference in magnitude under-emphasizes the smaller amplitudes because the fit method minimizes the absolute value of the residuals, which emphasizes large values. To try to correct for this, linear fits were performed on the logarithms of the calibration data. Taking the logarithm of the data reduces the amplitude difference between the high and low ends of the data, creating a more even emphasis across the data range. Since the linear calibrations of PCB-132 sensors are constrained to pass through the origin, they take the form \( P = mV \), and become \( \log P = \log V + \log m \), with \( P \) being pressure and \( V \) being voltage. It is easy to perform a linear best-fit in this second form, since it is essentially identical to the normal \( y = mx + b \) fit equation. The only difference is that the slope must be constrained to be unity, since otherwise the fit will likely become a power-law fit with an exponent close to one. This constraint could be easily added by using a golden-section search to compute the best value of \( \log m \) while holding \( \log P \) and \( \log V \) constant. A typical example is shown in Figure 7.5. There is no perceptible difference between the two fits. The data is shown on linear axes so that any difference between the slopes would be obvious.

Some analysis of the scatter in the calibrations was performed. Examination of the residuals between the measured points and the best-fit line allows estimates of the uncertainties in the best-fit line due to the random error using a standard sum-of-squares method. The uncertainties in the determination of the slope of the fit line due to random error are within about 5%.

The best-fit lines were constrained to pass through the origin. If the fits were left unconstrained, they tended to have intercepts on the order of 0.0001 mV. The uncertainty in the intercept due to random error was found to be on the order of
Figure 7.5. Linear best-fit lines computed with original data and logarithms of calibration data for PCB-132 Sensor #6657.

0.001 mV, so the assumption of a 0 V offset is valid. This was also made clear because the unconstrained fits tended not to fit the low-amplitude points as well as the constrained fits. The non-zero offsets were apparently generated by uncertainty in the large-amplitude inputs.
8. PITOT AND FREQUENCY RESPONSE MEASUREMENTS

Shock tube measurements are often used to measure the frequency response of sensors. The frequency response of the PCB-132 sensors is of particular interest, since it is important to the measurement of hypersonic instabilities due to their high frequencies. Additionally, measurements of the step response of a sensor with different input amplitudes can be used to determine if the sensor is a linear system.

Step inputs can be used to identify the entire frequency response of a system because they have content at all frequencies. A true step input is impossible to create, but a shock wave can approximate a step input. The shock approximates a step input if its passage is faster than the sensor’s response. The frequency content of the shock depends on the sensor orientation and shock Mach number and thickness, since these factors affect the shock passage time.

Passing over the sensing area in static configuration increases the duration of the shock input, which reduces its frequency content. If the sensor is mounted in pitot configuration, the frequency content is increased because the shock activates the entire sensing area at once. The only relevant length for the input in pitot configuration is the shock thickness, which is generally very small. The shock thickness is dependent upon the shock Mach number and the mean free path ahead of the shock. Shocks with lower Mach numbers are thicker. Since low-amplitude shocks either have low Mach numbers or occur at low densities, they are thicker. Thicker shocks may not be useful as step inputs, due to their increased passage time.

Pitot-response measurements were performed both with the pitot end plate and with single pitot probes designed to be installed in the ports in the shock tube wall. A single pitot probe is shown in Figure 8.1. The probe is a tube with a chamfered front.
The tube is 5.75 inches long to ensure that the PCB-132 response is finished before the shock reaches the brass arm. This ensures any vibrations from the interaction of the shock and the arm do not disturb the sensor response. The brass arm holds the probe in the center of the shock tube. The arm is angled to make it possible to install the probe through the 0.5-inch mounting holes. The brass arm is attached to a steel mount. An o-ring provides the seal around the mounting hole. A small pass-through hole for the sensor wires was drilled through the mount behind the brass arm. The steel mount allows a Conax fitting to be installed on the outer face to provide a seal around the sensor wires.

Figure 8.1. A single pitot probe with two PCB-132 sensors installed. The Conax fitting that provides the seal is not installed.

The probe shown in Figure 8.1 was designed so that two PCB-132 sensors could be installed at the same time. One sensor was installed flush with the front of the probe to measure the shock passage. A hole in the side of the probe tube allowed the wires from this sensor to exit the tube. The tape shown in Figure 8.1 was used to secure
the wire from the front sensor and block flow from entering the hole. Behind the hole, another PCB-132 sensor was installed as a blind sensor. The blind sensor was used to check if acceleration contamination was a significant factor for pitot-configuration measurements. It was anticipated that the long probe might develop an oscillation, introducing potentially significant acceleration contamination.

8.1 Pitot Measurements with Blind Sensor

The blind measurements were performed with two sensors mounted in the single probe. The two sensors used in the single probe were chosen so that they had manufacturer calibrations that matched closely. It was thought that the acceleration sensitivity of two sensors with very similar calibrations might also be similar. This would reduce the risk that the acceleration observed by the blind sensor would appear small simply because the sensor had a low sensitivity. The two sensors used were #6615 with a stated calibration of 151.0 mV/psi and #6618 with a stated calibration of 151.6 mV/psi.

Figure 8.2 shows a typical comparison between the flow sensor and the blind sensor in the single pitot mount. The time in the plot is measured relative to the shock arrival at the sensor used to trigger the scopes. The zero point is not meaningful for these measurements. The listed axial locations of the sensors are different to reflect the fact that the blind pitot is mounted several inches behind the flow sensor. This offset affects the time when flow features reach the position of each sensor, and may also affect the degree of acceleration experienced by each sensor.

The shock arrives at the pitot sensor just before 0.7 ms. The response is largely similar to the response to a large shock in static configuration. There is a large peak followed by a roll-off. The blind sensor never detects the shock, as expected. The signal on the blind pitot is very low compared to the signal on the flow sensor. This is especially true during the approximately 0.1 ms period in which the shock response occurs. By about 0.8 ms, the pitot sensor has reached an approximate steady-state
Figure 8.2. Measurements from a single pitot probe with two PCB-132 sensors installed. $P_{Driver} = 20.6$ psia, $P_{Driven} = 1.05$ torr, 1.5-mil mylar diaphragm with natural burst.

condition. It has not returned to 0 V, which was also sometimes observed for PCB-132 sensors in static configuration. From 0.7 ms until about 0.85 ms, the blind sensor shows very small oscillations which are not much larger than the electronic noise observed before the shock arrival. Some larger low-frequency oscillations appear on the blind sensor at about 0.85 ms, by which point the shock response on the flow sensor is over. At about 0.85 ms, the flow sensor also begins to show low-frequency oscillations. These might be due to an oscillation in the probe tube. However, it appears that the signal due to acceleration is small compared to the signal from the shock, and negligible during the actual shock response. This should allow shock
responses measured with this kind of probe to be used to measure the sensor frequency response.

Similar measurements would be desired in the pitot end plate, but were not performed. This was because the design of the probes for the pitot end plate could not be easily modified to accommodate two sensors mounted in the same probe. However, the designs of the mounts are similar enough that the single probe is a reasonable proxy for the pitot end plate, and the results can be assumed to be the same in both cases. Additionally, as will be shown, the results in the pitot end plate show no cause for concern about contamination of the measurements due to accelerations.

8.2 Step Response Repeatability & Sampling Rate Evaluation

The repeatability of the shock responses is of interest for checking the quality of the frequency response measurements. If the shock is acting as a step input, the response of the sensor should be nearly identical for multiple runs. It was also of interest to check the sampling rate required to measure the high-frequency response of PCB-132 sensors. Several runs were performed with different sampling rates at the same conditions.

There are two reasons to check different sampling rates with the oscilloscopes used in this research. The first is the need for sufficient resolution without generating a record too large to process efficiently. The second is due to the use of the Hi-Res recording mode. In Hi-Res mode, the oscilloscope samples at its maximum rate, averaging on the fly to re-sample down to the lower requested sampling rate. This improves the vertical resolution of the data. However, the degree of improvement depends on the amount of averaging performed. Lower sampling rates get more benefit from Hi-Res mode than higher sampling rates. Because of this, it may be desirable to use a lower rate.

Four sampling rates were checked: 500 MHz, 200 MHz, 100 MHz, and 50 MHz. These rates were chosen to ensure that the sensor rise was resolved well. It was desired
to identify the frequency response up to at least 1 MHz, so sampling rates of at least 10 MHz would be required to ensure good data quality. Since higher sampling rates were available, they were used.

Examples of step-response repeatability are shown in Figure 8.3. All runs were performed using 2-mil mylar diaphragms with the electrical burst system. They were performed on the same day using atmospheric pressure in the driver tube, ensuring that the driver pressure was essentially the same in each case. The driver pressure was 14.4 psi. The driven pressures were all close to 30 torr. They varied from 29.3-30.6 torr, a difference of less than 5%.

Raw voltages are shown. The times of the traces have been set so that \( t = 0 \) at the shock arrival. The shock arrival was defined to be at 50% of the rise, as usual.

Figure 8.3(a) and Figure 8.3(b) show data from the same set of four runs for two different sensors. A smaller portion of the response is shown in order to show more detail. Both sensors show very high repeatability. There are small differences in the responses up to about 5 \( \mu s \). These are likely caused by small variations in the shock amplitude. The initial peaks all appear to occur at nearly the same time. This indicates that the rise time is nearly constant. In each case, the rise time is about 0.3 \( \mu s \).

The general shock response shapes are similar between the two sensors. They exhibit a sharp peak followed by a gradual roll-off, as was also shown in Figure 8.2 and in the static-configuration measurements. However, more details are visible with the smaller time scale. The primary detail which was not observed in the static-configuration measurements is the complex oscillations after the initial peak. The oscillations are very repeatable for a particular sensor, but are significantly different between sensors. This indicates that the oscillations are a complicated resonance due to the sensor’s frequency response, and not a flow feature.

The resonance is relatively low-amplitude compared to that usually observed with diaphragm-based sensors such as the Kulites. It also damps fairly quickly, almost disappearing within 20 \( \mu s \) of the shock arrival. It does not exhibit the standard
Figure 8.3. Step response repeatability for two PCB-132 sensors mounted in pitot end plate.
second-order underdamped behavior. Instead of being a sinusoidal resonance at a nearly constant frequency, both sensors show a much more complicated shape. The amplitudes of adjacent peaks vary in a consistent, but complicated pattern which is difficult to understand. The peaks also vary in width, and higher-frequency oscillations are sometimes superposed within the larger low-frequency peaks.

The response is very repeatable between runs. There is essentially no difference between the different traces except near the top of the peak, where the maximum voltage varies by less than 5%. If the sensor responses are normalized by the maximum peak voltage, they collapse into a single curve, as shown in Figure 8.4. This shows that the responses are unaffected by the sampling rate or by the details of the run.

![Figure 8.4. Normalized step response repeatability for PCB-132 #6707.](image)

The large differences in the response shape between different sensors show that there are significant differences in frequency response between sensors. These differences are likely due to variations in the construction of the sensor. It is already
known that the epoxy layer thickness and sensing element placement can vary between sensors, which might affect the frequency response.

At the scale used in Figure 8.3, differences due to sampling rate are not evident. High sampling rates were used in order to get high-resolution measurements of the rise. This was desired because the high-frequency response up to 1 MHz is of the most interest, and this part of the frequency response is mostly expressed in the first microsecond of the response.

The same data are shown in Figure 8.5, but with an even smaller increment of time shown to detail the rise. Each sampling rate resolves all of the features of the response. Sampling rates below 50 MHz could be used in the future. There appears to be little reason to use sampling rates above 100 MHz, since no improvement in resolution is observed. The high resolution of the measurements at 50 MHz, as well as the fact that the responses normalize to a single line, shows that the difference is not due to resolution changes.

Another aspect of the complicated behavior of the PCB-132 sensors becomes clearly visible on the time scales used in Figures 8.5 and 8.6. Sensor #5411 shows a very clear pause in the rise at about 0.3 V in Figure 8.5(a). The voltage even decreases slightly before the rise is resumed. A second, smaller pause might be visible just before the peak, occurring at about 0.6 V. However, this pause may be due to the fact that the top of the response peak is being reached.

A single, smaller pause is also visible in Figure 8.5(b), occurring at about 0.8 V. Rather than appearing as another peak, it appears as an inflection point in the middle of the rise. Figure 8.6(a) shows an obvious pause at about 0.5 V, though without a reversal. Figure 8.6(b) shows the most subtle pause. It appears as just an inflection point at about 0.8 V.

These plots show pauses of various amplitudes for every PCB-132 sensor when high-resolution step-response measurements were performed. At lower resolutions, the pause is not always clear. Such a feature is rather unusual, and suggests a very high-frequency resonance faster than the rise of the sensor.
Figure 8.5. Detail of the rise for two PCB-132 sensors mounted in pitot end plate.
Figure 8.6. Detail of the rise for two PCB-132 sensors mounted in pitot end plate.
8.3 Normalized Step Responses

One of the main goals for performing pitot measurements with PCB-132 sensors was to determine if the sensors were a linear system. A linear system has the same frequency response regardless of the input amplitude. If the PCB-132 sensors are linear, it should be possible to collapse step responses at multiple shock amplitudes into a single curve by normalizing them. The responses were normalized by the maximum peak voltage.

Figure 8.7 shows measured step responses at different amplitudes for Sensor #6657. The input amplitudes span approximately an order of magnitude, from 0.1 psi to 1 psi. The responses are shown in raw voltage in Figure 8.7(a). The responses hold the same general shape, though the oscillations become less clear at the lower amplitudes.

Figure 8.7(b) shows the same responses normalized by the peak voltage. The colors match the same runs, but the plotting order is different for clarity, since some traces would occlude others if the original order was used. The three highest-amplitude responses (Runs 234, 232, and 236) normalize quite well over most of the response. Run 232 settles at a slightly higher level than the other two after about 8 µs for an unknown reason. The noise for Run 232 is higher because of an improperly selected vertical resolution in the oscilloscope.

Runs 231 and 229 match the higher-amplitude responses reasonably well up until about 2 µs, at which point they stay slightly higher than the rest of the responses. They return to the same level as the other responses by about 6 µs. There is another significant difference between the high-amplitude responses and the low-amplitude responses at about 1 µs. The high-amplitude responses show a small peak after the maximum response at about 1 µs. The peak is missing from the lower-amplitude responses. It is clear that the roll-off immediately following the maximum in Run 229 is slower than in the higher-amplitude responses. There is a slight inflection point which is reminiscent of the peak, but the response does not match.
Figure 8.7. Step responses at different shock amplitudes for Sensor #6657.
Figure 8.8 shows details of the rise for the normalized responses of Sensors #6657 and #6772. Sensor #6657 shows some significant differences between some of the responses. Runs 234 and 232 normalize well. Run 236 normalizes fairly well, but is offset by about 0.05 μs, due to its higher noise level distorting the measured shock arrival time. However, Runs 231 and 229 show differing responses. Run 232 is about 2% higher than the other responses after about 0.25 μs. Run 229 fails to show the small peak at 0.4 μs, and stays 5% higher than the other responses.

The low-amplitude responses have shocks with lower Mach numbers. This means the shock moves more slowly and is thicker. It is likely that the low-amplitude responses do not normalize properly because the shock at those conditions does not approximate a step input closely enough. The shock passage time can be calculated by calculating the shock thickness according to Taylor’s weak-shock theory, and dividing this thickness by the shock speed. When this is done, the higher-Mach shocks have passage times of 0.02-0.05 μs, about an order of magnitude lower than the rise time of the PCB-132 sensors. However, the lower-Mach shocks which produce the non-normalizing behavior have calculated passage times of 0.13 μs. This is about a third of the observed rise time. Since it is still shorter than the rise time, it may be sufficient to produce a step input, which would indicate that the non-normalizing behavior is due to some nonlinearity in the sensor. It is not clear how accurate the shock thickness calculations are, and it is possible that the actual shock passage time is larger than calculated. Additionally, if the passage time is close to the rise time, it is possible that the sensor response is affected. The actual reason is unclear, and requires further investigation.

Data from the same runs are shown for Sensor #6772 in Figure 8.9. The results are very similar. The details of the step responses look very different than those for Sensor #6657, as expected from the results shown earlier. Sensor #6772 comes closer than the other sensors to having a single dominant resonant frequency. However, it is clear that the response is still more complicated than a second-order underdamped
Figure 8.8. Detail of the rise of normalized step responses for two PCB-132 sensors.
response, especially from the shape of the response between 2 and 4 $\mu$s, where oscillations at multiple frequencies are clearly visible.

Again, the three highest-amplitude inputs normalize well in Figure 8.9(b). For Sensor #6772, the normalized trace for Run 236 settles at the same level as the other two traces. This seems to indicate that the non-zero settling level for Sensor #6657 was not due to the flow, but was likely due to the tendency for PCB-132 sensors to fail to return to zero after the shock.

The differences in the lowest-amplitude traces are similar to what was observed for Sensor #6657. The normalized responses match well up until about 2 $\mu$s. From 2 to 6 $\mu$s, the normalized responses for Runs 231 and 229 are higher than those for the higher-amplitude shocks. The shape of the curve is still generally similar for Runs 231 and 229. They still show peaks and valleys of approximately the same shape occurring at about the same time as seen in the higher-amplitude traces. Run 229 is consistently higher than Run 231. Since Run 231 had a higher-amplitude shock than Run 229 and more closely matched the step response, the difference further indicates that the low-amplitude shocks were not good approximations of a step input.

These results indicate that the PCB-132 sensors are approximately linear. In the context of the current capabilities of the 3-Inch Shock Tube, relatively high-amplitude and high-Mach-number shocks must be used to produce a step input for the sensors. This was expected, due to the fast response of the sensors. Such shocks should be within the capabilities of most shock tubes.
Figure 8.9. Step responses at different shock amplitudes for Sensor #6772.
8.4 Calibration Curves in Pitot Configuration

A Kulite sensor was mounted in pitot configuration to measure the stagnation pressure step across the shock. The response of the Kulite sensor was measured using the same process used for static-configuration measurements. No change in the process was required because the shocks are also step inputs for the Kulites in static configuration. With these measurements, it was possible to check the calibration of the PCB-132 sensors in pitot configuration, and see if the sensitivity was similar to what was measured in static configuration.

The amplitude of the sensor response was measured as the height of the peak using the maximum voltage in the peak. This method includes the overshoot due to the resonance, and may over-estimate the sensitivity of the sensors. Normally, the response of a resonating sensor is averaged to eliminate the effect of the overshoot. This is not possible for PCB-132 sensors because of the high-pass filter. Measuring the sensitivity of the PCB-132 sensor when using step inputs would require knowledge of the frequency response of the sensor. Since the frequency response was not characterized, a simple peak measurement was used. If the resonance of the sensor caused an overshoot, the effect might be accounted for by looking at the amplitude of the resonance. For typical second-order systems, the overshoot is about half the peak-to-peak amplitude of the resonance at the beginning of the response. If the resonance has an amplitude of 20% of the final value, the measurement method used here would overestimate the sensitivity by 10%.

Figure 8.10 shows calibration curves for two PCB-132 sensors. The results are representative of the rest of the sensors tested. For both sensors, the calibrations appear linear in Figure 8.10. The fit quality is similar to what was found in static configuration.

The sensitivities of the sensors are drastically different in pitot configuration. Since the plots show voltage on the horizontal axis, higher sensitivities are shown by lower slopes. In pitot configuration, the sensors have much higher sensitivities. Each of the
four sensors for which pitot calibrations were done shows a sensitivity 260-270% of that found in static configuration.

The reason for the difference is unclear. It is far too large to be accounted for solely by the resonance of the sensors, since the resonance amplitudes are only about 20% of the response maximum. For a second-order system, this level of overshoot should produce a sensitivity 110% of that measured in static measurements. There may be an acceleration effect, but no such effect was evident with the blind sensor tests. The difference may have something to do with the way the sensor reacts to having the entire face activated at once, rather than progressively. It may also be some sort of overshoot effect that does not produce a resonance, or that produces a much smaller resonance than would be expected from observing second-order systems. The PCB-132 sensors are clearly not a second-order system, but estimating the actual model for the sensor response is a complicated process. Without further information about the frequency response of the system, the cause of the increased sensitivity is unclear.

Beyond the sensitivity difference, there is evidence that the sensors may be nonlinear when mounted in pitot configuration. Fits were performed on the logarithms of the calibration data, as had also been done for the static-configuration calibrations. This resulted in no difference for the static configuration data, but a difference was found for the pitot configuration data.

An example is shown in Figure 8.11. The data are shown on linear axes to emphasize the difference in slope between the two calibrations. The slope is noticeably lower when the fit is performed on the logarithms of the data. A slight curve in the data may be evident, since most of the measured points fall below the fit line until about 2.75 psi, where the trend reverses. Power-law fits yield a small nonlinearity, with exponents of about 1.08. The reason for the nonlinearity is unclear. The problem may be in the pressure measurements, though the Kulites are typically reliable. The nonlinearity may be related to the increase in sensitivity.
Figure 8.10. Calibration curves for PCB-132 sensors in pitot configuration compared to calibrations in static configuration.
Figure 8.11. Comparison of calibration curves found for the original
data and the logarithms of the data.
9. CONCLUSIONS & FUTURE WORK

9.1 Conclusions

The goals of this research were: to develop a method for the creation of extremely low-pressure shock waves with amplitudes within the range of experimentally-measured second-mode waves; demonstrate the calibration of sensors in that amplitude range; and measure the high-frequency response of sensors used for instability measurements.

Only a few other attempts have been made to create low-amplitude shocks, which have been unsuccessful. The method attempted in this work was to use low burst pressures and low driven pressures in the moderate-vacuum range. This allows high pressure ratios across the diaphragm with low pressure differences, which creates shocks with relatively large Mach numbers and extremely small shock pressure rises. This method does not appear to have been previously proposed. Driven pressures even lower than the ones used in this research and low burst pressures have both been used in the past, but the two techniques had not been combined.

Automated methods for measuring the shock arrival times and amplitudes were developed. These methods were important to making shock-tube calibrations efficient, since the measurements took an inordinate amount of time to analyze manually. The methods use adjustable detection threshold levels, a minimum peak-width criterion, and moving averages for the detection of shocks in pressure traces with low signal-to-noise ratios. The automatic analysis of larger shock waves is simpler, since the larger shock front is usually detectable by a simple threshold test. The automatic detection methods reduce the processing time by approximately an order of magnitude.

Shock waves with static pressure rises as low as 0.001 psi have been demonstrated. These are believed to be the lowest-amplitude shock waves created repeatably in a
shock tube. The flow quality and repeatability have been shown to be good within the existing uncertainties even at the lowest amplitudes. The shock pressure step is independent of azimuthal position within the existing uncertainty. The shock speed exhibits the expected behavior, with levels of attenuation that are consistent with previous theoretical work. At low driven pressures, a significant shock formation distance is shown by shock acceleration, as expected. The axial shock pressure step does not always match the trends exhibited by the shock speed. The reasons are unclear, but the significant uncertainty in the sensors and run conditions makes determining the magnitude and cause of the discrepancies difficult. The measured Mach numbers and shock pressure steps match the theoretical expectations within the expected levels of uncertainty. The Mach numbers are often lower than the ideal theory predicts, but within the expectations for shock attenuation.

One of the main limits of the 3-Inch Shock Tube is the uncertainty in the run conditions. Automatic measurement systems using a Kulite to continuously measure the driver pressure and to record the output of the vacuum sensor were attempted, but were unreliable. The wires connecting to the driver Kulite and vacuum gauge were prone to breaking. The calibration of the vacuum gauge was also unclear. Additionally, the vacuum gauge has an uncertainty of 15% in the range of interest, which is significant.

Additional uncertainty in the run conditions was introduced due to the difficulty of controlling the driver and driven pressures. Both driver and driven tubes were subject to significant leaks with changing rates. Keeping both pressures steady while preparing for a run was impractical. The fact that the conditions were constantly changing made them harder to measure.

Calibrations were performed for ten PCB-132 sensors in the 3-Inch Shock Tube. The calibrations included measurements of shocks with pressure steps from 0.001 psi to 1 psi. The PCB-132 sensors were found to have a linear calibration over all of this range within the uncertainty of the measurements. The scatter in the calibrations increases by about a factor of 4 at the low end of the calibrations compared to the
high end, but this scatter is within the increasing uncertainty of the measurements at low amplitudes. In some cases, the calibration curves found in the 3-Inch Shock Tube differ significantly from those provided by the manufacturer. This suggests that for PCB-132 sensors the manufacturer’s calibrations should not be relied on for accurate amplitude measurements. However, independent calibrations performed with shock amplitudes much larger than second-mode waves could be extrapolated to second-mode amplitudes to give a more accurate measurement.

Step response measurements were examined in order to determine if the 3-Inch Shock Tube is capable of measuring frequency responses up to 1 MHz. The measured step responses show significant and repeatable oscillations near 1 MHz, indicating that the shocks created have frequency content at least that high. The step response of multiple PCB-132 sensors was measured. The response is found to vary significantly between different sensors. It exhibits a complicated, but consistent, step response which shows multiple resonant frequencies. It is not clear what sensor model would be appropriate for this response. The step responses normalize with the peak voltage across an order of magnitude of shock pressure step amplitudes. This indicates that the sensor is a largely linear system. The PCB-132 sensors seem to have a higher sensitivity when mounted in pitot configuration than in static configuration. The calibration curves also exhibit a slight nonlinearity in pitot configuration. The reasons for the increased sensitivity and nonlinearity are unclear.

9.2 Recommendations for Future Work

The primary need for the 3-Inch Shock Tube is to reduce the run condition uncertainty. First, the driver Kulite installation needs to be made more robust and reliable. It would also be helpful to add another port to the driver tube end plate, so that the Paroscientific gauge may be used at the same time as the driver Kulite and the air-supply line. This port was not added during the present research because doing so would have prevented the shock tube from being used while the end plate
was uninstalled, and the down time could not be afforded. Continuous measurement of the driven pressure must also be established. The calibration of the vacuum gauge must be reliably determined. This was difficult because the calibration is logarithmic, and the accuracy changes dramatically as the pressure rises. A vacuum gauge with uncertainty below 15% in the region of interest would also be useful.

Automatic control of the driver and driven pressures would be a very useful improvement. The valves connecting the driver and driven tubes to the vacuum pump can be throttled to control the pump rate. Introducing a system to automatically control the pump rates to maintain a set pressure would make operation of the tube much easier, as well as give much greater control over the run conditions.

The Laser Differential Interferometer available at Purdue was intended to be used as a reference instrument, but was not installed due to time constraints. It is recommended it be used in the future. The LDI integrates across the entire beam path, which means that variations in density within the shock tube cross-section will need to be taken into account. Likely sources of variation are shock curvature at low densities and the boundary layer behind the shock. Measurements could be performed with hot wires to determine the boundary-layer thickness at different conditions to allow that effect to be taken into account.

A wide variety of sensor types was used in the present research in order to evaluate which sensors were the most effective. Of the various kinds used, the Kulite XCQ-062-15A with A-screen, PCB-102B18, and PCB-106B52 were found to be the most effective. Future measurements should be performed using a larger number of these sensors. In the future, at least one reference sensor should be mounted in each axial location to ensure that any axial variation in the shock amplitude can be taken into account. Ideally, multiple sensors would be used to reduce the measurement uncertainty. The specific layout that should be used is still unclear because the relative advantages of each sensor type are not yet very well characterized.

A method of dynamically calibrating each of the reference sensors in the 3-Inch Shock Tube would help assess and potentially reduce the uncertainty of the reference...
sensors beyond the estimates used in this work. Such a method might use a highly-reliable sensor with higher shock pressure steps to perform calibrations of the reference sensors in a well-understood region of measurement. In particular, a model for the Kulite sensors is already known, making dynamic calibration of those sensors simpler. With better knowledge of the sensor behavior, measurements from different sensors might be compared at low amplitudes to attempt to reduce the uncertainty.

While the number of sensor mounts was increased during this research, the layout is still fairly sparse, especially in the third section of the shock tube. This section is the most useful, since in that section the shock is usually well-formed and the vibrations have died out. More sensor mounts should be added there. In particular, axial locations with at least four sensor mounts should be created. It should be possible to install up to eight sensors at a given axial location with the current mount design, though it is possible that doing so would compromise the structural strength of the section. The stress would need to be evaluated first.

The flow quality at low driven pressures remains somewhat uncertain due to the failure to measure the shock planarity at these conditions. The pitot mount design used in this research had insufficient seal quality, and low driven pressures could not be reached while those mounts were installed. A new design with better seals is required. It might be better to mount the sensors directly in the end plate for planarity measurements. This method would make a good seal easy to achieve.

The electrical burst system has proved useful, but difficult to use and time-consuming to install and maintain. The general design is sound, but the connections and insulations are unreliable, requiring frequent maintenance and re-installations. The installations are very difficult due to the presence of the crossbars and the small parts. A design which eliminates the need for the crossbars by attaching the bus bars directly to the shock tube interior would make the system much easier to work with. Additionally, tape is not a robust insulation method, though it was the simplest to develop. A more robust method would improve the system. Some of this work has already begun, such as the improvements made by Dally [93].
The rubber inserts were found to be useful in improving the signal-to-noise ratio of the measurements with PCB-132 sensors. However, installing them flush with the faces of both the sensor and the insert is very difficult. A tool or technique to improve this installation process should be developed.

In order to install the sensors in different orientations, it was necessary to remove the sensor from the insert and re-install it for each orientation. Because the adhesive takes a day to dry, performing sensing length measurements requires at least a week. This is far too long if these measurements are to be routine. If sensing length measurements are continued, a design which allows the sensor to be quickly and precisely rotated without requiring new adhesive will be necessary.

A method for identifying a model for each PCB-132 sensor must be developed. Some work toward this end has been performed at the University of Minnesota, but this was done with early step-response measurements and the method used appears to be non-trivial to learn [94]. Additionally, the work was performed only in the time domain, and frequency-domain results would be more useful to the understanding of the frequency response of the sensors. Accurate experimental transfer function estimation must also be performed by someone with the skills to do so properly.

The behavior of the PCB-132 sensors in pitot configuration must also be better understood. The increase in sensitivity and apparent nonlinearity are concerning. Since the cause is unknown, it may be possible that the step-response data in pitot configuration is not directly applicable to measurements in static configuration.

Many of the problems with the PCB-132 sensors are potentially attributable to the fact that they were not constructed for use in highly-accurate instability measurements. Changes in sensor design may yield a sensor with similar capabilities and more easily-understood characteristics. Such changes should be explored.
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APPENDICES
Appendix A: Shock Tube Operating Instructions

This guide contains basic step-by-step instructions for the main tasks involved in operating the shock tube, as well as tips and tricks for getting the system to work correctly. Operating the shock tube, especially the electrical burst system, relies rather heavily on proper techniques which are often difficult to describe and teach even in person. I have done my best to describe both what to do and why it is necessary in order to give as much of a head start as possible, especially in the case where the shock tube has fallen out of use and the techniques have been lost. However, since re-developing the proper techniques might take weeks or months, it’s best for at least one person in the group to maintain some currency with the shock tube, especially with the electrical burst system.

A.1 Operation Without Burst System

Operation without the burst system is fairly simple and reliable. Diaphragm materials used are aluminum foil and acetate, since they break quickly and cleanly. Mylar and polyethylene have poor natural burst characteristics, and should be avoided.

The following instructions assume that the vacuum pump has been warmed up for at least a half-hour, the tube has been cleared of debris, and is open. It is also assumed that the Paroscientific gauge is not installed. If that gauge is installed, it should be used to track the driver pressure, rather than using the oscilloscope to read the driver Kulite. Also, the relief valve on the driver control valves (see Figure A.8) was installed to protect the Paroscientific gauge from overpressurization. When the Paroscientific is installed, the cutoff valve for the relief valve should be opened, allowing the pressure to be limited. However, the relief valve puts a severe limit on the driver pressure, and when the Paroscientific is not installed, the relief valve should be cut off from the system.

Pictures of the actual system as it existed when this research was finished are included within the explanations. For greater clarity, a schematic of the air system
for the shock tube is shown in Figure A.1. Certain valves and other parts are labeled to reduce ambiguity in relating the schematic to the text. The legend identifies the different valve symbols. High-vacuum valves were differentiated from the other valve types to clarify which parts in the schematic are high-vacuum, and which use standard parts.

![Schematic of the air system for the shock tube.](image)

**Figure A.1.** Schematic of the air system for the shock tube.

1. If necessary, apply vacuum grease to the o-ring on the driven transition section (Fig. A.2). Vacuum grease is necessary for the diaphragm to stick when installed, and is also necessary for a proper seal at low pressures. For pressures above 0.1 torr, vacuum grease is not required to achieve a good seal. Between 0.01 and 0.1 torr, vacuum grease is necessary every few runs. Below 0.01 torr, it should be applied before every run.

2. Install the diaphragm by laying it over the driven transition section. The diaphragm should be somewhat taut and have no wrinkles, especially across the o-ring. The diaphragm should extend over one or two of the ridges on the face of the transition section in order to prevent slippage.
Figure A.2. The driven transition section, showing the o-ring that needs to be greased.
3. Close the tube by pulling the driver section up to the driven section. For the driver section to seat properly, it’s important to pull the sections together evenly. If one side pulls forward more than the other, the angle will result in the sections getting stuck. Significant force may be required to get the sections to close, but if tools are required, the transition sections may need to be realigned (See Section A.15).

![Image of transition assembly showing the driver and driven transition and the clamp rings.](image)

Figure A.3. The transition assembly, showing the driver and driven transition and the clamp rings.

4. Pull the clamp rings down over the transition sections. Close the latch on the bottom of the clamp rings. If the transition sections didn’t seat completely, it can be possible to force them to seat by bringing down the clamp rings several times.

5. Close the hydraulic ball valve, and pressurize to 1000 PSI. Use small strokes, not more than 15-20°. The pump re-gears around 600 psi to make pumping easier. See Figure A.4.
Figure A.4. The hydraulic ball valve at the end of the hydraulic hand pump.
6. Close the yellow vent valve. The green high-pressure cutoff valve should generally be open, unless a strong diaphragm which bursts well above 1 atm is being used. The green cutoff valve is meant to protect the vacuum system from high pressures, but also prevents the driver section from being pumped down, which is more commonly required. See Figure A.5.

Figure A.5. The valves and pressure gauge near the transition sections. The yellow vent valve and green high-pressure valve are shown.

7. Ensure that the high-vacuum valves at the end of the driven tube are set properly (Fig. A.6). The valve controlling the driver tube should always be open. The valve controlling the black vacuum line should be open if the diaphragm used will burst below 1 atm. If it will burst above or near 1 atm, it should be closed.

8. Visually check the positions of the yellow vent and green high-pressure cutoff valves. Also, check that the hydraulic pressure is near 1000 psi. Some relaxation in the pressure is normal and acceptable.

9. Open the high-vacuum valve controlling the vacuum pump. If using a weak diaphragm that breaks with less than 5 psi difference, only open the valve about
Figure A.6. The high-vacuum valves at the end of the driven section. Both valves are open. The driver tube valve is at the bottom. The vacuum gauge is shown to the left.

Figure A.7. The high-vacuum valve controlling the vacuum pump, shown closed.
Figure A.8. The driver control valves. From bottom to top: the yellow air-supply valve, the brass needle valve, the relief valve (with cutoff valve closed).
30°, to prevent accidentally bursting the diaphragm by building up a pressure differential during depressurization.

10. If the diaphragm will burst near 1 atm, quickly open and close the high-vacuum valve controlling the black vacuum line immediately after opening the vacuum pump. If the diaphragm bursts at a lower pressure, let the pressure drop below that pressure before closing the black line. For example, aluminum diaphragms should usually be cut off at 90-100 torr. If the run will be a minimum-pressure run, cut off the driver tube at 30 torr. Since the driver tube pressure will increase due to leaks, longer pumping times require a lower cutoff pressure to prevent an early burst.

11. After cutting off the driver tube, open the vacuum pump completely and close the green cutoff valve. The black line leaks at a particularly high rate, and should be cut off from the driver tube to prevent early bursts.

12. If performing a minimum-pressure run, periodically check the driver Kulite’s output, to ensure the driver pressure is not getting too high.

13. Allow a certain amount of driven-pressure undershoot. The amount varies with pressure— at low pressures, less undershoot is necessary. Adjust the vacuum pump valve to achieve a constant pressure. Since most of the ‘leaking’ is actually outgassing, the leak rate will constantly decrease, resulting in a slowly dropping driven pressure. It can be useful to let the pressure increase above the target pressure. For pressures above about 0.05 torr, it is possible to completely outgas the tube, close the vacuum pump completely, and let the tube settle for a few minutes. At lower pressures, leaks are generally too significant to close the pump and stay at a constant pressure.

14. When the target driven pressure has been reached, arm the oscilloscopes.

15. To initiate the run, open the needle valve about a quarter turn (this amount can be adjusted depending on the amount of additional pressure required to burst). Then, completely open the yellow air-supply valve (see Figure A.8). Quickly
move to check the vacuum gauge, since the diaphragm may leak just before bursting. Remember to keep checking the scopes, since they may trigger at any time due to electronic noise spikes. These noise spikes are from an unknown source, and are not influenced by the large vacuum pumps.

16. After the diaphragm bursts, close the yellow air-supply valve, attached to the red air line directly under the shock tube. Also quickly ensure that the vacuum pump is closed off, or it will fill the room with oil mist. This is a good time to record the driven pressure at burst, and to note whether or not the diaphragm leaked.

17. Open the black line and the green cutoff valve. Then, open the yellow vent. This method ensures that both the driver and driven tubes reach atmosphere in the event of a failed or incomplete burst.

18. Save the data on the oscilloscopes.

19. Open the hydraulic ball valve and lift the clamp rings.

20. Push the driver tube back. If it is stuck, pry it open with a screwdriver. It’s best to place the screwdriver where the gap is the smallest, since that’s where the two pieces have stuck together.

21. Remove the diaphragm and throw it away (the vacuum grease makes the diaphragm unrecyclable).

22. Clear the tube before the next run.

A.2 Clearing the Tube

1. Place a dummy 1.5-mil mylar diaphragm in the tube.

2. Close the tube and apply 1000 psi of clamp pressure.

3. Ensure that the green cutoff valve and yellow vent valves are both open.

4. Ensure that the black line is closed.
5. Fully open the vacuum pump.

6. When the driven pressure reaches 20 torr or less, close the vacuum pump.

7. Fully open the black line, filling the driven tube from the back and blowing any debris toward the diaphragm section.

8. Repeat the depressurization cycle three more times, to ensure all fragments are blown to the front of the tube.

9. After the fourth repressurization, open the hydraulic ball valve and open the tube.

10. Remove the dummy diaphragm and save it, if it is still useful. Avoid mounting it with the corners from the insert slots in the same location by rotating the diaphragm a few degrees each time.

11. Remove debris from the tube.

12. Check the tube with the flashlight for other debris that got stuck farther down the tube.

13. If debris is found, further clearing cycles will not move it. If the debris is in an unimportant location, it should be dislodged during the next run. If the debris would affect the next run, it should be removed by opening the shock tube at the nearest joint (see Section A.6). Be careful to clean any hand oils that may get on the interior of the shock tube.

A.3 Operation With the Burst System

The burst system adds significant complexity to maintaining the shock tube and reduces the vacuum performance of the tube, but also enables the creation of smaller pressure rises and improves control over the conditions of the test. Design improvements to increase the reliability of the system, as well as the ease of installation, would be welcome.
1. The power supply and capacitor box should both be plugged in, but turned off. The fan on the capacitor box runs whether the box is armed or not.

2. Check that the two high-current resistors are plugged into the capacitor output BNC. Doing so ensures that the capacitors are either discharged or discharging. If the resistors were not plugged in, carefully check the voltage on the capacitors.

3. Use the single high-current resistor to short the leads to the shock tube. This will ensure that the electronics inside the shock tube are discharged, and prevent an accidental shock or burn.

4. Check that the current and voltage knobs on the power supply are turned all the way down (the black part, not the red part).

5. Check the interior of the shock tube for debris. Clear any diaphragms and whatever wire fragments you can with a reasonable amount of effort. Pay particular attention to wire fragments around the burst system hardware. Look closely around the screws and in the gap between the inserts and the shock tube, especially the bottom insert. Also check underneath the bus bars with the flashlight. It’s important to align your eyes with the flashlight and the gap underneath the bus bars, which can take some attention and practice.

6. If a diaphragm fragment needs to be removed, ensure that the forward-facing brass screws are tightened in the inserts.

7. If the tube is clear, it’s now ready for installation. The brass screws should be unscrewed until they are about 3/8” extended (far enough to easily attach the wires and fit the small flat screwdriver underneath the head of the screw).

8. Cut two 0.010” Nichrome wires for installation. Cut them somewhat longer than 5” initially (the actual length is unimportant). Bend one end of each into a fairly small hook (the screw should fit snugly into the hook). Cut the hook so that it is about 1/8” long. It is important that the hook not be too long, so that it doesn’t stick out from underneath the screw head and break through the
diaphragm when clamped. It must also not be too short, or it will slip out from underneath the screw head when tightened.

9. Place the hook of each wire over an insert (I tend to use the top and the right insert, both opposite the power wires). Make sure the hook is oriented so that tightening the screw will tend to draw the wire toward the screw, tightening it.

10. Wrap the second end of each wire around the opposite screw. Again, wrap it so that tightening the screw will draw the wire more taut. This will always involve crossing the wire across the screw, instead of bringing the wire straight across the gap. Leave the excess wire for now.

11. Use the small screwdriver to wrap the hook end of each wire around the screw.

12. Tighten the two screws with the wrapped wires. Keep a finger on the wire to ensure that it stays in the notch in the insert, to prevent it from breaking through the diaphragm. Also, watch to see if the wire starts slipping out from underneath the screw head, or if the end pokes out.

13. Now that one end of the wire is tightened, cut off the excess wire from the other end to create a similar hook. Wrap the wire around the screw with the screwdriver, and tighten the screws.

14. The wires should be somewhat taut, though a certain amount of slack is normal. They may flex by as much as half an inch in the center. Check that the screw heads are flush with or below the insert surfaces. Check that the wires are properly installed, with no pieces sticking out that might break through the diaphragm.

15. Now, install the diaphragm as normal. Diaphragms used with the burst system are the 0.31-mil polyethylene, 1.0-mil mylar, 1.5-mil mylar, and 2.0-mil mylar.

16. Close the shock tube and pressurize the hydraulics to 1000 PSI, as normal.

17. If the burst system is freshly installed, hasn’t been used in a while, or was recently modified or changed, it’s worth performing a check for electrical contact before
depressurizing the shock tube. Do this by using the multimeter to check the resistance between the ground lead on the burst electronics and the exterior of the shock tube. It should read open line. Any contact will require aborting the run. See the troubleshooting instructions. Also, check the resistance across the entire circuit. It should read 1-2 Ω.

18. If the resistance is fine, bring the shock tube to the correct conditions. If using the polyethylene, be sure to control the rate of depressurization. If the Paroscientific gauge is installed, keep the rate of depressurization to 0.5-1.0 psi per update. If it is not, open the pump valve only about 30° until the pressure is below about 100 torr. This is to prevent pressure differences between the driver and driven tube from getting large enough to break the diaphragm, which will occur if you open the pump valve all the way immediately.

19. The burst system does not exhibit any problems with the diaphragms beginning to leak before bursting, so the driver pressure may be reduced to whatever pressure is convenient to getting the run done as quickly as possible. Leave the driver tube a bit below the target pressure, since it will leak up while the burst system is prepared.

20. When the pressures are set properly, check the burst system resistances. It’s important to check again at this point, since now the diaphragm has been pushed out into the driven tube and made contact with the wires, and the wires may have broken or electrical contact may have been made with the shock tube. It is normal for the resistance across the circuit to have increased somewhat due to the deformation and stretching of the wires.

21. If the resistances are fine, check again that the dials on the power supply are all the way down.

22. Remove the resistors from the capacitor BNC plug. The power supply is able to overcome the resistors if they are plugged in, which is somewhat dangerous due to the lack of insulation on the resistors and the potential for high temperatures.
23. Turn on the power supply and the arming switch for the capacitor bank (at the bottom-center of the panel).

24. Dial the current on the power supply all the way up.

25. Slowly increase the power supply voltage to 36 V. Note that the capacitors take some time to charge, and there will be some lag between your input and the response.

26. After the burst system is charged, arm the scopes and check the conditions. Make any necessary adjustments.

27. Trigger the run with the button.

28. Immediately turn off the power supply and the arming switch. Attach the resistors to the capacitor BNC. Discharge the leads with the large resistor.

29. Close the vacuum pump.

30. Pressurize the shock tube, being sure to do a positive fill.

31. Dial down the power supply.

32. Save the data.

33. Discharge the leads again, since charge may have slowly leaked into them through the capacitors. It takes a few minutes for the capacitors to discharge, but the leads are mostly independent from the capacitors and hold little charge on their own.

34. Unclamp the hydraulics and open the tube.

35. Remove the diaphragm. Be sure to check the quality of the cut and record any problems.

36. Unscrew the brass screws partway and remove the wires. Make sure not to leave any wire wrapped around the screws. It may be necessary to use the clippers.

37. Check for any damage to the burst system or shock tube that might indicate undetected electrical contact.
38. Clear the tube, if necessary.

39. Remove wire fragments, as practical.

40. If a significant amount of wire fragments have accumulated on the bottom of the tube, it may be desirable to remove all the sensors and clean the tube with the plunger. This should always be performed when the burst system is removed from the shock tube (see Section A.6).

A.4 Installing the Burst System

Installing the burst system typically takes at least a full day, and may take two if there are problems with the electrical insulation. For this reason, frequent installations and removals should be avoided. If pitot measurements are desired, the burst system must be installed. When running with natural bursts, the majority of the diaphragm flies down the tube in a single mass. If this large mass strikes a pitot sensor, the sensor will break. Many pitot runs were completed with the burst system without a sensor failure, but only about 10 runs could be completed without it before a sensor would break. Calibrations should be planned to group as many sensors together as possible for frequency-response identification in order to minimize the number of installations required.

The burst system consists of several pieces. These are: two crossbars, two bus bars, four inserts, two passthroughs, two lead wires, the burst electronics box containing the capacitors, and the power supply. All burst-system pieces inside the shock tube must be electrically insulated from the shock tube. If electrical contact is made, the primary danger is burn damage to the shock tube and the burst electronics. The burn damage can be severe enough to cause large pits in the metal. While a single burn is not critical, if enough burns accumulate, re-machining may be required. This would be particularly unfortunate for the driven transition section, which represents a very large cost in terms of hours in the machine shop. For this reason, maintaining proper insulation is critical during installation and while running the system.
1. Remove the inserts from the crossbars, and remove any dowel pins that may be left in the inserts.

![The burst insert assembly, with kapton tape applied to everything but one crossbar.](image)

Figure A.9. The burst insert assembly, with kapton tape applied to everything but one crossbar.

2. Apply Kapton tape to insulate the brass electrical inserts.

   (a) Inspect any tape left over from the last installation. If there’s no signs of wear (no corners peeling up, no scratches or dents), it can be left on. Otherwise, remove the tape. If in doubt, remove the tape. Replacing tape is much easier than re-doing the installation.

   (b) If necessary, clean the inserts with steel wool to remove any oxidation or burn marks. Oxidation can result in burning if it increases the resistance enough. It can also prevent good cuts.
(c) Get a scalpel, and replace the blade. The blades need to be very sharp in order to cut the tape properly, without risk of tearing it. The blades will become noticeably more dull over the course of replacing the tape on four inserts, and may even need to be replaced during the tape application. I prefer to use the curved blades for cutting tape.

(d) When applying tape, make sure to keep the adhesive side clean and avoid touching it too much, since it loses its stickiness quickly. Maintaining tension on the tape when applying it to the insert is important to ensure a good application.

(e) First, apply a single piece of tape around the sides and bottom of the insert (after application, the tape will be U-shaped).

   i. Unroll an inch or two of Kapton tape. Maintain tension on it.

   ii. Stick one side of the insert onto the Kapton tape, away from the edges. The long side of the insert should be parallel to the end of the tape, with the top of the insert away from the roll. Check the application for bubbles. You can smooth out the bubbles with your finger, or take the insert off and re-apply.

   iii. Unroll another two inches or so of tape.

   iv. Maintaining tension on the tape, wrap it over the bottom surface of the insert. Again, check for and remove any bubbles.

   v. Wrap around the other side of the insert. Again, check quality.

   vi. With the scalpel, cut the excess tape from the first side you applied tape to. Get close to the top surface, but don’t try to be flush with it. You just want to prevent the tape from being able to stick to the insert or to itself. It’s best to push the point of the scalpel through the center of the tape, cut out to one side, and then cut or carefully tear the other side from the middle. Beginning the cut at the edge tends to induce uncontrolled tears.
vii. Cut the roll away from the other side of the insert.

viii. Lay the insert on its side on the cutting board. For both sides, cut the tape nearly flush with the top of the insert. It’s fine to leave a little extra, but too much will be messy and may catch wire fragments or cause the tape to peel off. Again, it’s best to start in the middle. Firmly apply the curve of the blade to the tape and smoothly cut to the edge of the tape. The cut will tend to end up lower than it looks like it will, so err on the side of too much tape.

ix. Check the cuts to see if you cut too low or if a tear exposed some of the insert. Hold the insert up, and from each side look to see if you can see bare brass. If you can, you’ll need to start the process over. Also look for pits and dents in the tape or debris caught under the tape that might break the insulation.

x. Cut the excess tape from the front and back of the insert. These need to be very nearly flush, but exposed brass will result in contact with the shock tube. Lay the insert on its side, and firmly apply the blade with the side of the blade flat against the front or back face of the insert. Rock the blade back and forth to perform the cut. It will be necessary to do this at least three times, once for each taped side. This step can be prone to tears.

xi. Check to see that the tape is flush and there is no exposed brass. If the tape is not flush enough, you may be able to clean it with additional cuts, though the risk of mistakes is greater the less tape there is. If there is any exposed brass, remove the tape and restart.

(f) Place a piece of tape covering the back surface of the insert. Stretch out about an inch of tape, and press the back of the insert onto the tape. Cut the excess tape at the end away before cutting the tape away from the roll. Place the back of the insert flat on the cutting board, and then cut the excess away from the sides of the insert. Now cut the tape flush with all
four sides, again using the rocking motion to avoid tearing. Leave the extra that hangs over the beveled corners. It will not interfere with anything.

(g) Perform the above steps for each insert that needs tape.

(h) Place all the inserts in a row, facing the same way with their backs approximately flush with each other, and all in contact and right side up.

(i) Take about 3/4” of tape off the roll, and place it across all of the inserts at once, taping them together from the top. The tape should cover the small dowel pin holes, and leave at least 1/4” at the back for the ring terminal to make electrical contact. This piece of tape is to insulate the crossbar from the insert, so it needs to cover all the areas that the crossbar will touch. If electrical contact is made with the crossbar on both sides when the assembly is installed, the current will go through the crossbar instead of the wires. The usual application can be seen in Figure A.9.

(j) Flip the row of inserts upside down, and cut the excess tape flush with the outside edges of the row of sensors.

(k) Flip the row of inserts over again. Carefully place the scalpel in the groove between two of the inserts. Smoothly run the blade down the groove, angling the blade so that the curve smoothly cuts the tape. It’s generally not necessary to start in the middle, but do whatever works best.

(l) Separate all of the inserts.

(m) Inspect all of the inserts for problems. Check that the tape on the top is properly sized, and no brass is visible on any surface except the top and the front.

(n) Using the tip of the scalpel, push the blade into one of the dowel pin holes. This will cut a line across the hole, but not cut outside the hole, which might cause electrical contact with the crossbar.

(o) Rotate the scalpel 90°, and cut again in the same manner. This cuts the tape enough to allow the dowel pin to be installed.
(p) Repeat the above two steps for each dowel pin hole.

(q) Again, inspect the inserts for problems.

3. Insulate the rear edges of each crossbar at the ends of the bar. Use about a 3/4” width of tape. Cut it with the scalpel so that it is flush with the end of the crossbar, and extends up to about half the width of the bar (into or near the flat portion in the middle- see Fig. A.9). This is to prevent the bus bars from making contact with the crossbars and short-circuiting.

4. Insulate the bottom of the bus bars using electrical tape. Kapton tape could be used, but electrical tape seems to be more robust.

(a) Replace the scalpel blade. For this step, I prefer to use the straight-edged blades because of the greater control over the cut length.

(b) Stretch out 5-6” of electrical tape.

(c) Maintaining tension, apply the tape to the bus bar on the face to the outside of the curve. It’s best to push one end of the bus bar into the tape, and then roll the bus bar into the rest of the tape. Check for bubbles and re-do as necessary to get a clean application.

(d) Cut the electrical tape away from the roll.

(e) Cut the excess tape away from the bus bar. The front edge (closest to the holes) needs to be flush, while the rest just need not to have excessive extra tape which might catch wire fragments or flap around during runs. Cut with the taped side down. Firmly push the blade into and through the far side of the tape, and smoothly pull it across the cut while maintaining downforce. When cutting the long edges, you’ll need to place one finger on either end of the bus bar and roll it as you cut, keeping the part you’re cutting in contact with the table.

(f) Check for any tears, pits, and exposed brass, as well as bubbles or debris under the tape.
(g) Flip the bus bar over (taped-side up) and place one end on the edge of the table, with the rest curving down over the edge.

(h) Press down on the tape with your finger to reveal the hole.

(i) Cut just to the outside of the hole from the front edge. Less than 1/16” should be exposed to the side or rear of the hole. The cut should be nearly flush with the edges of the hole to prevent the bare area from extending past the insert and making contact with the shock tube when installed. Remove the rectangle of tape that was covering the hole area.

(j) Inspect the cut for tears and appropriate sizing. In particular, look to see if the cuts extended past the outline of the removed tape. Any cracks can allow contact when the screws are tightened, so if they are present, you should start over.

(k) Repeat for both holes and both bus bars.

5. Remove the blank inserts from the driven transition section.

6. Apply vacuum grease to the threads of two 1/8” NPT Conax fittings with 1/8” diameter glands after cleaning them with acetone. Wear gloves, since hand oils can affect vacuum performance.

7. Install the Conax fittings in the two passthrough inserts (Figure A.10). It’s important to have the Conax fittings installed whenever working with the passthroughs, since the passthrough walls are so thin at the hex flats. The Conax reinforces the passthrough, preventing it from deforming when being tightened and especially when being removed.

8. Install the wire in the passthrough/Conax. Apply vacuum grease to the glands of the Conax to improve the vacuum performance of the seal. The wire should only extend 2-3 inches past the face of the passthrough. The wire must be solid-core to prevent leaks, and needs to be able to handle at least 40 A, with a 1/8” O.D. to fit the Conax.
9. Solder a ring terminal to the end of the wire. Strip the wire to extend just past the end of the terminal sleeve. Tin the wire, and then install the terminal. Balance a small piece of solder between the wire and the sleeve, and then melt it into the sleeve. Repeat this process until the sleeve is full of solder. Then apply prolonged heat to melt the solder (required due to the heat capacity and conductivity of the wire). When the solder melts fully, it will suddenly form a smooth face.

10. Clean the passthrough threads and the vacuum-exposed surfaces with acetone. Apply vacuum grease to the threads.

11. Install the passthroughs in the driven transition section. Apply torque to the passthrough, not the Conax.

12. Check the orientation of the ring terminal. The ring should be parallel to the wall it will be up against (the bottom or left wall) with the wire toward the back of the shock tube (so that the ring terminal will lie flat on the wall of the shock tube when bent 90° forward).

13. Push each wire forward and bend it until the back of the ring is just past the rear edge of the insert slot. It’s necessary to wiggle the wire a lot and push fairly
hard, since there is little clearance and the wire will be warped. Make sure the Conax is very loose.

14. Bend the wire as close to the wall of the tube as possible. The curve of the wire will probably extend up about 1/2 - 3/4”. Keep the wire flush with the wall for as much of the length as possible. The length may need to be readjusted.

15. Check the orientation of the ring. It needs to be almost exactly horizontal, but generally won’t be. If it’s off by a small amount, take pliers and twist the ring to be horizontal. If it’s off by too much for twisting to fix, retract the wire until perpendicular with the wall again, and turn the wire to correct the misalignment. Then, re-extend the wire.

16. Bend the ring toward the wall. This corrects for the thickness of the insulation on the ring terminal, which would contact the wall of the tube before the ring contacts the insert if the ring were left flat.

17. Assemble the interior burst electronics. Install the dowel pins into the brass inserts first, and then attach the crossbars. One crossbar should have the notch facing forward, the other should face the rear. Interlock the notches.

18. While the electronics are outside the tube, attach the bus bars to the upper and rightward inserts (the opposite sides from the wires). Use 1/8” iron-oxide socket-head screws. Leave the screws loose so that the bus bar can easily slide over the shock tube wall. However, make sure they are well-seated.

19. Carefully slide the assembled electronics into the slots. Keep the inserts even with each other. If the crossbars get to a sharp angle with the inserts, the tape or dowel pins may break.

20. Check the position of the rings. You should be able to bend them so they are centered over the screw hole in the insert. Adjust the wires until you can do this without needing to hold the wire in place. It may be necessary to remove and re-install the inserts to do the adjustments.
21. Ensure the wires and bus bars are placed properly so that the screw hole is centered.

22. Place a 1/4" iron oxide socket-head screw in the ring terminal on the bottom.

23. Using the ball end of the magnetic 1/16" allen key, seat the screw in the bottom insert. Generally, you will need to have the allen key vertical behind the crossbars. To do this, bring it in over the horizontal crossbar. You will need to “walk” it down to the screw with your fingers, simultaneously bringing your fingers farther down on the allen key, which takes some practice and is difficult to describe. At the end, you’ll want to have your index finger above the horizontal crossbar, your middle finger below it, and your thumb above and wrapped around the opposite side of the vertical crossbar. You may want to grab the
lower end of the screw with your other hand for extra control and force when you begin turning the screw. Only turn the screw until it’s well-seated, don’t tighten it with this method. Note that the magnetic allen key will try to take the screw with it when you are done.

24. You will now need to seat another long screw through the ring terminal on the side. This time, you will need to place the screw on the allen key and get it through the ring terminal while you are walking the allen key into position. Use the same method as before, but rotated 90°. Iron oxide screws are used because they are the most strongly magnetic, and don’t fall off as easily during this process.

25. Use a ball driver to tighten all four screws. Ensure that the bus bars are shoved forward into the crossbars, so that the bare brass doesn’t run over the back of the insert and contact the shock tube.

26. Pull back on the wires from outside the tube to eliminate any remaining slack. Pull firmly, but not so hard that you damage the tape or the screws.

27. Tighten the Conax fittings.

28. The burst system is now installed, but nine times out of ten is making electrical contact with the shock tube somewhere or has a problem with the bus bars (or both). Check the resistance between each insert and the shock tube. If any contact is made, see Section A.13. Also check the resistance between each pair of inserts connected by a bus bar. They should both read about 0.3 Ω (shown as 00.3 on the multimeter). If one or both does not, see Section A.14.

A.5 Removing the Burst System

Removing the burst system is fairly simple, and should take a couple of hours at most. As always before working with the burst system, make absolutely certain that it is discharged before working with it.
1. Remove all four screws using a ball driver. Dispose of the screws.

2. Carefully and evenly remove the burst insert assembly. The goal is to preserve as much of the tape as possible for next time. Check for any tape left behind in the slots, particularly that covering the back of the insert.

3. Loosen the Conax fittings so that the wires can rotate freely.

4. Pull the wires back through the passthroughs until they can be bent perpendicular to the shock tube wall, so that they can rotate freely inside the shock tube.

5. Unscrew the inserts, applying torque to the insert and not the Conax.

6. Carefully pull the wires out through the shock tube wall. The goal is to avoid damaging the insulation on the wire, so that it can be re-used.

7. Pull the wire back through the Conax fitting until only 2-3” are left beyond the passthrough, to prepare it for the next installation. If the Conax has cut through the insulation, leaving bare wire, cut off the end of the wire. If the remaining length is not enough for the next installation, order more wire (1/8” outer diameter (of the insulation), solid core copper wire capable of handling at least 40 A).

8. Clean the passthrough blank inserts with acetone.

9. Apply vacuum grease to the threads on the blanks.

10. Install the blanks in the driven transition section.

A.6 Cleaning the Interior of the Shock Tube

Cleaning the shock tube interior is necessary if any machining has been done involving the interior (such as adding new sensor locations), or periodically after wire fragments and other debris have accumulated inside. Cleaning is primarily done with the plunger, which is a wooden dowel rod with a small circular wooden plate screwed into the end. A diaper cloth should be folded in thirds, with the two thin flaps
overlapping the thick middle, and wrapped around the plate. Another diaper should also be wrapped around the plate, but with only one of the thin flaps. The goal is to have a tight fit in the shock tube, so that it’s clear that all parts are being cleaned, but not to make it so tight that the plunger can’t be inserted or moved easily.

1. Select which part of the shock tube is to be cleaned. Remove all sensors from that section.

2. Open the section on both ends, **UNLESS** that section is the first section or the driver section. **Don’t remove the first section or the driver section from the transition sections!** The transition sections require the regular pipe sections for support, and should never be detached unless they’re being removed.
   
   (a) Loosen the bolt on the band clamp holding the split clamp rings on. It shouldn’t be removed, it just needs to be loosened enough that the band clamp can be moved.
   
   (b) While keeping your hand on the lower split clamp ring, move the band clamp off the rings. Leave it on the shock tube. Some of the split clamp rings will fall immediately when the band clamp is removed, so keep your hand on it to prevent this.
   
   (c) If the lower clamp ring didn’t fall, use a screwdriver to pry one half loose, and take it off the joint. Again, keep your hand on the lower clamp ring in case it decides to let go.
   
   (d) Using the rubber mallet, tap the remaining half on each side to loosen it, and take it off.
   
   (e) Repeat for the other side, if applicable.

3. Push one end of the free section to the side until it clears the nearby fixed section. Move the free section towards the fixed section until the two flange rings have cleared each other, then let the free section rest on the fixed section. This angles the free section so you can look through it and insert the plunger.
4. If not already done, wrap the plunger with the diapers. Spray acetone around the widest part until the diaper is wet.

5. Carefully push the plunger into the shock tube. This may require some force, but be careful not to damage the o-rings or dislodge the diapers.

6. Push the plunger all the way to the other side, until it is just about to exit the shock tube. Then pull it back. You may wish to repeat this several times before removing the plunger, depending on how dirty the interior is. If clearing wire fragments, get as many out of the shock tube as possible before pulling the plunger back, and don’t repeat. Dragging the wire fragments against the side runs the risk of scratching the tube.

7. Repeat until the tube is clean. Any dirt removed by the diaper will darken the cloth. As the tube gets cleaner, the cloth will need to be changed more often.

8. Unhook the free section from the fixed section.

9. Clean the flat face with acetone.

10. Inspect the o-ring on the other face. You may need to remove, clean (or replace), grease, and re-install the o-ring. You may also need to clean out the groove.

11. When re-installing the o-ring, wear gloves. Apply vacuum grease, and then place one part of the o-ring in the groove. Then, place both of your index fingers next to each other on the installed part. While pressing down, drag your fingers in opposite directions around the circle until they meet again. This method stretches the o-ring evenly and prevents it from popping out due to uneven tension in the rubber.

12. Place the two faces against each other. Check the alignment of the two sections. You want both sections to be centered, and the gap at the top and bottom should be the same length, indicating the angles of the two sections are matched. Otherwise, raise and lower each section (or one end of the sections, in the case of mismatched angles) to fix the discrepancy.
13. Using the mallet, hammer on the top section. Use substantial force, since most of the clamping force is applied this way.

14. Now, hammer on the bottom section. Don’t use too much force, or it may fall off again. Be sure that the numbers match and are positioned next to each other. Also, ensure that the gaps on each side are even. Hammer until the bottom section bites, and then stop. You may need to readjust the clamp rings if they became very uneven during the hammering.

15. Hold on to the lower section to ensure it doesn’t fall off. Slide the band clamp over the rings. You may need to loosen the nut to get the clamp to fit.

16. Center the band clamp, and tighten the nut.

17. Install the other clamp ring.

18. Repeat the cleaning process for any other sections required.

19. In the case of the last section, the end plate will need to be removed. This is the same process as for the other joints, but the end plate is slightly thicker, and it may be more difficult to pry the clamp rings apart. Also, the high-vacuum line should be removed from the plate first. Rest the end of the high-vacuum line on a diaphragm on the ground. A method to loosen the rings initially is to place a screwdriver in the gap on one side, parallel to the tube. Then, hammer the screwdriver forward, using it as a wedge to widen the gap. Repeat for both sides. Also, take care not to let the end plate fall. If the pitot end plate is installed, see Section A.7.

20. When cleaning the first section with the burst system installed, be careful not to push the plunger into the burst wires. It is easy to break off the ring terminals, requiring a re-install of the burst system.
A.7 Installing and Removing the Pitot End Plate

The pitot end plate can be used to measure shock planarity and to get multiple step responses in a single run. For measuring step responses, higher driven pressures are necessary. 10 torr at minimum, and preferably above 15 torr. All diaphragms should yield step responses at those pressures. Whenever pitot measurements are performed, the burst system should be used in order to prevent diaphragm pieces from breaking the sensors. The diaphragm fragments that sometimes rip off when running the burst system, such as one quarter of the diaphragm, do not seem to pose a risk to the pitot sensors. Nevertheless, it is good practice to avoid creating them as much as possible without limiting your ability to get the necessary data. Diaphragm fragments tend to be lost when running higher-pressure shocks for a given diaphragm material. Most likely, they are ripped off by the reflected shocks. When working with the end plate, be careful that you don’t pinch any wires under the probe tubes or the vacuum fitting.

Figure A.12. The pitot end plate with pitot probes installed.
1. Mount the sensors in the pitot probes using nail polish. They should be flush or slightly outside of the beveled end of the tube. Allow to dry overnight.

2. Install Conax fittings or blanks as appropriate for your sensor layout. The outer holes will always need blanks, as pitot probes do not fit into the tube from these positions. It’s necessary to install and adjust the Conax fittings from the center outward, since the holes are placed close enough together that you cannot fit a wrench on one if it is surrounded on two sides. The PCB probes require an additional sleeve around the probe tube in order to meet the I.D. of the Conax fitting. They can seal without this, but the probe can wobble and affect alignment and possibly introduce acceleration noise. The Conax fittings go on the outer side of the plate (the side with the beveled edge).

3. When the sensors have dried, install them into the Conax fittings. The probes should extend about 3.5 inches past the plate, to give enough measurement time before the reflected shock arrives.

4. If performing planarity tests, it’s important for the probes to all extend past the end plate by the same distance. However, it is not important what the actual distance is.

   (a) Take a metal piece with a flat end and a diameter of at least 0.5 inches. Mark it with a fine-tip marker. The line should be a bit less than 1 mm thick.

   (b) Place this piece alongside the probe, with the bottom flat against the end plate. Be careful not to press it into the probe too hard, or the probe will be pushed out at an angle.

   (c) Adjust the probe until the sensor face is touching the line. You may need to adjust the Conax tightness to get a useful level of friction for this process.

   (d) When the probe is lined up, tighten the Conax.

   (e) The sensor may move forward slightly when tightening the Conax, so it will be necessary to check it again afterward. This movement can be reduced
by leaving the Conax tighter, though this makes the position adjustments more difficult. You can also try to correct for the movement by positioning the sensor a little low. If all sensors are touching the line, they should be within 1 mm of each other, which is sufficient for planarity tests.

5. Remove the standard end plate. See Section A.6.

6. The actual installation or removal of the end plate is a two-person process to ensure that the plate doesn’t unseat and fall, damaging the probes. The required tools are: a large screwdriver, a rubber mallet, acetone, vacuum grease, Kimwipes, a small screwdriver, and the wrench for the band clamp. Gather all the tools and place them on the optical bench. Place the pitot end plate on a diaper on the optical bench. Keep another diaper on the floor behind the optical bench for the high-vacuum line to rest on.

7. Get both people behind the optical bench.

8. Inspect the o-ring and groove for any dirt or debris, and see if the o-ring needs to be replaced or re-greased. Perform whatever maintenance is necessary.

9. One person should pick up the end plate and carefully insert the probes into the tube. Seat the plate and hold it in place.

10. The other person should pick up one of the clamp rings and hammer it down on the top of the joint. Use force, since this is where most of the clamping force which forms the seal comes from.

11. Now the end plate is firmly in place, and no longer needs to be held. Hammer the bottom half on.

12. Slip the band clamp over the two rings and tighten.

13. Attach the high-vacuum line. Clean the o-rings of any debris as necessary.

14. It may be easiest to have one person on each side of the optical bench when connecting the sensors to the data acquisition equipment.
A.8 Aligning the Shock Tube Transition Sections

The clearances for the joint between the transition sections are not large. Because of this, small misalignments between the two pieces result in them getting stuck together. Misalignments often develop because of movement of the supports on the driver section. The alignment can usually be corrected by keeping track of the position of the supports and putting them back when they move. In addition, pulling the driver section forward slowly and waiting for the rollers when they get stuck tends to prevent the supports from moving in the first place. In other situations, misalignments are caused by removing and re-installing sections of the shock tube.

It is important to align the pieces not only in position, but also in angle. When the pieces go together easily but need to be pried apart, they are typically well-aligned positionally but are at different angles to the horizontal. For this reason, the digital protractor is useful when aligning the shock tube, since it is able to measure the angles with high accuracy.

1. Adjust the supports closest to the transition sections first. Extend or retract the turnbuckles to adjust. Adjust until they seem lined up visually. The support for the driven transition section is particularly difficult to turn, especially to tighten. It’s usually best to adjust the other sections to line up with the driven transition section.

2. Test the alignment by trying to join the sections. Observe where the sections seem to get stuck. When squeezing the sections together, try squeezing harder with one hand and then the other, causing the driver section to rock back and forth. This can make it easier to tell which side is stuck.

3. Adjust accordingly until the sections slide together. Use small adjustments—no more than a quarter of a turn.

4. If the sections slide together roughly, continue adjusting by less than an eighth of a turn each try. If they slide together roughly and get stuck, continue by adjusting the angles. If they slide together and apart smoothly, you’re done.
5. The angles can sometimes be adjusted visually, but it is generally easier to start by immediately using the digital protractor.

6. Place the protractor on a machined surface on the driven section. If possible, use the actual driven transition section, but it may be easier to measure on the first tube section.

7. Adjust the protractor until it is lined up on the top or bottom of the shock tube. If the protractor is angled off-centerline or not close enough to vertical, it will affect the measurement.

8. You can either remember the angle that it reads, or re-zero the protractor.

9. Perform the same measurement on the driver section, but do not re-zero.

10. Remove the protractor and place in a safe spot before performing the adjustments.

11. Adjust the far turnbuckle for the driver section. You will need a ladder. Raise or lower the turnbuckle by 1/8 turn increments.

12. Repeat the previous three steps until the angles match within a few tenths of a degree.

13. Check the fit of the sections. If it is still sticking, reduce the angle difference further. Alternatively, try to improve the positional alignment, if joining the sections is also difficult.

14. Continue until the sections join and separate smoothly and without the use of the screwdriver to pry them apart. Occasional use of the screwdriver is normal.

A.9 Installing and Removing Sections of the Tube

The pipe sections of the shock tube are fairly easy to move, but due to their length, care must be taken not to hit anything when in motion. They are not very heavy and can be picked up by one person, at least briefly. Two people should be able to move one easily. However, the easiest way to move all the pieces is by using
Installing and removing shock tube pieces can be done by one person, but should generally be done by two people. An experienced person could install or remove a piece on their own if it became necessary. Special care must be taken when working with the transition sections, due to their weight and irregular shape. It’s recommended that you request help from the machine shop when moving those pieces.

A.10 Installing a Section

1. Clear any Lista cabinets and other furniture from the area in front of the supersonic tunnel on the side with the BAM6QT vacuum pump.

2. Begin with the section laying flat on a cart. Move the cart next to the supersonic tunnel. Move the schlieren hardware out of the way as much as possible. Keep the section as far away from the I-beam’s vertical steel supports as possible, as well. Also, make sure that none of the section is underneath the table for the supersonic tunnel. The axis of the section should be perpendicular to the supersonic tunnel.

3. Move the crane above the section.

4. Get a 6 or 8-foot strap.

5. Wrap the strap around the center of the shock tube section several times. Leave about 1.5 - 2 feet of lead on either side.

6. Attach both of the loops of the strap to the crane’s hook.

7. Lift the crane until the shock tube section just starts to lift. Note which side lifts first.

8. Move the straps away from the side that lifted first. Use small adjustments of less than an inch.
9. Repeat the process of lifting and adjusting until the two sides lift nearly simultaneously. The section should be approximately level when only supported by the crane.

10. Have one person keep a hand on one end of the section at all times to prevent it from tipping. Make sure not to stand directly under the section while it is suspended.

11. Start lifting the section. Move the crane as far away from the centerline as possible. The section starts out perpendicular to the supersonic tunnel, and will eventually need to be turned parallel whenever convenient. Keep the section oriented in a way that collisions are easy to prevent.

12. When the section is at about shoulder height, stop lifting and begin moving it towards the platform.

13. When the section is close to the vertical steel support, begin lifting it again. Keep a hand on it the entire time.

14. As the section rises, eventually the person holding the section will need to get on the platform in order to keep a hand on it. To let them get on the platform, the person controlling the crane should hold it while the other person moves.

15. Continue lifting the section until it is clear of the platform railing and other hazards.

16. Rotate the section until it is parallel with the rest of the shock tube, if you haven’t already.

17. Begin moving the section over the platform.

18. As the tube clears the platform railing and the working table becomes a hazard, begin moving the section back toward the centerline.

19. Lift the crane chains over the platform railing as necessary.

20. Continue moving the section until it is in the correct axial position and the crane is as close to the centerline as possible. The crane will be prevented from being on
centerline by the I-beam and the wire rope for the counterweight system. Make sure the section is oriented so it will mate properly with the other sections.

21. Remove the u-brackets on the pipe hangers for the section, if they are not already removed.

22. One person should push the section towards the I-beam, while the other person positions the hangers on the section and re-installs the u-brackets so that the section is held by the turnbuckles. The nut for the U-bracket bolt only needs to be finger-tight. Adjust the height of the section as necessary if the hangers do not easily fit over the section.

23. Slowly lower the crane until all the weight is on the turnbuckles. The section will swing down to the centerline. The crane has a tendency to resist lowering, and getting the chain to start moving down may require substantial force.

24. Remove the strap from the crane and the section.

25. Rotate the section until it is properly oriented with the 000 ray on top.

26. Connect the section to the adjacent sections. Be sure to perform any necessary maintenance on the o-rings and sealing surfaces.

A.11 Removing a Section

Removing a section is just the reverse of the installation instructions, except that it is slightly more difficult to balance the section properly on the strap. The strap must be installed while the section is still in the pipe hangers. While performing the tests to see if it is balanced properly, it will be pulled to the side. One end or the other will begin to lift further, and come off the pipe hanger earlier. The strap should be moved away from this side. It can be difficult to tell how severe the imbalance is, but generally if the section appears fairly well-balanced in the hangers, it will be well-balanced when removed from them. Care must be taken when removing the hangers, since the section will want to swing out away from centerline without the hangers to
hold it back. One person should hold the section in place while the other removes the hangers. The section can then be slowly allowed to hang straight down. If the imbalance is severe, one person can hold the section level while it is lowered to the platform floor. It can then be readjusted according to the installation method. Make sure diaphragms are in place for the ends of the section when lowering the section on to the cart.

A.12 Working with the Transition Sections

The transition sections are more complicated to work with due to their much higher weight as compared to the tube sections, and because of their odd shape which makes locating the CG difficult. However, the straps can be mounted directly behind the flanges. This places the CG behind the strap, forcing the flange into the strap, which is fairly secure. A particular problem is the tendency to swing back to the vertical when the hanger is removed. This tendency is easy to correct with the tube sections, but is substantially more difficult with the heavier transition sections. Additionally, the transition sections need to be suspended from the straps before the joint with the tube section is undone. This means that the swing-back will happen suddenly, and also that the joint will be under stress as it is disassembled, and that the tube section will tend to fall back into the pipe hanger. It may be useful to have more than two people for this operation.

Additionally, the transition sections are both at least partially suspended off the platform. To make it easier to work with the sections, and to avoid damaging the supersonic tunnel if anything goes wrong, at least one pipe section should be removed first so that the transition sections can be slid back over the platform.

A.13 Troubleshooting Electrical Contact with the Shock Tube

Electrical contact between the burst system and the shock tube is a fairly common problem. It can be difficult to fix because of the many failure modes, the tendency
for multiple failures to occur at once, and the tendency for fixing one problem to cause another. In addition, many of the failures exhibit similar behavior, and careful investigation is required in order to be sure what the actual problem is. Due to the tight spaces inside the shock tube, fixing any problem is time-consuming, and it’s important not to waste time trying to solve nonexistent problems (and potentially creating new real ones). This guide attempts to illustrate the most common problems and how to differentiate between them. It should also serve partially to further explain some of the details of the burst system and how problems can arise.

1. The first step is to identify that contact with the shock tube has been made using the multimeter.

   (a) If the multimeter constantly reads a low resistance (on the order of a few Ohms) then contact has definitely been made. Pay attention to which lead from the burst system you are using (ground or power). If the resistance is very low, such as 0.1 Ω, then contact has been made on one of the two inserts connected to that power wire. If, instead, it measures 1-2 Ω, then the contact is made at the other lead and the measurement is including the resistance of the Nichrome wire. If contact was made with the lead being used, it may even be possible to figure out which insert has made contact, since the resistance of the bus bar is generally 0.3 Ω.

   (b) Any constant contact indicates that contact has actually been made. If the resistance is high, it may indicate that the damage to the insulation is very small.

   (c) Intermittent contact with high resistance (≈1 MΩ) can sometimes be caused by your fingers touching both multimeter probes. The multimeter measures the resistance across your body. For intermittent contact, ensure you aren’t touching the metal portion of either probe.

   (d) Intermittent contact that does not depend on your hands and comes and goes several times should be treated as actual contact. This type has a
tendency to disappear after the tube is opened, without any clear reason for the change. The multimeter will sometimes have fluke contact readings, but consistent intermittent contact will probably damage the tube and needs to be eliminated.

2. Now that contact is identified, open the tube and check for contact.

3. If the contact has disappeared, it may have been due to something breaking through the diaphragm, or due to contact only present when the system is clamped. Check the screws to see if any have burrs or are sticking out beyond the insert surfaces. If so, replace the wires (and screws, if necessary) and try the run again.

The screw heads vary in thickness, and some are too large to fit properly in the insert, causing contact through the diaphragm. This problem can be fixed by filing down the head of the screw. It’s important not to file too much, since doing so makes the slot shallower, making it harder to apply torque with the screwdriver. The screws can be filed easily by mounting them in the hand vise.

Also check if any of the inserts themselves are sticking out. This is usually caused by one of the power wires forcing the insert forward. If so, loosen the screw holding the ring terminal, loosen the Conax, and pull the wire back. It may also be necessary to bend the wire to make it shorter.

Also, check for contact between each insert and the shock tube by pressing hard on the front of the insert, to simulate being clamped shut. If contact is present, the insert will need to be taken out and re-insulated. However, it may be worth loosening the screw and pushing the bus bar forward, since contact may be occurring when the bus bar moves backward. After removing the insert, check the slot for any debris or burrs which may have broken the insulation.

4. If the contact is still present after opening the tube, most likely there is an insulation failure. However, the burst system should be closely inspected for
debris, since this may also be causing the contact and is substantially easier to fix.

5. Determine which pair of inserts is making contact (if possible, determine the specific insert by paying close attention to the resistance). Loosen the screws on that bus bar and measure the resistance again. If the contact did not disappear, then the insulation of an insert has failed, and it will need to be removed and re-taped. If the resistance does disappear, there are several possibilities.

6. Position the bus bar, paying special attention to making sure it is properly lined up (the screws are approximately centered in the holes) and pushed forward. Also check that the ring terminal has not been bent in such a way that it can make contact with the shock tube. Re-tighten the screws and check for contact again. If the contact is gone, the bus bar had just come out of position. Make sure the screws are tight enough that the bus bar can’t be moved with your finger.

7. If the contact re-appears when the bus bar is tightened, there are still several possibilities. Try loosening the screw very slightly. Occasionally the electrical tape can be overcompressed, causing contact. It may be possible to loosen the screw such that the contact disappears, but the bus bar is still firmly held in place.

8. If the contact reappears when the bus bar is tightened enough to be held firmly, remove the screw holding the bus bar into the problem insert. Test the resistance between the insert and the shock tube while firmly pressing the back of the insert down into the shock tube. Sometimes the insert’s insulation fails in such a way that it only makes contact when pressed into the shock tube by the bus bar, making it appear that the bus bar is making contact.

9. If the insert does not make contact when pressed, then the bus bar’s insulation has failed. Remove the bus bar completely. Inspect the underside of the bar for possible problems. Contact is frequently caused by wire fragments getting
stuck underneath the bus bar and breaking the insulation. It’s also possible for the rectangular cut-outs to have grown too large due to the tape being pushed around, or cracks growing out from the corners. The tape may also be somewhat melted, causing contact.

10. Remove the bus bar insulation, and clean any corrosion. Re-tape according to the installation procedures (Section A.4).

11. Re-installing the bus bar is a bit more difficult than installing it during normal installation procedures, since both screws have to be installed inside the shock tube, behind the crossbars. However, it’s easier than removing and re-installing the entire system. The lower bus bar can be installed by one person. If the upper bus bar was removed, two people are needed.

12. If the lower bar is being installed, position the bar behind the crossbars and underneath the ring terminal. If the upper bar is being installed, position the bar and have the second person hold it in place with one or two fingers.

13. Install the short screw in the insert without the ring terminal first. This is easier to install because fewer items need to be lined up. Use the same technique for installing the screw as was described in the normal installation procedures.

14. Install the long screw in the insert with the ring terminal. The ring terminal may stick up too far from the surface of the shock tube to enable the screw to be fit into the ring terminal. For the lower bus bar, this can be solved by dropping the screw inside the ring terminal and then positioning the allen key. For the upper bus bar, the ring terminal must be bent down enough that the screw can be installed. This can be done by pushing on the wire near the curve by the passthrough with a screwdriver.

A.14 Troubleshooting Bad Cuts with the Burst System

“Bad” cuts with the burst system are cuts in which the burst system failed to work as designed, and did not cut the diaphragm completely all at once. This is probably
the most common maintenance problem that occurs with the burst system. These problems are evidenced by a wire or half of a wire failing to cut the diaphragm, or by a double shock pattern (most common with the polyethylene). Bad cuts are nearly always caused by electrical contact problems within the burst system, as opposed to problems with electrical contact being made with the shock tube.

The usual problem is that electrical contact between a bus bar and an insert is degraded, for any of several reasons. This creates a bad cut by changing the normal paths of the electrical current in the burst system circuit. In normal operation, the current enters through the power supply wire on the wall of the shock tube. Half passes directly into the insert, while the other half goes through the bus bar to the other insert. The current passes through both wires. On the other side of the wire, the current that went through the bus bar passes through the insert directly into the ground wire, while the current that went directly into the insert now has to pass through the other bus bar to get to the ground wire. In this way, the whole circuit is balanced, and half the current goes through both halves of the circuit.

An important point about the burst system is that the Nichrome wires are not insulated, and come into contact with each other in the middle of the shock tube. Because of this contact, current that has not gone through the first bus bar can move from one wire to the other in the middle of the shock tube and avoid the other bus bar. Instead of being two halves, the center contact makes the circuit into four parts. This typically doesn’t matter, since the resistances are balanced between all four parts of the circuit. However, if the resistance across one of the bus bars increases, one part of the circuit will now receive less current, making that half of the wire heat more slowly. Very small variations in resistance (< 0.5 Ω) can change the heating rate enough to prevent part of the wire from heating quickly enough to cut the wire before the burst is started by the other three parts of the circuit. The polyethylene is thin and weak enough that rather than one part of the diaphragm not being cut at all, it is instead cut slightly later, producing a double-shock pattern.
Typically, the problem is caused by degraded contact due to any number of factors, but it is also sometimes caused by a complete lack of contact. Problems with bad cuts will arise periodically due to the repeated heating of the burst system components, as well as the repeated jolts during each run. They also frequently arise after the system has been installed or repaired. For this reason, it is a good idea to check the resistances across the bus bars before each run for about three runs after any change to the burst system, until the system has shown itself to be stable. Again, the problem can be caused by many different failures which tend to look the same unless a careful examination of the system is made. Significant care in identifying and fixing the problems is recommended in order to minimize wasted effort.

1. After identifying that a bad cut has occurred, check the resistance across the two bus bars. One will likely show high resistance (anything above 0.3 Ω, typically 0.6 Ω).

2. If neither side shows an abnormal resistance, the problem may have been the contact between the Nichrome wire and the insert. Problems with the wires are usually one-off, but check the screw and screw holes for corrosion. Replacing the brass screws is a good idea.

3. If one bar shows higher resistance, try measuring the resistance between each insert and the bus bar itself. One end should have higher resistance than the other.

4. Tighten the screw on the end with higher resistance (or both ends, if they were equal). Sometimes the problem is that solder on the bus bar settled after being heated, and the contact degraded. This problem can repeat for several runs in a row until the solder reaches a steady state. Other times, the screw has simply come loose due to normal operation.

5. Check the resistance across the bus bar again. It can be worth several attempts at tightening the screw if the first one was not successful.
6. If tightening the screw doesn’t work, the problem will require removing the bus bar. Typically, corrosion due to the repeated heating has degraded the contact, and will need to be cleaned with steel wool. The bus bar should be re-insulated.

7. If the problem is a complete lack of contact, it may be possible to fix without removing the bus bar. Sometimes it is possible for the bus bar to fail to make contact with the insert despite being completely tightened down. In order for the circuit to be complete, the bus bar should be in contact with the insert and the ring terminal. It is possible for this not to occur if the ring terminal has not been bent far enough downward (causing the insulation to press into the shock tube wall before the ring has pressed into the bus bar), or if the bus bar’s insulation keeps it off the insert. The solution for the first problem is simply to undo the joint in question and bend the ring terminal. If the bus bar is failing to contact the insert, solder may need to be added either to the top of the insert or the bottom of the bus bar, to raise the point of contact above the insulation. In order to determine what is happening, the contact between the screw, ring terminal, bus bar, and insert should all be individually measured. It is possible for corrosion on the bottom of the bus bar to cause an open circuit, so the bus bar may still need to be removed and cleaned. It is also possible for the insert to have corrosion, requiring more removals, but thankfully this is rarely the case.

A.15 Troubleshooting Difficulties With Opening and Closing the Shock Tube

In nearly all cases, difficulty with opening and closing the tube simply requires realigning the driver section. This can usually be done simply by moving the supports slightly, since they have a tendency to move when the tube is opened or closed, causing misalignments.

Difficulty with the transition sections sticking together can also be caused by debris in the joint. Debris is not always visible, and even something as small as a
single flat piece of the polyethylene can cause a problem. Run your finger around the mating surfaces on both the driver and driven transition sections to see if anything is stuck.

Misalignment of the clamp rings can cause difficulty in closing the rings. Look at the support for the rings to see if it’s at an angle. If it is, open the rings and bring them back down more carefully so that it doesn’t come out of alignment. It’s also possible for the rings to be out of alignment due to movement of the driven transition section. If the axial location of the driven transition section is off, the rings will have to come down at an angle. You can change the location of the driven transition section by hitting the fixed turnbuckle (the one not supported by a roller) with a mallet.

The opening mechanism for the shock tube relies on a collar with several metal springs on the driver transition section. This section pushes the collar on the driver transition section forward when the hydraulic pressure is released. The slight forward motion removes the friction between the clamp rings and the transition sections. If the springs aren’t compressed, the friction won’t be removed, and the clamp rings will be stuck. Re-compress the springs by adjusting the position of the band clamp that serves as a stop for the springs. This problem is very rare, however.
Appendix B: Source Code

B.1 Shock Tube Calculations

This code is used for computing the shock properties from the run conditions.

```matlab
% Dennis Berridge, November 2009
% Code for shock tube equations, now solving given experimental conditions
% Units used are confusing, but easy for computation,
% and it doesn't matter if they agree.
% Pressure is in PSI, Temperature in Kelvin, gas constants in metric. Since everything but pressure
% is only used in ratios, it doesn't matter.

close all

P1 = [Driven pressures...];

P4 = [Driver pressures...]

P1Metric = P1*6894.76; % Convert from PSI to Pa

gamma1 = 1.4; % Gamma for both gases (N2 & air)
gamma4 = 1.4;

% gamma4 = 1.2; % Gamma for CF4
% gamma4 = 1.0; % Gamma for SF6 (approximate)
% gamma4 = 1.67; % Gamma for Xe (monoatomic gases) Encyc. airliquide

T1 = 293; % Temperature of driven section
T4 = 293; % Temperature of driver section
R1 = 287; % R_Air
% R1 = 2078; % R_He
R4 = 297; % R_N2
% R4 = 2078; % R_He
```
%R4 = 94.49; \%R_{\text{CF}_4}
%R4 = 56.93; \%R_{\text{SF}_6}
%R4 = 208.12; \%R_{\text{Ar}}
%R4 = 63.33; \%R_{\text{Xe}}
%\mu = 23.2e-6; \%\text{viscosity of xenon}, \text{from CRC handbook}
\mu_0 = 1.716e-5; \%\text{viscosity of air}, 293K, \text{engineering toolbox}
%\mu = 2.38e-5; \%\text{viscosity of air}, 433K, \text{engineering toolbox}
%\mu = 1.61e-4; \%\text{viscosity of CF}_4, \text{encyclopedia.airliquide.com}
Z_2 = 1; \%\text{Compressibility factor, from Roshko}
d = 3.5; \%\text{Shock tube inner diameter, in inches}
rho_1 = P_1 \text{Metric.}/(R_1 \cdot T_1);
a_1 = \sqrt{\gamma_1 \cdot R_1 \cdot T_1};
\rho_0 = 1.273; \%\text{Sutherland's law constants taken from White}
S = 1.11;
aRatio = \sqrt{\gamma_1 \cdot R_1 \cdot T_1/(\gamma_4 \cdot R_4 \cdot T_4)}; \%\text{Ratio of sound speeds}
\text{minErr} = 1E-6; \%\text{Termination Error}
P_4P_1 = P_4/P_1;
Ms = 1.0;
\text{for } i=1:\text{length}(P_4P_1) \%\text{Solve for Mach numbers using interval bisection}
Mlow = 0.99; \%\text{Looping through, finding one at a time}
Mhigh = 30;
rhigh = 1;
rlow = -1;
rmiddle = 0;
Mmiddle = 0;
\text{while } (\text{abs}(rhigh-rlow) > \text{minErr})
Mmiddle = Mlow + (Mhigh-Mlow)/2;
rhigh = Msolve(P_4P_1(i), Mhigh, aRatio, \gamma_1, \gamma_4);
rlow = Msolve(P_4P_1(i), Mlow, aRatio, \gamma_1, \gamma_4);
rmiddle = Msolve(P_4P_1(i), Mmiddle, aRatio, \gamma_1, \gamma_4);
\text{if } (\text{sign}(rlow) == \text{sign}(rmiddle))
Mlow = Mmiddle;
else
Mhigh = Mmiddle;
end
end
Ms(i) = Mmiddle;
end
t2 = t1 * (1 + (2 * (gamma1 - 1)) / (gamma1 + 1)^2 * (gamma1 * Ms.^2 + 1) ./
(Ms.^2).*(Ms.^2-1));
u = mu0*(t2./t0).^(3/2).*((t0+S)./(t2+S));

% Ratio of P2 to P1 (this naming convention used for other ratios)
P2P1 = 1 + 2.*gamma1 ./ (gamma1 + 1).* (Ms.^2-1);
% Speed of contact surface
U2 = (2.*sqrt(gamma1*R1*T1)/(gamma1 + 1).* (Ms-1 ./ Ms));
% Density in Region 2
rho2 = (gamma1 + 1) * Ms.^2 ./ ((gamma1-1) * Ms.^2 + 2). * P1Metric / (R1*T1);
% Speed of Shock
Us = Ms * sqrt(gamma1 * R1 * T1);

% Quantities for Mirels theory
ue = Us - U2;
uwue = Us ./ ue;

% Shock thicknesses, and time to pass
% eqn's from Thompson (Compressible-Fluid Dynamics), 7.109 & 7.110
% Find mean free path (mfp)
mfp = u ./ (0.67 .* rho1 * a1);  % Relation from White 1-32
% Use the appropriate line for the intended configuration
sensingElementLength = 0; % Pitot configuration
sensingElementLength = 0.000762 % Static config, in meters
%calculating time to pass
P2 = P2P1.*P1;

\[ \Delta M = 3 \frac{mfp}{(M_s - 1)}; \quad \text{%thickness from Mach number} \]

\[ \Delta P = 12 \frac{\gamma_1 mfp}{(\gamma_1 + 1)} \frac{P_1}{(P_2 - P_1)}; \quad \text{%thickness from } P \]

\[ t_{\text{shock pass } M} = \frac{(\Delta M + \text{sensingElementLength})}{U_s}; \]

\[ t_{\text{shock pass } P} = \frac{(\Delta P + \text{sensingElementLength})}{U_s}; \]

PStep = (P2P1-1).*P1;

%Mach number behind shock
M2 = \(2 \left( M_s \right)^2 - 1 \right) \left(1/(2) \right) \left((\gamma_1 - 1) \frac{1}{2} \left(M_s \right)^2 + 1 \right) \left(M_s \right)^2 \right)^{0.5};

\[ \%P2StagStep = P2 + 0.5 \cdot \rho_2 \cdot U_2^2 - P_1; \]

%Have to convert dynamic pressure from metric
P2Stag = P2.\left(1 + (\gamma_1 - 1)/2 \cdot M_2^2\right)\left(\gamma_1/(\gamma_1 - 1)\right);

P2StagStep = P2Stag - P1;

%Calculate flow duration (taking the 90% value)
T2T1 = \left(1 + 2 \cdot (\gamma_1 - 1)/(\gamma_1 + 1) \cdot \gamma_1 \cdot (M_s^2 + 1)/M_s^2 \cdot (M_s^2 - 1)\right);

\eta = \left(\gamma_1 + 1\right) \frac{M_s^2}{\left((\gamma_1 - 1) \cdot M_s^2 + 2\right)};

G = \frac{1}{\gamma_2} \cdot T2T1 \cdot (\eta - 1) \cdot \eta / M_s;

\tau_{M} = 0.9 \cdot 1.13/1000 \cdot P_1 \cdot 51.71 \cdot d^2 / G; \%1.13 \text{ is for air}

%calculate shock attenuation from eq. 41 in Roshko flow duration paper
Msa = M_s \left((\eta - 1)/\eta\right);

P2P1a = 1 + 2 \cdot \gamma_1 / (\gamma_1 + 1) \cdot (Msa \cdot 2 - 1);

PStepa = (P2P1a-1).*P1;

%Calculate tube length for flow time (from Roshko flow duration paper)
F = \frac{1}{\gamma_2} \cdot T2T1 \cdot (\eta - 1) / \eta / M_s;

x_0 = 62 \cdot P_1 \cdot 51.71 \cdot d^2 / F \cdot d^2/12; \quad \%62 \text{ is for air}

%Now incorporating reflection times, too (from Fig. 5.1-3 in handbook)
%Calculate reflected shock M (taken from Matt Borg’s code)
T2 = T2*T1;
val=Ms./(Ms.^2-1).*sqrt(1+((2*(gamma1-1))./((gamma1+1).^2)).*(Ms.^2-1).*(gamma1+1./Ms.^2));
Mr=(1+sqrt(1+4*val.^2))./(2*val)-M2;
ur=Mr.*sqrt(gamma1*R1*T2);

%calculate ratio of driven section to testing length (x0 from above)
U21 = U2/a1;
L1x0 = Ms./U21.*((U21+Mr)./(Ms+Mr));
%length of driven section
L1 = x0.*L1x0;

%calculate length of driver section (long eq, split into two lines):
%calculate sound speed ratio:
A41 = 1/aRatio;
L1L4 = 2*Ms/A41.*(1-(gamma4-1)/(2*A41).*U21).^((-gamma4+1)/(2*gamma4-1));
L1L4 = L1L4.*( (U21+Mr)./(Ms+Mr));
L4 = L1./L1L4;

%Calculate Reynolds # to check for possibility of transition
%Find distance between shock & contact surface:
tDevelop = Us./x0;
distance = (Us-U2).*tDevelop;
Re = rho2.*U2.*distance./mu;

%for assuming 12 ft driven section, which is settled on
xf = 12./L1x0; %testing location for a 12-foot section
%find similarity parameter X for x0
X1 = 4*(xf./x0);

B.2 Plotting Full Runs
runNum = 334;
plotSame = 1; %if you just want to plot over the same time interval
plotNorm = 0; %if you want to normalize time to match shock peaks
normV = 0;
%offset = -.9035;
plotP = 1; %if you want to plot actual pressures instead of voltages

skip = [2 3 6]; %sensors that shouldn't be normalized if normV=1
low = -.006;
high = 0.004;

initString = 'Run';
midString = '_Ch';
endString = '.wfm';

averaging = 0; %set to 1 if you want to low-pass average, 0 otherwise
n = 50;
inc = 1;

%list the sensors by channel
sensors = [1 4 5:8 10:16]; %8 13

colors = {color cell string};
legstr = {'P96R-180 (6773)', 'Driver', ...other trace names}
offset = [offsets for traces]*70;
cals = [Sensor calibration factors];

figure(runNum)
hold on;

if(~plotSame)
    for j = sensors(1):sensors(end)
if (~ismember(sensors,j))
    continue;
end

if (plotNorm)
    %vMax = max(squeeze(vc(runNum,j,:)));
    %iMax = find(vc(runNum,j,:)==vMax,1,'first');
    % use following line if it's a badly formed shock
    iMax = find(vc(runNum,j,:)>.02,1,'first');
    tp = squeeze(tc(runNum,j,:));
    tp = tp-tp(iMax);
    plot(tp*1000,squeeze(vc(runNum,j,:)))
    xlabel('Time (ms)');
    ylabel('Voltage');
else
    vp = squeeze(vc(runNum,j,:));
    if (normV && ~ismember(j,skip))
        vp = vp/max(abs(vp));
    end
    plot(squeeze(tc(runNum,j,:)) * 1000, vp+offset(j), colors{j})
    xlabel('Time (ms)');
    ylabel('Voltage');
end
end

if (plotSame)
    % hold on
    for j = sensors(1):sensors(end)
if (~ismember(sensors, j))
    continue;
end

if (j <= 4)  %first scope
    filename = strcat('tek10', num2str(runNum), 'CH', num2str(j), '.isf');
    if (runNum > 99)
        filename = strcat('tek1', num2str(runNum), 'CH', num2str(j), '.isf');
    end
    [v, t] = isfread(filename);
elseif (j > 4 && j < 9)  %second scope
    p = j - 4;
    filename = strcat('tek30', num2str(runNum), 'CH', num2str(p), '.isf');
    if (runNum > 99)
        filename = strcat('tek3', num2str(runNum), 'CH', num2str(p), '.isf');
    end
    [v, t] = isfread(filename);
elseif (j > 8 && j < 13)  %third scope
    p = j - 8;
    filename = strcat('tek30', num2str(runNum), 'CH', num2str(p), '.isf');
    if (runNum > 99)
        filename = strcat('tek3', num2str(runNum), 'CH', num2str(p), '.isf');
    end
    [v, t] = isfread(filename);
else  %fourth scope
    p = j - 12;
    filename = strcat('tek30', num2str(runNum), 'CH', num2str(p), '.isf');
    if (runNum > 99)
        filename = strcat('tek3', num2str(runNum), 'CH', num2str(p), '.isf');
    end
    [v, t] = tekread(filename);
end

[v, t] = isfread('tek0025CH1.isf');
one = find(t > low, 1, 'first');
two = find(t > high, 1, 'first');
if (isempty(one))
    one = 1;
end

if (isempty(two))
two = length(v);
disp('Requested second time is after end of record')
end

vp= v(one:two)-mean(v(one:one+200));

if (plotP==1)
    vp = vp*cals(j);
end

tp = t(one:two);

if (averaging)
    [tpa,vpa] = AverageFilter(tp,vp,n,inc);
clear tp vp
    tp = tpa;
    vp = vpa;
end

if (plotNorm)
    vMax = max(vp);
iMax = find(vp==vMax,1,'first');
% use following if it's a badly formed shock
%iMax = find(vp>.018,1,'first');
%tp = tp-tp(iMax);
end

if (normV && ~ismember(j,skip))
    vp = vp/max(abs(vp))*1;
end
plot(tp*1000,(vp+offset(j)),colors{j});
xlabel('Time (ms)');
ylabel('Voltage (mV)');

if(plotP == 1)
ylabel('Pressure (psi)');
end
end
legend(legstr{sensors})
xlim([low high]*1000)
end

B.3 Shock Tube Run Processing Code

clear all;
close all;

runArray = [264];%[375];
channels = [1 4 5:8 11 12 13 14 15 16];
plots = 0;
skip = [];
kulites = [16]; %which channels are Kulites (or, not PCB-132s)
refPCBs = [5:8];

initString = 'Run';
midString = '_Ch';
endString = '.wfm';
cutInterval = 1000; %number of points to use in the extracted interval
kuliteInterval = 1000; %same, but to be used with the Kulites
invPos = .2; %where the shock should appear in the interval

%Shock Detection Parameters
level = .005*ones(1,16);
bigShock = zeros(1,16)+1;
spike = zeros(1,16);

zoomWindowSize = ones(1,16)*3e-4;

minPeakWidth = ones(1,16)*2e-6;%1e-6;%1e-5;

filter1 = ones(1,16)*100;
filter2 = ones(1,16)*5;

coarseStep = ones(1,16)*20;
avgInts = ones(16,4);

kuliteWindowSize = zoomWindowSize(1);
kulitePeakWidth = 2e-5;
kulitePos = invPos;
kuliteFilter1 = 100;
kuliteFilter2 = 30;
kuliteInts(1) = -20e-5;
kuliteInts(2) = -5e-5;
kuliteInts(3) = 5e-5;
kuliteInts(4) = 16e-5;
kuliteSpike = 0;

refPCBWindowSize = zoomWindowSize(1);
refPCBInts(1) = -35e-5;
refPCBInts(2) = -15e-5;
refPCBInts(3) = 10e-5;
refPCBInts(4) = 20e-5;
refPCBSpike = 0;

ts = zeros(length(runArray),length(channels));
vs = zeros(length(runArray),length(channels));
s = zeros(length(runArray),length(channels));
vc = zeros(length(runArray),16,cutInterval);
tc = zeros(length(runArray),16,cutInterval);
driver = zeros(length(runArray),1);
driven = zeros(length(runArray),1);
drivenV = zeros(length(runArray),1);
slopeD = 0;
offsetD = 0;
linstyl = char('b','r','g','k','c','y','m','r:');
for i=runArray(1):runArray(end)  %begin looping through the runs
if (~ismember(i,runArray))  %skip run if it wasn't called out
  continue;
end
if ( ismember(i,skip) == 1)
  continue;  %skip if this run is noted as one to skip
end

if  i<11  %stored driver kulite calibrations for different run ranges
  slopeD = 6.9976;
  offsetD = -1.4913;
elseif i<43
  slopeD = 6.611;
  offsetD = -1.8665;
elseif i<63
  slopeD = 4.8639;
  offsetD = -1.5534;
else
slopeD = 0;
offsetD = 0;
end
for j = channels(1):channels(end)  %begin looping through sensors
  %if this channel isn't in the channel array, skip
  if (~ismember(j,channels))
    continue;
  end

  if (ismember(j,kulites))
    bigShock(j) = 0;
    zoomWindowSize(j) = kuliteWindowSize;
    avgInts(j,:) = kuliteInts;
    minPeakWidth(j) = kulitePeakWidth;
    filter1(j) = kuliteFilter1;
    filter2(j) = kuliteFilter2;
  end

  if (ismember(j,refPCBs))
    bigShock(j) = 0;
    zoomWindowSize(j) = refPCBWindowSize;
    avgInts(j,:) = refPCBInts;
    minPeakWidth(j) = kulitePeakWidth;
    % filter1(j) = kuliteFilter1;
    % filter2(j) = kuliteFilter2;
  end

  if (j≤4)  %first scope
    filename = strcat('tek10',num2str(i),'CH',num2str(j),'.isf');
    if (i>99)
      filename = strcat('tek1',num2str(i),'CH',num2str(j),'.isf');
    end
  elseif (j>4 & & j<9)  %second scope
    p = j-4;
filename = strcat(initString,num2str(i),'-2',
    midString,num2str(p),endString);
elseif (j > 8 && j < 13) % third scope
    p = j-8;
    filename = strcat('tek30',num2str(i),'CH',num2str(p),'isf');
    if (i > 99)
        filename = strcat('tek3',num2str(i),'CH',num2str(p),'isf');
    end
else % fourth scope
    if (i < 43)
        continue;
    end
    p = j-12;
    filename = strcat(initString,num2str(i),'-4',
        midString,num2str(p),endString);
end

[ts(i,j), vs(i,j), ns(i,j), tc(i-runArray(1)+1,j,:),
    vc(i-runArray(1)+1,j,:)] = LowPassDetectFilteredF(filename,
    zoomWindowSize(j), level(j), minPeakWidth(j), bigShock(j),
    filter1(j), filter2(j), coarseStep(j), cutInterval, invPos,
    squeeze(avgInts(j,:)), spike(j), j);

if (plots == 1)
    figure(j)
    hold on
    plot(squeeze(tc(i,j,:)), squeeze(vc(i,j,:)-vc(i,j,1)), linestyle(j));
    end

clear v t;

end
if (length(runArray) == 1) % if you're not batch processing, display
    disp('Times')
    ts(i,:);
B.4 Shock Detection Code

This is the LowPassDetectFilteredF function found in the previous code.

```matlab
function [shocktime, shockSize, shockInd, exportT, exportV] = 
    LowPassDetectFilteredF(filename, filterWindowSize, shockLevel, 
    falseWidth, bigShock, n1, n2, incl, cutInterval, invPos, avgInts, 
    spike, channel)

%the time interval in which to look for the peak maximum
maxInterval = 5e-5;
%maximum number of false positives before abandoning the attempt
maxFalsePositives = 800;

%the time to look before and after the shock for updated shock time
searchIntervalTime = 5e-6;
%use a multiple of this interval to search for the maximum if using
%BigShock.
multi = 3; %this is the multiple to use for the BigShock routine.
try
    if (isempty(strfind(filename, '.wfm')))
        [v,t] = isfread(filename);
```
else
    [v,t] = tekread(filename);
end

catch
    disp(strcat('Problem reading ', filename, '! Probably does not exist'))
    shockSize = -1;
    shockInd = -1;
    shockTime = -1;
    exportT = zeros(cutInterval,1);
    exportV = zeros(cutInterval,1);
    return;
end

%shockLevel = 0.0002;
%falseWidth = 2e-5; %maximum peak width for a false positive
%read data
[v,t] = tekread(filename);

if (length(v) ≤ 300)
    disp(strcat(filename, ' record too short, skipping'))
    shockSize = -1;
    shockInd = -1;
    shockTime = -1;
    exportT = zeros(cutInterval,1);
    exportV = zeros(cutInterval,1);
    return;
end
%de-trend data so that detecting Kulite shocks
%doesn't depend on mean pressure of that run
v = v - mean(v(1:300));
sampleRate = t(2)-t(1);
searchInterval = round(searchIntervalTime/sampleRate);
% Rough-cut low-pass filter
ind = 1;
count = 1;
n = n1;
inc = inc1;
exportT = zeros(cutInterval,1);
exportV = zeros(cutInterval,1);
if(n == 1) % if you're not filtering, just skip the loop
v2 = v;
t2 = t;
else
while ind+n < length(v)
v2(count) = mean(v(ind:ind+n));
t2(count) = t(ind+round(n/2));
ind = ind+inc;
count = count+1;
end
end

% use low-pass data for shock detection
shockFound = 0;
startInd = 1;
shockInd = 4;
vs = v2;
absoluteInd = 1;
count = 0;
while(shockFound == 0)
shockInd = find(vs(1:end)>shockLevel,1,'first');
count = count+1;
if (count > maxFalsePositives)
    disp('Too many false positives in first filter! :/')
    disp(filename)
    shockSize = -1;
    shockInd = -1;
    shocktime = -1;
    exportT = zeros(cutInterval,1);
    exportV = zeros(cutInterval,1);
    return;
end

if we accidentally stumbled right into the shock,
% keep backing up until we're out of it
while (shockInd == 1)
    absoluteInd = absoluteInd - 2 * round(falseWidth/sampleRate/inc);
    clear vs;
    if (absoluteInd < 1)
        disp('Threshold crossed, but not a shock! :-O First')
        disp(filename)
        shockSize = -1;
        shockInd = -1;
        shocktime = -1;
        exportT = zeros(cutInterval,1);
        exportV = zeros(cutInterval,1);
        return;
    end
    vs = v2(absoluteInd:end);
    shockInd = find(vs(1:end)>shockLevel,1,'first');
    end

if (isempty(shockInd))
    disp('No shock found :(')
    disp(filename)
    shockSize = -1;
shockInd = -1;
shocktime = -1;
exportT = zeros(cutInterval,1);
exportV = zeros(cutInterval,1);
return;
end

widthLevel = max(vs(shockInd:shockInd+
    round(maxInterval/sampleRate/inc)))/2;
maxInd = find(vs(shockInd:shockInd+round(maxInterval/sampleRate/inc))
    ≥widthLevel*2,1,'first');

first = round(shockInd-.1*falseWidth/sampleRate/inc);

%if the shock is too close to the beginning of the interval
%to back up the normal amount, just go to the beginning
if( first<1 )
    first = 1;
end

width1 = find(vs(first:end)>widthLevel,1,'first');
width2 = find(vs(shockInd+maxInd:end)<widthLevel,1,'first');

if(isempty(width2))
    width2 = length(vs);
end

if((width2+maxInd-width1)*sampleRate*inc+.1*falseWidth>falseWidth)
    shockFound = 1;
else
    %Move index forward behind false shock
    startInd = round(shockInd+falseWidth/sampleRate/inc+.1);
    absoluteInd = absoluteInd + startInd - 1;
vs = v2(absoluteInd:end);

end
end

shockInd = shockInd + absoluteInd - 1;
shocktime = t2(shockInd)

lowInd = find(t>shocktime-filterWindowSize,1,'first');
highInd = find(t>shocktime+filterWindowSize,1,'first');

%t3 = t;
v3 = v;

%re-do fine filter only over the period where shock is located

t4 = t(lowInd:highInd);
v4 = v(lowInd:highInd);

ind = 1;
count = 1;
n = n2;
inc = 1;
clear t2 v2

if(n == 1)  %if you're not filtering, just skip the loop
v2 = v;
t2 = t;
else
while ind+n < length(v4)
v2(count) = mean(v4(ind:ind+n));
t2(count) = t4(ind+round(n/2));
end
%use low-pass data for shock detection

shockFound = 0;
oldshockInd = shockInd;
oldshockTime = shocktime;
startInd = 1;
shockInd = 4;
vs = v2;
absoluteInd = 1;
iterations = 0;

while (shockFound == 0)
    iterations = iterations +1;
    if ( iterations > maxFalsePositives )
        disp('Got caught in a loop! :(
              Too many false positives in second filter')
        disp(filename)
        shockInd = [];
        break;
    end
    shockInd = find(vs(1:end)>shockLevel,1,'first');

%if we accidentally stumbled right into the shock,
%keep backing up until we're out of it

while (shockInd == 1)
    absoluteInd = absoluteInd-2*round(falseWidth/sampleRate);
clear vs;
    if(absoluteInd < 1)
        disp('Threshold crossed, but not a shock! :-O Second')
        disp(filename)
        shockSize = -1;
shockInd = -1;
shocktime = -1;
exportT = zeros(cutInterval,1);
exportV = zeros(cutInterval,1);
return;
end
vs = v2(absoluteInd:end);
shockInd = find(vs(1:end)>shockLevel,1,'first');
end
if isempty(shockInd)
disp('No shock found :( Second')
break;
end
widthLevel = max(vs(shockInd:shockInd+
    round(maxInterval/sampleRate)))/2;
maxInd = find(vs(shockInd:shockInd+
    round(maxInterval/sampleRate))>widthLevel*2,1,'first');
first = round(shockInd-.1*falseWidth/sampleRate);
if( first<1 )
first = 1;
end
width1 = find(vs(first:end)>widthLevel,1,'first');
width2 = find(vs(shockInd+maxInd:end)<widthLevel,1,'first');
%if the shock is wider than the vs window, width2 comes up empty
if isempty(width2)
width2 = length(vs);
end
\begin{verbatim}
if ((width2+maxInd-width1)*sampleRate+.1*falseWidth>falseWidth)
    shockFound = 1;
else
    startInd = round(shockInd+falseWidth/sampleRate*1.1);
    absoluteInd = absoluteInd + startInd - 1;
    vs = v2(absoluteInd:end);
end
end

% re-calculate shock position with correct midlevel
%(different from first iteration because coarse filter reduces max)
if (isempty(shockInd))
    disp('Using previous shock time')
    disp(filename)
    shocktime = oldshockTime;
    shockInd = find(t2>shocktime,1,'first');
else
    shocktime = t2(shockInd);
end

cutInd = find(t>shocktime,1,'first');
first = cutInd-invPos*cutInterval;
last = cutInd+(1-invPos)*cutInterval;
if (first<1)
    first = 1;
end
if (last > length(t))
    last = length(t);
end

% the initialization of these is just to prevent ProcessRunsFancy
\end{verbatim}
% from breaking if there's an unexpected end to this script

clear exportT exportV;

exportT = t(first:last-1);
exportV = v(first:last-1);

if(length(exportT) < cutInterval)
    exportT = [zeros(cutInterval-length(exportT),1); exportT];
    exportV = [zeros(cutInterval-length(exportV),1); exportV];
end

lateTime1 = avgInts(3);
lateTime2 = avgInts(4);

% measure shock jump
first = shockInd+round(avgInts(1)/sampleRate);
last = shockInd+round(lateTime2/sampleRate);

% correct for intervals accidentally going outside the v2 bounds
if(first < 1)
    first = 1;
end

if(last > length(v2))
    last = length(v2);
end

hold on
% plot(t2,v2)
early1 = t2(first);

second = shockInd+round(avgInts(2)/sampleRate);
if(second<1)
    disp('Pre-shock average out of range')
end

disp(filename)
oldshockInd = find(t >= oldshockTime, 1, 'first')
clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

clear t3 v3 t2 v2;
numawun = oldshockInd + round(1.1 * avgInts(1) / sampleRate);
numadoo = oldshockInd + round(1.1 * avgInts(4) / sampleRate);
[t3, v3] = AverageFilter(t(numawun:numadoo), v(numawun:numadoo), n2, 1);
t2 = t3;
v2 = v3;

early1 = t(oldshockInd + round(avgInts(1) / sampleRate));
second = oldshockInd + round(avgInts(2) / sampleRate) - numawun;
last = oldshockInd + round(lateTime2/sampleRate) - numawun;
shockInd = oldshockInd - numawun;

if (bigShock == 0)
    shockSize = findjump(early1, early2, late1, late2, t, v)
else
    shockSize = max(v2(start:last))
        - mean(v2(first:shockInd+round(avgInts(2)/sampleRate))));
    if(spike == 1)
        shockSize = shockSize +
            mean(v2(first:shockInd+round(avgInts(2)/sampleRate))) -
            min(v2(start:shockInd));
end
shockSize
end

start = shockInd-searchInterval;
last = shockInd+searchInterval;

if(start<1)
    start = 1;
end

if(last > length(v2))
    last = length(v2);
end;

shockLevel = shockSize/2+findmean(early1, early2, t, v);
shockInd = find(v2(start:end)>shockLevel,1,'first')+start;
shocktime = t2(shockInd)

if(isempty(shockInd))
    shockInd = find(v2>shockLevel,1,'first');
    shocktime = t2(shockInd)
if(abs(shocktime-oldshockTime>1e-4))
    shocktime = [];
if (isempty(shocktime))
    shocktime = oldshockTime;
    shockInd = find(t2>shocktime,1,'first');
    % shockLevel
    % channel
    disp('Using old shock time because search was empty!')
end

early1v = v2(first);
early2v = v2(second);

late1v = v2(shockInd+round(lateTime1/sampleRate));
late2v = v2(OldLast);

avgt = [mean([early1 early2]), mean([late1 late2])];
avgv = [findmean(early1, early2, t2, v2),
        findmean(late1, late2, t2, v2)];

% use these lines if you want to plot with
% shock at t=0 (compare multiple runs directly)
% early1=early1-shocktime;
% early2 = early2-shocktime;
% late1 = late1-shocktime;
% late2 = late2-shocktime;
% t = t-shocktime;
% t2 = t2-shocktime;
% shocktime = 0;
figure(channel)
plot(t*1000, v*1000, 'b')
hold on
plot(t2*1000, v2*1000, 'k');
start = shockInd-searchInterval*multi;

if(start<1)
  start = 1;
end

if(spike == 1 && bigShock ==1)
  plot(t2*1000,ones(1,length(t2)) *
       (shockSize+findmean(early1,early2,t,v) 
        +min(v2(start:shockInd)))*1000,'r')
else
  plot(t2*1000,ones(1,length(t2)) *
       (shockSize+findmean(early1,early2,t,v)))*1000,'r')
end

%plot(t2,v2,'r')

plot([early1,early2,late1,late2]*1000, 
     [early1v,early2v,late1v,late2v]*1000,'ro')

plot(avgt*1000,avgv*1000, 'kp');

plot(shocktime*1000,shockLevel*1000,'mx');

if(spike == 1 && bigShock ==1)
  plot((t2)*1000,ones(1,length(t2))*
       (min(v2(shockInd-searchInterval*multi:shockInd)))*1000,'r');
end

plot(t2*1000,ones(1,length(t2)) *
     (findmean(early1,early2,t,v)))*1000,'r');

xlim([shocktime-5e-4,shocktime+5e-4]*1000)
B.5 Averaging Function

This is the code for the function AverageFilter referenced in the previous code.

```matlab
function [t2, v2] = AverageFilter(t, v, n, inc)
    count = 1;
    ind = 1;
    while ind + n < length(v)
        v2(count) = mean(v(ind:ind+n));
        t2(count) = t(ind+round(n/2));
        ind = ind + inc;
        count = count + 1;
    end

    if (inc == 1)
        t2(count:count+n-1) = t(ind+1:end);
        v2(count:count+n-1) = v(ind+1:end);
    end
```
B.6 Function findmean

```matlab
function [ average ] = findmean( lowtime, hightime, t, v )
indLow = find( t>lowtime,1,'first' );
indHigh = find( t>hightime,1,'first' );
average = mean(v(indLow:indHigh));
end
```
Appendix C: PCB-132 Calibrations

Ten PCB-132 sensors were calibrated in the 3-Inch Shock Tube with the electrical burst system. Here, the data from all ten calibrations are shown with the calibration curves on logarithmic axes, so that the fit for each sensor can be evaluated.

![Figure C.1. Sensor #6830](image-url)
Figure C.2. Sensor #6831

Figure C.3. Sensor #6819
Figure C.4. Sensor #6657

Figure C.5. Sensor #6773
Figure C.6. Sensor #5411

Figure C.7. Sensor #6707
Figure C.8. Sensor #5396

Figure C.9. Sensor #6772
Figure C.10. Sensor #6617
VITA
VITA

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