EXPERIMENTAL METHOD TO MEASURE PRESSURE-COUPLED RESPONSES OF INDUCED SOLID ROCKET INSTABILITIES USING A NEXT-GENERATION MAGNETIC FLOWMETER

A Thesis in Aerospace Engineering

by

Jan R. Herzog

© 2012 Jan R. Herzog

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

August 2012
The thesis of Jan R. Herzog was reviewed and approved* by the following:

Michael M. Micci  
Professor of Aerospace Engineering  
Director of Graduate Studies  
Thesis Advisor

Sven G. Bilén  
Associate Professor of Engineering Design, Electrical Engineering, and Aerospace Engineering

George A. Lesieutre  
Professor of Aerospace Engineering  
Department Head of Aerospace Engineering

*Signatures are on file in the Graduate School
ABSTRACT

The increased use and further development of high-energy-density propellants requires a method to quantitatively characterize the propellant’s stability. There are several methods, such as the T-burner, Rotating Valve Burner, and Impedance Tube that measure the acoustic admittance of the burning surface of solid propellant; however, each has its drawbacks. This study sought to improve techniques for measuring acoustic admittance using a magnetic flowmeter in a system that created a strong, uniform magnetic field, increased the number of velocity measurements taken in a single burn, and increased the amplitude of the forced pressure oscillation.

Samples of a composite solid rocket propellant were burned inside a stainless steel combustion chamber. Acoustic oscillations were forced inside the chamber using two methods in an effort to impose an oscillating pressure on the burning propellant surface. The first method used a rotating toothed gear that passed over the exit area of a sonic nozzle. The second method took advantage of the deformation of a piezoelectric stack actuator to vibrate a titanium shim over the exit area. In both methods, the mean and oscillatory pressures were measured. Additionally, a permanent magnet and a flowmeter were utilized to measure the velocity of the combustion gases as they flowed from the burning surface. These measurements were then used to calculate the acoustic admittance of the burning propellant surface.

A 0.5 ± 0.06 Tesla magnetic field was successfully created inside the stainless steel combustion chamber by using eight N42-grade nickel-coated neodymium rare earth magnets. The magnetic field helped to increase the signal to noise ratio of the velocity measurement. A combustion chamber that allowed for eight velocity measurements was also successfully created. The use of eight velocity measurements in a single burn improved the statistical accuracy of each
test. At the close of this investigation, the rotating toothed gear and piezoelectric actuator both failed in increasing the magnitude of the pressure modulation inside of the combustion chamber.
# TABLE OF CONTENTS

LIST OF FIGURES ......................................................................................... vi
LIST OF TABLES .............................................................................................. vii
NOMENCLATURE .............................................................................................. ix
ACKNOWLEDGMENTS .................................................................................. x

Chapter 1 Introduction .................................................................................. 1
   Acoustic Admittance .................................................................................. 1
   Magnetic Flowmeter Theory ................................................................... 2
   Piezoelectric Fundamentals ................................................................... 4
   Motivation for Improvements to Measuring the Pressure-Coupled Response ............. 6
   Thesis Overview ...................................................................................... 7

Chapter 2 Review of Other Response Measuring Devices .................................. 8
   T-Burner ................................................................................................. 8
   Rotating Valve ....................................................................................... 10
   Impedance Tube .................................................................................... 12

Chapter 3 Techniques and Experimental Setups ............................................. 14
   Pressure Modulation Techniques ....................................................... 14
      Piezoelectric Actuators .................................................................... 14
      Piezoelectric Actuator, Setup 2 ....................................................... 19
      Toothed Gear ................................................................................... 23
   Combustion Chamber .......................................................................... 28
   Magnetic Circuit ................................................................................... 30

Chapter 4 Controls and Data Acquisition, Test Procedure, and Analysis ............ 31
   Controls and Data Acquisition ......................................................... 31
   Testing Procedure ............................................................................... 33
   Linear Acoustic Analysis ...................................................................... 37

Chapter 5 Test Results and Discussion .......................................................... 40
   Magnetic Field Measurements ......................................................... 40
   Cold Flow Tests with the Toothed Gear Setup ................................... 44
   Cold Flow Tests with Setup 2 ............................................................. 47
   Hot Fire Tests ...................................................................................... 47
      Toothed Gear Setup Hot Fire 1 ....................................................... 48
      Toothed Gear Setup Hot Fire 6 ....................................................... 52

Chapter 6 Conclusions and Recommendations ............................................ 57

References .................................................................................................. 59
LIST OF FIGURES

Figure 1-1: U × B (3) ........................................................................................................ 3
Figure 2-1: Simplified Drawing of the T-Burner .............................................................. 8
Figure 2-2: Simplified Drawing of Rotating Valve Burner ............................................. 11
Figure 2-3: Simplified Drawing of an Impedance Tube Burner .................................. 13
Figure 3-1: Piezoelectric Actuator Setup 1 ................................................................. 16
Figure 3-2: Aluminum C ......................................................................................... 17
Figure 3-3: Teflon Tunnel .................................................................................... 18
Figure 3-4: Aluminum Block ............................................................................... 19
Figure 3-5: Setup 2 ............................................................................................. 21
Figure 3-6: Cutaway of the Slot Nozzle and Graphite Plate .................................. 23
Figure 3-7: Experimental Setup A ....................................................................... 24
Figure 3-8: Toothed Gear and Collar .................................................................. 26
Figure 3-9: Photo of Complete Toothed Gear Assembly ..................................... 26
Figure 3-10: Electrode Configuration .................................................................. 28
Figure 3-11: Magnetic Circuit ............................................................................. 30
Figure 4-1: Flowchart of Data for Toothed Gear Setup ........................................ 32
Figure 4-2: Flowchart of Data for Setup 2 .............................................................. 33
Figure 4-3: Toothed Gear and Aluminum Extrusions ............................................. 36
Figure 5-1: Principal Axis Definitions with Respect to the Magnetic Circuit .......... 40
Figure 5-2: Magnetic Field inside the Combustion Chamber ............................... 42
Figure 5-3: Volumetric Plot of the Magnetic Field ............................................. 43
Figure 5-4: Fast Fourier Transform of the Pressure Signal during a Toothed Gear Coldflow Test .............................................................. 45
Figure 5-5: Percent Modulation as a Function of Frequency for Toothed Wheel Setup .......... 46
Figure 5-6: Hot Fire 1 Pressure and Velocity Data ......................................................... 49
Figure 5-7: Hot Fire 1 Filtered Data ........................................................................... 51
Figure 5-8: Hot Fire 6 Pressure Data ........................................................................... 53
Figure 5-9: Hot Fire 6 Velocity Data ........................................................................... 54
Figure 5-10: Phase Angle as a Function of Distance above a Burning Surface .......... 55
LIST OF TABLES

Table 3-1: PICMA 885.91 Properties ................................................................. 15
Table 3-2: HPA-260-18-10 Properties ............................................................... 20
### NOMENCLATURE

- $a$ Speed of Sound, m/s
- $A$ Nozzle Area, m$^2$
- $A_0$ Acoustic Admittance
- $B$ Magnetic Field Strength, T
- $c$ Burn Rate Coefficient
- $d_{33}$ Strain Coefficient
- $i$ Imaginary Constant, $\sqrt{-1}$
- $f$ Frequency, Hz
- $f_0$ Resonance Frequency, Hz
- $F_{\text{dyn}}$ Dynamic Forces on Piezo Actuator, N
- $k_p$ Piezo Actuator Stiffness, N/m
- $L$ Distance between tungsten electrodes, m
- $m$ Mass Flow Rate, kg/s
- $m_p$ Volumetric Mass Injection Rate, kg/s/m$^3$
- $m_{\text{eff}}$ Effective Mass, kg
- $M$ Mach Number
- $n$ Burn Rate Exponent
- $N$ Number of Ceramic Layers
- $p$ Pressure, Pa
- $P_{\text{ref}}$ Reference Pressure, Pa
- $r$ Propellant Regression Rate, m/s
- $R_p$ Pressure-coupled Response
- $T$ Temperature, K
- $T_f$ Isentropic Flame Temperature, K
- $u$ Velocity, m/s
- $V$ Electric Potential, V
- $\alpha$ End-shortening constant
- $\gamma$ Ratio of Specific Heats
- $\Delta L$ Displacement of Piezo Actuator, m
- $\varepsilon$ Dimensionless Pressure Amplitude
- $\mu$ Dimensionless Burning Rate Amplitude
- $\rho$ Density, kg/m$^3$
- $\rho_s$ Solid Propellant Density, kg/m$^3$
- $\omega$ Angular Frequency, Radians
- $\omega_f$ Dimensionless Temperature Amplitude
- $\lambda$ Dimensionless Temperature Amplitude
- $\Delta L$ Displacement of Piezo Actuator, m
- $\varepsilon$ Dimensionless Pressure Amplitude
- $\mu$ Dimensionless Burning Rate Amplitude
- $\rho$ Density, kg/m$^3$
- $\rho_s$ Solid Propellant Density, kg/m$^3$
- $\omega$ Angular Frequency, Radians
- $\omega_f$ Dimensionless Temperature Amplitude
- $\lambda$ Dimensionless Temperature Amplitude
I wish to take the time to extend my gratitude to the many people that have helped me with this research. First, I wish to thank Dr. Michael Micci, Dr. Sven Bilén, and Dr. Dean Massey for all their guidance, assistance, and time that they gave me throughout the course of this project. Second, I would also like to thank Mr. Bob Dillon, Mr. Larry Horner, and Eric Viges for their skills in machining. I would like to also thank the electric propulsion group including Jeff Hopkins, Erica Capalungan, Jesse McTernan, Rohit Adusumilli, Chris DeForce, Brian Taylor, Russell Moore, Pierre-Yves Tuanay, Adam Cavovino, Megan Kwolek, and anyone I may have missed. It was great to be able to share ideas with you and get your feedback. I would finally like to thank my father, Dr. Siegfried Herzog for all his time spent sharing ideas with me and checking lines of computer code.
Chapter 1

Introduction

Acoustic Admittance

Acoustic waves will arise in rocket motors due to structural vibrations and fluid dynamic and combustion noise. According to the Rayleigh Criterion, instabilities can occur if heat and/or mass are added in phase with these acoustic oscillations. A parameter that is used to quantify the instabilities is the acoustic admittance and is given by

\[ A_p = \frac{u'/a}{p'/\bar{p}} \tag{1} \]

where the primes denote fluctuating quantities and overbar denote mean quantity. In Equation 1, \( u \) is the velocity of the combustion gases, \( a \) is the speed of sound, \( p \) is the pressure, and \( \gamma \) is the ratio of specific heats. Upon inspection of Equation 1, it is seen that the acoustic admittance is a nondimensionalized ratio of the fluctuating gas velocity to the unsteady pressure. The acoustic admittance is a complex number with the real part representing the velocity that is in phase with the pressure and the imaginary part representing the velocity that is 90 degrees out of phase. If the real part of the acoustic admittance is a positive number, then energy is being added to the system and an instability may be excited; however, if the real part is negative then damping occurs in the system and no instability will arise.

The pressure-coupled response function is a parameter that is related to the acoustic admittance and is used to quantitatively measure the addition of energy to the acoustic wave (1). The pressure-coupled response is given as
\[ R_p = \frac{(m' \bar{m}) + (\Delta T' \bar{T})}{p' \bar{p}}, \]  
\( (2) \)

where \( m \) is the mass flux of the combustion gases, \( T \) the gas temperature, \( \Delta T' \) is the nonisentropic temperature fluctuation, and \( p \) is the pressure. The relationship between the acoustic admittance and pressure-coupled response is given by

\[ R_p = 1 + \frac{A_0 \gamma}{M}, \]  
\( (3) \)

where \( M \) is the Mach number. It should be noted that there are different definitions of the pressure-coupled response and different relationships for the acoustic admittance. Great care must be taken when comparing these values with those given in other papers. Refer to Cardiff (1) for a full explanation of these differences. By knowing the acoustic admittance, the pressure-coupled response can be calculated and, hence, knowledge of the propellant’s stability can be obtained.

**Magnetic Flowmeter Theory**

The magnetic flowmeter operates on the principle of Faraday’s Law. As a conductor moves perpendicularly through a magnetic field, a potential is created perpendicular to both the direction of the motion and the magnetic field. The potential is given by (2).

\[ \Delta V = uLB \]  
\( (4) \)

where \( u \) is the velocity of the conductor, \( L \) is the distance across which the potential is being measured, and \( B \) is the magnetic field strength given in tesla. Figure 1-1 depicts the operation of the flowmeter schematically.
Two things should be noted from Equation 4: the first is that there is no stipulation that the conductor must be a solid. This experiment uses the exhaust gas from the combustion process as the conductor that moves perpendicular to the magnetic field. The exhaust gas is weakly ionized, which allows it to act as a conductor. Although Equation 4 does not state any limits on the conductivity of the conductor, there are practical limits. The upper limit may arise if the fluid is liquid metal, which would cause magnetohydrodynamic issues, such as the distortion of the magnetic field due to induced currents (3). The lower conductivity limit is $\sim 0.001 \text{ mΩ/m}$. Conductivities below this value cause the resistance of the exhaust gas to be on the same order of magnitude as the input impedance of the voltage measuring devices. As a result, current would
flow between the electrodes measuring the potential making the measurement unreliable (4). The propellant used in these experiments was a composite propellant of HTPB with an ammonium perchlorate oxidizer. Bestgen (5) has shown that several propellant’s containing ammonium perchlorate have conductivities that are above 0.001mΩ/m, thus proving that the propellant used in these experiments are above the lower conductivity limit.

Equation 4 must be modified to account for end-shortening and other losses so that the resulting equation is

\[ \Delta V = \alpha uLB, \]  

where \( \alpha \) is a nondimensional constant between 0 and 1. End-shortening arises when the electrodes measuring the potential are near the edges of the magnetic field where the field lines start to fringe (3). The value of \( \alpha \) can be calculated by measuring the potential of a known fluid velocity in a calibration test. It is discussed later as to why it was unnecessary to calculate \( \alpha \) in these experiments.

**Piezoelectric Fundamentals**

Piezoelectric materials convert electrical energy to mechanical energy and vice-versa. They exhibit the piezoelectric effect, which is the generation of an electric potential when a pressure is applied to the material. They also experience the inverse piezoelectric effect, which is that the material will change shape when an electric potential is applied. These materials exist naturally in the world, but are also manufactured so that piezoelectric and inverse piezoelectric effects are more pronounced.

Piezoceramics, a specific piezoelectric material, are manufactured through a poling process. Before the poling process, the piezoceramic is composed of many different cubic cells
that deform in different directions when an electric potential is applied. The poling process orients the cells so that when an electric potential is applied they all deform in the same direction producing a macroscopic displacement. Sometimes piezoceramics are layered and bonded together to form multilayer actuators or stack actuators. The displacement of a stack actuator can be estimated by (6)

$$\Delta L \approx d_{33} NV,$$

(6)

where $\Delta L$ is the displacement of the stack actuator, $d_{33}$ is the strain coefficient that corresponds to the direction of both the applied electric field and poling direction, $N$ is the number of ceramic layers, and $V$ is the operating voltage.

When using piezoceramic actuators that experience a tensile force, it is important to apply a preload, which is a compressive force that prevents the actuator from pulling itself apart. A preload should not be applied to the actuator if the electrode leads are open. If a preload is applied when the leads are open, then the piezoelectric effect will cause a charge to build up in the piezoceramic, which can adversely affect the operation of the actuator.

Piezoceramic actuators can be used in sinusoidal operation. In this form of operation, the dynamic forces and resonance frequency must be considered. In general, the actuator should not be operated at a frequency higher than $1/3$ of the resonance frequency otherwise it may shorten the lifespan or cause the actuator to fail. The resonant frequency and peak dynamic force are given by (6)

$$f_0 = \left(\frac{1}{2\pi}\right) \sqrt{\frac{k_i}{m_{\text{eff}}}},$$

(7)

$$F_{\text{dyn}} = \pm 4\pi^2 m_{\text{eff}} \left(\frac{\Delta L}{2}\right) f^2,$$

(8)
where \( f_0 \) is the resonance frequency, \( k_t \) is the piezo actuator stiffness, \( m_{\text{eff}} \) is the effective mass defined as 1/3 the mass of the ceramic stack plus any additional mass added to the end of the actuator, \( F_{\text{dyn}} \) is the peak dynamic force, \( \Delta L \) is the peak to peak displacement, and \( f \) is the operational frequency. Equation 8 can be used to check that the operational frequency is below 1/3 of the resonance frequency if the dynamic forces are known.

**Motivation for Improvements to Measuring the Pressure-Coupled Response**

This study sought to improve techniques for measuring acoustic admittance using a magnetic flowmeter in a system that created a strong, uniform magnetic field, increased the number of velocity measurements taken in a single burn, and increased the amplitude of the forced pressure oscillation. The measurement of the velocity of the combustion gases coming off of a burning surface is a crucial parameter in determining the pressure-coupled response. The velocity is proportional to the magnetic field, so increasing the magnetic field strength would increase the signal-to-noise ratio of the velocity measurement. By having the capability of taking multiple measurements of the velocity, the statistical accuracy of each test is increased. The other parameter that is needed to calculate the pressure-coupled response is the pressure. Increasing the amplitude of the forced pressure oscillation inside the combustion chamber will also increase the magnitude of the velocity signal. By increasing the magnetic field strength, the number of velocity measurements, and the amplitude of forced pressure oscillations, a more confident calculation of the pressure-coupled response could be made.
Thesis Overview

This thesis discusses the development and testing of three setups that were studied in improving the measurement of the pressure-coupled response. Chapter 2 outlines the general theory of three different devices that have been used to measure the pressure-coupled response. Chapter 3 presents various techniques and setups that were used to increase the pressure modulation inside the combustion chamber. In addition, the design of the combustion chamber and magnetic field are explained. In Chapter 4, the controls and data acquisition, testing procedure, and data analysis are discussed. Chapter 5 presents a detailed view of the magnetic field and the results of cold and hot fire experiments for each setup. Finally, conclusions of this study and the recommendations for future work are given in Chapter 6.
Chapter 2

Review of Other Response Measuring Devices

T-Burner

The T-burner has been used to measure the pressure-coupled response and is one of the most widely accepted devices used for this measurement. The T-burner consists of a long tube with samples of propellant placed on the ends. The combustion products are vented through an orifice that is located at the midpoint of the tube. This location corresponds to the nodal point of the first harmonic of the tube’s longitudinal mode. By having the vent located at the midpoint of the tube and burning the propellant samples at the ends, the burning surfaces are exposed to the maximum acoustic pressures. As a consequence, each tube size can be used to investigate only one frequency and different frequencies require different tube lengths. A simplified drawing of a T-burner can be seen in Figure 2-1.

![Figure 2-1: Simplified Drawing of the T-Burner](image)

Two different methods for measuring the pressure-coupled response have been used with the T-burner: the variable area T-burner (VATB) and the “pulsed during burning and pulsed after burning” method. The VATB uses a series of tests to calculate the pressure-coupled response and
is based on the assumption that the growth rate is proportional to the burning area of the propellant. Several tests are run, each using a different propellant burning area and then a graph of the growth rate of each test is plotted against the burning area. This plot should be a straight line for which the slope is related to the pressure-coupled response and the intercept of the line corresponds to damping (8).

The “pulsed during burning and pulsed after burning” method is sometimes referred to as the DB/AB method or simply as the pulsed method. Pressure pulses are injected into the T-burner with either pistons or some type of detonation. Sometimes the pulses are introduced into the T-burner through a hole in the propellant samples or through the sides of the T-burner. These locations are illustrated in red and in Figure 2-1. A measurement of the pressure decay rate is taken directly after the pulse is introduced. The decay rate is proportional to the difference in energy loss and energy gain in the T-burner. Immediately after burnout, another pulse is made and another measurement of the decay rate is taken. However, since the propellant is no longer burning, there is no source of energy gain and the decay rate is a measure of the energy loss. Both decay rate measurements are used to calculate the energy gain, which is then used to find the acoustic admittance (8).

There are several disadvantages that are associated with the T-burner. The first is that it is not the most cost effective method. Many tests must be run to obtain usable data, especially if the VATB method is used. A second disadvantage is with the measurement of the decay rate. When this measurement is taken, the conditions in the T-burner, such as the temperature, have changed because the propellant is no longer burning. This has the potential to be a misrepresentation of the admittance during burning.
Rotating Valve

A second method of measuring the pressure-coupled response is the rotating valve method. With this particular method, solid rocket fuel is burned in a combustion chamber and exhausted out of a nozzle that controls the mean chamber pressure. On the opposite end of the combustion chamber, is a second nozzle that is periodically covered and uncovered by a rotating valve. This valve causes small pressure oscillations to occur inside the combustion chamber. The frequency of the pressure oscillation is controlled by varying the speed of the rotating valve. The pressure and amplitude of the oscillations created by the rotating valve, relative to those occurring at the nozzle that controls the mean pressure, depend on the transient combustion properties of the propellant and the dynamics of the chamber (9). A relationship between the pressure-coupled response and the phase and amplitude of pressure oscillations is given by

\[
\text{Re}\left(\frac{\mu}{\varepsilon} + \frac{\omega_f}{\varepsilon}\right) = 1 + \frac{\gamma - 1}{2\gamma} + \frac{\cos(\phi)}{(p' A)/(A' \bar{p})},
\] (9)

where \(\text{Re}\left(\frac{\mu}{\varepsilon} + \frac{\omega_f}{\varepsilon}\right)\) is the real part of the pressure-coupled response, \(\mu\) is the dimensionless burning rate amplitude, \(\varepsilon\) is the dimensionless pressure amplitude, \(\omega_f\) is the dimensionless temperature amplitude, \(\phi\) is the phase between the pressure oscillation and the exhaust area oscillation, \(\bar{A}\) is the mean nozzle area, and \(A'\) is the oscillating nozzle area. The dimensionless burning rate, pressure and temperature amplitudes are each defined as a ratio of their instantaneous amplitude divided by their mean amplitude. Equation 9 was derived under the assumptions that the pressure oscillation was small when compared to the mean pressure, the oscillation was sinusoidal, and that the frequency was much lower than the first acoustic harmonic of the chamber.
Accurate knowledge of how the nozzle area changes with time is required to compute the pressure-coupled response. To do this, Brown, Erickson, and Babcock (9) measured a voltage between the rotating valve and an electrostatically charged probe that was directly related to the instantaneous nozzle area. In addition, the phase angle needs to be known. To measure the phase angle, the investigators created an auxiliary chamber that was connected to the rotating valve 180 degrees from the primary combustion chamber. This chamber was pressurized with nitrogen or helium when the solid rocket fuel was being burned and both the mean and unsteady pressures were measured. The measurements made in the auxiliary chamber were then used to determine the phase between the combustion chamber and the area. A drawing of a Rotating Valve Burner with the auxiliary chamber can be found in Figure 2-2.

![Figure 2-2: Simplified Drawing of Rotating Valve Burner](image)

As with the T-burner, there is a disadvantage to the rotating valve burner. The frequency and pressure amplitudes that can be tested are limited by the assumptions made in the derivation of Equation 10.
**Impedance Tube**

The third technique to measure the acoustic admittance is the impedance tube method. With this method, a sample of solid propellant in the shape of a disk is placed inside a tube. At the opposite end of the tube there is a nozzle and an acoustic driver. The acoustic driver is used to produce a standing acoustic wave of a predetermined frequency inside the tube. The combustion of the propellant will change the structure of the standing wave and by measuring this new wave structure and using the solutions to the impedance tube wave equations, the acoustic admittance can be determined (10). The impedance tube wave equations have been omitted as the impedance tube method is not the focus of this study. However, to use these equations the acoustic pressure and phase of the standing wave must be known. The impedance tube method utilizes several pressure transducers that are placed along the tube to obtain this information. There must be enough pressure transducers placed along the impedance tube to cover a distance that spans two standing wave pressure minima. In the study conducted by Baum, Daniel, and Zinn, a total of 15 pressure transducers were used (10). One of the reasons so many pressure transducers are needed is because the analysis requires that the phase and amplitude information of the standing wave be collected for a distance that spans at least two minima. A drawing of the impedance tube burner without a nozzle can be seen in Figure 2-3.
Figure 2-3: Simplified Drawing of an Impedance Tube Burner
Chapter 3

Techniques and Experimental Setups

Pressure Modulation Techniques

Two different modulation techniques were investigated in this study. The first used a piezoceramic actuator to temporarily block the exit of a choked nozzle. The second used a rotating toothed gear that interrupted the flow of combustion gases after they were accelerated through a sonic nozzle.

Piezoelectric Actuators

The first modulation technique used a piezoceramic actuator to temporarily block the exit of a choked nozzle. Two different setups were created to utilize this technique. The first setup was investigated early in the program and will hence be referred to as Setup 1. The second piezoelectric setup has not been tested and is currently being studied. It shall be referred to as Setup 2 from this point forward.

Setup 1 used a PICMA 885.91 Ceramic-Insulated High-Power Actuator purchased from Physik Instrumente to push a titanium shim that temporarily blocked the exit of a sonic nozzle. The properties of the PICMA 885.91 are presented in Table 3-1. Titanium was chosen for the shim because it would be able to withstand the high temperatures of the exhaust gases and is a lightweight material. This setup was used to test modulation frequencies up to 20 kHz. Upon inspection of Figure 3-1, one can see some of the major components of the system. In the top half of Figure 3-1, an “Aluminum C” is shown in green, a titanium shim shown in red, the piezoceramic actuator shown in blue, a “Teflon Tunnel” shown in gold, an aluminum block
shown in gray, and ultra-fine threaded screws shown in black. Note that the permanent magnet is not shown in Figure 3-1 to allow the other components to be seen.

Table 3-1: PICMA 885.91 Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions W × H × L</td>
<td>5 × 5 × 36 mm</td>
</tr>
<tr>
<td>Nominal Displacement at 100 V</td>
<td>32 ± 10% μm</td>
</tr>
<tr>
<td>Maximum Displacement at 120 V</td>
<td>38 ± 10% μm</td>
</tr>
<tr>
<td>Blocking Force at 120 V</td>
<td>950 N</td>
</tr>
<tr>
<td>Stiffness</td>
<td>25 N/μm</td>
</tr>
<tr>
<td>Electrical Capacitance</td>
<td>3.1 ± 20% μF</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>40 ± 20% kHz</td>
</tr>
</tbody>
</table>
Figure 3-1: Piezoelectric Actuator Setup 1
The titanium shim is not physically attached to the actuator. It was forced against the actuator by the pre-load thumbscrews. As the actuator expanded, it pushed on the center of the titanium shim causing it to flex over a portion of the exit nozzle area and upon contraction of the actuator the shim uncovered the nozzle area. The shim was constrained to a bowing motion by an “Aluminum C”. The additional lip on the edge prevents the shim from being blown away by the rocket exhaust. Greater detail of the Aluminum C may be found in Figure 3-2.

![Figure 3-2: Aluminum C](image)

Referring back to the top half of Figure 3-1, one can see a gold piece sitting on top of the actuator. This was a piece of Teflon with a “tunnel” cut into the underside. The purpose of the Teflon tunnel was to secure the actuator in a fixed orientation and allow it to have only one degree of freedom. Teflon was chosen as the material because it would be able to withstand the heat generated from the piezoelectric and it also acted as a lubricated surface so as not to hinder the displacement of the actuation. Prolonged use of the actuator causes the ceramic to rapidly heat up which adversely affects its performance. To help alleviate this problem, several holes were drilled in the top of the Teflon to allow for convective cooling. The Teflon piece is shown in Figure 3-3.
The aluminum block was created so that a preload could be applied to the actuator. Setup 1 originally used two stack actuators epoxied end-to-end. However, due to the high frequency motion of the actuators, the epoxy was unable to keep the two pieces attached. The setup was changed so that only one actuator was used and, as a consequence, the aluminum block was modified to have an extruded “finger”, illustrated in Figure 3-4.
The final thing to note about this setup, are the adjustable screws seen in Figure 3-1. These screws were used to apply a compressive load to the actuator. This was necessary because of the high frequency displacement of the actuator. If an appropriate preload was not applied, the actuator would pull itself apart. Furthermore, the preloaded had to be applied in such a manner as not to induce any lateral stresses in the actuator. Because of these difficulties it was decided that the return to a setup that used a toothed gear to cause a pressure oscillation would be best.

**Piezoelectric Actuator, Setup 2**

Setup 2 was designed to avoid some of the problems that were associated with Setup 1. This setup used a HPA-260-18-10 piezo stack actuator from PiezoSystem Jena which was manufactured with a built-in preload. The properties of the HPA-260-18-10 can be found in Table 3-2. Due to the dynamic limitations of the piezo stack, the maximum modulation frequency was 3 kHz. A titanium shim was attached to the end of the piezo actuator so that, as
the actuator expanded and contracted, it pushed and pulled the shim. When the shim was pushed it covered a portion of a slotted nozzle and as it was pulled it uncovered the nozzle.

Table 3-2: HPA-260-18-10 Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions L × D</td>
<td>185 × 18 mm</td>
</tr>
<tr>
<td>Displacement at 0 V to 1000 V</td>
<td>200 μm</td>
</tr>
<tr>
<td>Displacement at –200 V to 1000 V</td>
<td>260 μm</td>
</tr>
<tr>
<td>Blocking Force</td>
<td>4000 N</td>
</tr>
<tr>
<td>Stiffness</td>
<td>10 N/μm</td>
</tr>
<tr>
<td>Electrical Capacitance</td>
<td>510 nF</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>3 kHz</td>
</tr>
</tbody>
</table>

The various components of Setup 2 can be found in Figure 3-8, in which 1 marks a piezoelectric actuator, 2 a titanium shim, 3 a graphite plate, 4 a slotted nozzle, 5 the combustion chamber, and 6 a block of aluminum designed to hold the actuator. The permanent magnet is not shown in Figure 3-8 so that the all the features of the setup can be seen. Also not shown in the Figure 3-8 is a protective covering that is placed over the actuator. The protective covering shields the actuator from the harsh environment that is produced by the exhaust.
The piezo-actuator was placed inside the aluminum block. The aluminum block was designed to attach to the top of the combustion chamber and allow the titanium shim to pass through a small slot. The aluminum block also held the piezo-actuator in a secure position preventing it from moving.

As the shim covered up part of the nozzle exit area, it was pushed upward by the combustion gases. To help prevent the tip of the shim from being deflected upward, the shim was designed to extend past the exit area of the nozzle. This made it necessary to cut a slot into the shim to allow the combustion gases to pass through. A groove was also cut into the underside of the graphite plate, which guided the titanium shim and kept the motion in one direction. Graphite was chosen because it would be able to withstand the heat of the combustion gases, and, more importantly, because the graphite acted as a lubricated surface. This is a desired property because the piezo-actuator can only generate a finite force, all of which needs to be used to move the shim. Any energy lost to friction will hinder the motion.

It was thought that ten percent of the nozzle exit area had to be covered to produce an acoustic wave strong enough to yield favorable measurements of the oscillating pressure and velocity. Since the piezo-actuator has a maximum displacement of 0.0011 inches (28 micrometers), a converging nozzle had to be created so that 10 percent of its exit area could be covered. A slot nozzle was designed that had an exit area in the shape of a rectangle with a width of 0.011 inches and a length of 0.171 inches. The converging part had a 45 degree half angle. Figure 3-9 shows a cutaway view of the graphite plate, slot nozzle, and titanium shim.
Another setup that was investigated used a toothed gear to create a pressure oscillation inside the combustion chamber. There were several challenges that had to be overcome such as maintaining a constant modulation frequency and producing a strong pressure modulation inside the combustion chamber.

The gear was spun using a Leeson DC motor that had a maximum revolutions per minute (rpm) of 3500, which allowed a modulation frequency of 20 kHz to be obtained. The rpm of the motor was adjusted with a proportional–integral–derivative controller (PID) along with a photomicro sensor. The photomicrosensor was attached to the front face of the motor and a needle was bonded to the motor shaft. For each revolution, the needle passed through the photomicrosensor, which transmitted a signal to the PID. The PID then allowed the motor to draw enough power to obtain a specified rpm. This arrangement created a feedback loop in which the specified rpm was controlled by a user via a computer.

Figure 3-5 depicts the Toothed Gear Setup in which 1 denotes the motor, 2 the toothed gear, 3 the permanent magnet, 4 the combustion chamber, and 5 a vertically adjustable table. Note that in Figure 3-5 no measuring devices are shown.
It can be seen in the drawing above that the motor is mounted upside down. The motor was mounted in this specific orientation because it was feared that if the magnet inside the motor was too close to the permanent magnet around the combustion chamber the maximum rpm of the motor could not be utilized.

The design of the toothed gear was driven by several key parameters. Knowing that the target modulation frequency was 20 kHz and the rpm of the motor was 3500, the toothed gear was fabricated with a diameter of 7.5 inches and a total of 377 teeth. The magnetic field generated from the magnets around the combustion chamber was also a driving factor in the design of the toothed gear. When a solid metal cylinder is spun inside a magnetic field, eddy
currents are induced in the solid. These currents produce a force that opposes the motion of the cylinder. To reduce the induced eddy currents, the toothed gear was made out of 304 stainless steel, which has a resistivity of $6.897 \times 10^{-7} \ \Omega \cdot m$. Steel was also chosen because it would be able to withstand the high temperatures of the exhaust gases. In addition to the choice of material, spokes were cut into the toothed gear and the thickness was chosen to be 0.25 inches to reduce the effects of the eddy currents. These features enabled the toothed gear to spin faster than the targeted rpm.

Another challenge of the toothed gear was designing it so that it would be able to spin parallel, to within fractions of an inch, to the plane of the nozzle. Furthermore it must not “crash” into the magnet when the engine was fired. This meant that surface of the toothed gear that was facing the combustion gases had to be surface ground to achieve the desired flatness. Even with grinding, some residual aberrations still existed.

A third challenge was ensuring that the toothed gear was level when it was fixed to the motor shaft. A collar was designed to be attached to the motor shaft with two set screws. The toothed gear was placed over the collar and connected with four screws. An O-ring was placed between the collar and the toothed gear. The O-ring and four screws allowed fine adjustment when leveling the toothed gear. The collar, O-ring, vertically adjustable table, and grinding of the toothed gear permitted the combustion chamber and nozzle to be brought to a distance of 0.0031–0.0039 inches below the toothed gear. Figure 3-6 depicts both the collar separately and assembled with the toothed gear. Figure 3-7 shows the full setup early in the stages of the hot-fire preparation.
Figure 3-8: Toothed Gear and Collar

Figure 3-9: Photo of Complete Toothed Gear Assembly
After analyzing the data that was collected with the Toothed Gear Setup, it was concluded that the magnitude of the pressure modulation inside the combustion was not strong enough to allow for the pressure-coupled response and acoustic admittance to be confidently determined. It was decided to investigate a more refined piezo-actuator setup.
Combustion Chamber

The combustion chamber was made out of 316 stainless steel, so that the magnetic field of the permanent magnet could pass through the walls without being greatly affected. The chamber is composed of three main parts: a nozzle, body, and a bottom cover. These three formed a cavity that was 1.125” in diameter with a depth of 2.25”. The operating pressure of the chamber is 2000 psi, but was designed to exceed the ASTM pressure vessel standards for the 5000 psi rating by a factor of 4. As an additional safety precaution to prevent an overpressurization, a 3000 psi burst disc was attached to the chamber. A burst disc is a hollow tube with a metal disk sealing one end. The disc fails when a certain pressure is reached. In this instance, when 3000 psi is reached the metal disk fails creating an opening to the outside of the chamber through which the exhaust gases vent. The burst disc was located 0.65” below the top surface of the chamber body. In addition, there was a port for the igniter at this same axial position.

Figure 3-10: Electrode Configuration

One of the goals of this study was to increase the number of velocity measurements made during one experiment because the only usable data are those which are collected when the regressing propellant surface is a few millimeters below each velocity measuring electrode. This was done by creating two measuring stations, each with the capability of making four velocity measurements. One station was 0.65” below the top surface of the chamber body and the other
1.3” below it. At each station, four pairs of electrodes were threaded into the chamber using Conax connecters. Both stations allowed for a combined total of 8 usable electrode pairs. The electrodes were made out of 2% ceriated tungsten and had a diameter of 0.02”. Figure 3-10 shows a cross sectional view of the electrode configuration for one side of the chamber. In addition to the electrodes, a 111A23 PCB pressure transducer was located at the top measuring station and a 111A22 PCB pressure transducer was located at the bottom measuring station. Both were used to record the mean and unsteady pressures.
Magnetic Circuit

Another objective of this study was to create a strong, uniform magnetic field so that the velocity signal could be easily discerned from any noise. This was achieved using eight N42-grade nickel-coated neodymium rare earth magnets to create the magnetic field for the magnetic flowmeter. Each magnet was 4” × 4” × 1” and was assembled into two clusters that were 4” × 4” × 4”. To create a 3” gap between the clusters, a cast-iron horseshoe was fabricated. The clusters were held to the horseshoe by their inherent magnetic field and nothing else. Cast iron was chosen because it is highly magnetic and would be able to hold the two clusters apart that had a combined holding force of approximately 3,000 lbs. The magnetic circuit can be seen in Figure 3-11.
Chapter 4

Controls and Data Acquisition, Test Procedure, and Analysis

Controls and Data Acquisition

During the course of this study, a total of eight hot fire tests using the Toothed Gear Setup were performed. Five hot fire tests were conducted at Electrodynamic Applications, Inc. (EDA) in Ann Arbor, Michigan while three additional hot fire tests were conducted at Penn State. The two setups varied slightly and these differences are discussed below.

At EDA two PCB 111A22 pressure transducers were used. However, one was destroyed by a faulty seal before it was used at Penn State and was replaced with a PCB 111A23. The other difference was that a signal conditioner was built at EDA to accept two signals, one from each pressure transducer. The output of this signal conditioner was AC-coupled and had a gain of ×10. The reason for building the new signal conditioner was because it was thought the one of the signal conditioners from PCB, the 482B11, was acting faulty. This behavior may have been due to the magnetic field from the neodymium magnets.

The PID controller was a QualityKits KT-5194A that was powered by an Agilent model E3632 DC power supply. The PID received its specified rpm command from a user that sent it via computer.

As mentioned above, two different pressure transducers were used to measure the pressure inside the combustion chamber during testing at Penn State. Toward the aft end of the combustion chamber, a PCB model 111A23 pressure transducer was used and connected to a PCB model 442A101 signal conditioner. The signal conditioner allowed the user to choose whether the signal was AC or DC coupled along with the choice of a gain of ×1, ×10, or ×100. It
was set to be DC-coupled so that the mean chamber pressure could be measured. The gain was set to different values on different fires. Toward the head end of the combustion chamber, a PCB model 111A22 pressure transducer was connected to a PCB model 482B11 signal conditioner. This signal conditioner was AC-coupled and also set to different gain settings for different fires.

The velocity-measuring electrodes were connected to a signal amplifier that had a gain of ×10. This amplifier was built at Penn State; however, it only had enough inputs to accept 4 velocity signals. As such, not all the electrodes were used. The amplifier was powered by two different DC power supplies: a Topward model 6303 and an Agilent model E3615A.

All four signals from the electrodes along with both pressure signals were attached to a National Instrument USB-6259 connector board via BNC cables. This board was connected to a computer that used LabVIEW program to collect the data. Figure 4-1 shows a flowchart of the data path for the Toothed Gear Setup.

![Figure 4-1: Flowchart of Data for Toothed Gear Setup](image)
The data acquisition for Setup 2 used at Penn State is very similar; however, there are some differences. There is no motor or PID controller used in this setup. The piezo-actuator was controlled by a Piezo Jena ENT 40 main power supply and a Piezo Jena ENV 800 voltage amplifier; both were incorporated into a single unit. A separate Hewlett Packard 33120A signal generator was used to control the output of the ENT 40/ENV 800 to provide the actuator with a sinusoidal voltage. The final difference between the setups was that the pressure signals and the electrode signals were attached to a National Instrument BNC 2110 connector board. Figure 4-2 shows the flowchart of data for Setup 2.

![Flowchart of Data for Setup 2](image)

**Testing Procedure**

The experiments burned samples of AP/HTPB composite propellant that were formed into cylinders and surrounded by phenolic tubing that was 1.125” in diameter and 1.25” long.
These samples were loaded into the combustion chamber from the bottom. A Viton o-ring was placed into the bottom cover o-ring groove and a small cylindrical insert that was 0.25” thick was placed on top of the bottom cover. The purpose of the insert was to bring the top surface of the propellant cylinder to a position that was approximately 0.1” below the lowest electrode in the top-most measuring station. The bottom cover was then attached to the combustion chamber body with four screws. For the Toothed Gear Setup, the next step was to connect the bottom plate to the vertically adjustable table with four screws. For Setup 2, this step was not necessary. Next, two holes were drilled into the propellant with a handheld drill through the bottom measuring electrode ports. The holes were drilled to a depth of approximately 0.22”, which was the distance the electrodes in the top-most measuring station penetrated into the chamber. The holes were then filled with epoxy and two of the Conax transducer glands that contained the electrodes were immediately screwed into the chamber before the epoxy had time to set. After this step, the remaining two Conax transducer glands that held the electrodes were attached to the top two velocity measuring station ports. It was ensured that the electrodes on the left side of the chamber had the same orientation as the electrodes on the opposite side. A Fluke 83 multimeter was used to ensure that none of the electrodes were snapped in this process by ohming out the connection to ensure continuity. The pressure transducers and burst disk were screwed into the chamber. Finally, the last Conax transducer glad containing the ignition wire was screwed into the chamber.

The ignition wire was made out of nichrome and formed into a loop. The loop was carefully pressed into the propellant in several places to ensure that the entire propellant surface ignited. The multimeter was used again to check that the nichrome wire was not shorted to the combustion chamber. Once the nichrome wire was in its final position and there were no shorts, the distance from the top of the combustion chamber body to the top of the propellant was measured and recorded. In addition, the distance from the top of the chamber body to the top
electrode was measured, as well as gap between the tips of the electrodes on the left of the chamber and those on the right.

A second Viton o-ring was placed on top of the chamber in the o-ring groove and a sonic nozzle was attached to the chamber with four screws. The next step was to secure the vertically adjustable table to the bottom optical breadboard with a single screw. Before tightening the screw, it was checked that the nozzle exit was approximately under the rim of the toothed gear; more precise positioning would be taken care of later.

The permanent magnet was carefully slide around the combustion chamber and each pressure transducer was connected to a separate signal conditioner with a low noise coaxial cable. All the electrodes were connected to the same signal amplifier, which accepted four inputs. The multimeter was used to ensure that there was not an open circuit between each electrode and the appropriate input on the amplifier.

The vertically adjustable table was used to raise the nozzle so that it was less than 0.003–0.005” away from the bottom surface of the toothed gear. The nozzle exit was positioned directly under the rim of the gear and held firmly in place by two aluminum extrusions that were attached to the magnet assembly. These extrusions can be seen in Figure 4-3.
All the equipment was turned on and the wheel was spun to the desired rpm. Data from both pressure transducers and all the electrodes were collected for one second and saved. This was done for comparative purposes in the event that something unexpected in the data was found after the hot fire. The data collection program was started again and the leads to the nichrome wire were attached to a power supply to ignite the propellant. Following each test, the chamber was disassembled and all the components were cleaned with hot water.

A hot fire test has not been done with Setup 2 and as such there is currently not a testing procedure.
Linear Acoustic Analysis

By combining this study with a linear acoustic analysis, the pressure-coupled response can be calculated with a high degree of accuracy. The analysis closely follows the one performed by Micci (11). His final equations for momentum and energy are

\[
i \omega \rho \hat{u} + \rho \frac{d\hat{u}}{dx} + \rho \frac{d\hat{u}}{dx} + \frac{d\hat{p}}{dx} = 0,
\]

\[
i \omega \hat{p} + \frac{\hat{p}}{dx} + \frac{\hat{u} d\hat{p}}{dx} + \frac{\hat{p}}{dx} = \frac{\hat{u}}{\hat{m}_b} \left[ \frac{\hat{m}_b}{\hat{m}_b} + \frac{\Delta \hat{T}}{\hat{T}} \right],
\]

where \( i \) is the square root of \(-1\), \( \omega \) is the angular frequency, \( \rho \) is density, \( u \) is the gas velocity, \( p \) is pressure, \( \gamma \) is the ratio of specific heats, \( \bar{a} \) is the mean speed of sound, \( m_b \) is the volumetric mass injection rate, and \( T \) is the temperature. Also, the barred quantities are mean values and the terms with hats denote complex perturbation quantities.

For Equations 10 and 11 to be applicable to this investigation, they first must be modified. First, there is no distributed combustion so the mass injection terms can be eliminated. Second, it is assumed that the mean pressure and gas velocity do not vary with respect to the distance above the burning surface. With these modifications Equations 10 and 11 become

\[
i \omega \rho \hat{u} + \rho \frac{d\hat{u}}{dx} = 0,
\]

\[
i \omega \hat{p} + \frac{\hat{p}}{dx} + \frac{\hat{u} d\hat{p}}{dx} = 0.
\]

Equation 12 was solved for \( \frac{d\hat{u}}{dx} \) and substituted back into Equation 13. The resulting equation was then solved for \( \frac{d\hat{p}}{dx} \):
\[
\frac{d\hat{p}}{dx} = -i \omega \rho \hat{u} + i \omega \rho \hat{u} \gamma \quad \frac{\rho \hat{u}^2 - \gamma \rho}{.}
\]

(14)

In a similar manner, an expression for \( \frac{d\hat{u}}{dx} \) was derived:

\[
\frac{d\hat{u}}{dx} = -i \omega \rho \hat{u} + \hat{u} + \hat{p} \quad \frac{\rho \hat{u}^2 - \gamma \rho}{.}
\]

(15)

To obtain the pressure-coupled response, theoretical curves of the phase difference between the oscillating pressure and velocity were created as a function of the distance above the burning propellant surface for a specified propellant acoustic admittance that serves as the initial condition at the propellant surface. The acoustic admittance was then modified until the predicted phase angle as a function of distance above the propellant surface matched the experimentally measured values. The equations were solved simultaneously using a MATLAB program.

A cross spectrum was created to compute the phase angle from the measured pressure and velocity values. The cross spectrum is defined as

\[
CS = FFT(VelocitySignal)[\text{conj}\{FFT(PressureSignal)\}],
\]

(16)

where \( FFT(signalA) \) is the Fast Fourier Transform of the velocity signal and \( \text{conj}\{FFT(signalB)\} \) is the complex conjugate of the Fast Fourier Transform of the pressure signal. A cross spectrum was calculated for each velocity signal measured from the top measuring station using the pressure signal from the same location. The same was done for the velocity signals from the bottom measuring station using the pressure data gathered from the same measuring station.

The phase difference between the velocity and pressure signals was computed by calculating the phase angle of each of the cross spectra at the modulation frequency. The phase
angles of the cross spectra were plotted with the theoretical curves of the phase difference between the oscillating pressure and velocity so that a comparison could be made.
Chapter 5

Test Results and Discussion

Magnetic Field Measurements

The velocity measurement is dependent on the magnetic field, so an accurate knowledge of the field is crucial. The magnetic field between the two magnetic clusters was measured using a Lakeshore Model 460 3-Channel Gaussmeter. This probe can measure the magnetic flux in the x, y, and z directions simultaneous. A translation table that could move along three different axes was constructed to which the probe was attached. Measurements were taken in increments of 0.02” across the gap. Figure 5-1 shows the principal axis definitions with respect to the magnetic circuit.

Figure 5-1: Principal Axis Definitions with Respect to the Magnetic Circuit
The combustion chamber and magnetic circuit were designed to allow a uniform magnetic field to exist in the cavity of the combustion chamber, particularly at the two measuring stations. Figure 5-2 shows a map of the magnetic field in the x–y plane, looking down on the combustion chamber. The plane is at the top measuring station that is approximately 1” below the top surface of the magnet clusters. In the Figure 5-2, the inner and outer walls of the combustion chamber are denoted by two black circles. It can be seen that the interior of the combustion chamber is quite uniform having a magnetic field of 0.5 ± 0.06 Tesla. The difference at \( y = 0" \) and \( y = 3" \) can be attributed to the thickness of the probe and the proximity to the magnet clusters.
Figure 5-3 shows a volumetric plot of the magnetic field with the $x$, $y$, and $z$ directions being the same as those defined in Figure 5-1. The vertical plane shown is the mid-plane that separates the air-gap into equal halves in the $y$-direction, whereas the horizontal plane separates the air-gap into equal halves in the $z$-direction. As before, significant uniformity can be seen in the magnetic field.
Figure 5-3: Volumetric Plot of the Magnetic Field
Cold Flow Tests with the Toothed Gear Setup

Before any live propellant was used, a series of cold flow tests were conducted to verify the amplitude and frequency of the pressure modulation. This included setting up the combustion chamber and toothed gear as it would be for a hot fire. The igniter, burst disc, and three of the four velocity measuring ports were plugged. The remaining velocity port was connected to a compressed nitrogen tank that was regulated to 500 psi and a pressure transducer was attached to each pressure transducer port. The permanent magnet was not in position as it would not contribute to the test being performed. A PCB 111A23 pressure transducer was connected to a PCB 442A101 signal conditioner that was DC-coupled and had a gain of ×10. This measured the mean pressure in the combustion chamber. The other pressure transducer was the PCB 111A22 and was connected to the PCB 482B11 signal conditioner that was AC-coupled and had a gain of ×100. This measured the fluctuating pressure. Both of these signals were connected to an oscilloscope and real-time FFTs were performed on each signal. In the top of Figure 5-4, one can see an FFT of the pressure signal when the toothed gear was rotating at 1500 rpm, which corresponds to a modulation frequency of 9.4 kHz. The bottom of Figure 5-4 shows the FFT when the tooth gear was rotating at 1700 rpm that corresponded to 10.4 kHz. In both instances, the magnitude of the modulation frequency was 13.75 dBV. This test was repeated for several other frequencies as well.
Figure 5-4: Fast Fourier Transform of the Pressure Signal during a Toothed Gear Coldflow Test
In addition to performing an FFT on the pressure signals, the mean and fluctuating pressures were measured and recorded for frequencies 5–20 kHz. The percent modulation plotted against the frequency can be found in Figure 5-5. It is seen that the percent modulation was predominately 1% except around 15 kHz. The first radial mode for this combustion chamber was calculated to be approximately 14.3 kHz and could account for the spike in the percent modulation.

![Graph showing percent modulation as a function of frequency for a toothed wheel setup.](image)

**Figure 5-5: Percent Modulation as a Function of Frequency for Toothed Wheel Setup**
Cold Flow Tests with Setup 2

During initial cold flow testing with Setup 2, it was discovered that the vibrations from the motion of the piezo-actuator were mechanically coupled to the combustion chamber. The actuator produced accelerations of approximately 450 g when the actuator had a displacement of 0.0011". Both of the pressure transducers have an acceleration sensitivity of less than 0.002 psi/g, yet this meant that both pressure measurements were drastically influenced by the vibrations.

To test whether or not decoupling the actuator from the combustion chamber would improve the signal from the pressure transducers, the aluminum block that held the actuator was unattached from the combustion chamber and clamped to a table. The combustion chamber was also clamped to the same table. The actuator was turned on and it was discovered that neither of the two pressure transducers was influenced by the vibrations.

Hot Fire Tests

There were a total of eight hot fire tests that were conducted with the Toothed Gear Setup. The first five of these experiments were performed at EDA. The last three tests were carried out at Penn State. All of the experiments exhibited the same general trends and yielded inconclusive data and for those reasons only one test from each location will be presented.
Toothed Gear Setup Hot Fire 1

Hot Fire 1 was the very first test that was executed using the entire integrated setup. To simplify this experiment, only the electrodes in the top measuring station were used. The toothed gear was positioned 0.005–0.007” above the nozzle. It was rotated at 3183 rpm, which corresponds to a target modulation frequency of 20 kHz. Both pressure signals can be seen in Figure 5-6 along with two of the velocity signals. Note that the top and bottom pressure transducers and velocity 1 are all shown with an offset in Figure 5-6. The data are presented in this manner so that all the signals could be seen clearly. After the test was completed, it was discovered that velocity signals 3 and 4 did not have a secure connection to the National Instrument USB-6259 connector board and have been omitted from Figure 5-6.
In Figure 5-6, the top pressure transducer is shown in blue and ignition is marked by a dip in the signal at 0.92 s. The downward slope at 3.2 s indicates burnout. The bottom pressure
transducer can be seen in green. This pressure transducer was located below the surface of the propellant and does not show ignition; however, the onset of the dip in the signal at 2.92 s indicates when the propellant burned past the pressure transducer. It should be noted that both pressure transducers were AC-coupled.

Filters were applied to both the pressure and velocity signals and can be found in Figure 5-7. A 200-Hz low pass filter was used on the pressure signals. The filtered signals allow the ignition and burnout times to be seen more clearly in Figure 5-7. Again, the pressure signals were AC-coupled so only the pressure transients are shown. A 100–20-kHz bandpass filter was applied to both of the velocity signals and can be found in the bottom half of Figure 5-7. The bandpass filter removed the DC drift that the amplifier created. Ignition, the exposure of the bottom pressure transducer, and burnout can be seen in both velocity signals.
Figure 5-7: Hot Fire 1 Filtered Data

Chamber Pressure, 200 Hz Low Pass Filtered

Velocity, 100-20kHz bandpass

---

**Figure 5-7: Hot Fire 1 Filtered Data**

- **Chamber Pressure, 200 Hz Low Pass Filtered**
  - Upper Transducer
  - Lower Transducer

- **Velocity, 100-20kHz bandpass**
  - Velocity #1
  - Velocity #2
Toothed Gear Setup Hot Fire 6

Hot Fire 6 was the first experiment conducted at Penn State that used the Toothed Gear Setup. The toothed gear was positioned 0.003–0.004” above the nozzle and spun to 3183 rpm, which corresponds to a target frequency modulation of 20 kHz. Hot Fire 6 differed from Hot Fire 1 in that it utilized both measuring stations to measure the velocity. Two electrode pairs were placed in the top measuring station and two in the bottom measuring station.

As mentioned previously, there were some changes in the hardware that was used at Penn State. One change was the use of different signal conditioners for the pressure transducers. The 482B11 and the 442A101 signal conditioners allowed the user to select a gain. The 442A101 also allowed the user to choose whether the signal was AC or DC coupled. The pressure signal in the top measuring station was DC-coupled with a gain of ×10. The lower pressure transducer signal was AC-coupled and also set with a gain of ×10. Both signals can be seen in Figure 5-8.
Ignition occurred at 0.92 s and burnout can be seen to have taken place at 2.9 s. It can also be observed in Figure 5-8 that both signals saturated the DAQ. For the top pressure transducer, this happened between 1.18 s and 1.43 s. For the bottom pressure transducer, this took place between 1.09 and 1.29 s. The gain settings were changed on both signal conditioners in subsequent firings to avoid saturating the DAQ. One final thing to note in Figure 5-8 is the dip seen on the top pressure signal. This marks the time when the propellant burned passed the lower measuring station. Holes had to be drilled into the propellant to make room for the electrodes. The holes changed the burning surface area and caused a clear change in pressure.
All four velocity signals can be found in Figure 5-9. Velocities 1 and 2 were measured at the top measuring station and velocities 3 and 4 were from the lower measuring station.

![Hot Fire 6 Velocity Vs Time](chart.png)

**Figure 5-9: Hot Fire 6 Velocity Data**

Velocity signals 1 and 2 show a response to ignition and also to burnout. Velocity signals 3 and 4 do not show any response to ignition because the electrodes for these signals are not exposed to the combustion gases; however, there is a spike in both signals when the propellant burns past their respective electrode pairs. Velocity signals 3 and 4 also show a
reaction to burnout. Velocity signal 4 is extremely noisy and it is thought to be the result of the amplifier.

Figure 5-10 shows the relative phase angle between the top pressure transducer signal and the velocity signal from electrodes closest to the propellant surface in the top measuring station for Hot Fire 6. Also shown in this plot are the theoretical phase angle curves for three values of the real part of the pressure-coupled response: 1, 5, and 10. A pressure-coupled response real part of 1 corresponds to an acoustic admittance value of 0 and a phase angle of 90 degrees. These are the values obtained at a solid wall.

Figure 5-10: Phase Angle as a Function of Distance above a Burning Surface
It can be seen that the phase angle for the experimental data is not plotted until approximately 4 mm above the propellant surface. The reason is because the electrodes that measured the velocity were 0.8 mm above the propellant surface prior to ignition. As mentioned earlier, the DAQ was also saturated for 0.25 s during which time no useable data was collected. As a result of not having data closer to the propellant surface, a pressure-coupled response could not be derived.

Even though the majority of the experiments yielded pressure curves like the one seen in Figure 5-8, there was not a strong enough pressure modulation to generate a velocity oscillation signal that was sufficiently distinct from the background noise. As a result, the gas velocity was not coherent to the pressure wave and quantitative measurements of the real part of the pressure-coupled response could not be obtained.
Chapter 6

Conclusions and Recommendations

This study had three main objectives: create a strong uniform magnetic field in the interior of a combustion chamber to increase the signal-to-noise ratio of the velocity measurement, increase the number of velocity measurements taken in a single burn, and increase the amplitude of an oscillating pressure inside a combustion chamber to increase the signal to noise ratio of the velocity measurement.

A uniform magnetic field was successfully created inside the combustion chamber by using eight N42-grade nickel-coated neodymium rare earth magnets. The use of 316 stainless steel for the combustion chamber body, allowed a $0.5 \pm 0.06$ T magnetic field to exist in the chamber cavity.

Two measuring stations were created in the combustion chamber. At each location, four electrode pairs were implemented that permitted a total of eight velocity measurements to be made during one burn. Data was successfully collected at each station thus helping to improve the statistical accuracy.

Several attempts were made to improve the technique of creating a strong pressure modulation. Due to the limitation of the dynamics of the piezo-actuators used in Setup 1 and the difficulty of applying a precise preload, a strong pressure modulation was not achieved. Setup 1 was abandoned and attention was turned to the Toothed Gear Setup. Even though pressure modulations greater than 20 kHz were achieved with the Toothed Gear Setup, it too failed to produce a strong enough pressure modulation.
In Setup 2, the vibrations from the piezo-actuator were coupled to the combustion chamber causing the pressure transducers to give inaccurate measurements. Setup 2 is currently being redesigned to mechanically decouple the actuator motion from the chamber. Once the new setup is fabricated, cold flow testing, and eventually hot fire testing, will be able to commence and the investigation of increasing the pressure modulation can be completed.
References


