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DYNAMIC PRESSURE CALIBRATOR / CHECKER

A Major Qualifying Project Report
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WORCESTER POLYTECHNIC INSTITUTE
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Degree of Bachelor of Science

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Abstract

Pratt and Whitney currently has a Dynamic Pressure Calibrator/Checker system that is incomplete and difficult to use. Our goal was to provide Pratt and Whitney with a flexible and user-friendly system that can accurately show the response of any pressure transducer. The original system was simplified, transducer mounting structures were designed and fabricated, and an improved method of analysis was discovered. Through experimentation and analysis, our group provided Pratt and Whitney with a modified system and recommendations for system operation.

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1 Introduction

Pratt and Whitney is one of the leading companies in the aviation industry. "We Pioneer, We Build, We Serve" is the motto of this aircraft engine company. The goal of Pratt and Whitney is to provide their "customers with the services it needs to concentrate on flying people and cargo safely around the world" (http://www.pratt-whitney.com/about.asp). In order to achieve their goal, Pratt and Whitney focus on improving aircraft engine technologies in areas including Design, Manufacturing, Maintenance, Operation, and Recycling.

Pressure calibration is vital in the design and operation of aircraft engines. Pressure sensors are needed in order to control and/or monitor numerous components of the engine system. Some of these components include torque, oil, fuel, and hydraulics. More importantly, accurate and reliable sensors are needed to validate design concepts and determine the capabilities of the aircraft engines. Dynamic pressure and steady state pressure changes can affect the performance of aircrafts. It is vital to use pressure sensors to determine the changes and the effects they have on an aircraft (http://www.kulite.com/industry_aerospace.asp).

The importance of pressure sensors leads to the necessity for Pratt and Whitney to have a system that can verify the accuracy and calibration of pressure transducers. Our goal is to provide Pratt and Whitney with a system that can accurately show the response of any pressure transducer. This system will be low cost and effective. In addition, our objective is to make the system flexible and user-friendly.

Currently, Pratt and Whitney has a system that is incomplete and difficult to operate. The original system utilized a B&K calibrator to measure the pressure created by a frequency generator. Pratt and Whitney wishes to simplify the system by using a JBL speaker driver. The speaker driver will create pressure in the form of sound waves. However, the system is not suited for a JBL speaker driver. Pratt and Whitney does not know if pressure transducers can be calibrated properly using the speaker driver. There is also a lack of knowledge of the system performance under different environments.

We hope to complete the development of a pressure calibration system using a JBL speaker driver. Pressure transducer housing mounts for the JBL speaker driver will be designed and fabricated. Test will be performed using these mounts to test the accuracy of our system with controlled variables. These tests will verify the capabilities of our JBL speaker driver. We will determine the best environment that will enable the system to produce accurate pressure measurements. Finally, recommendations with be provided to further improve our system.

2 Literature Review

The following section provides background research that we have done as preparation for this project. There were many aspects we needed to be familiarized before we started designing and experimentation. This section addresses most of the issues and problems we faced through our design, fabrication, experimentation, troubleshoot, and analysis. Our system components are also introduced.

2.1 Waves

In physics, the wave can be defined as a disturbance which travels through a medium, transferring energy from one particle of the medium to another. A medium is considered to be any substance or material that has the potential to carry a wave. An important characteristic of waves is that the disturbance caused by waves causes no permanent displacement of the medium. For example, waves in an ocean can be seen moving across the surface, yet the water (the medium) itself, always returns to its rest position after the wave has passed through. Waves are experienced in our lives more than realized. Aside from the obvious waves of sound and light, there are many other things that represent a motion that could be described as wavelike. Radio waves, water waves, microwaves, and even the motion of a pendulum are examples of waves.

2.1.1 Wave Interference

Wave interference is an occurrence of two waves meeting while being transferred through the same medium. Interference causes the medium to take a shape that is the result of both waves. When two compressions meet together within a medium from two separate waves, the result is the addition of the amplitude of the two compressions. This case of wave interference is known as constructive interference. Constructive interference also exists when rarefactions from two different waves meet within the medium. When constructive interference continually occurs at a point within a medium, that point is known as an anti-node.

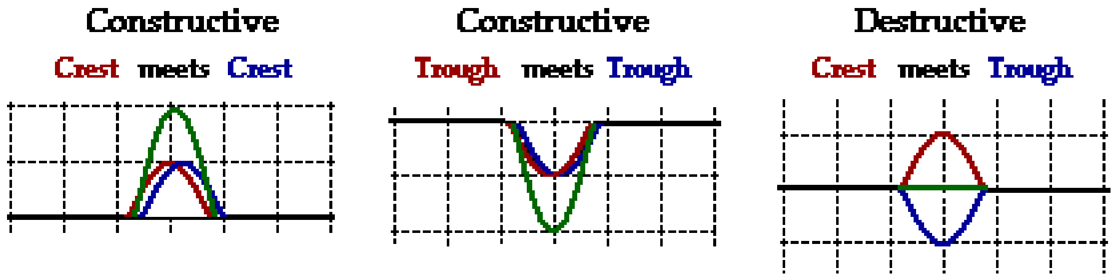


Figure 1 - Types of Wave Interference

The other type of interference is known as destructive interference. In this case, a compression will meet up with a rarefaction, and the result will be the difference between the absolute value of the two amplitudes. If the amplitude for both waves at the point of destructive interference is equal, the result will be zero amplitude. If destructive interference continually exists at a point within a medium, this point is known as a node.

2.1.2 Classifying Waves

There are major ways to characterize waves and their properties. The first is by observing the displacement of the medium as the wave transfers energy through it. The motion of different types of waves can be classified as either transverse, longitudinal, or surface. These types of wave motion are described in the paragraphs that follow. Another way of grouping different kinds of waves is by simply determining whether the waves can transmit energy within a vacuum. This determination will separate waves into two groups, electromagnetic and mechanical waves.

2.1.2.1 Transverse, Longitudinal and Surface Waves

A transverse wave is one in which particles of particles of the medium move perpendicular to the direction in which the wave moves. Consider the spring system with the red circles being nodal points in between spring elements (1), shown below in Figure 2. To begin a transverse wave, node 1 is moved up or down (up in this case) perpendicularly to the spring S1 (2). The wave energy would be transported to the right. As node 1 returns to its initial position, node 2 would undergo a perpendicular displacement relative to the displacement that node 1 experienced (3). Again, the wave continues to the right, inducing perpendicular displacement onto element 3 as element 2 returns to its initial location (4). Waves deep under the surface of the ocean can be characterized as transverse waves, since water is displaced perpendicularly as energy is transferred through it.

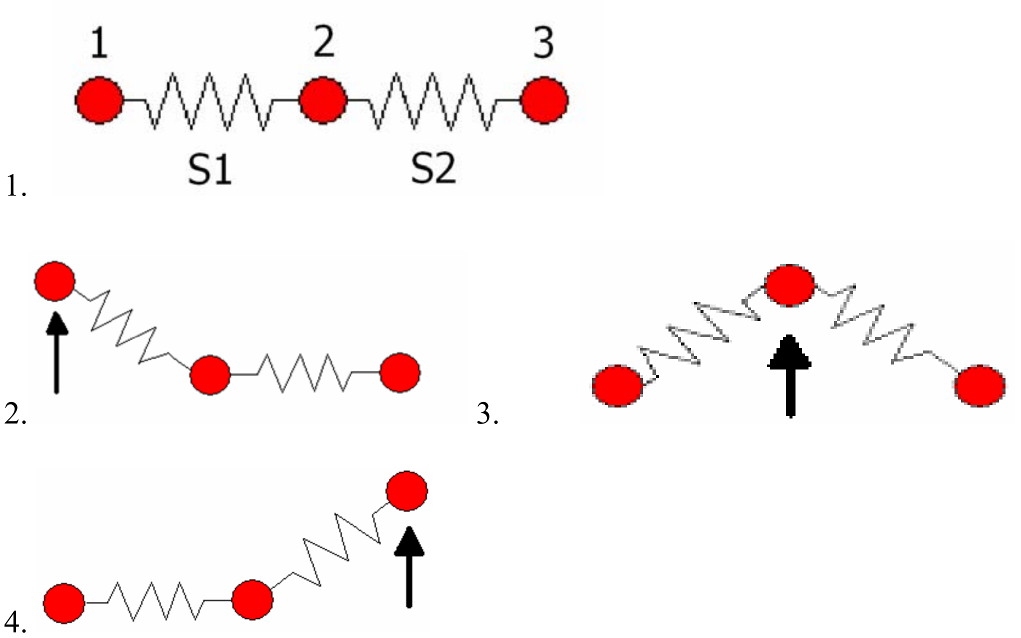
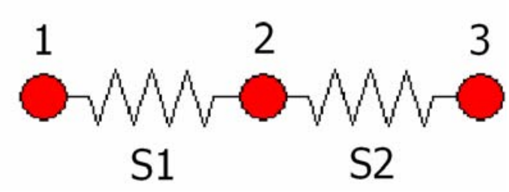


Figure 2 – Spring Systems

A longitudinal wave is one in which particles of the medium move in parallel with the direction of the wave. Sound is classified as a longitudinal wave because particles of the medium, in which the sound is traveling, vibrate in parallel with the direction of the wave. As a longitudinal wave flows through a medium, it creates points of compression and rarefactions. An example of interaction between nodes within a medium under longitudinal vibration can be seen in Figure 3. The system lies at rest (5) with three nodes, 1, 2, and 3 connected by two spring elements S1 and S2. The longitudinal wave begins with translation of node 1 to the right (6). This causes S1 to be in compression at this moment in time. Reacting to this compression, node 2 is forced to the right as node 1 returns to its initial position (7). Now, there is a rarefaction between node 1 and 2 and compression between node 2 and 3. The wave continues through the system, transferring energy from node 2 to node 3 (8). Node 2 returns to its initial position while node 3 is forced to the right, thus creating another rarefaction between those nodes. As energy is transferred through and finally out of the system, all nodes return to their initial positions (5). It is important to note that the principle of all elements returning to their initial position once energy is transferred out of the system separates waves from other forms of energy transfer.



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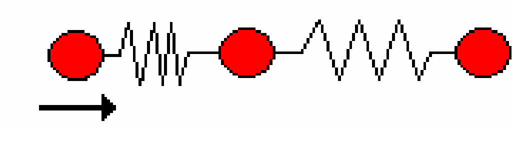

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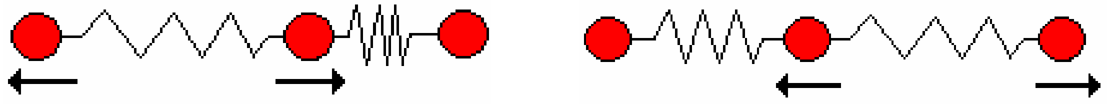


7. 8.

Figure 3 - Spring Systems (Vibration)

Surface waves are also known as circular waves. This is because the particles in the medium travel in a full circle as energy is transferred, before the particles return to their initial positions. While ocean waves far beneath the surface represent longitudinal waves, waves at the surface exemplify characteristics of surface waves.

2.1.2.2 Electromagnetic and Mechanical Waves

Electromagnetic waves have the ability to transfer energy within a vacuum. The main type of electromagnetic wave is the light wave. The electromagnetic waves of light, which originate from electron vibrations on the earth's surface, travel through the vacuum of space, where they eventually reach the earth.

Mechanical waves, unlike electromagnetic waves, can not transmit energy through a vacuum. They require a medium within which to transfer energy. Sound waves, aside from being longitudinal waves, are a type of mechanical wave. Water waves, radio waves, and microwaves are also examples of mechanical waves.

2.1.2.3 Sound Waves

Sound waves result from longitudinal motion of particles in a medium. Sound waves are also known as pressure waves because they consist of patterns of high and low pressure areas which move through the medium. The high pressure areas are known as compressions and the low pressure areas are known as rarefactions.

2.2 Sound and Pressure

Sound is “an alteration in pressure, stress, particle displacement, and particle velocity” (Carlin, 1978). The frequency of sound is the number of cycles per unit time. Audible sound frequencies range from 20 Hertz (Hz) to 20,000 Hz. Ultrasonic sound frequency is higher than 20,000Hz. Infrasonic sound frequency falls below 20 Hz. Sound is created by changes in air pressure and can be represented by a waveform. Sound waves propagate through air in longitudinal waves, however, for practicality; sound waves can be represented as a transverse wave, sine wave.

Sound is primarily affected by two parts of the wave. The frequency of the wave is related to the pitch of the sound. The amplitude of the sound sine wave is the energy of the wave. The intensity, perceived loudness, of the sound is related to the amplitude of the wave. Sound intensity is “the average rate of sound energy transmitted through a unit area normal to the wave direction at a point” (Carlin, 1978). Sound intensity is expressed in decibels (dB), which is power. Since amplitude relates to the size of the pressure variations, decibels can be measured in terms of pressure units. The sound-pressure level in decibels is defined by:

$$dB = 20\log\frac{P}{Po}$$

where dB = decibels

P = pressure

P_o = reference pressure

Pressure measurements in air use a reference pressure of 0.0002 dyne/cm^2 (2.9 x 10^{-9} psi). Measurements underwater use reference pressure of 1 dyne/cm^2 (1.45 x 10^{-6} psi).

Pressure is defined as the force per unit area acting on or by a fluid (Baumeister, 1978). The equation for pressure is:

$$p = \frac{F}{A}$$

where p = pressure

F = normal force

A = area

The units of pressure are lb/ft^2 which is equivalent to 47.88 N/m^2. There are 3 different types of pressure, gage, absolute, and vacuum. Gage pressure is pressure measured with reference to atmospheric pressure. Atmospheric pressure is defined as pressure exerted upon the earth's surface by the air due to the gravitational attraction of the earth. Absolute pressure is gage pressure plus atmospheric pressure. Vacuum is a region where the gas pressure is less than the atmospheric pressure.

Static and dynamic pressures are two types of measured pressure. Static pressure is the pressure that is exerted by a still fluid. Dynamic pressure is the pressure that is created due to the motion of a fluid. Total pressure is the sum of static and dynamic pressures.

2.3 The Measurement System

There is a wide range of measuring instruments for dynamic pressure measurements available in the market today. It is imperative to fully understand the physical properties of these instruments before successfully performing measurements.

A dynamic pressure measurement system must at least include a transducer, an electrical supply, an amplifier, and devices for signal processing and measurement storage and control. It is important to mention that the characteristics of each of these components in the system effect the uncertainty obtained in an actual measurement situation. A diagram of the system can be seen in Section 2.5.

2.3.1 Frequency Generator

The job of a function generator is to send a sinusoidal waveform out with a given frequency and amplitude. Once the waveform is generated it is sent to an amplifier to increase the signal. The pulsating waveforms are then sent to a speaker which turns them into pressure waves for the sensor to pick up. During the process noise inevitably interferes with the signal. This is why knowing the original input from the function generator is necessary to measure the difference from each component. By having this function generator send specific frequencies we can see if the sensor outputs the same values in its recorded data.

2.3.2 Amplifier

In order for a speaker to drive a sound wave, the signals from the function generator need to be controlled and boosted. This is the job of the amplifier in our pressure sensing system. In a perfect amplifier the quality of the signal would not be sacrificed when the quantity is increased. However, in all amplifiers, along with a boosted signal comes added noise and distortion. Filtering out this added interference is of key importance in this specific pressure system. This is the only way to see the true outputs of each component of the system.

2.3.3 Loudspeaker

One device for generating low amplitude and acoustic frequencies is a loudspeaker. An experiment conducted by Zakrzewski and Wróbel, where a loudspeaker was placed at one end of a tube with a diameter corresponding to the diameter of that loudspeaker, was set up (Zakrzewski, 2001). An electronic generator and power amplifier drove the loudspeaker. The other end of the tube was closed by a piston that could slide along the tube. Through proper positioning, a standing wave could be obtained. The experiment was then conducted and the dynamic characteristics of the transducer-tube system were examined by measuring the frequency response relative to the response of a flush-mounted reference transducer. Unfortunately, no real calibration was performed and the only output was a resonance frequency which can be obtained without the aid of a reference transducer.

2.3.4 Pressure Sensor

Numerous pressure sensors rely on strain gage technology. The physical principle used in this technology is that pressure acting on a diaphragm causes the diaphragm to deflect, and the change in resistance of the bonded strain gages is detected due to the mechanical strain. The relative change in resistance is shown by

$$k = r / \varepsilon = 1 + 2\upsilon + (1 / \varepsilon)(\Delta\rho / \rho),$$

where k is the gage factor, r is the relative change in resistance, ε is the mechanical strain, υ is Poisson's ratio, and ρ is the material resistivity. Depending on the relevant pressure, we use the terms absolute (where the reference is a vacuum), gauge (where the reference is atmospheric pressure), or differential (where the sensor has two ports for the measurement of two different pressures.

The piezoresistive pressure sensor consists of a micro-machined silicon diaphragm with piezoresistive strain gages diffused into it which is fused to a silicon or glass back plate. The resistive have a value of approximately 3.5 kOhm. Pressure-induced strain increases the value of the radial resistors and decreases the value of the resistors transverse to the radius. This resistance change can be as high as 30%.

By connecting one or more strain gages in a Wheatstone bridge circuit, a voltage output proportional to the change in resistance is obtained. Amplification is necessary due to the fact that the output from the strain gage is low (typically a few mV/V). For dynamical measurements, a DC-system is preferred (generally 5-10 VDC) because an AC-system may be disadvantageous due to substandard high-frequency properties. The small size of the piezoresistive silicon sensor means that it has a high frequency response and may be used for dynamic pressure measurements.

In order to obtain sufficient signal strength, the strain must be relatively high because of the low gage factor of metallic strain gages. In turn, the diaphragm must be flexible, causing low natural frequencies. The resistance change for these materials does not largely depend on the geometric change when strained, but more on a strain-related change of material resistivity. Due to this reason, these transducers are called piezoresistive and are one of the most popular dynamic pressure measurement instruments.

2.3.4.1 Pressure Transducers

Dynamic pressure is the component of fluid pressure that represents fluid kinetic energy. The measurement of pressure is the difference between two points or ports. There are three types of pressure measurements. Differential pressure is measured between two points or a pipe connection. Absolute pressure is the difference between two points where one is in a vacuum. The third type of measured pressure is gauge pressure where one port is measured against atmospheric pressure. There are two types of gauge pressure. Sealed gauge pressure contains a sealed chamber that has atmospheric pressure. Vented gauge pressure compares pressure to a local opening or a vent.

2.3.4.1.1 Transducer Components

Transducers are electromechanical pressure sensors that can only measure one convention of pressure at a time. Most transducers are made with stainless steel due to its high strength and ability to resist corrosion. Transducers convert motion generated by a force-summing device into an electrical signal. The force-summing device can be bellows, a capsule, a “C” Bourdon tube, a spiral Bourdon tube, a diaphragm, or a convoluted diaphragm. These force-summing devices are the mechanical component of the transducer. Pressure is converted into a proportional displacement or strain. The movement of the diaphragm senses a force per unit area. The stiffness of the diaphragm governs the relationship between the applied pressure and the movement of the diaphragm. The strain or displacement is then transmitted to an electrical transduction element which generates the required signal. The output of the transducer is voltage, which could in turn, be converted into current.

Besides the mechanical component of a transducer, there is an electrical component. This electrical component is a bridge circuit which can be quartz crystal or a semiconductor bridge. A simple bridge circuit has four resistors. There is constant current in which splits to two voltage-out points by two resistors. One voltage-out goes through the sensing element and the other goes through a reference resistor. The sensing element and the reference resistor are both grounded. A simple bridge circuit is illustrated in Figure 4.

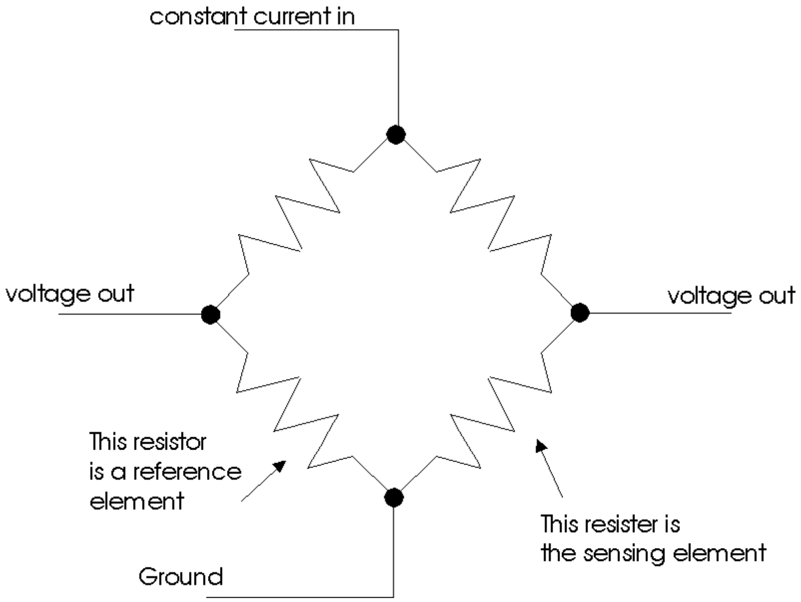


Figure 4 - Wheatstone Bridge Circuit

The Wheatstone Bridge Circuit is commonly used in transducers. Figure 5 illustrates the bridge circuit. Three main components make up the Wheatstone Bridge Circuit. There is a battery, a galvanometer, and four resistors. The first two resistors are set resistors, the third has variable resistance, and the last is the measured resistor. The fourth resistor can be a strain gauge transducer or a resistance thermometer. The theory of the Wheatstone Bridge Circuit is that the fourth resistor is measured and current flows via 2 resistive limbs: R1-R2 and R3-R4.

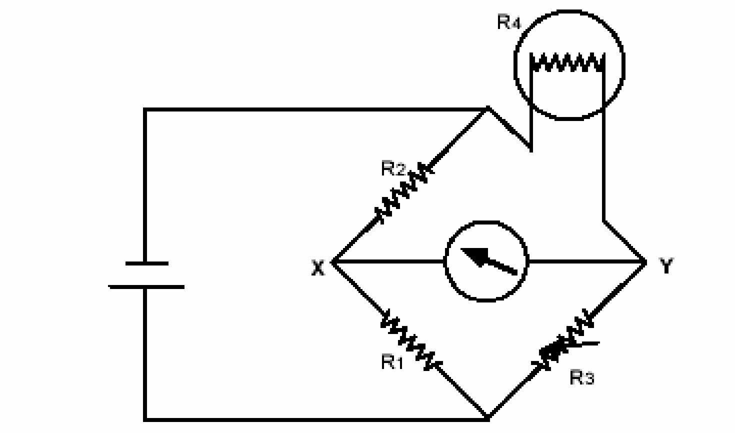


Figure 5 - Wheatstone Bridge Circuit Schematic

Transducers have a round tubular body with pipe fitting on one end and a cable on the other. The first end is the threaded pipe end which leads to the opening or the port. A stainless steel diaphragm which serves to protect the sensor element from the measured media follows the opening. The sensor element can be found on the other side of the diaphragm. This element is a strain gauge which precedes a resistive element whose resistance changes with the amount of applied strain. This acts as the variable resistor and is a part of the bridge circuit. A circuit board is next which leads to the voltage out. The voltage-out travels into an amplifier that changes the voltage to 0-5V or 4-20mA. The reading is then fed out of the cable on the other side of the transducer.

2.3.4.1.2 Types of Transducers

Strains gauges, variable capacitance, and piezoelectric are the most common pressure sensors. Strain gauge transducers are based on metal or silicon semiconductor gauges. These gauges are discrete units attached to the surface of the strained element or un-bonded gauges. The gauge material is fumed onto the diaphragm or diffused into the silicon diaphragm structure. This material exhibits significant resistance change when strained. Three characteristics of change are length, cross-sectional area, and the bulk resistance of the material. The force-summing device of strain gauge transducers is a diaphragm which is either flat or sculpted.

There are a number of different strain gauge transducers. Metal strain gauge transducers consist of a network of wires or patterns of thin metal foil fabricated onto or into the backing material with protective film. Bonded strain gauges are ones where the strain gauge is glued to the surface where the strain is measured. Un-bonded strain gauges have stretched wire around an array of posts which are linked to the force-summing device. This creates relative motion of the wire and the device. Sputtered strain gauges have material sputtered onto a nonconductive diaphragm. Semiconductor stain gauges contain semi-conducting silicon. Diffused diaphragm sensors are fabricated using semiconductor masking and processing techniques. Sculptured diaphragm sensors use anisotropic etching to allow optimum combinations of linearity, sensitivity, and frequency response characteristics.

Variable capacitance transducers follow the principle where if one plate of a capacitor is displaced relative to another plate, the capacitance between the two plates changes. In the transducer, the diaphragm acts as one of the plates. The capacitance is correlated to the pressure applied. The change is either used to vary the frequency of the oscillator or is detected by the bridge circuit. The advantages of variable capacitance transducers are the low hysteresis and good linearity, stability, repeatability.

Hysteresis, linearity, stability, and repeatability are characteristics of transducers. Hysteresis is the ability of the transducer to give the same output when the same increasing and decreasing of pressures are applied consecutively. Temperature hysteresis involves similar output at a given temperature before and after a temperature cycle. Linearity is the derivations of the measurements from the ideal line using the equation:

$$V_{out} = k_0 + k_1P.$$

where k_0 is the offset and k_1 is the pressure sensitivity.

Repeatability is the ability of the transducer to produce the same output with consecutive applications of the same pressure. The gauge factor of a transducer refers to the sensitivity of the sensor, which is the ratio of change in the electrical transduction parameter over the full range of pressure to the value of the parameter at zero pressure.

The third type of pressure sensor is piezoelectric transducers. These transducers use piezoelectric crystals or ceramic elements to convert the motion of the force-summing device to an electrical output. Some piezoelectric crystals include quartz and tourmaline. These crystals generate an electric charge when strained. The ceramic elements are specially formulated which can be artificially polarized to be piezoelectric. These have higher sensitivities than the natural crystals. Piezoelectric devices require charge amplifiers and noise-treated coaxial cables due to their high impedance outputs and low signal levels. These transducers are not usable with DC or steady-state conditions since they are self-generating, reliant on the changes of strain to generate an electrical charge. The primary advantage of piezoelectric transducers is their ruggedness. They are also useful at high temperatures without integral electronics. However, these transducers are sensitive to shock and vibration.

2.3.5 Data Acquisition

Once the transducer senses the change in pressure, it sends the signal directly to the Data Acquisition Board. The board connects the piezoresistive transducer to a PC with LabVIEW installed on it to collect and store the experimental data. The major conversion occurring in the DAQ board is an analog to digital conversion (ADC). This is mainly taking the data sensed by the transducer and putting it into two columns of time and digital code. After selecting the correct sampling rate, the data acquisition board just converts the data so that LabVIEW can process it.

2.3.6 LabVIEW

In order to view the results of our dynamic pressure readings, the program LabVIEW will be used. LabVIEW is a versatile program that will be used specifically for data acquisition regarding our dynamic pressure readings. There are many signals that LabVIEW can output including those of digital and analog. The two output types of digital signals are the on-off switch and the pulse train. There are three types of analog outputs which include DC, time domain and frequency domain. The differences of all 5 signals will be discussed in the following sections.

A digital signal is only processed on a high (on) level or low (off) level. This is also referred to in LabVIEW as the digital state of the signal. Measuring this on-off state is usually a simple digital state detector. The other form of digital signal is called a digital pulse train, otherwise known as the rate that transitions occur in a signal. This also can be measured by the time in between individual state transitions, or that of a series of state transitions.

The first type of analog signal is called DC, and shows the exact amplitude at a given moment during the signal. This DC signal varies slowly, sometimes static, so the number of samples taken per unit time is not critical, but the accuracy of those readings are crucial. Such signals can include strain gauges, temperature, or flow rate. These readings are taken at a requested time, so that they are as accurate as possible. This is why the sampling rate of these tests tends to be relatively slower than other such rates.

Analog time-domain signals are the second type of analog signals in that they take readings over a period of time, and focus on the amplitude changes. During a test there can be a time to peak, peak maximum, time to settle, and slope, which are all conveyed in the output on the computer screen. The shape of these amplitude waves are the main focus of a analog time-domain signal. In order to process these signals, the data acquisition (DAQ) must have an analog-to-digital conversion (ADC) section. This data collection method is different than that of a DC signal because the sampling rate must be much higher in order to convey the true shape of the signal. Due to this high sampling rate, the bandwidth must be high on the DAQ system in order to maintain accurate readings. Generally there is a triggering method that starts the readings at a specific time, and samples consistently over that period. Each measurement is an ADC, and the outputs can be shown in nearly any graphical arrangement.

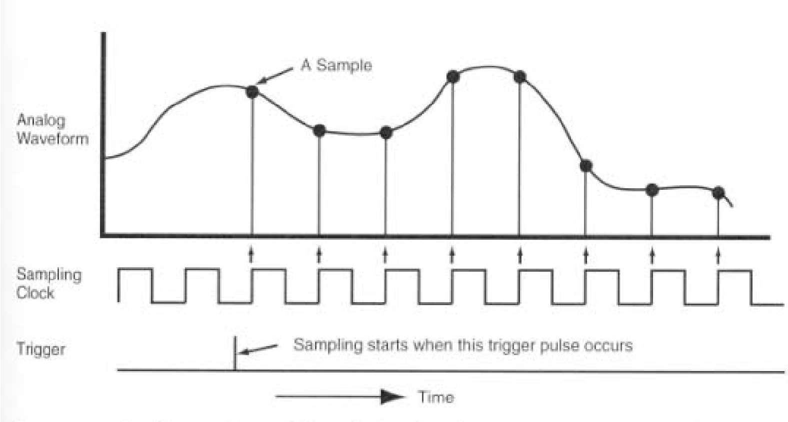


Figure 6 - How the Triggering Switch Takes Measurements (LabVIEW, 2004)

The last analog signal is called the analog frequency-domain signal. This is the type of signal that our group will be working with on our LabVIEW program.

Frequency-domain signals are extremely close to time-domain signals except for the frequency content is extracted with each measurement, not just the shape of the amplitude. Digital signal processing (DSP) technology is required for the convergence of time-domain to frequency-domain measurements at each sample of data taken. Some examples for usages of this type of frequency-domain signal are vibrations, geophysical signals, as well as what our group will be using it for, acoustical (pressure) analysis. Figure 7 shows how any signal can be converted into either analog or digital signals and how they can be represented graphically.

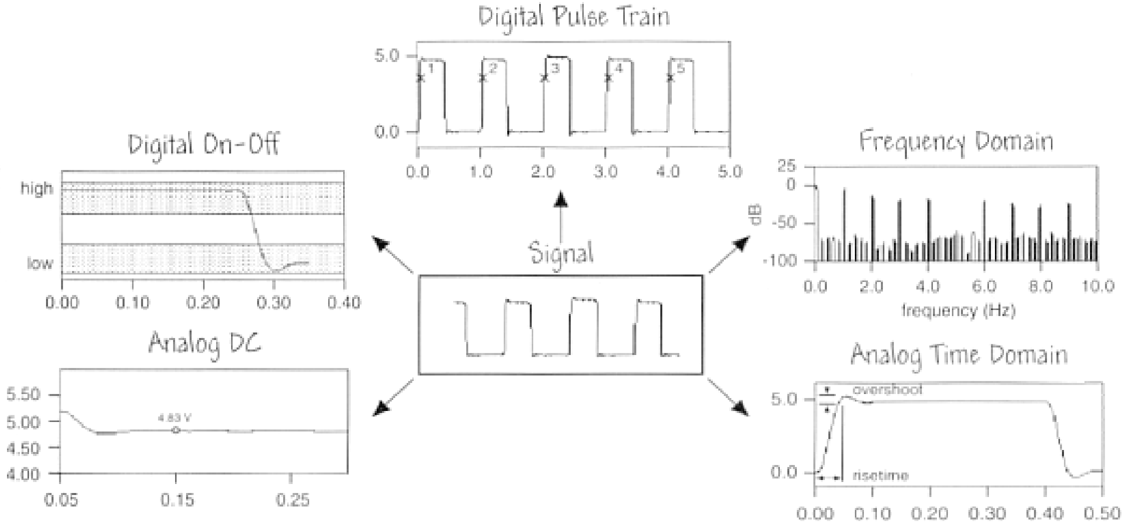


Figure 7 - Representation of Each Signal Class (LabVIEW, 2004)

2.3.6.1 Considerations

When converting analog signal to digital signal there are four main considerations for concern. These include resolution, range, sampling rate, and signal limit settings. All of these parameters affect the quality, accuracy and precision of the AD conversion.

Analog to digital conversion resolution is determined by the total number of bits used during the measurements. The greater number of bits used determines the overall accuracy of the representation on the screen. If there is a smaller resolution, instead of a sin wave looking smooth, it will show up in a step like pattern. This is because each AD conversion will be done with smaller increments in between them, creating a greater precision in measurements.

The second consideration is the range of the signals that can be handled by the ADC. Once a specific resolution has been determined, the best fit range should be implemented accordingly. If the range selected is too large for the samples, the measurements will be less accurately displayed because of the set resolution. When the range is close to the actual measurements it leads to more precise data collection. With this in mind, determining whether the signal is unipolar or bipolar is very important. Our range is in both the negative and positive values (like a sinusoidal wave), therefore it is bipolar. Unipolar data is when the values are only positive ones. Once again, sizing the range to the closest fit both for positive and negative values is necessary for collecting accurate data.

The rate at which signal sampling occurs determines how many analog to digital conversions take place during the measurements. Knowing the maximum frequency and the noise affecting the signal are necessary to gauge the proper sampling rate. A faster sampling rate will ensure proper signal measurements, as opposed to a slower sampling rate, which could misrepresent the incoming analog signal. The frequency would be disguised differently if a slow sampling rate was used and the maximum values could be invalid. In order to guarantee a correct sampling, the maximum frequency value of the incoming signal must be doubled in order to find the correct rate (LabVIEW, 2004).

2.3.6.2 LabVIEW Data Outputs

All of the data collected in LabVIEW is saved and stored on the computer. LabVIEW samples all measurements at a given rate, and then appends these values to a spreadsheet in Microsoft Excel. All of these values can be accessed as soon as the program is finished running. All of the frequency and AD conversions are processed in the program and outputted into Excel as well as shown on the computer .vi screen (LabVIEW, 2004).

2.3.7 Filter Circuits and Response

Data filtering is a concept which can be used to ease the process of statistical analysis. Filters can be used to remove unnecessary data points from a data set, while having little effect on the important data. When using a filter, a cutoff point must be determined in which the filter will begin removing data. There are three ways that data filters can be used. They are used as high pass, low pass, and band pass. In an ideal filter, a high pass configuration will remove the data below the cutoff. All data above the cutoff point will remain unscathed. Figure 8, below, shows an ideal high pass filter response, where for this case the cutoff point equals 1 (x-axis). The y-axis values are represented by points at 0 (filtered) or 1 (original values).

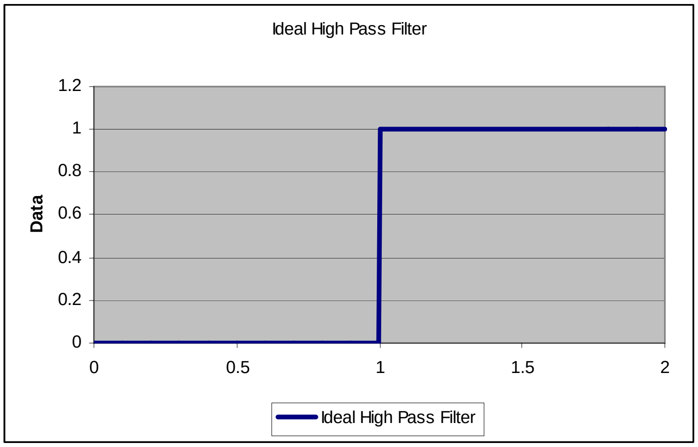


Figure 8 - Ideal High Pass Filter Response

The low pass filter works on the same premise, except it removes data above the cutoff point rather than below. An example of how data responds using an ideal low pass filter is Figure 9.

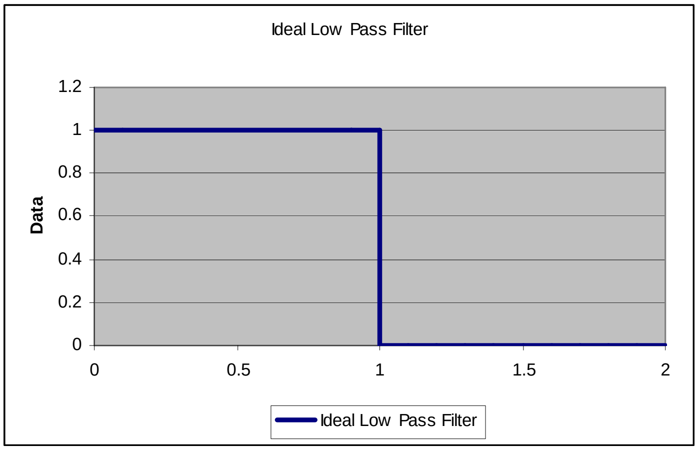


Figure 9 - Ideal Low Pass Filter Response

The third way that data can be filtered called band pass. This filter makes use of two cutoff points, one low cutoff and one high cutoff. The example of an ideal band pass filter, in Figure 10, uses the cutoff points at 0.5 and 1.5 (x-axis). As you can see, when using the band pass filter, data below the low cutoff and above the high cutoff points are removed.

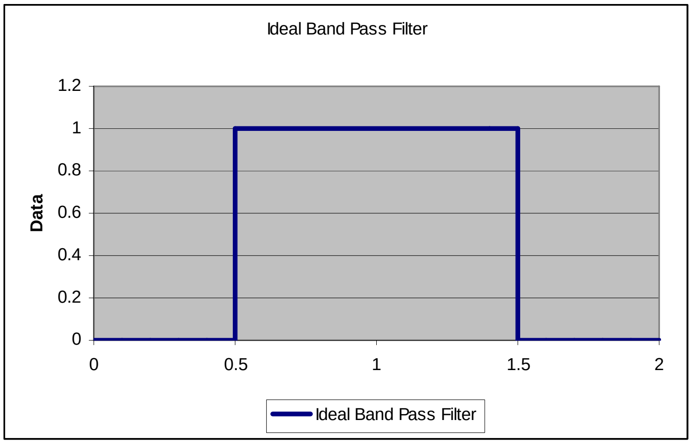


Figure 10 - Ideal Band Pass Filter Response

When looking at these three types of ideal filters, it important to understand that they are *ideal* and that they are only being used to introduce the concept of how a filter can be used. In real world application, there are no filters capable of performing with the same response that the ideal graphs display. In fact, filters can be put into classes based on how they perform with respect to the ideal.

2.3.7.1 Filter Classes

The main type of filter that was considered for use was the Butterworth filter. A Butterworth filter has a relatively steep response curve which gets steep as the order is increased. An advantage of using this filter is that it does not affect the data on the side of the cutoff in which the data is desired to remain untouched.

A Butterworth filter also has variations which do use the area before the cutoff to create a steeper response curve. A Chebyschev filter is essentially a Butterworth filter with an applied gain to generate the steep response curve. In our case, using a highpass filter, we do not want to modify the data after the cutoff at all. A Bessel filter is another type of filter however, the response curve is just not steep enough.

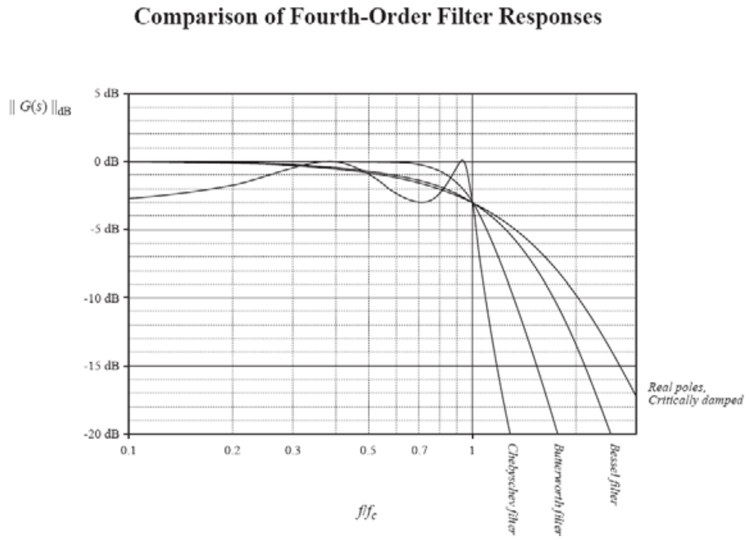


Figure 11 - Comparison of Fourth-Order Filter Responses (http://ece-www.colorado.edu/~ecen2260/slides/FilterSlides.pdf)

For this application, we will be using a 4th order Butterworth high pass filter. With a cutoff of 100 hertz, the data acquired will be affected minimally. A MathCAD model of the transfer function for Butterworth Filters was developed to help decide on these settings, and to calculate the effect on the data. This model can be found in Appendix A.

2.4 Calibration of Pressure Instruments

The recognized definition of calibration is a “set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards” (National, 2005). This means that in a calibration, the output from a pressure measurement system is compared to the pressure realized by a pressure standard.

2.4.1 Traceability

A requirement of all modern systems is that calibrations performed must be traceable to national or international standards. The concept of traceability is formally known as “the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties” (National, 2005). This requirement must be met in order to ensure that measurements of the same quantity completed at different times, at different locations, and by different people can successfully be compared.

When dynamic pressure measurements are considered, it is evident that there is a problem when trying to meet these traceable standards. This is because the only country having national dynamic pressure standards (sound pressure neglected) is France. Their standards consist of a series of shock tubes and fast-opening devices. It is argued that pressure measurements are traceable only if a static calibration has been performed. However, this argument relies on the part of the definition of traceability that is only concerned with the measured quantity of pressure. It would be more reasonable to state that the difference between static pressure measurements and dynamic pressure measurements prompts traceability to a dynamic standard rather than a static standard. The need for traceability to a dynamic standard is recognized and necessary in all applications of dynamic pressure measurement.

2.4.2 Primary and Secondary Standards

When considering the calibration methods and equipment used, it may be easier to understand if it is broken up between primary and secondary methods. A primary method of calibration is a method that uses primary standards to examine pressure. A primary standard is recognized as having the highest metrological qualities and is accepted without the need of reference to another standard of the same quantity. Alternately, a secondary standard is defined as a standard whose value is assigned through association with a primary standard of the same quantity. It is essential to understand that just because a method is primary, the uncertainty acquired in the calibration is not necessarily lower than the uncertainty acquired for the same instrument when using a secondary method.

2.4.3 Static Calibration

Unlike dynamic pressure calibration, the matter of static pressure calibration is well developed. Many calibration methods exist for the different modes of pressure measurement (absolute, gauge, and differential) and different pressure amplitude systems (low vacuum, vacuum, medium pressure, and high pressure).

2.4.4 Dynamic Calibration

A significant amount or work on dynamic calibration methods for pressure transducers has been performed during the last forty years due to the need for accurate pressure measurements within the United States space programs. Bearing in mind the number of people involved in the research it is surprising that even today there are still no traceable dynamic pressure calibration services on the market.

There is a difference between the need for traceable calibrations communicated by people involved in dynamic pressure measurements and the methods actually taken. In the majority of cases, used measurement systems are calibrated statically, and it is argued that since the lowest natural frequency of the measurement system is much higher than the relevant frequency information of the dynamic pressure to be measured, the obtained uncertainty should be quite low. However, most people feel that this is not enough because there are no principles on how to incorporate the uncertainty due to the difference between the static calibration and the dynamic use into the uncertainty plan. Sometimes the static calibration is used along with a dynamic checking of the measurement system natural frequency.

In dynamic calibration, there needs to be a way of producing a dynamic pressure, as well as a way of determining that dynamic pressure. The pressure generator may produce a periodic pressure or an aperiodic pressure. Although it is easy to create a recognized high-amplitude static pressure or even a low-amplitude dynamic pressure at acoustic frequencies, it is difficult to produce well-known dynamic pressures of any other type.

In many cases, a reference pressure transducer is used to measure the pressure produced by the pressure generator. It is imperative that the dynamic characteristics of a used reference transducer are well understood. It is recommended that the maximum frequency of the generated pressure should not exceed one-fifth of the natural frequency of the reference transducer (ANSI B88.1-1972). This is to maintain high-accuracy calibrations. When deciding between periodic and aperiodic pressure generation, it is important to choose the generation that will most closely resemble the actual measurement situation. In some instances, aperiodic pressure generators are preferred because the related calibration consists of only one test.

2.4.4.1 Periodic Pressure Generators

The pressure produced by a periodic pressure generator is a periodic function (harmonic, square-wave, etc.). In many cases, it is desired that a sinusoidal pressure wave be generated at distinct frequencies. Unfortunately, sinusoidal pressure waves cannot be produced in a gaseous medium at higher amplitudes and frequencies. If this scenario is forced, a saw-tooth waveform will result. In the scientific world, there is no absolute periodic pressure generator; therefore, a reference transducer is needed.

The reference transducer must be placed very close to the transducer being tested in order for the same pressure to be seen by both transducers. To ensure that this is the case, the distance separating the transducers should be less than a tenth of a wavelength of the pressure wave. This wavelength, λ, is defined by

$$\lambda = a / f,$$

where a is the speed of sound and f is the frequency.

2.4.5 Interference

There are several factors that need to be taken into consideration when converting dynamic pressure to an electrical signal. Once the transducer senses the difference, there are several ways for interference to affect the output. The compatibility of the wires to the transducer is a major contributor to collecting valid data. These cables are suggested to be recommended by the transducer's manufacturer. Also, noise in the system can totally mask the calibration signal. Noise can occur in the transducer, the cabling, the amplifier, and even the system itself.

When wiring the entire system there should be no loose or frayed wires in contact with other connections. Cabling should be of a high-quality, low-noise shielded type.

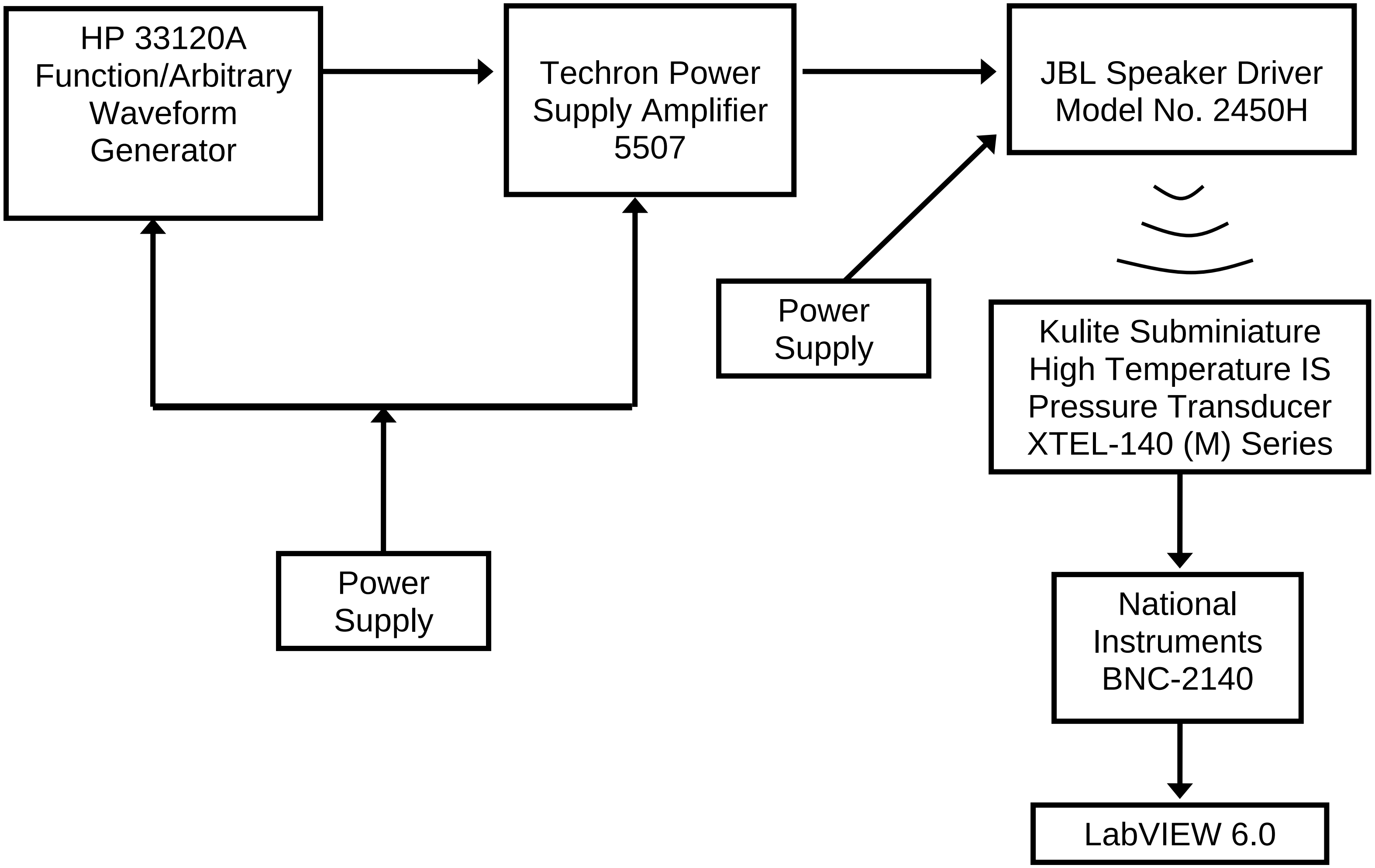
Cable length is also an issue because when the cable length is increased the capacitive loading is also increased, thus decreasing the signal. By keeping the wiring as concise as possible, our group has eliminated the errors that could result from lengthy cabling. A key formula regarding cabling is that the output is equal to the charge divided by the capacitance: $V_o = Q / C$. There is an increase in noise as a direct function of cable length. All wiring needs to be kept dry and clean to prevent the loss of low frequency-response. In order to accommodate these needs, the system will be kept in a room that is of room temperature and low humidity. There could be a possibility of running the system with both longer and shorter wires to see exactly the affect that it has on our specific dynamic pressure system.

Transducers are very susceptible to electromagnetic fields, temperature changes, and mechanical accelerations. Transducers that provide a high-voltage, low-impedance output are not as affected to these changes as a charge-mode transducer that has a high-impedance.

Cabling noises can affect the overall output of the system by their length, the stress on each one, and other disturbances. They contribute to the noise level by making internal noise signals, or by picking up magnetic or electrical fields. With a higher impedance circuit, it is more susceptible to the noise. Amplifiers tend to have a noise constant associated with them. It usually is referred to by the input. Amplifying a signal more than one time adds to the total noise of a system.

All of the previously mentioned noise contributors can affect the whole system's noise level. When there is more than one ground loop, inductive coupled noise usually exists. Reducing this noise can be done by using differential amplifiers, similar to the ones in our system. Another contributor to the overall system noise is the addition of more than one ground point. Grounding the system at only one point near the recording location is preferable. Stray capacitance can not be totally eliminated even if all the necessary precautions are taken, but minimizing it is the goal (ISA).

2.5 Our System Components



3 Methodology

3.1 Designing the Transducer Mounting Structures

In order to begin conducting the necessary tests for our project, we first needed a design for the top mounted transducer housing. Shortly after it was fabricated, a side-mounted housing needed to be designed. Before these housing units could be drawn out, a list needed to be compiled to state the overall specifications of the design. To summarize this list, first the cavity, which would extend up from the speaker driver, must be flush and airtight when the housing is on top of it. A study of pressure and sound sine wave behavior was performed to help assist in choosing a height from the end of the driver to the transducer mounting. Also, the size of the diaphragm for the pressure calibrator was much larger and could handle bigger mount plugs than our speaker driver cavity would require. The plugs needed to be made smaller, retaining the thread type in order to accommodate the speaker driver. The side mount plugs would need to be designed differently, due to the curvature of the inside surface of the housing cavity. Lastly, a study of wave reflections and interference along with knowledge about machining certain materials helped us in choosing a material.

3.1.1 Top Mounted Housing Design

The top mounted housing was designed using similar features as the existing mount for the pressure calibrator.

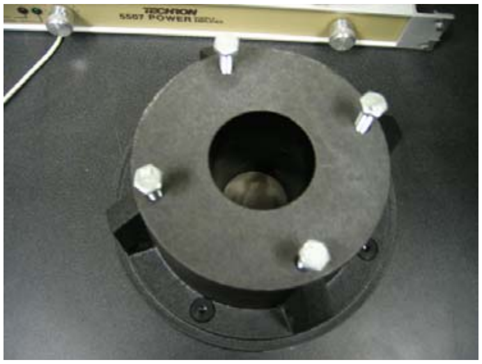


Figure 12 - JBL 2450H Speaker Driver

The major differences between the new and old designs are the size of the mount and the placement of the transducer. With the old calibrator, the transducer sat right down next to the diaphragm. Now, using the speaker driver, it was desired to get the transducer to a height of 3.35 inches off of the speaker diaphragm. Pictured below are the two main components to the housing assembly: the transducer mounting plugs and the top mounted housing design. Two sets of plugs were fabricated, one threaded for #6-32 and the other for #10-32 thread sizes, in order to satisfy the two different transducers we had. The plug is 0.5 inches thick, and the transducer's end is flush when screwed in. Those plugs snap into the holes on top of the housing. Using a rubber o-ring will help to reduce vibration and will hold the plugs in place more firmly. There are four thru holes on the housing spaced in a 5 inch diameter which are used to screw the mount into the speaker driver. These designs are fairly simple and have been effective for mounting the transducer onto the speaker.

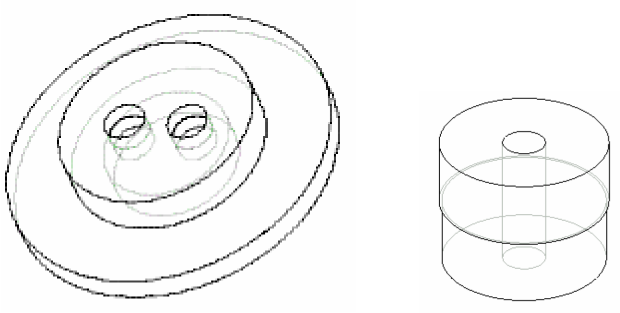


Figure 13 - Top Mounted Housing Design

3.1.2 Side Mounted Housing Design

The side mounted housing takes similar concepts of the top mount design. The main differences are that the cavity within the mount continues upwards past the sampling point and that the plugs must be made with a curvature to match up with the curvature of the cavity. Pictured below are the overall housing mount design and two pictures of the plug design. The plug retains the #6-32 and #10-32 thread sizes and was dimensioned so that the transducer will still sit flush with the cavity walls. The side mounted housing sits on top of the speaker driver in the same way that the top mounted housing does.

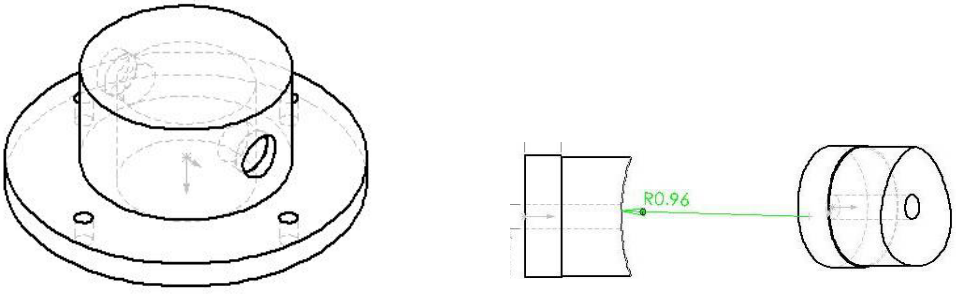


Figure 14 - Side Mounted Housing Design

3.2 Conducting Pressure Tests

After the design and fabrication processes of the top and side mounts were completed, we began conducting the experiments using our pressure calibration system. The main goal for running the various tests was to determine whether there were any differences when running the experiments in different environments and with the different mounts. We came up with a list of experiments that would eventually allow us to determine which mount is more effective and what environment would yield the most accurate and consistent data. We conducted experiments inside and outside of the black dampening box with both the top and side housings in place, as well as an experiment inside the box with no housing at all.

3.2.1 Types of Experiments

3.2.1.1 Free–Hanging Transducer

The goal of suspending the transducer vertically above the speaker cavity was to identify any relations between a closed mount and open air. For all of the tests with the transducer hanging freely (vertically) there were frequency increments ranging from 500 – 2000 Hz in 100 Hz increments, and from 2000 – 10000 Hz in 500 Hz increments. There were five trials taken with each of the frequencies, in order to ensure that the data was consistent. Another variable held constant was the use of the black dampening box. All of the tests run with the transducer suspended without restraint were completed inside the box. We were not capable of running the free-hanging transducer tests outside of the black dampening box simply because the noise level was far too loud to conduct the tests.

The transducer was suspended so that it was level with the top of the speaker driver cavity. This height was chosen so that it would be comparable to the data with the top housing in place. We also placed the transducer directly above the center of the cavity.

3.2.1.2 Top Mounted Housing Cover

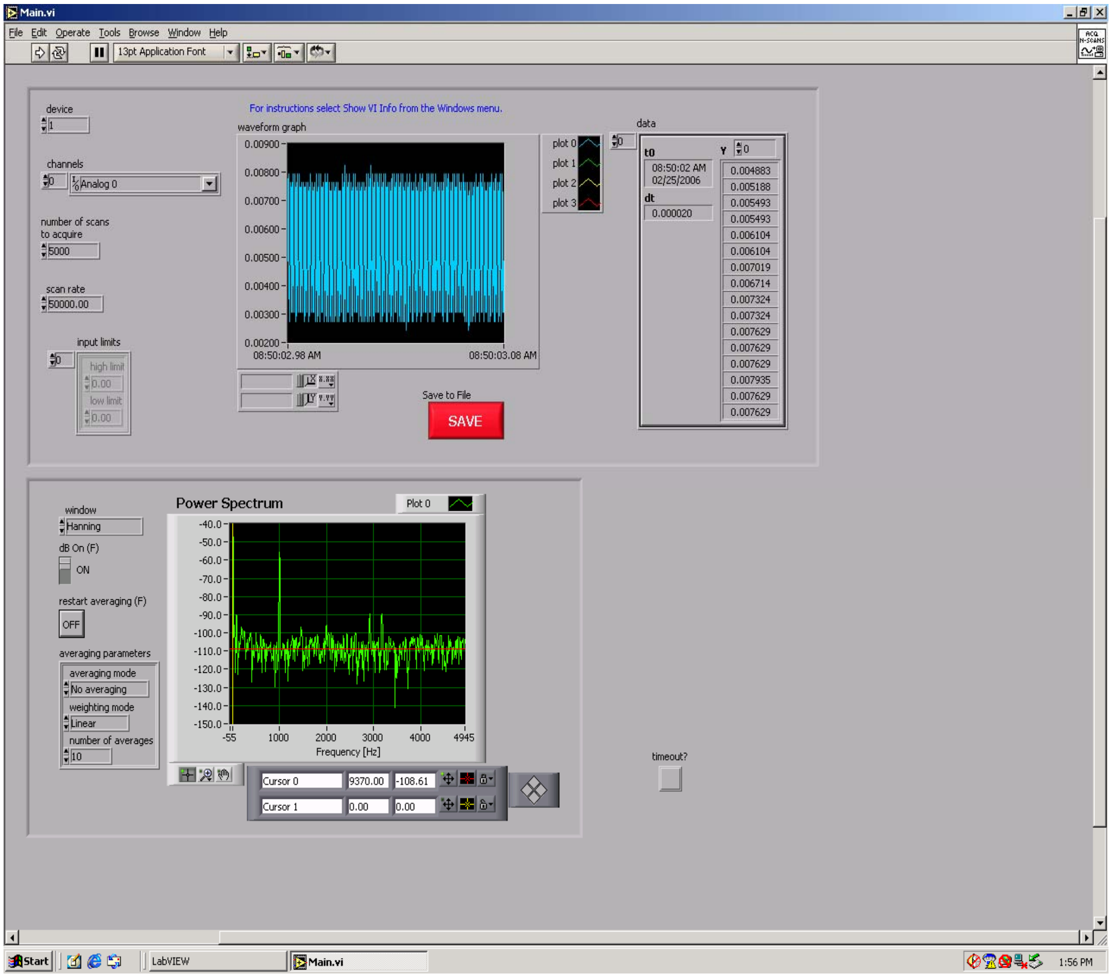
With the transducer seated in the plug on the top-mount housing design, we were able to run multiple tests both inside and outside of the black dampening box. For all of the tests with the transducer placed in the top mount, there were frequency increments ranging from 500 – 2000 Hz in 100 Hz increments and from 2000 – 10000 Hz in 500 Hz increments. Again, we ran five different tests at each of the frequencies for consistency. Once the experiments were run inside the dampening box, the speaker driver, transducer, and housing cover were moved outside of the black box and the tests repeated.

3.2.1.3 Side Mounted Housing Cover

The final set of tests included the side mounted housing design. Again, for all of the tests with the transducer placed in the side mount, there were frequency increments ranging from 500 – 2000 Hz in increments of 100 Hz, and from 2000 – 10000 Hz in increments of 500 Hz. As in each of the previous experiments, we ran five trials at each frequency to ensure consistency. Unfortunately, when we tried to conduct this test outside of the black dampening box, the noise levels were too high and the experiment was dismissed.

3.2.2 Data Acquisition

Throughout the testing process, there were some key variables that we needed to remain constant so that we could effectively analyze the data when considering our results. On our amplifier, we kept the amplification knob at its highest reading throughout the project. This was necessary because it was the only possible point where we would know for sure that the amplification was the same as the previous tests. Inside our LabVIEW Data Acquisition program, we determined that a scan rate of 50,000 samples per second would provide us with the best possible resolution for our acquired data. Once each of these variables was set, we ran each experiment in full, and all of the acquired data was appended to a Microsoft Excel file. A screenshot of the Data Acquisition program is shown in Figure 15.



For instructions select Show VI Info from the Windows menu.

device: 1

channels: 0, Analog 0

number of scans to acquire: 5000

scan rate: 50000.00

input limits: 0

high limit: 0.00

low limit: 0.00

data: 0

t0: 08:50:02 AM 02/25/2006

dt: 0.000020

Y: 0

Y
0.004883
0.005188
0.005493
0.005493
0.006104
0.006104
0.007019
0.006714
0.007324
0.007324
0.007629
0.007629
0.007629
0.007935
0.007629
0.007629

window: Hanning

dB On (F): ON

restart averaging (F): OFF

averaging parameters

averaging mode: No averaging

weighting mode: Linear

number of averages: 10

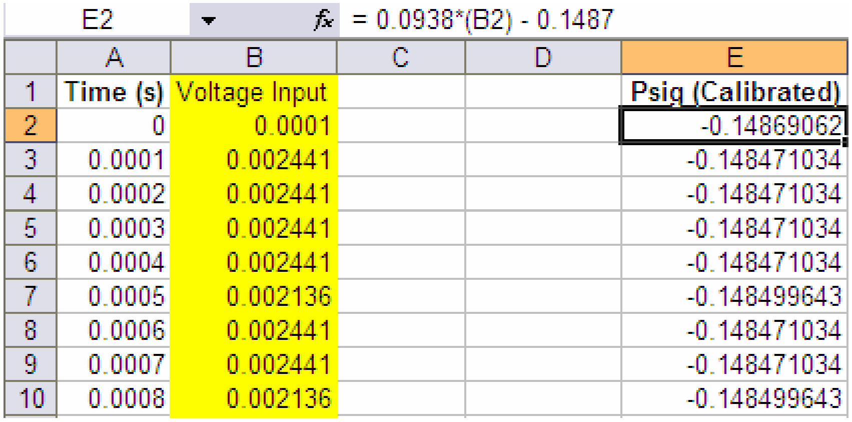
Cursor 0	9370.00	-108.61
Cursor 1	0.00	0.00

Figure 15 - LabVIEW Data Acquisition Program Screenshot

3.3 Determining the Pressure Output

3.3.1 Original Method

Once all of the necessary experiments were completed, we needed to decide on the most efficient method of determining the pressure output for each test. We began by creating a template that we would be able to follow for each of our trials. The following is a screenshot of the Excel template and the process we utilized to determine the pressure output of the speaker driver for one test trial:



E2 fx = 0.0938*(B2) - 0.1487

	A	B	C	D	E
1	Time (s)	Voltage Input			Psig (Calibrated)
2	0	0.0001			-0.14869062
3	0.0001	0.002441			-0.148471034
4	0.0002	0.002441			-0.148471034
5	0.0003	0.002441			-0.148471034
6	0.0004	0.002441			-0.148471034
7	0.0005	0.002136			-0.148499643
8	0.0006	0.002441			-0.148471034
9	0.0007	0.002441			-0.148471034
10	0.0008	0.002136			-0.148499643

Figure 16 - Excel Template for Original Analysis method

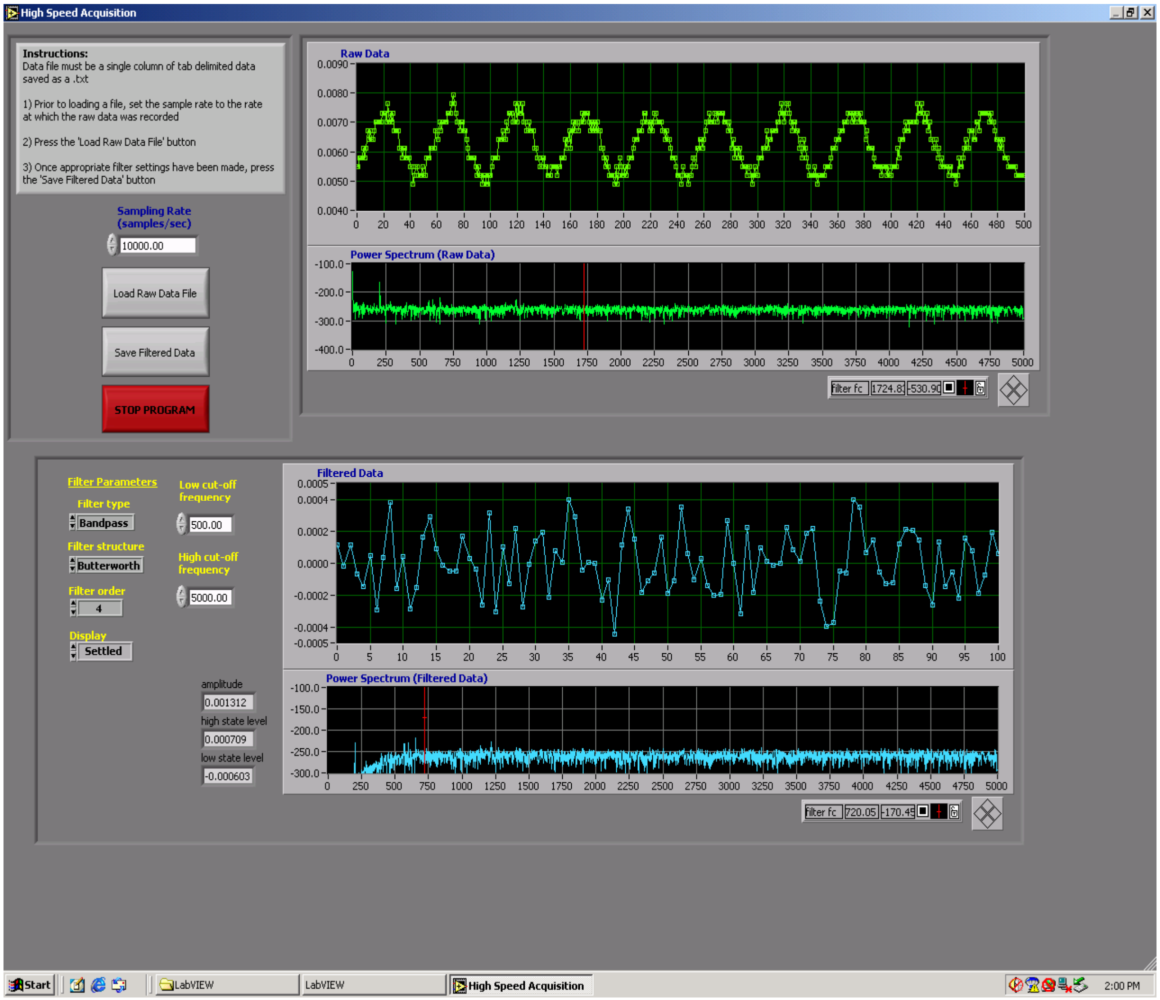
1) We copied the Excel file that we obtained from the Data Acquisition program into the 'Voltage Input' column of our template
2) Using the equation from the transducer specifications sheet, we would calculate a calibrated pressure from the voltage input (the equation is f(x) = 0.0938*(Voltage Input) – 0.1487)
3) We then needed to determine the Root Mean Square (RMS) of the pressure, which can be determined through the equation RMS = [(Maximum Pressure – Minimum Pressure)/2]*0.707; therefore, we manually obtained ten consecutive maximum values and ten consecutive minimum values and computed the average for each. These values were then plugged into the aforementioned equation to give us the RMS pressure value for each frequency.
4) This RMS value was then plotted versus each frequency to give us a data curve from 500 – 10000 Hz for that particular experiment

3.3.2 Filtered Method

The original method described above turned out to be very time consuming and tedious. Since we were only taking ten maximum and ten minimum values from each trial, it also turned out to be less accurate than we hoped. Therefore, we were in need of an alternate way of obtaining our RMS pressure values.

After we had completed the RMS graphs for some of the data using the original method, we were given a dynamic analysis program that was compatible with LabVIEW that would allow us to observe our data. In addition to filtering data, it also is capable of giving us the average maximum and minimum vales, as well as the amplitude, over large ranges. Therefore, we had run into a much easier and time effective method of analyzing our data.

Before using the program, we had to determine which of the options would be most appropriate for our project. Through research and investigation, we concluded that a Butterworth fourth order filter would be most appropriate. In addition, we chose a sampling rate of 10,000 which is the highest the program offers. Once these settings were chosen, we were able to run the program with each of our test trials. The following is a screenshot of the dynamic analysis program and the steps we took in analyzing our data:



Instructions:
Data file must be a single column of tab delimited data saved as a .txt

1) Prior to loading a file, set the sample rate to the rate at which the raw data was recorded

2) Press the 'Load Raw Data File' button

3) Once appropriate filter settings have been made, press the 'Save Filtered Data' button

Sampling Rate (samples/sec): 10000.00

Filter Parameters

Filter type: Bandpass

Filter structure: Butterworth

Filter order: 4

Display: Settled

Low cut-off frequency: 500.00

High cut-off frequency: 5000.00

amplitude: 0.001312

high state level: 0.000709

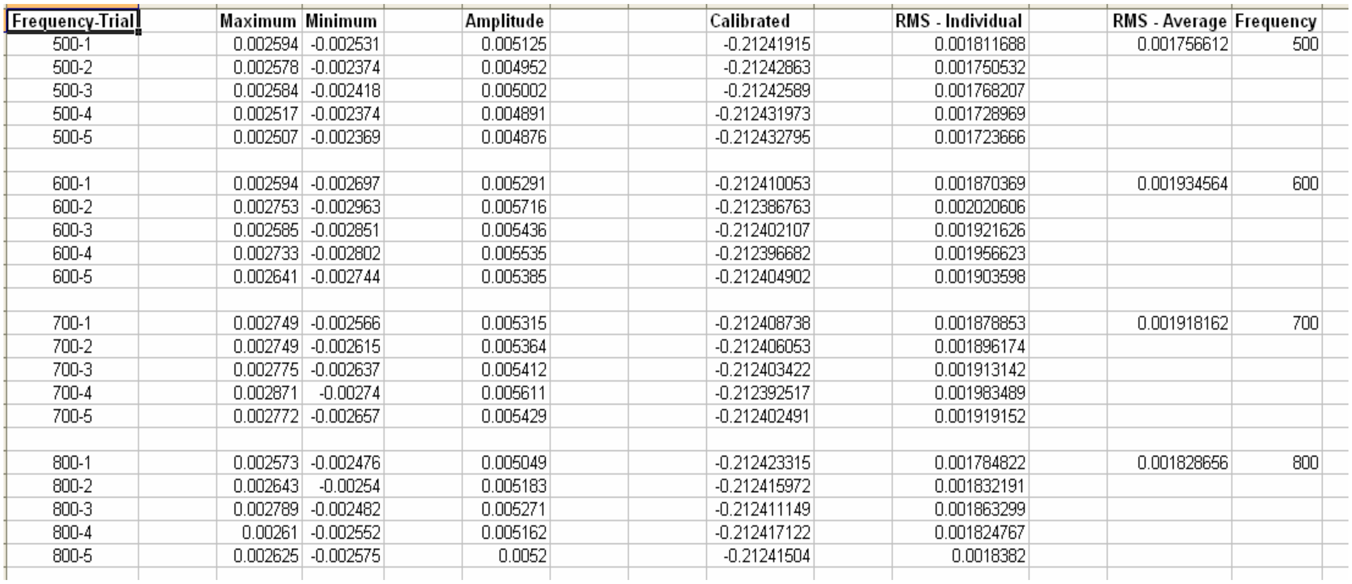
low state level: -0.000603

Figure 17 - Dynamic Analysis Program Screenshot

1) We would first load our raw data file obtained from the data acquisition program into the dynamic analysis program (which also involved us converting each file from Excel to text format)

2) We would then record each average maximum and minimum for each frequency increment from 500 – 10000 Hz

3) We then created another Excel template that we could use repeatedly (as shown below in Figure 14), and plugged our average values into the appropriate columns



Frequency-Trial	Maximum	Minimum	Amplitude	Calibrated	RMS - Individual	RMS - Average	Frequency
500-1	0.002594	-0.002531	0.005125	-0.21241915	0.001811688	0.001756612	500
500-2	0.002578	-0.002374	0.004952	-0.21242863	0.001750532		
500-3	0.002584	-0.002418	0.005002	-0.21242589	0.001768207		
500-4	0.002517	-0.002374	0.004891	-0.212431973	0.001728969		
500-5	0.002507	-0.002369	0.004876	-0.212432795	0.001723666		
600-1	0.002594	-0.002697	0.005291	-0.212410053	0.001870369	0.001934564	600
600-2	0.002753	-0.002963	0.005716	-0.212386763	0.002020606		
600-3	0.002585	-0.002851	0.005436	-0.212402107	0.001921626		
600-4	0.002733	-0.002802	0.005535	-0.212396682	0.001956623		
600-5	0.002641	-0.002744	0.005385	-0.212404902	0.001903598		
700-1	0.002749	-0.002566	0.005315	-0.212408738	0.001878853	0.001918162	700
700-2	0.002749	-0.002615	0.005364	-0.212406053	0.001896174		
700-3	0.002775	-0.002637	0.005412	-0.212403422	0.001913142		
700-4	0.002871	-0.00274	0.005611	-0.212392517	0.001983489		
700-5	0.002772	-0.002657	0.005429	-0.212402491	0.001919152		
800-1	0.002573	-0.002476	0.005049	-0.212423315	0.001784822	0.001828656	800
800-2	0.002643	-0.00254	0.005183	-0.212415972	0.001832191		
800-3	0.002789	-0.002482	0.005271	-0.212411149	0.001863299		
800-4	0.00261	-0.002552	0.005162	-0.212417122	0.001824767		
800-5	0.002625	-0.002575	0.0052	-0.21241504	0.0018382		

Figure 18 - Excel Template for Filtered Method Screenshot

4) From the maximum and minimum values, we were able to calibrated pressure values using the formula given to us by the transducer specification sheet: Calibrated Pressure = 0.0548*Amplitude – 0.2127
5) We then were able to determine the RMS values for each trial using the equation: RMS = (Amplitude/2)*0.707
6) In order to get one RMS value for each frequency, we averaged the RMS values from each of the five trials
7) The average RMS values were then plotted against each frequency in intervals from 500Hz – 10000Hz

4 Results

At the beginning of the project, much effort was focused on background research. When testing eventually did commence, a number of tests were done which introduced some problems. A few tests were completed and the data was analyzed only to find out that the data was not legitimate. The reasoning behind the failed tests was determined, and successful experiments were then run.

4.1 Troubleshooting

During the process of running the system and acquiring data, there were several parts that needed troubleshooting. When a problem was encountered, it needed to be evaluated, researched, and then solved. There were several problems that came up in the current system that was used. These included things such as the wiring, components, environmental noise, a 60 Hz signal, and the side-mounted housing.

4.1.1 Wiring

If the cabling of a system has a bad connection or frayed wires, there can be a serious problem with the outputted data. When the system was first set up, there were several cables that seemed to have inadequate connections. This can be a major problem when acquiring data because static and other outside noises can enter the system. All of the wires were re-connected using the best connections available. The dilemma of replacing all of the wire with new cables was discarded and the process moved on.

4.1.2 Components

The components of any system need to be functioning properly. Problems tend to occur when parts are not functioning at their highest standard. This includes age, connections, and even functionality of the components. There was trouble encountered with the DAQ board of the system and how it was connected to the cabling from the transducer.

Figure 19 - Analog-to-Digital Output

The locking mechanism for the fittings (shown above) was not at its full capability, so when pressure was slightly applied, the data output reflected such movements. When running the system for data acquisition, the actual board was not touched, but kept constant throughout all of the tests as to not disrupt the output. If a newer board was present, this precautionary measure would not have been necessary.

4.1.3 Environmental Noise

Environmental noise is the total noise at a given location other than the source. Such sound also includes reflections of the original noises. If this background noise level is too high compared to what is being measured, than it can throw off all of the measurements. There are certain ways to test whether or not the environmental noise at and around the system was too great for the actual measurements. If the difference between the focus sound being measured and the environmental noise is less than 3 dB, then the data will be invalid.

If there are 2 or more sound pressure levels present that make up the environmental noise, they must first be added to get a total SPL which can then be compared to the focus sound. However, dB’s can not be added together because of the logarithmic scale, so this is how to go about it:

1. Measure the Sound Pressure Level (SPL) of each noise source separately (Lp1, Lp2)
2. Find the difference between those levels (Lp2 – Lp1)
3. Find the difference on the horizontal axis of the chart. Move up until you intersect the curve, and then find the value on the vertical axis on the left
4. Add the value indicated (L+) on the vertical axis to the level of the noisier noise source (Lp2). This gives the sum of the SPL’s of the two noise sources
5. If three or more noise sources are present, steps 1 through 4 should be repeated using the sum obtained for the first two sources and the SPL for each additional source

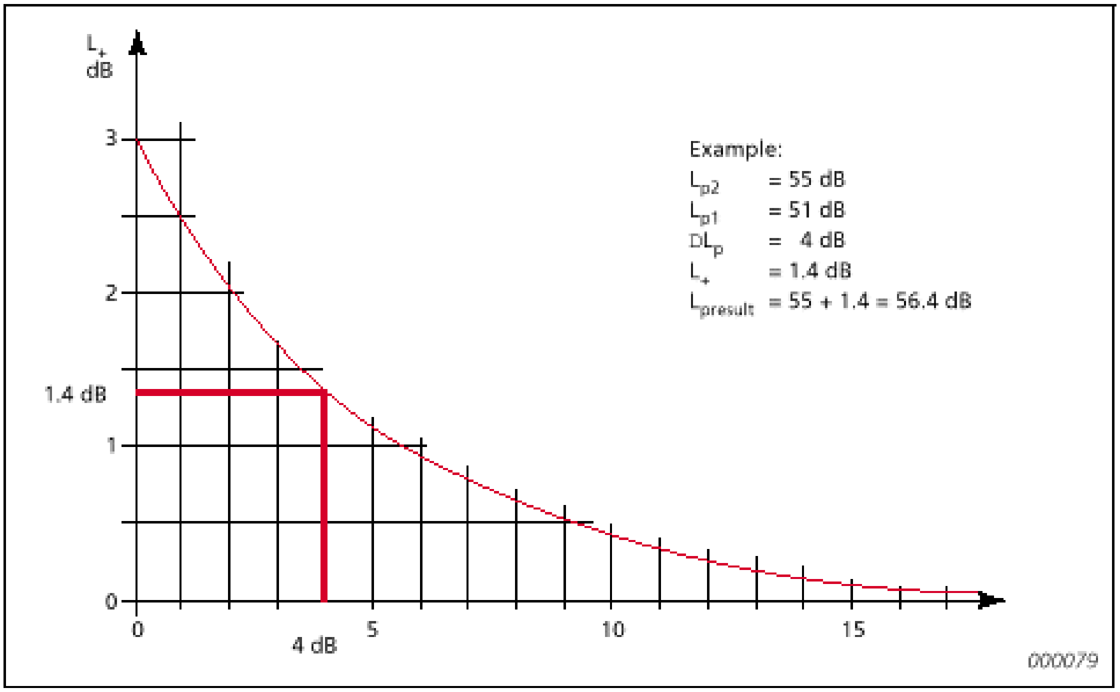


Figure 20 - SPL Addition

Once this total pressure is calculated, the difference between the focus sound and the environmental noise can be found by doing the following:

1. Measure the total noise with the machine (focus noise) running (Ls+n)
2. Measure the background noise with the machine off (Ln)
3. Calculate (Ls+n) – (Ln). If it is less than 3 dB, the background noise is too high for accurate measurement. If 3<(Ln)<10, correction is necessary, if (Ln)>10, no correction is necessary
4. Corrections: go to chart below, use (Ls+n) – (Ln) to interpolate
5. Subtract the value on the horizontal axis ΔL from L(s+n) = Ls of the machine

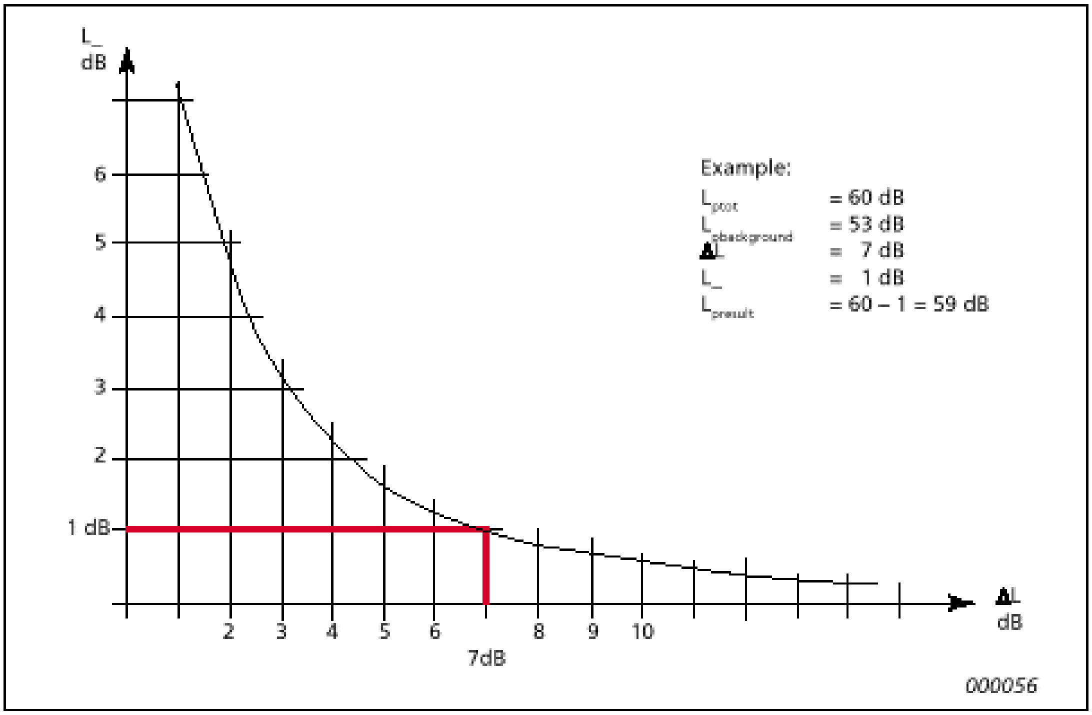


Figure 21 - SPL Difference

Since the environmental noise was greater than 10 dB, there was no correction necessary for pressure transducer calibration system.

4.1.4 60 Hz Signal

When any system draws power from an electrical outlet, an "earthly" ground loop can inject a 50 Hz – 60 Hz signal into the signal cables. This in turn skews all of the outputted data with a sin wave of 60 Hz in the recorded values. The second transducer used was picking up a 60 Hz signal somewhere in the system. The problem that was faced was to locate where the signal was coming from and eliminate it. After checking all of the components with a voltmeter to see if any could be the source of the problem, the transducer was finally switched out. This proved to be the cause of the unwanted signal and was discarded. The third and final transducer that was used in the system had no 60 Hz signal and produced clean data.

4.1.5 Side-Mounted Housing

The final dilemma encountered while running the system dealt with the side-mounted transducer housing. The data acquisition sampling rate was set at 50,000 samples per second, and the outputted data appended 5,000 points to an excel file. However, when running the side-mounted housing, the 5,000 points that were supposed to be outputted to an excel file were not always present. At times there would be 1,000 values, and at other times less than that. This presented a problem because when run through the filter, it needed all 5,000 values to correctly calculate the maximum and minimum values. All of the incomplete readings of less than the appropriate number of values needed to be discarded, and the data outputted again. At each frequency the side-mounted transducer housing needed to be appended roughly eight to ten times instead of the five times for all of the top-mounted tests. After using only the excel files with the correct number of values, the side-mounted tests were then complete. This is the reason that the side-mounted housing problem of the correct number appended values needed to be troubleshot.

4.2 Failed Test 1: Transducer #1 Wiring Issue

The first experiments that were run took place while the top and side mounted transducer housing parts were being manufactured. The tests were failing because the first transducer that was provided has faulty wiring. Most of the time, the data acquired was completely invalid.

4.3 Failed Test 2 & 3: In Box, 60 Hz Interference (Without Mount & Top Mount)

These experiments were performed inside the black noise dampening box. Amplitude is held constant, while frequency was varied. The first set of experiments was run using the Top Mounted Housing for the JBL Speaker. The second set of experiments was run with the JBL Speaker without housing. The transducer was free-hanging at the same height as it would be with the housing.

The first transducer was acquiring data successfully; however, it is obvious that there is some noise in the sine waves which cause it to display fluctuating magnitudes. This noise was determined to be a 60 hertz sine wave which was infiltrating our data. A number of man-hours went into researching and identifying how and why this 60 hertz interference was getting into the system. Just when it seemed that the wave couldn't be removed other than by utilizing a data filter, a new transducer was tested, and results showed that no 60 hertz interference was present. The first transducer was not run with the system again.

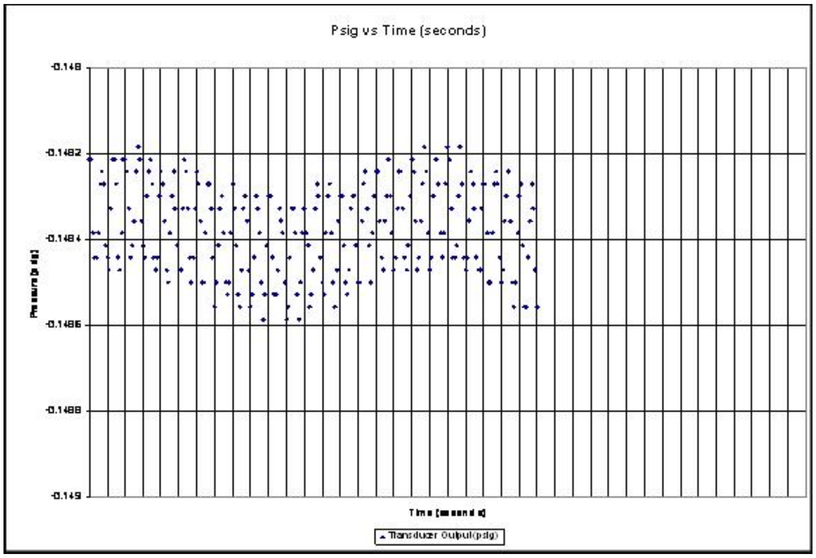


Figure 22 - Top Mount Data with 60 Hz Interference

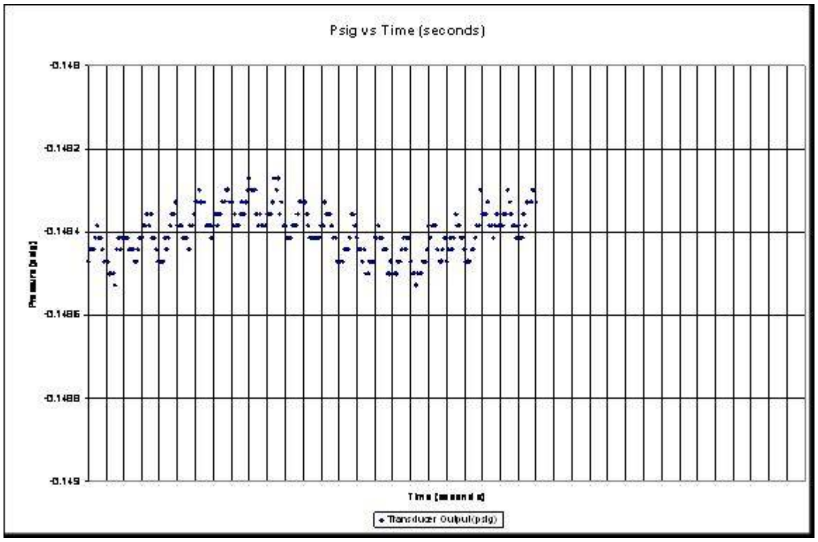


Figure 23 - No Mount Data with 60 Hz Interference

4.4 Successful Test 1: No Housing

As the design and fabrication of the top and side mounted housings were being completed, tests were run with the transducer hanging freely above the speaker cavity. The transducer sensor hung in such a way that it was aligned flush with the top face of the cavity. First, data was acquired without the speaker running at all, so that it could be determined if the sensor was calibrated as its data sheet claimed. Once that was confirmed, tests were run with the system settings as described in the methodology for a frequency range of 500 hertz to 2000 hertz in increments of 100 hertz. In a later session, an identical test was performed for frequencies from 2500 to 10000 hertz in increments of 500 hertz.

The data analysis was performed with compliance to the Standard Operating Procedure that was developed for the system and found in the Appendix B. What the data shows is that from 500 hertz to 2000 hertz, there is a somewhat steeply increasing trend. As you continue across the frequency domain, going from 2000 hertz to 10000 hertz, there is a steady, but less dramatic trend of decreasing pressure values. It is important to note that, due to the 500 hertz increments that separate data points from 2000 to 10000 hertz, there is a chance that the fit line does not represent exactly what value we would see at frequencies in between the increments. However, in the interest of time and the need to perform a number of different tests, it was a necessary choice to use 500 hertz increments.

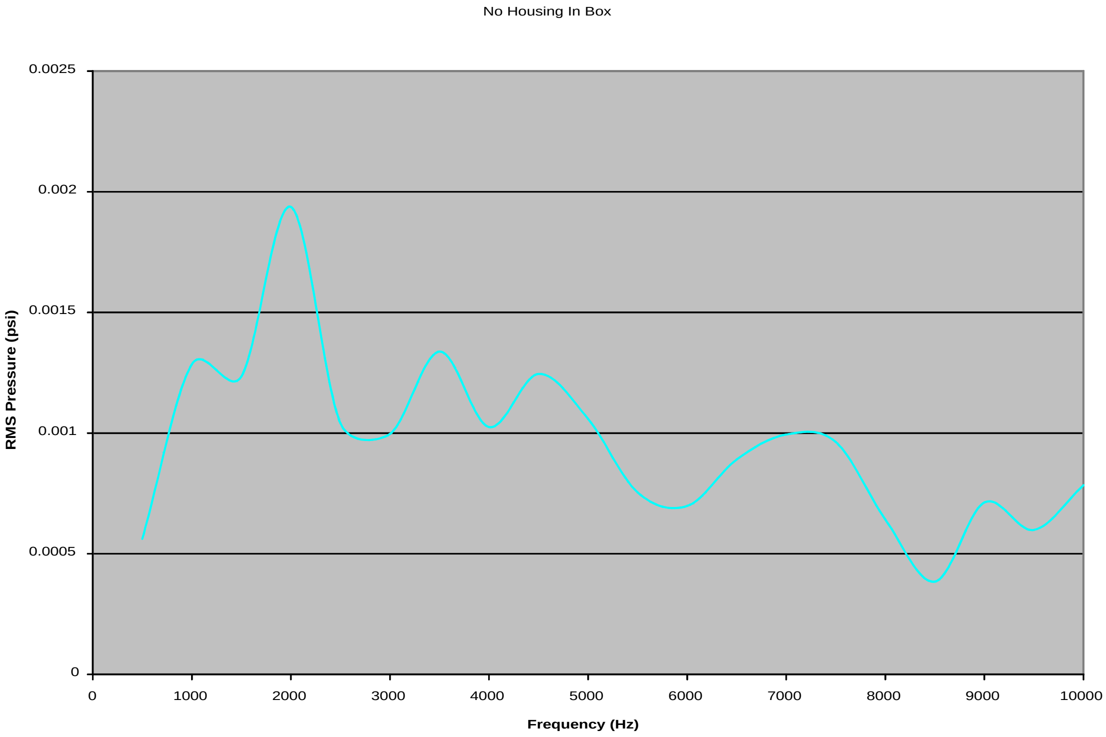


Figure 21 - No Housing - In Box Pressure

When running the system without a mount, it was incredibly loud, and at one point it was unclear whether or not it was going to be feasible to continue the tests throughout the frequency range. Even though the setup was contained within the sound dampening box, it was entirely necessary to have earplugs for this test. Even then, the sound was unbearable with the system settings used universally for all tests.

4.5 Top Mounted Housing Tests

The first housing that was created was the top mounting design. The housing and transducer plugs were both machined from aluminum, and testing began immediately after they were done.

The initial test was run with the setup in the sound dampening box. Analyzed results for the experiment are represented by the pink data curve in the graph below. The test was performed with the same frequency ranges and intervals. The analysis was completed, and the data displays a trend of decreasing pressure across the frequency entire domain. Looking past all of the peaks and valleys of the data, you could fit an almost linear curve sloping downward through the points. The fact that there are many peaks and valleys could be attributed to sound reflections within the speaker and housing cavity. While initial sound waves can be calculated for their wavelengths, and we can determine the magnitude of the wave at the height of the sensor above the speaker, it was not possible to determine how sound reflections effect the data with the tools we had. The real result that was desired was that at no frequency across the range did the pressure drop to zero.

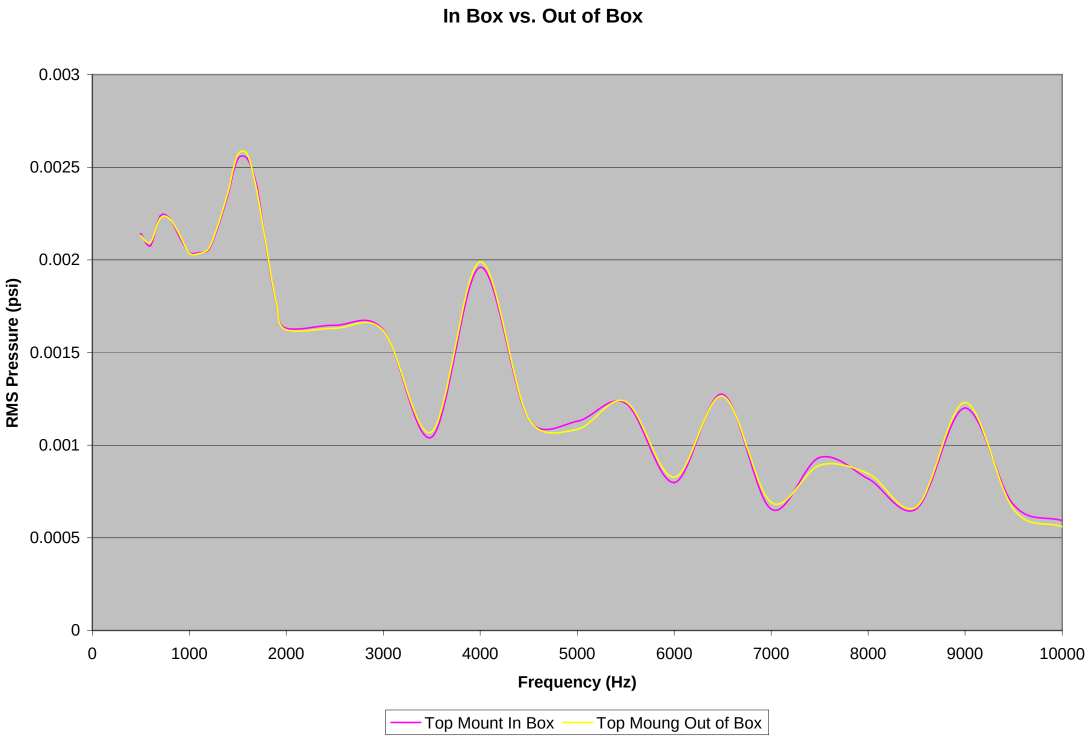


Figure 25 - In Box vs. Out Box Pressures

After the system was run using the top mount within the dampening box, the next step was to repeat the test outside of the box. Running the system was unbearably loud and required ear plugs to make testing possible. Analyzing the data resulted in the yellow curve on the graph above.

It is immediately evident that the in-box and out-of-box experiments resulted in pressure curves that were almost perfectly parallel to one another across the entire frequency domain.

4.6 Side Mounted testing

Next, experiments were run to determine the effectiveness of the side mounted transducer housing design. In previous experiments, it was determined that the sound dampening box has little or no effect on the data which is acquired. Because this was already proven, tests using the side mount did not need to be compared in and out of the box. As the experiments were run in the box, for some reason the sound was much louder with the side mount. This could potentially be because the cavity in the side housing has more volume than the top mount. The real reason that the side mount experiments are louder remains to be somewhat unclear.

When running the side mount, there were also problems acquiring data. For example, when the experiment called for 5000 samples to be taken at a time, for some reason at times the side mount would output a number of samples much less than 5000. The number of samples that did get appended when this happened was completely randomized. Because of the noise and this acquisition problem, working with the side mount was more difficult and time consuming than using the top mount.

The test that was run using the side mount was run with the speaker in the dampening box with a frequency range and intervals consistent with the previous experiments. The results for the side mount test display similar characteristics when compared to the top mount. The magnitude of the pressure is substantially larger between 500 and 2000 hertz than the rest of the range.

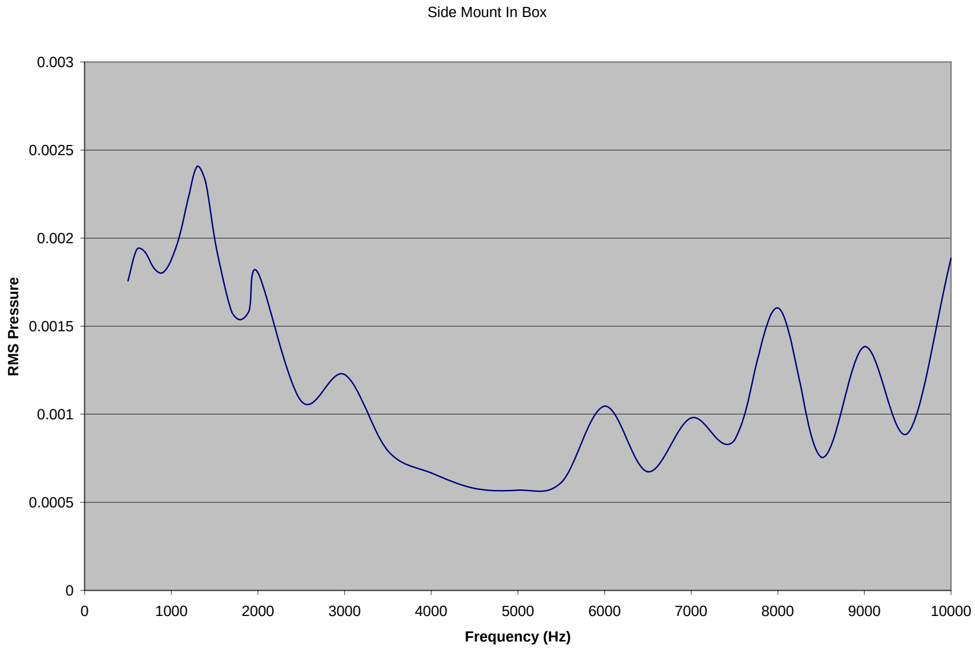


Figure 26 - Side Mount - In Box Pressure

Looking at the top and side mount data side by side, it appears that the parts would be performing quite similarly. In reality, the data does show variation from experiment to experiment, but the pressure that we are measuring is quite small. A few small differences between test variables can have a large effect on the results. The largest difference between the side mount and top mount pressure data lies from 3500 hertz to 5500 hertz. The cavity size is different for this mount, so that could explain some of the pressure differences.

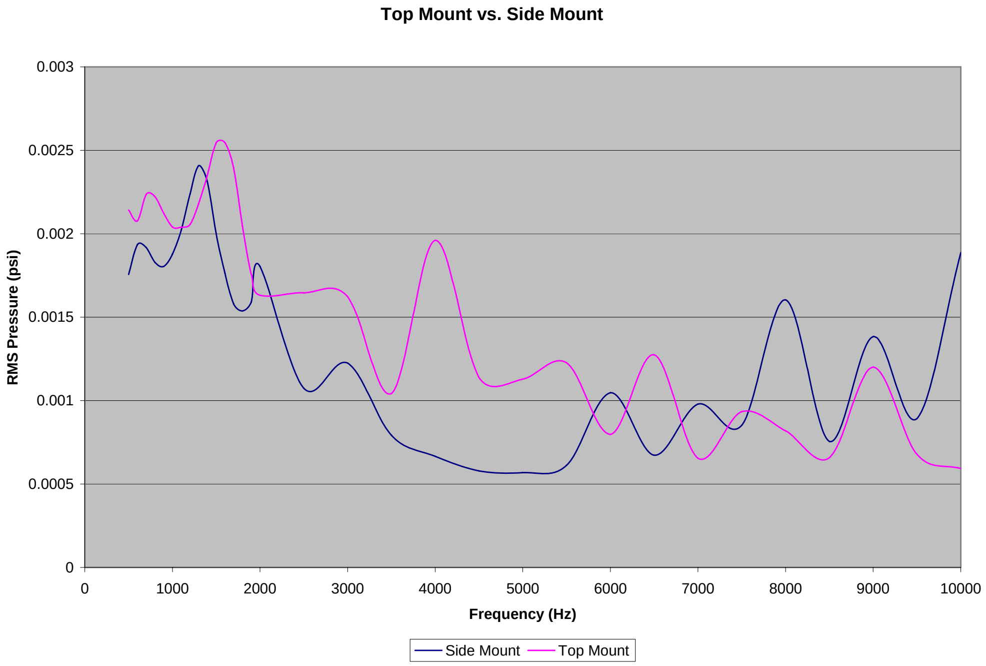


Figure 27 - Top Mount vs. Side Mount - In Box Pressure

After all experiments and placing four of the main experimental data together on a graph, Figure 24, we can make some observations. No holes were found in our range of frequencies in our chosen intervals. Our housing designs enabled us to obtain pressure readings for all our tested frequencies. Looking at the yellow and pink curves in Figure 24, you can see that the two lines are very similar. Since there are no major discrepancies with the 2 sets of data, the black dampening box does not show to affect data acquisition of the system. Experiments with the Top Mount Housing produced more consistent data. You can see the consistency by looking at the yellow and pink curves, which are the tests, run with the Top Mount Housing.

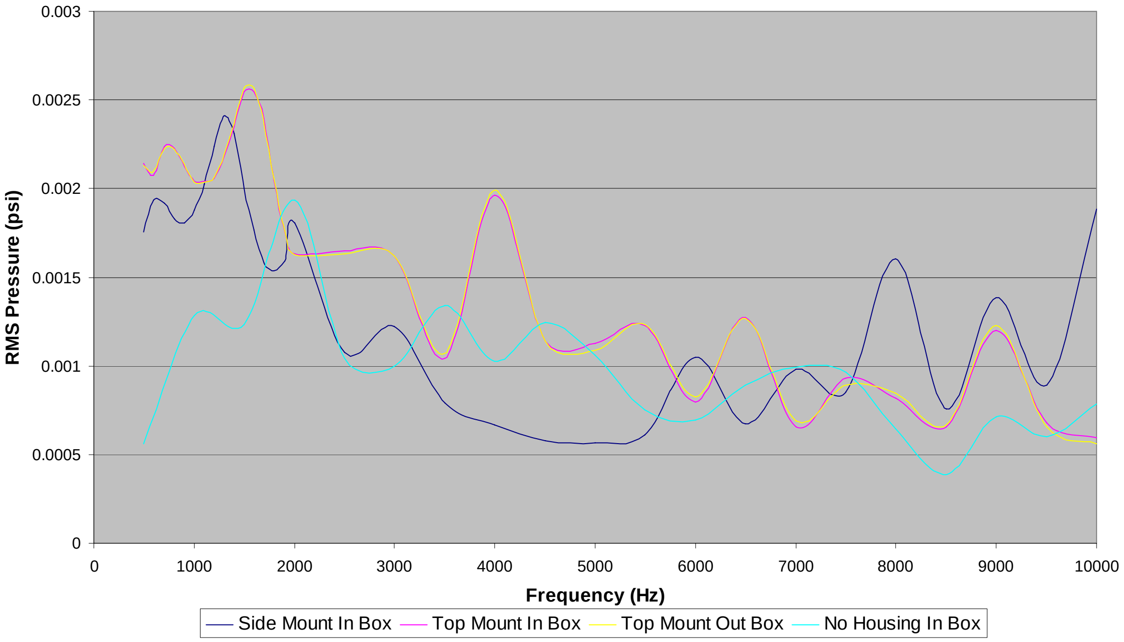


Figure 28 - Average RMS Pressure vs. Frequency

5 Conclusions

When we began this project with Pratt & Whitney, we were asked to develop a system that could efficiently and accurately show the response of any pressure transducer. In order to fulfill this goal we would need to reach a few main objectives, such as: evaluating the effectiveness of the sensor to be calibrated in response to the input pressure change with different frequency components; designing and fabricating top and side transducer mounts for the speaker drive; determining which mount is more effective; establishing an environment that will yield the most accurate and consistent data; and developing a user-friendly and flexible standard operating procedure. Much research and iteration throughout the testing and analyzing processes would be necessary for a successful project.

Initially, we ran into many problems with the acquired data which caused us to fall behind schedule. As pointed out in the results section, we learned after a significant amount of time that the first transducer we had been given had a wiring problem. Once this was realized and corrected, we continued to test with this transducer. However, although we were reading an accurate signal, there was some obvious interference with the data. A 60 Hz sine wave could be seen interrupting our data. We believed this to be some sort of either internal interference within the system, or possibly an environmental signal that the transducer was picking up outside of the system. A considerable amount of time went into revealing where the problem was originating; however, we tested a second transducer and there was no sign of any interference. Therefore, we continued to test with the second transducer, and determined that the data acquired with the first transducer would be invaluable to this project.

After these initial setbacks were overcome, we finally were ready to begin the testing and analyzing that would provide us the necessary information for our project. As noted in the results, we ran numerous trials with four main experiments: (1) No Housing in the Black Dampening Box; (2) Top Mounted Housing in the Black Dampening Box; (3) Top Mounted Housing out of the Black Dampening Box; and (4) Side Mounted Housing in the Black Dampening Box. We were unable to run experiments such as No Housing out of the Black Dampening Box and Side Mounted Housing out of the Black Dampening Box strictly because the noise level was too high at certain frequencies. However, with the results and analyses from those four tests, we were able to determine some constructive and beneficial conclusions for our project.

The most obvious conclusion we could gather from each of the experiments was that the JBL speaker driver is capable of performing over the range of frequencies that the manufacturer's specifications sheet claims of 500 – 10,000 Hz. Of course, this was of importance to us because it allowed us to run tests over a wide frequency range. Pratt & Whitney has stated that they are more concerned with the lower frequency levels (hence, the reason we ran trials at smaller frequency intervals from 500 – 2,000 Hz); however, if necessary, the JBL speaker driver has proven capable of performing at much higher frequencies.

After all of the tests and subsequent analysis had been completed, we began comparing our different variables. We first wanted to decipher which transducer housing, if either, outperformed the other. As seen in our results section, the top mounted housing consistently acquired the correct number of samples during all testing. On the other hand, there were instances throughout the data acquisition process with the side mounted housing where we would obtain “empty data”. Although we believe this not to be a design issue, the lack of repeatability questions the resiliency of the side mounted housing, which allowed us to eliminate it as a possible recommendation to Pratt & Whitney. Therefore, the consistency and repeatability given by the top mounted housing allows us to confidently maintain that the top mounted housing outperforms the side mounted housing.

Our next focus was to determine whether there was any effect on the data due to the black dampening box. As you can see in our results, the tests run in and out of the black dampening box with the top mounted housing displayed minimally varying results over the complete range of 500 – 10,000 Hz. We were pleased to see that the black dampening box does not have a profound effect on the data acquisition simply because it decreases the noise level considerably, and also packages the system for better organization.

Lastly, we aimed to develop a much improved standard operating procedure for testing and analysis compared to the original. In the preliminary tests, in order to calculate a root mean square pressure value, we would need to manually pick out the maximum and minimum data points from our data acquisition. This proved to be extremely time consuming, and if we had to continue with this method, would most likely have hindered the progress of our project. Fortunately, we came across a filtering device that displayed the maximum and minimum values for us. Once we had this program, the rest of the testing and analysis process fell into place. Eventually, we developed a time efficient and user-friendly standard operating procedure that can be seen in Appendix B.

After overcoming a few initial setbacks and questions, we made several significant advancements within our project up to its fruition. Through simplifying the original data acquisition system, designing a capable transducer mounting structure, and establishing a proper standard operating procedure for testing and analysis, we feel we have met our main goals for this project. We firmly believe that with our developments and aforementioned conclusions, we may offer Pratt & Whitney with a system and procedure that will be of great help to their company.

6 Recommendations

Our main recommendation for Pratt and Whitney is to incorporate the Top Mounted housing design in this pressure transducer calibrator/checker system. With our results and conclusion, we believe that the Top Mounted housing is more reliable than the Side Mounted housing. As you can see from our results, the top mounted housing does not hinder the pressure transducer to read the pressure values at the frequencies that we tested. The results and conclusions sections explain this determination.

Due to the time constraints and limited resources, our group was not able to enhance some aspects of our designed transducer mounting housings. Firstly, through experimentations we performed, we noticed that the transducer holding plugs did not sit in the housing firmly. We recommend that gaskets be incorporated into our top mount housing to secure the plugs. This can be achieved by using rubber O-rings that fit snugly in the plug holes of the top mounted housing.

As mentioned above, our conclusions lead to recommend using the top mount housing over the side mount housing. In order for Pratt and Whitney to use this pressure transducer calibrator/checker system, we recommend more experiments be performed. There were many variables that we did not have the opportunity to control. There are some experiments with the top mounted housing that we were not able to perform. We recommend the use of the spacers be used with the top mount housing, in an attempt to find a height that will allow for the most accurate pressure readings. These spaces will be height adjustable in order to test various heights.

Also, due to time constraints, we were not able to work with the side mount as much as we had hoped to. We recommend that more work should be performed with the side mount. After fabrication of the side mount housing, we noticed that the cavity of the two mounting structures were very different. Not only were the housing cavities different, the height at which the transducers measured the pressure was not the same. We recommend spacers be designed and fabricated for the top mount housing. This will enable the height of the cavity to increase. Thus, the size of the housing cavity and the height at which the transducer takes pressure measurements can be constant within both transducer mounting housings. Also, the spacers can be used for both housings, to alter the height at which the transducers take readings. We recommend the spacers be used with the top mount housing to test for holes in the data at different heights.

Reflections of the sound waves within the cavity created by our transducer mount housing caused inconsistencies within our data. We recommend the use of an absorbent material on the inner surface of the top mount housing. The absorbent material may decrease the interference the reflections of the sound waves produce, which can be seen at the 'peaks' and 'valleys' in our pressure graphs.

At the beginning of our project, we were informed that most of the failures within aircraft engines occur at lower frequencies. We recommend a speaker driver that has lower frequency capabilities. The current JBL 2450H is capable of running at frequencies between 500 and 10000 Hz. With a speaker driver with a lower frequency range, the system can be more effective and compatible with the purpose it will serve for Pratt and Whitney.

We recommend an update of the other system components. Many of the wiring components are old, and the connections may not be as precise as they should be. The computer in our system is quite ancient. With an updated computer system, analysis of the data could be more efficient. One of our objectives was to create a user-friendly and efficient system that can calibrate pressure transducers. Our Standard Operating Procedure has proved to be more efficient. However, there are some aspects of our process of analysis that can be further improved. We recommend the development of a program that will expedite the filtering and determination of the RMS pressure averages. This program will automatically convert the Excel files to text format instead of manually doing so for each trial. The program should also be able to take the minimum and maximum values for each trial, insert the values into our template, which will ultimately determine the RMS pressure values.

Lastly, in regards to the efficiency of using the Pressure Transducer Calibration system, we recommend the fabrication of the top mount transducer plugs for all transducer thread sizes. Pratt and Whitney would like to use the system to quickly calibrate and check their transducers. With the fabrication of plugs for all transducer thread sizes, Pratt and Whitney can have a stock of the housing plugs. All transducers can be checked and calibrated by using a plug that the transducer can simply be screwed into.

In order for Pratt and Whitney to use this pressure transducer calibrator/checker system, we recommend more experiments be performed. There were many variables that we did not have the opportunity to control. Many of these variables are related to the recommendations mentioned above. There are some experiments with the top mounted housing that we were not able to perform. We recommend the use of the spacers recommend above, to be used with the top mount housing, in an attempt to find a height that will allow for the most accurate pressure readings.

Also, due to time constraints, we were not able to work with the side mount as much as we had hoped to. We recommend that more work should be performed with the side mount. After the fabrication of the side mounted housing, we saw that the cavity of the two housings were different. We recommend experiments using the spacers, which will allow the cavities to be the same size. This can further prove or disprove our conclusion that the top mount is more effective than the side mount design.

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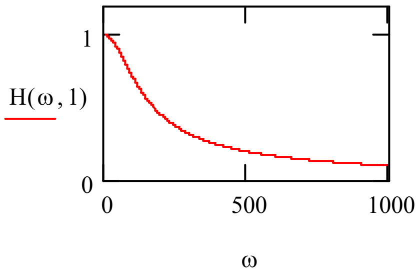
Appendix A: Butterworth Filter Transfer Function Model

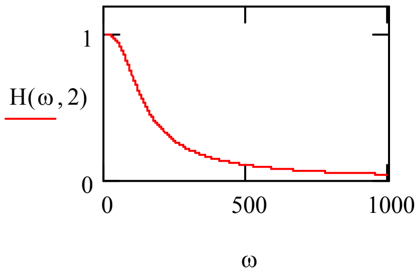
Butterworth Filter Transfer Function Model

$n := 1, 2 .. 4$	FILTER ORDER
$\omega := 0, .1 .. 1000$	FREQUENCY (Hz)
$\omega_c := 100$	CUTOFF FREQUENCY (Hz)
$H(\omega, n) := \dfrac{1}{\sqrt{1 + \left(\dfrac{\omega}{\omega_c}\right)^{2 \cdot \sqrt{n}}}}$	BUTTERWORTH TRANSFER FUNCTION

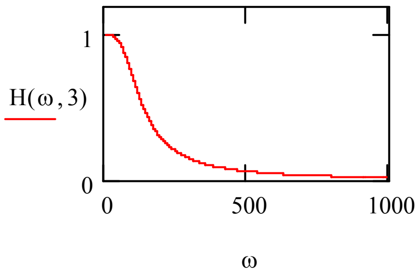
First Order Filter Response



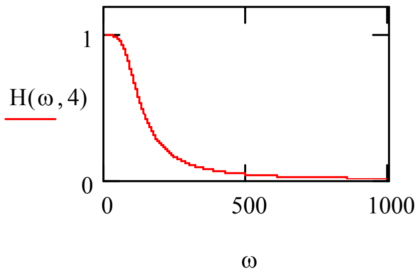
Second Order Filter Response



Third Order Filter Response



Fourth Order Filter Response



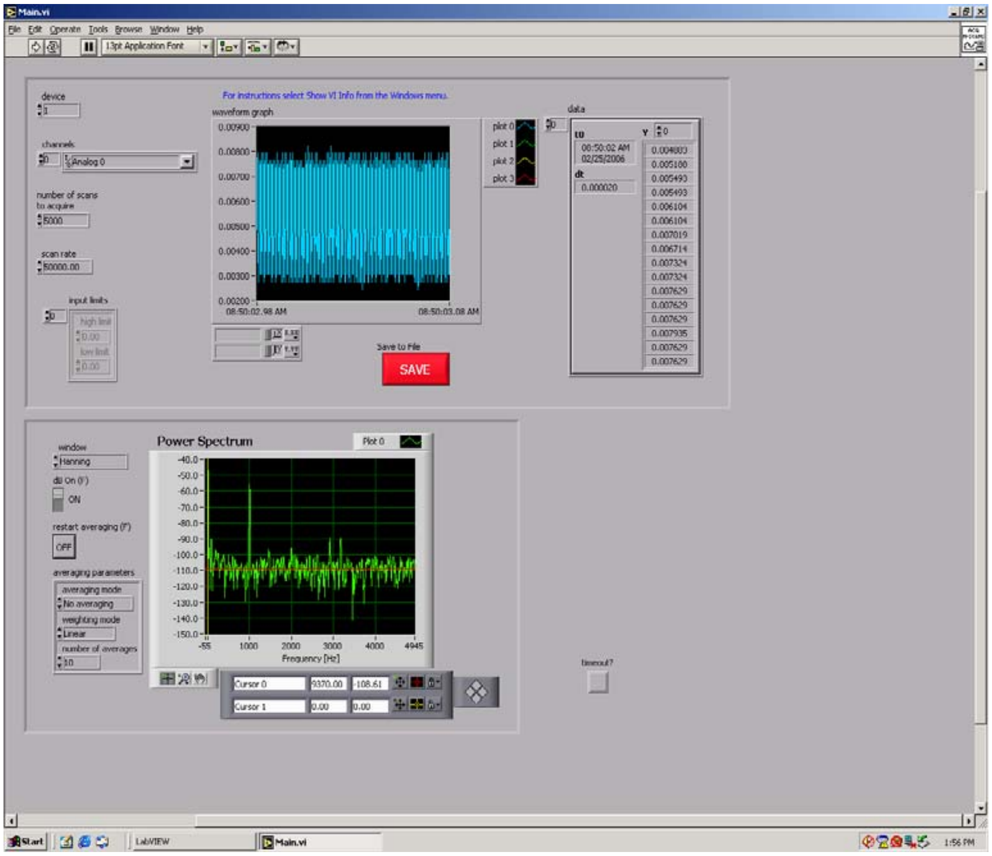
$H(100, 1) = 0.707$	$H(100, 2) = 0.707$	$H(100, 3) = 0.707$	$H(100, 4) = 0.707$
$H(500, 1) = 0.196$	$H(500, 2) = 0.102$	$H(500, 3) = 0.061$	$H(500, 4) = 0.04$
$H(1000, 1) = 0.1$	$H(1000, 2) = 0.039$	$H(1000, 3) = 0.019$	$H(1000, 4) = 10 \times 10^{-3}$

Based on the function of a Butterworth Filter Transfer, increasing the order of filter used minimizes the effect on the data's amplitude. Using a first order filter with a cutoff frequency of 100 Hz, data taken at 500 Hz will receive a 19.6% reduction in magnitude due to the filter. Increasing the order one at a time, eventually getting to 4th order with 100 Hz cutoff, we see that at 500 Hz, the data experiences only 4% reduction in amplitude. For our purposes in this project, we can accept this magnitude loss, as any reduction in amplitude will be uniform throughout our testing when using a standardized filter.

Appendix B: Standard Operating Procedure

The following is a developed standard operating procedure to follow when testing with this system in the future:

1) Check to make sure that transducer is securely fastened to housing on speaker driver
2) Power up entire system
    - Computer, function generator, amplifier
3) Turn amplifier knob to highest setting
4) Set function generator’s internal amplifier to 300 millivolts
5) Open LabVIEW Data Acquisition program
    - Set program to acquire 5,000 scans at a scan rate of 50,000



For instructions select Show VI Info from the Windows menu.

device: 1

channels: 0, Analog 0

number of scans to acquire: 5000

scan rate: 50000.00

input limits: 0

high limit: 0.00

low limit: 0.00

data: 0

t0: 08:50:02 AM 02/25/2006

dt: 0.000020

Y: 0

Y
0.004803
0.005100
0.005493
0.005493
0.006104
0.006104
0.007019
0.006714
0.007324
0.007324
0.007629
0.007629
0.007629
0.007935
0.007629
0.007629

window: Hanning

dB On (F): ON

restart averaging (F): OFF

averaging parameters

averaging mode: No averaging

weighting mode: Linear

number of averages: 10

Cursor 0	9370.00	-108.61
Cursor 1	0.00	0.00

6) Set function generator to desired frequency (500 – 10,000 Hz with JBL speaker driver)

7) Save each trial as an Excel file

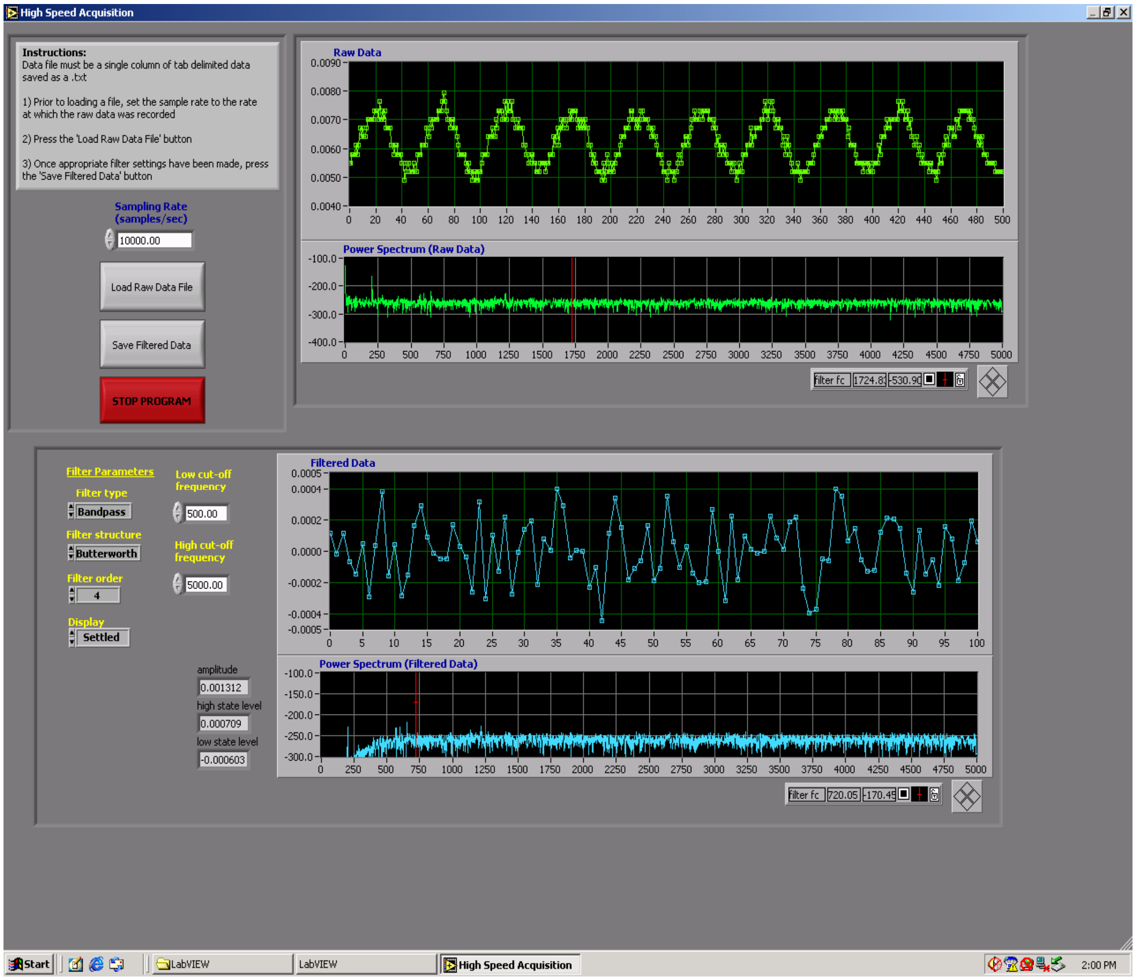
   – Repeat for desired number of trials and frequencies

8) Convert excel file(s) to text file(s)

9) Open LabVIEW Dynamic Analysis Filter program

   – Set program to a sampling rate of 10,000

   – Use following parameters: Filter type- Bandpass, Filter structure- Butterworth, Filter order- 4, Display- Settled



High Speed Acquisition

Instructions:
Data file must be a single column of tab delimited data saved as a .txt

1) Prior to loading a file, set the sample rate to the rate at which the raw data was recorded

2) Press the 'Load Raw Data File' button

3) Once appropriate filter settings have been made, press the 'Save Filtered Data' button

Sampling Rate (samples/sec): 10000.00

Filter Parameters
Filter type: Bandpass
Filter structure: Butterworth
Filter order: 4
Display: Settled
Low cut-off frequency: 500.00
High cut-off frequency: 5000.00

amplitude: 0.001312
high state level: 0.000709
low state level: -0.000603

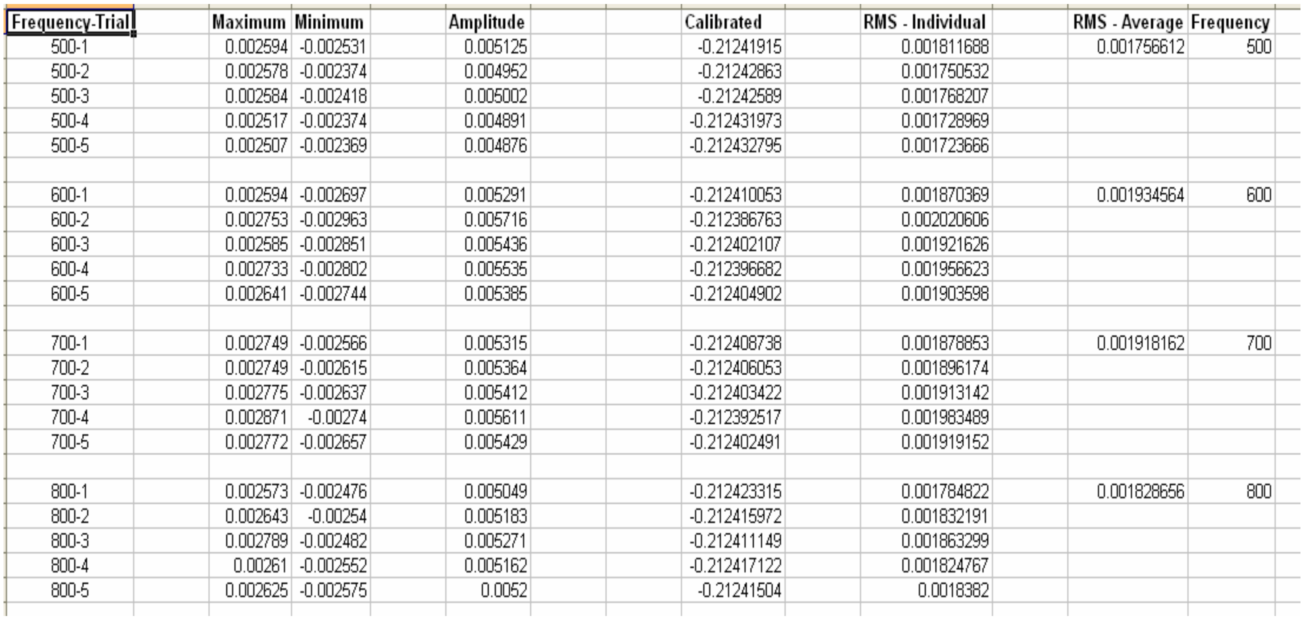
10) Load desired text file into LabVIEW Dynamic Analysis Filter program

11) Record each maximum and minimum value (amplitude is also shown) displayed by the program

   - *Note: if possible, a program to append these values to an excel file would prove to be much more time efficient*

12) Plug in maximum and minimum values into created Excel template (shown below)

   - Calculate amplitude (Maximum – Minimum)
   - Calculate calibrated pressure value (equation given by transducer specification sheet
   - Calculate root mean square pressure value [(Maximum – Minimum)/2]*0.707



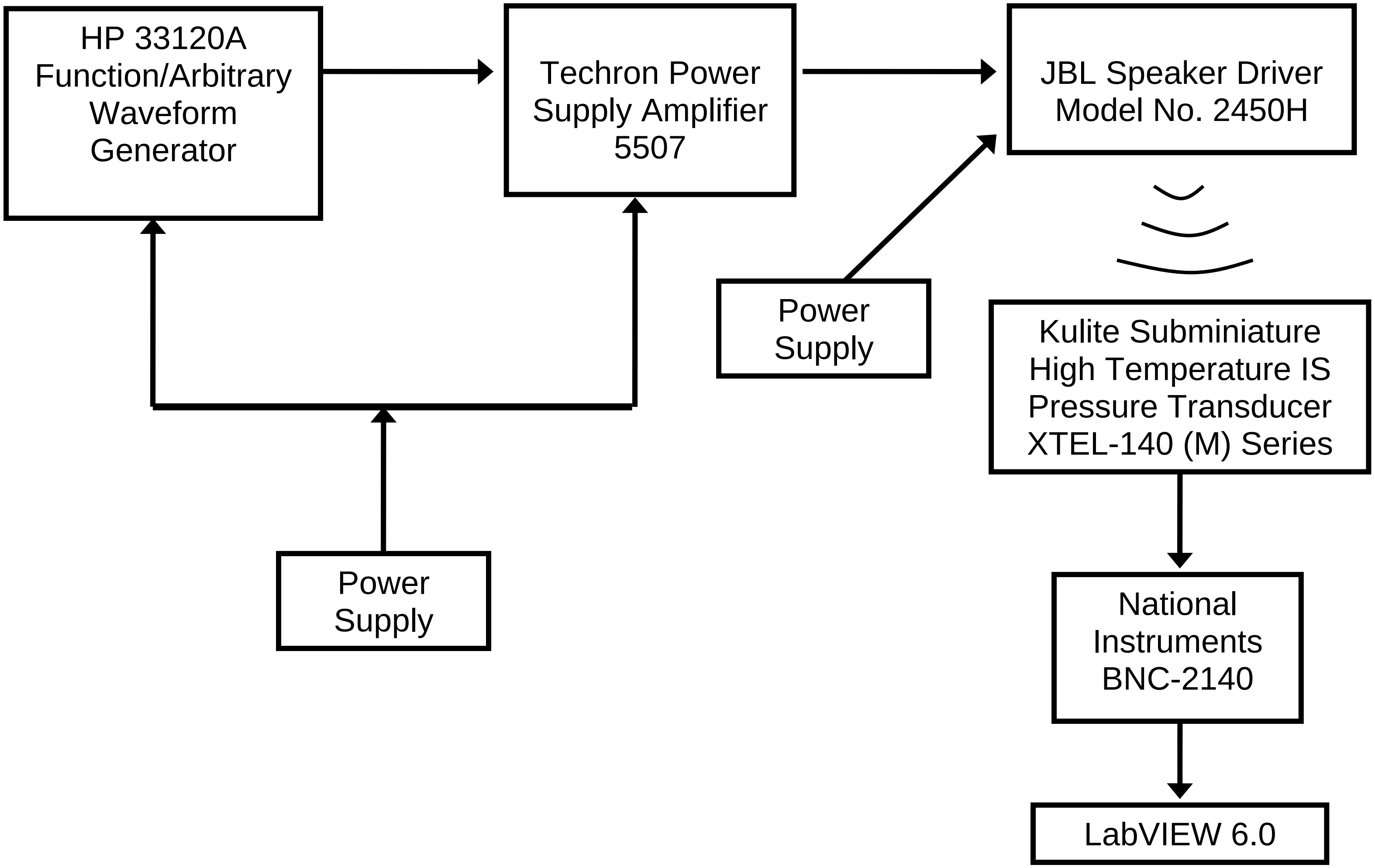
Frequency-Trial	Maximum	Minimum	Amplitude	Calibrated	RMS - Individual	RMS - Average	Frequency
500-1	0.002594	-0.002531	0.005125	-0.21241915	0.001811688	0.001756612	500
500-2	0.002578	-0.002374	0.004952	-0.21242863	0.001750532		
500-3	0.002584	-0.002418	0.005002	-0.21242589	0.001768207		
500-4	0.002517	-0.002374	0.004891	-0.212431973	0.001728969		
500-5	0.002507	-0.002369	0.004876	-0.212432795	0.001723666		
600-1	0.002594	-0.002697	0.005291	-0.212410053	0.001870369	0.001934564	600
600-2	0.002753	-0.002963	0.005716	-0.212386763	0.002020606		
600-3	0.002585	-0.002851	0.005436	-0.212402107	0.001921626		
600-4	0.002733	-0.002802	0.005535	-0.212396682	0.001956623		
600-5	0.002641	-0.002744	0.005385	-0.212404902	0.001903598		
700-1	0.002749	-0.002566	0.005315	-0.212408738	0.001878853	0.001918162	700
700-2	0.002749	-0.002615	0.005364	-0.212406053	0.001896174		
700-3	0.002775	-0.002637	0.005412	-0.212403422	0.001913142		
700-4	0.002871	-0.00274	0.005611	-0.212392517	0.001983489		
700-5	0.002772	-0.002657	0.005429	-0.212402491	0.001919152		
800-1	0.002573	-0.002476	0.005049	-0.212423315	0.001784822	0.001828656	800
800-2	0.002643	-0.00254	0.005183	-0.212415972	0.001832191		
800-3	0.002789	-0.002482	0.005271	-0.212411149	0.001863299		
800-4	0.00261	-0.002552	0.005162	-0.212417122	0.001824767		
800-5	0.002625	-0.002575	0.0052	-0.21241504	0.0018382		

14) Plot root mean square pressure value versus frequency.

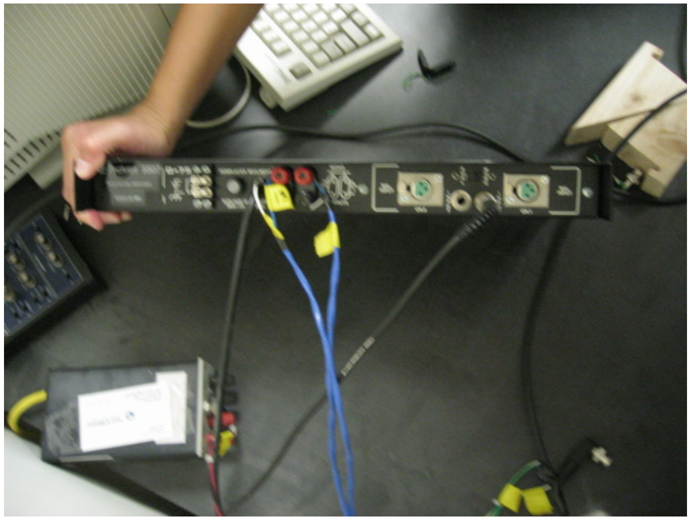
Appendix C – RMS Pressure Values for All Successful Experiment

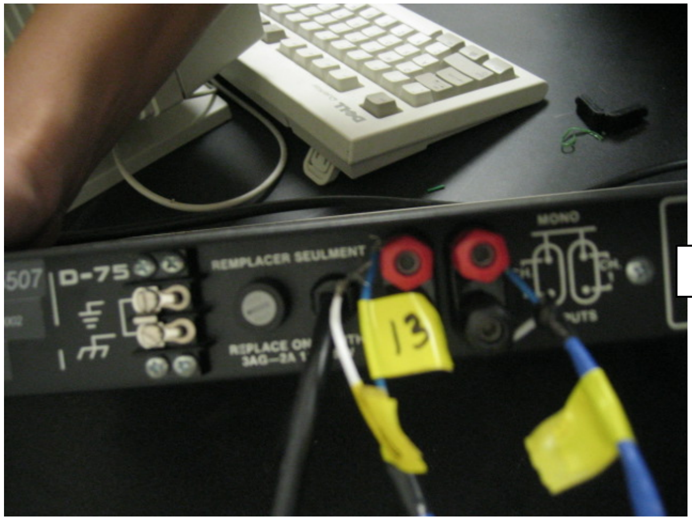
Top Mount Out Box	Frequency	Side Mount In Box	No Mount In Box (low freq)	Frequency	Top Mount In Box	Freq
0.002130527	500	0.001756612	0.00067066	500	0.002142422	500
0.002094528	600	0.001934564	0.000757056	600	0.002076954	600
0.002224657	700	0.001918162	0.000883184	700	0.002235817	700
0.002223374	800	0.001828656	0.000892093	800	0.002223374	800
0.002122697	900	0.001804123	0.001129715	900	0.002122697	900
0.002041038	1000	0.001878287	0.001161955	1000	0.002041038	1000
0.002039624	1100	0.002022374	0.001241633	1100	0.002039624	1100
0.002055249	1200	0.002239635	0.001276418	1200	0.002055249	1200
0.002179822	1300	0.002408466	0.001262914	1300	0.002179822	1300
0.002351199	1400	0.002312244	0.001263975	1400	0.002351199	1400
0.002544352	1500	0.00200081	0.001106879	1500	0.002544352	1500
0.002546331	1600	0.001763824	0.001124413	1600	0.002546331	1600
0.002392842	1700	0.001580569	0.001114586	1700	0.002392842	1700
0.002048391	1800	0.001537301	0.001200557	1800	0.002048391	1800
0.001757461	1900	0.001590114	0.001244391	1900	0.001757461	1900
0.001630908	2000	0.001804476	0.001251037	2000	0.001630908	2000
0.001630483	2500	0.001074216			0.001646462	2500
0.001618959	3000	0.001224807			0.00162306	3000
0.001072448	3500	0.000791416			0.001043673	3500
0.001989427	4000	0.000666913			0.001960158	4000
0.001140745	4500	0.000578538			0.001139401	4500
0.001085952	5000	0.000568711			0.001129715	5000
0.001234705	5500	0.000612474			0.001226857	5500
0.000825776	6000	0.001046501			0.000798344	6000
0.001264964	6500	0.000672852			0.001274155	6500
0.000691093	7000	0.000978842			0.000655036	7000
0.000891456	7500	0.000852642			0.000933311	7500
0.000845926	8000	0.001603264			0.00081814	8000
0.000667479	8500	0.000755854			0.0006585	8500
0.001229827	9000	0.001384023			0.001201334	9000
0.000654329	9500	0.000891739			0.000678932	9500
0.000560015	10000	0.001886276			0.000593314	10000

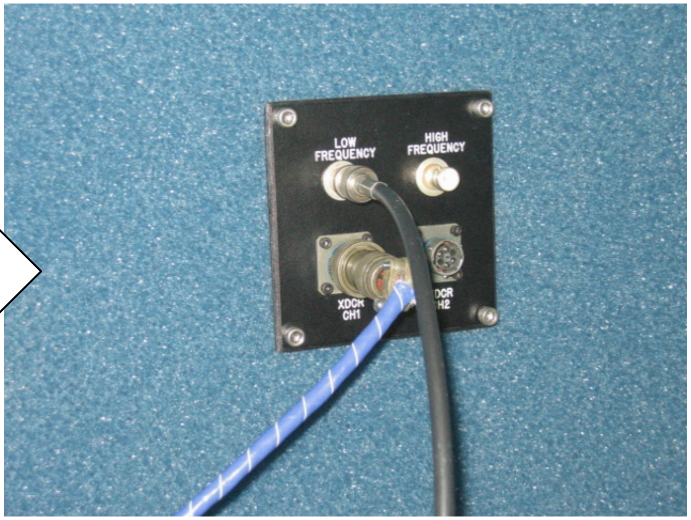
Appendix D -System Schematic

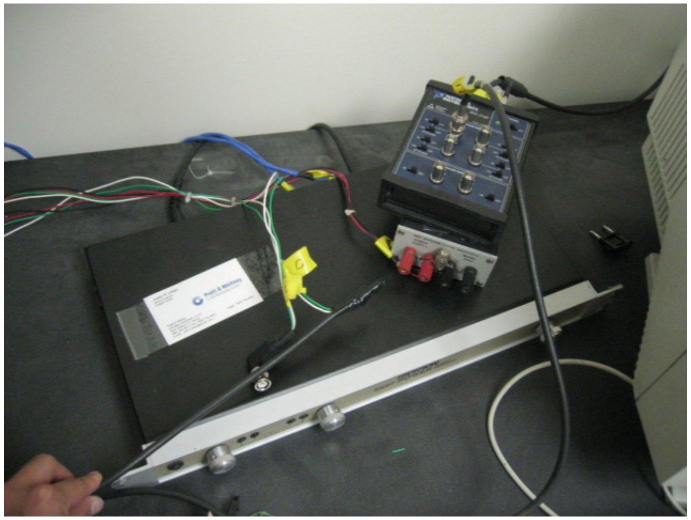


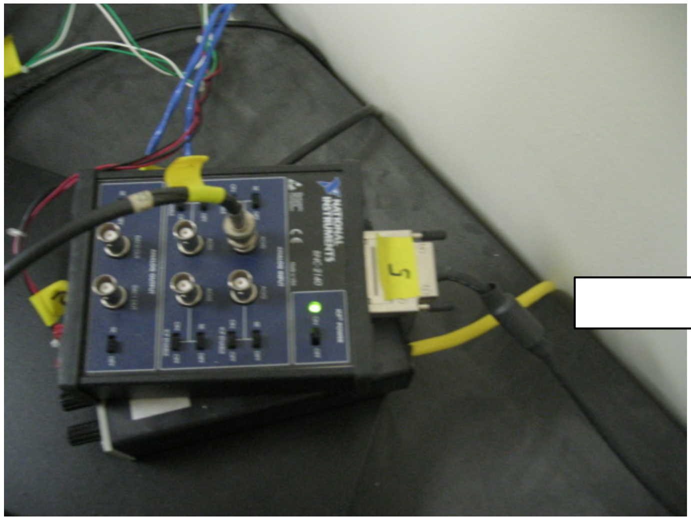
Appendix E: Pictures of System

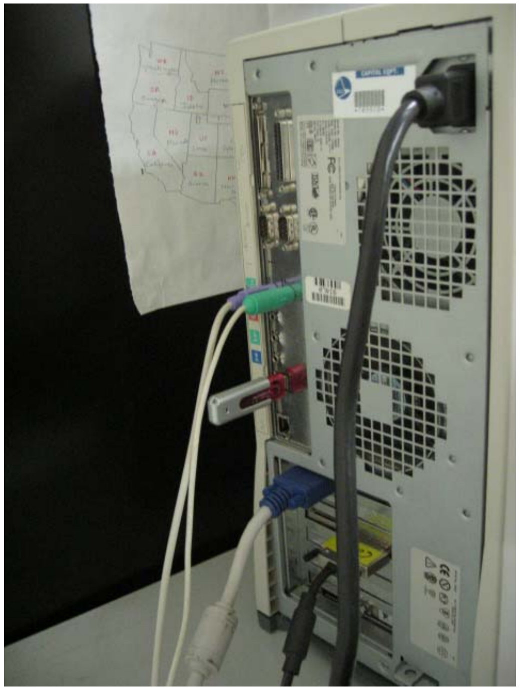












1. Function Generator connects to the back of Techron Amplifier
2. Amplifier connects to back of Black Dampening Box
3. Low Frequency connection leads to speaker driver, while CH1 connects to transducer
4. Speaker driver is powered by Power Supply
5. Transducer output connects through black box – Green and White wires
6. Green and white wires connect into DAQ
7. DAQ connects to computer