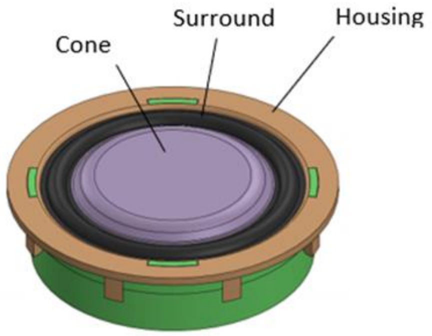
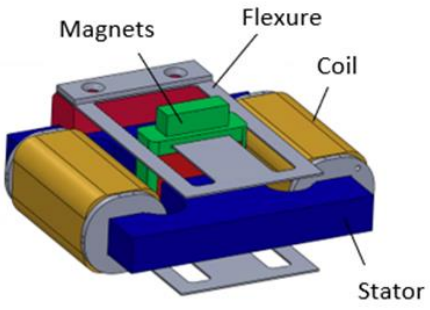
Low Profile Home Speaker: Moving Magnet Transducer

A Major Qualifying Project Report submitted to the Faculty of the WORCESTER POLYTECHNIC INSTITUTE in partial fulfilment of the requirements for the Degree of Bachelor of Science in Mechanical Engineering.





By:
Steven D’Agostino
Raymond DiMestico
Harrison Roy

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Sponsor Organization:
Bose Corporation

Project Advisor:
Professor Joe Stabile

Abstract

This report describes the development of a novel moving magnet transducer. Typically, speakers that produce bass have a large footprint because they require a sufficient acoustic volume to deliver quality sound. Our team’s goal was to develop a moving magnet transducer capable of generating quality bass while maintaining the slimmest possible profile. This unique moving magnet transducer was inspired by an E-Core transformer and can produce more force per mass of magnet than commonly used moving coil transducers. In our design, current flows through coils that are wound around opposing arms of the low carbon-steel stator. The current induces a magnetic flux in the stator that causes it to act as an electromagnet. The permanent magnets centered in our design oscillate up and down as they interact with the electromagnet. In our design the permanent magnets are bonded to the speakers’ cone, so as they oscillate, the cone oscillates, and sound becomes audible. The final transducer measured 0.80” tall with a 2.94” diameter and produced a measured 1.24 N/Amp force output. An in-depth breakdown of our design process, manufacturing process, and operational performance results are contained within our report.

Acknowledgements

Our group would first and foremost like to thank our advisor Professor Joe Stabile for his tremendous support and guidance throughout this project. Our team would also like to thank several other members of the Worcester Polytechnic Institute Mechanical Engineering Department, specifically Barbara Furhman and the Washburn Shops Staff for their help in ordering materials and offering CNC machining advise.

We would also like to thank our sponsor, Bose Corporation, for providing us with the funding and use of their facilities to create a novel Moving Magnet Transducer. We want to specifically thank Guy Torio, Bill Berardi, Jeff Copeland, Binu Oommen, Dan Sheehan, and Carl Kallgren from Bose Corporation for all of their support.

Executive Summary

Project Overview:

Innovations in technology have improved sound quality and the profile of today's speakers. In recent years there has been an emphasis on lower frequencies (40-200 Hz) that produce the bass in sound. In addition to quality bass, speaker design has progressed toward low profile discrete models for increased portability. However, the desire for better bass response contradicts the desire for lower profile. The overarching goal of this project was to address the inadequacies of bass response in low profile speakers. This project designed, analyzed, manufactured, and tested a novel speaker transducer. Specifically, the project realized a low profile moving magnet transducer capable of producing bass.

Methodology:

Our team used several different software programs during the design and analysis stages of our project work. Each individual component of our model was designed and assembled in SolidWorks. The mechanical properties of several components were investigated using Ansys structural and vibrational analysis tools. The magnetic behavior of the speaker was investigated using Ansys Maxwell and Finite Element Methods Magnetics (FEMM).

Several different methods of manufacturing were used to realize the projects final design. The team operated CNC mills to produce both the two part stator and the C-block used in our final transducer design. Water Jet Cutting was used for both the M-flexure and flexure fastener components of our model because of material thickness limitations and complex geometry. All rigid plastic parts and flexible surrounds were 3D printed which allowed our team to iterate designs with little downtime. Coils were wound using a 3D printed sleeve and drill motor.

The team performed Instron testing to verify spring constants and force outputs of our model. A scanning laser vibrometer was used to confirm that our speaker was operating in phase throughout the range of bass frequencies.

Results:

The final transducer measured 0.80” tall with a 2.94” diameter. The speaker produced a measured 1.24 N/Amp force output. Ten speakers were manufactured. Six of which were implemented into passive radiator boxes designed by another MQP team. Three of which were implemented onto a resonant panel designed by another MQP team.

Recommendations:

The goal of this project was to create a moving magnet transducer capable of generating quality bass while maintaining the slimmest possible profile. While our team did accomplish its goal, we feel that the overall performance of our design could be improved by following our three major recommendations:

1. Replace 3D Printed Parts with injection molded components
2. Improve upon the design of the magnet holder
3. Increase length and width of stator while maintaining the same height.

With these recommendations, the next iterations of the speaker design could produce smoother sound, be more powerful, and be more reliable.

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1.0 Introduction

Innovations in technology have improved sound quality and the profile of today's speakers. Sound quality refers to the ability to produce clean and continuous sound across a large band of frequencies. The profile refers to the shape and size of the speaker.

In recent years there has been an emphasis on lower frequencies (40-200 Hz) that produce the bass in sound. In order to achieve the desired bass frequencies, large acoustic volumes are required. A common example of products that produce a strong bass are subwoofer boxes used in vehicles.

In addition to quality bass, speaker design has progressed toward low profile discrete models for increased portability. For example, portable Bluetooth speakers are becoming increasingly popular in today’s marketplace. Bulky speakers of the past have become antiquated.

The desire for better bass response contradicts the desire for lower profile. The overarching goal of this project was to address the inadequacies of bass response in low profile speakers.

Utilizing computer modeling and simulation software, a unique moving magnet-based transducer design was developed. Modern manufacturing techniques such as 3D printing and CNC machines have been used to prototype. An iterative design process was used to improve the transducer. The final product was combined with a double passive radiator speaker system designed by another MQP group in order to increase the bass quality. It was also combined with a resonant panel system designed by another MQP group.

2.0 Background

2.1 Speaker Types

A speaker transducer is a device that creates noise using an electromechanical response. The response is usually driven by an AC current signal that is generated from a device. The alternating current causes oscillations in the speaker. The oscillations create sounds waves of pressurized air that your ears interpret as sound. The electromechanical response can be created using a number of different configurations. A literature review of speaker designs used in industry came up with the following designs; standard voice coil, piezoelectric, electrostatic, planar voice coils, and finally moving magnet. All of these designs accomplish the same tasks of creating sound. The teams goal was to develop a low profile speaker with good bass response utilizing one of these technologies.

2.2 Standard Voice Coil

The most common type speaker transducer is the standard voice coil speaker, shown in Figure 1 below. Voice coil speakers are used for a variety of frequency ranges. These transducers are used in larger sound systems. For example, cars, portable Bluetooth speakers, and headphones.

2.2.1 Components and Operation of a Standard Voice Coil

The voice coil of the speaker is a coil of wire acting as a solenoid. The coil is fastened to a cone. The cone is the part of the speaker that pushes the air back and forth, creating pressure waves. The cone is fastened to a flexible surround that allows the cone to move linearly. In order for the speaker to oscillate, an interaction between the solenoids electromagnetic field and a permanent magnet must occur.

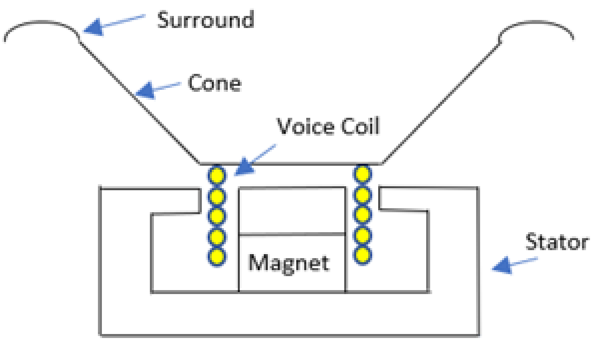


FIGURE 1: VOICE COIL SPEAKER DIAGRAM

A permanent magnet is located inside of the coil, in between two pieces of magnetically conductive metal. The permanent magnet is oriented so that the field lines travel through the metal and cross the voice coil perpendicularly to induce a resultant force to push the cone. The voice coil is a solenoid like the one pictured below in Figure 2. Alternating current is flowed through the solenoid.

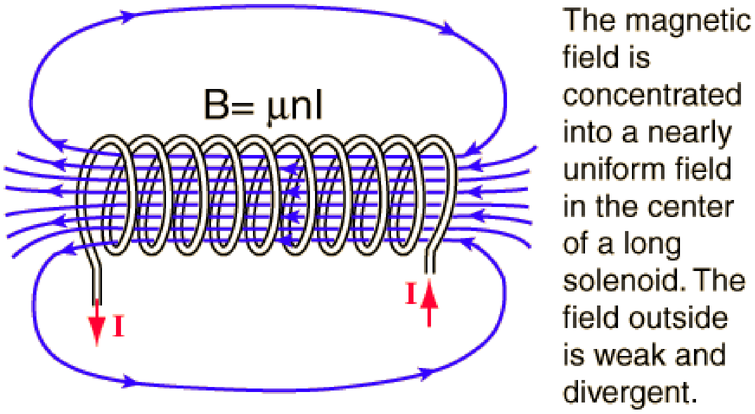


FIGURE 2: SOLENOID DIAGRAM [17]

The alternating current causes the solenoids magnet field to constantly flip directions. Due to the flipping of the solenoid's magnetic field, the permanent magnet and solenoid rapidly attract and repel each other causing the oscillatory motion in the speaker.

2.2.2 Simple Mathematical Model of Voice Coil Speaker

This type of speaker is often modeled as a mass-spring-damper system. The equivalent mass of the system is modeled as the mass of the voice coil and the mass of the cone. The stiffness of the system is modeled as the stiffness of the surround. The inverse of the stiffness is often called the compliance of the speaker. The damping of the system is also modeled as the damping of the surround. The ordinary differential equation (Equation 1) below is used to model the dynamic performance of the speaker where m is the mass, b is the damping constant, and k is the stiffness of the system.

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F(t) \tag{1}$$

This is a basic model of a voice coil speaker but can be used to estimate the performance of the speaker in the frequency domain. A useful parameter that can be determined from the equation above is the damped natural frequency (Equation 2). This frequency is where the speaker naturally oscillates at when not being forced. This a good indicator of what frequency range the speaker will perform at.

$$\omega_d = \sqrt{\frac{\mathrm{k}}{m} - \frac{b^2}{4m^2}} \tag{2}$$

A Bode plot can be used to determine the performance of the system as a function of the frequency of the force input. This plot is an extremely useful tool for speakers because it demonstrates what frequency range the speaker will excel and where the performance will decrease. An example of a Bode plot for a simple mass-spring-damper system is shown in the Figure 3 below. However, an actual speaker bode plot would be more complicated since a mass-spring-damper is not a perfect model.

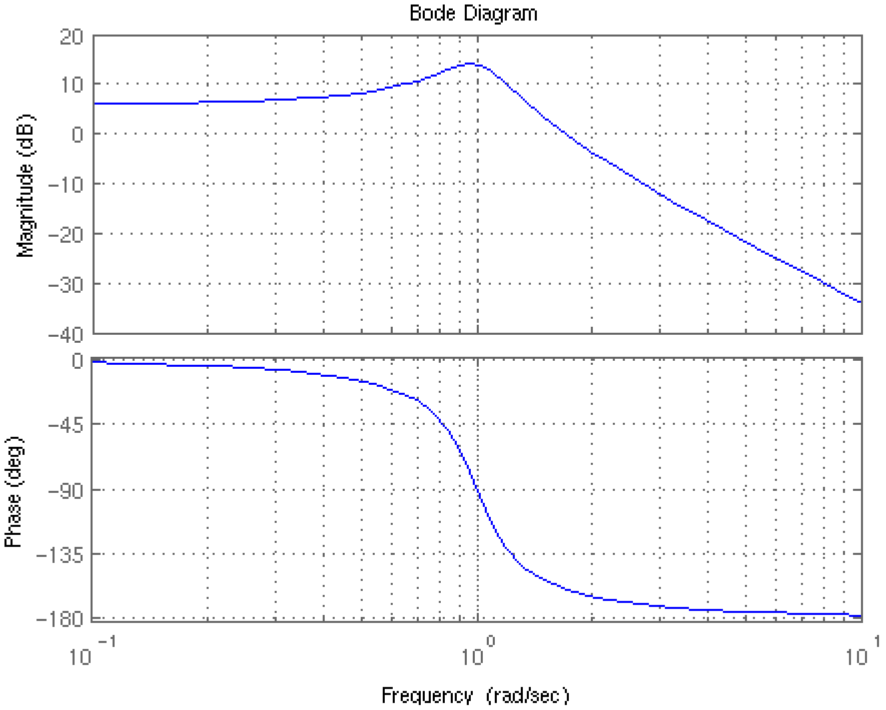


FIGURE 3: BODE PLOT EXAMPLE [18]

There are three major frequency ranges when talking about any type of speaker. The ranges are bass (40-200 Hz), mid-range (200-2000 Hz), and treble (over 2000 Hz). Knowing the frequency response of the system is important depending on if you want to make a woofer (bass to mid-range), tweeter (mid-range to treble), or full range speaker (full spectrum).

3.3 Piezoelectric Speakers

A second common type of speaker is the piezoelectric speaker. Typically, only used for high frequency applications, piezoelectrics are generally used as buzzers, and other applications where sound quality is not an important factor.

3.3.1 Components and Operation of Piezoelectric Speakers

The heart of each piezoelectric speaker is either a crystal or a ceramic disc that interacts when it feels a certain voltage difference. An increase of the signal amplitude V_{pp} (Voltage peak to peak), will result in a larger piezo deformation and result in a larger sound output. Therefore, piezoelectric speakers demand voltage variations to produce sound. The current consumption is extreme small and the voltage peak to peak level goes up to 60V peak to peak [2].

Piezoelectric Theory can be explained as applying an electric field to a piezoelectric material leads to the addition or removal of electrons. The movement of the electrons causes the material to deform and thereby generate a small physical force [2]. As shown in the picture below the materials react through axial loading. When you apply an electric field to a piezoelectric material it will change size. The piezoelectric material will shrink or grow as charges are introduced or removed, but the base material will not [2]. This causes elastic deformation of the material toward or away from a direction that is perpendicular to the surface of the speaker. As soon as the electric field is removed from the piezoelectric material, it will return to its original shape.

Because a difference between the two inputs of a piezoelectric speaker is created they are essentially acting as a capacitor when designing circuits. Compared to their electrodynamic counterparts, piezoelectric speakers require higher drive voltages, and their low impedance at higher frequencies means that large amounts of drive current are required for high-frequency audio signals [3].

Another problem with piezoelectric speakers is their insufficient diaphragm area to reproduce bass frequencies [3]. Piezo speakers are limited by the fact that their diaphragms are unable to move large distances. Therefore, moving the volume of air required for bass requires a huge area of diaphragm to compensate. The performance of the piezoelectric speaker is poor from 20 Hz to 200 Hz. They are not capable of producing high quality of sound due to the low sound pressure level (SPL) [2].

FIGURE 4: PIEZOELECTRIC EFFECT [2]

Voltage given to the ceramic wafer(grey) causes it to expand and contract. This will create tension in the attached metal sheet (pictured in yellow) and causing it to emit sound.

3.3.2 Piezoelectric Materials

Piezoelectric materials can be divided in two main groups i.e., crystals and ceramics. The most well-known piezoelectric material is the crystal, quartz (SiO2). Piezoelectric materials exhibit the reverse piezoelectric effect. That means when a voltage is applied across the surface of a piezoelectric crystal, it responds by generating a mechanical force. A surrounding mechanical diaphragm converts the electrical energy into acoustic energy. Below is the design the two engineers used for their speakers (2).

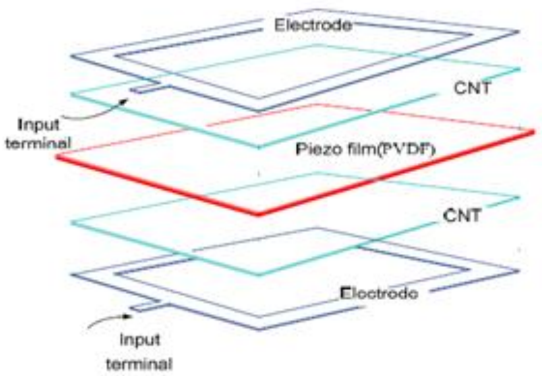


FIGURE 5: PIEZOELECTRIC SPEAKER LAYERS [2]

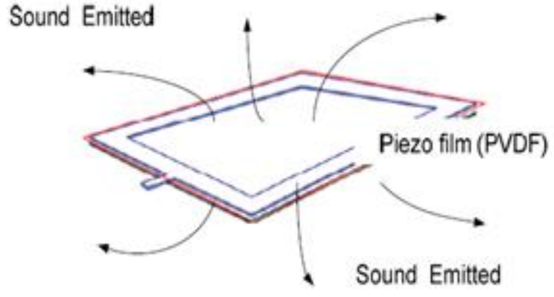


FIGURE 6: PIEZOELECTRIC SPEAKER [2]

3.4 Electrostatic Speakers

Electrostatic speakers are a much less common form of speaker. Very few companies manufacture these speakers because of the high-power requirements and price.

3.4.1 Components and Operation of Electrostatic Speakers

Electrostatic speakers rely on a thin conductive diaphragm and an electrode plate. As the electrode plate is charging, an electrostatic attraction force is created with the diaphragm and can push and pull the air. This attraction is described in Coulomb's Law shown below. Also, below Figure 7 is an example of a simplistic electrostatic speaker design.

$$F = \frac{q_1 q_2}{2S\varepsilon} \text{(Coulomb's Law)} \qquad (3)$$

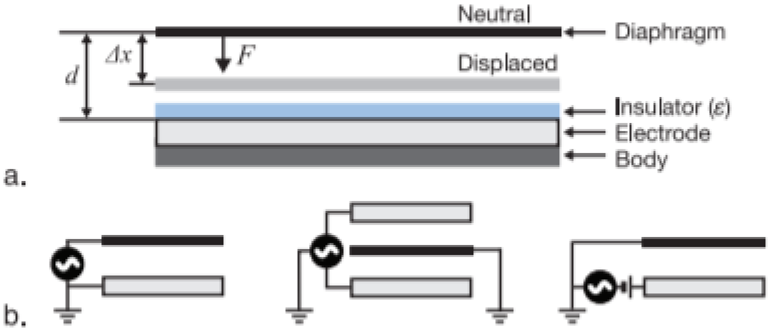
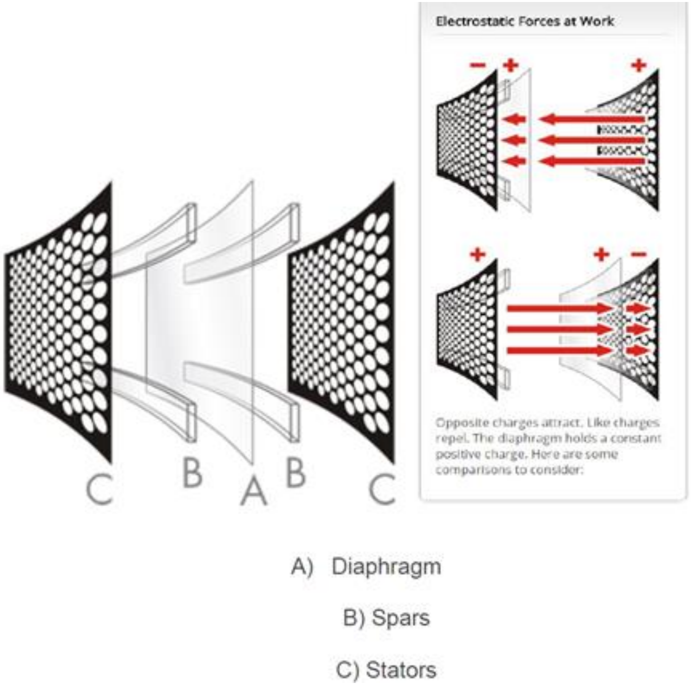


FIGURE 7: ELECTROSTATIC SPEAKER CONSTRUCTION [5]

Instead of using an electromagnet to move a cone-shaped diaphragm, an electrostatic speaker takes advantage of conductive panels/diaphragms. Once these panels are charged, an electrical field is created. This electric field has a positive and negative end. The audio signal runs a current through the diaphragm panel and can rapidly switch between positive and negative charges. This creates the push and pull motion of the other two conductive panels and also creates sound.

A company that manufactures electrostatic speakers is Martin Logan. They have modified the simplistic design of ordinary electrostatic speakers to produce a high-quality sound experience. Their electrostatic transducer incorporates three components- stators, diaphragm, and spars. The spars act as spacers to protect the diaphragm from over extending or from arching. They also help tune out resonance. It is the same concept, however. A diagram of their design can be seen on the next page [5].



Opposite charges attract. Like charges repel. The diaphragm holds a constant positive charge. Here are some comparisons to consider:

FIGURE 8: ELECTROSTATIC COMPONENTS [5]

A thin diaphragm is suspended between the two stators that receive the audio signal from the amplifier. This diaphragm is usually a plastic sheet covered with a conductive material such as graphite. These diaphragms can be made of multiple different materials. For the plastic material, a polyester film made from polyethylene terephthalate (PET) is very common. You could also use Saran Wrap if you really wanted. The higher quality material you use, the better the sound quality will be. The conductive material can be any material that can give the sheet a very high surface resistivity [7].

The diaphragm is connected to a high voltage power supply that provides 2,500-3,500 volts of electricity at the diaphragm's surface. That power supply is converted to a positive bias of a few thousand volts. The stators are receiving their charge from the music signal via an amplifier. The actual audio signal goes into a step-up transformer and it knocks out entirely any current amperage and boosts up the voltage. This voltage is then applied to the front and back panels and are opposite yet full equal in strength. So, when one stator is negative, the other is positive. This creates the forces talked about above that is able to move the diaphragm back and forth. As the music, millisecond by millisecond, pulses into the speaker, the charges flip back and forth [6].

Martin Logan speakers have a crossover that takes the signal from an amplifier and separates it into high frequencies and low frequencies. In your traditional voice coil system, you may have two or three-way crossover. When there are multiple crossovers you add more parts to the speaker and you also put more in the way of the signal path. Martin Logan covers beyond human hearing down to somewhat low base (200-250 Hz to 20,000 Hz). Their speakers have only one cross over at 250-400 hertz [6].

There also some major disadvantages to these electrostatic speakers. The most relevant one is the fact that there is little to no bass produced without the addition of a subwoofer. On top of not having bass, electrostatic speakers also take in a lot of power. Martin Logan produces a planar electrostatic speaker that has a recommended amplifier power of 20-140 watts. This is fairly high for a speaker.

Other reasons for why electrostatics speakers can be cumbersome are the cost and the sound dispersion. The sound dispersion is a problem because there is a narrow “sweet spot” created by the planar aspect of the speaker. This “sweet spot” refers to the area where you can hear the best acoustic dispersion. For example, you could have a Martin Logan speaker point directly at you and hear great quality sound, but if you walked three feet to the left or right, you would not hear the same quality.

Martin Logan lives by the electrostatic design, but it is because they have drastically improved the sound outputs of these speakers by spending a lot of money on materials. For instance, they use aerospace-grade billet and extruded aluminum alloy to create the panels of the speaker. They also use high-tech coatings and vacuum bond a lot of the interior parts of their speakers. All of these processes help produce a very high-end speaker, but the cost is clearly seen. Martin Logan speakers can cost as much as $40,000.

3.5 Planar Voice Coil/ Ribbon Transducers

The planar voice coil and ribbon style speaker is commonly used in small electronics like phones, laptops, headphones, and tv. They are able to keep a very low profile while producing mostly in the higher frequency range (500 Hz to 20 kHz)[19].

3.5.1 Components and Operation of Planar Voice Coil/ Ribbon Transducers

Planar voice coil speakers are similar to the standard voice coil, however in this case the voice coil is no longer wrapped around the magnet, but flat and suspended over a magnet. The picture below is from a patent for a planar voice coil loudspeaker. The coil in this case forms a long race track shape as seen in Figure 9. The cone of the speaker is actually an extremely thin (as thin as 7.5 µm) made of a polyamide thermostable film [19]. This film has very stiff properties to prevent as much deformation in the cone as possible. The thinness of the cone is why they are commonly called ribbon speakers. A surround is attached to the cone to allow it to displace linearly.

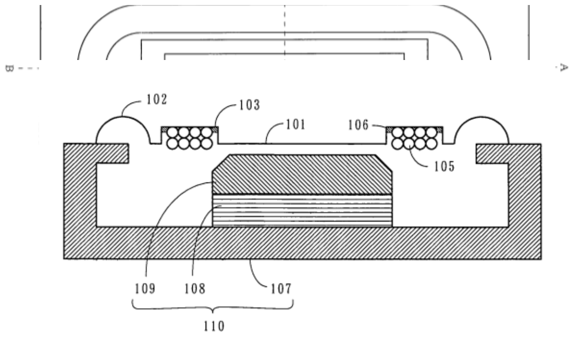


Figure 9: Planar Voice Coil Patent [19]

The operation is the same as the standard voice coil speaker with the voice coil becoming a solenoid that interacts with the permanent magnet field lines, creating a resultant force. However, this type of voice coil is unable to produce quality bass due to the size of the speaker. Equations 1 and 2 used to estimate the performance of the standard voice coil also can be used for a planar coil. Using this model, we can intuitively see that since the cone and coil are so small, they will not have a large mass. A small mass means the damped natural frequency will increase. A higher natural frequency means the speaker will tend to perform better in higher frequency signals. A frequency response Bode plot of a planar voice coil speaker is shown below. The speaker has very low performance before 200 Hz before it begins to reach its fundamental frequency[19].

FIG. 4A

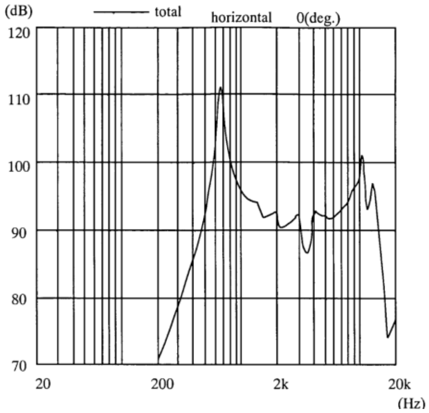


FIGURE 10: PLANAR VOICE COIL FREQUENCY RESPONSE [19]

3.6 Moving Magnet Speakers

Moving magnet technology is not widely used in the speaker industry. The idea is that it operates like a standard voice coil, but instead of the coil being fixed to the cone, the magnet is fixed to the cone. The technology is specifically tuned for bass frequencies.

3.6.1 Components and Operation of Moving Magnet Speakers

Moving magnet speakers take advantage of much of the same technology as the standard voice coil. They have a cone, surround, and coils. The moving magnet transducer tend to be specialized for bass applications. They are used for bass because of the mass of the magnet. The mass of a magnet is much heavier than the mass of a voice coil with similar size. According to Equation 2, the larger the mass, the lower the frequency response.

Multiple patents have been filed that are associated with this type of speaker in a variety of configurations. Apple Inc. holds a patent (US8811648B2) for a moving magnet transducer. Their design for the moving magnet transducer is shown below in Figure 11 [9]. The design inverts a common voice coil speaker so that the coil surrounds the magnet. The magnet is then able to travel up and down inside the coil. To prevent the magnet from traveling side to side, a track system has been designed into the frame to only allow linear motion up and down. This design is specifically designed for a laptop computer [9].

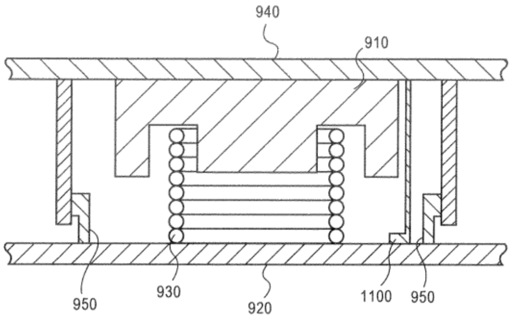


FIGURE 11: MOVING MAGNET SPEAKER BY APPLE INC. [9]

A second patent (US4010334A) uses a moving magnet transducer as a microphone pickup [8]. Vibrations from an instrument or other source of sound vibrate the permanent magnets. The motion of the permanent magnets induce a current in the coils. The current acts as a sound signal that is sent to an amplifier. The amplifier then amplifies the signal and sends it to a device to either be recorded or played louder. Figure 12 below is a representation of the moving magnet microphone [8].

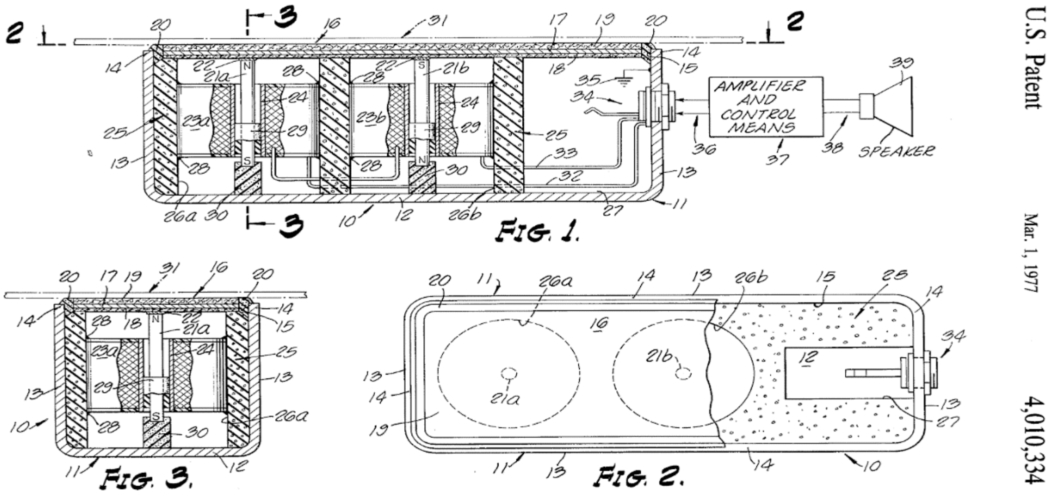


FIGURE 12: MOVING MAGNET MICROPHONE [8]

Finally a third patent (US3937904A) provides a third configuration used to create a moving magnet transducer. Pictured below in Figure 13, this transducer utilizes an “electroacoustic transducer device comprising a (U-shaped) core of magnetically permeable material having solely a simple U-shape.”[10].

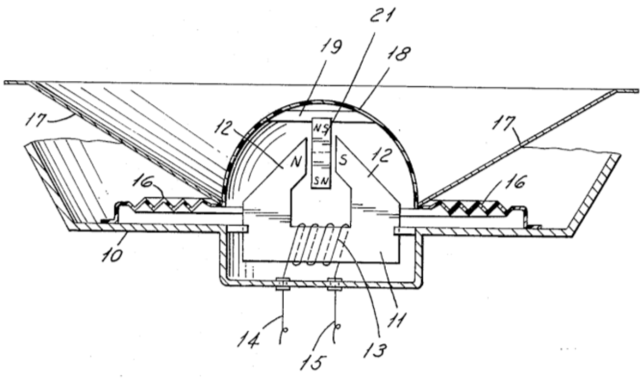


FIGURE 13: MOVING MAGNET LOUDSPEAKER [10]

The coil is wrapped along the base of the U-shaped core. This creates an electromagnet out of the core. Two magnets lie in the middle of the core and are fixed to the cone. The magnet fields of the two magnets are reversed so that they are always engaged with the magnetic field created by the electromagnet [10].

3.7 E-Core Transformer

Our design is based off a three phase E-core transformer. Three phase means that there are solenoids on each of the three arms of the transformer. A transformer is usually used to bring voltage up or down in an AC electrical circuit or even can be used to convert AC power to DC power. A picture of a single-phase transformer is seen in Figure. As you can see the electromagnetic field lines generated from charging the coil in the middle creates a flow that goes away from the middle and towards the arms [15].

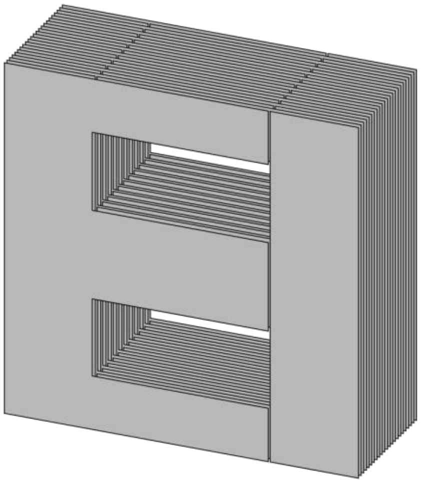


FIGURE 14: LAMINATED E-CORE TRANSFORMER [14]

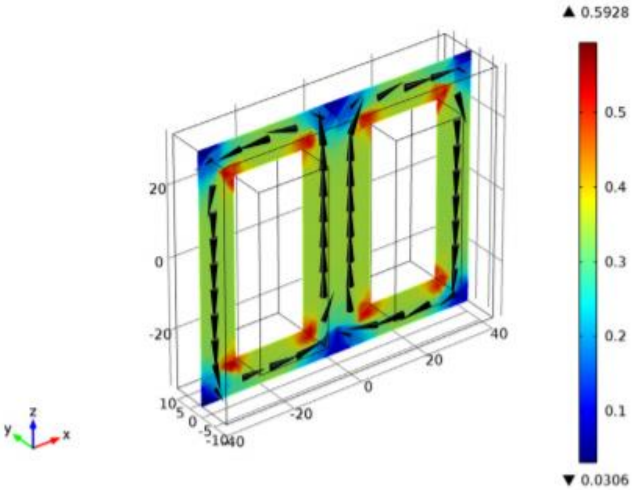


FIGURE 15: SINGLE PHASE E-CORE TRANSFORMER FIELD LINES [15]

4.0 Methodology

The project was accomplished using an iterative process that involved design, analysis, manufacturing, and testing. Over the course of the project each component was reviewed and modified periodically to achieve a final design.

4.1 Computer Aided Design

4.1.1 Finite Element Methods Magnetics

Finite Element Method Magnetics (FEMM) is a program capable of solving magnetics, electrostatics, heat flow, and current flow problems. The team's initial efforts were focused on using this program to understand the magnetic field lines and forces produced in a variety of speaker configurations.

Figures 16 and 17 below show the setup and solution that is created in FEMM. The setup is created by plotting and connecting points to resemble the system. Next the materials are assigned to each section of the system, making sure the polarity of magnetic materials are assigned. Finally, an external boundary is created so that the system is constrained to a space filled with air.

The solution is created by meshing the system and then running it. The solution depicts the magnitude of the magnetic field using color intensity charts. The direction of the magnetic field is shown using lines that run along the system. The density of the lines also shows the magnitude of the lines. A resultant force can be obtained at specified points in the system.

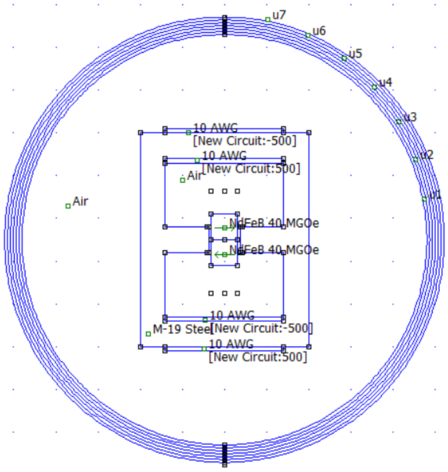
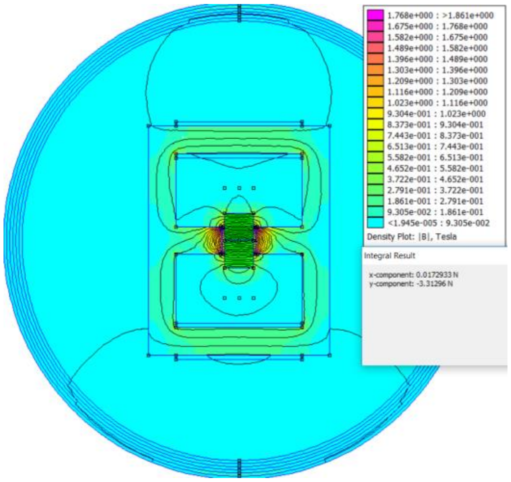


FIGURE 16: FEMM MODEL SETUP



```
x-component: 0.0172933 N
y-component: -3.31296 N
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Figure 17: FEMM Model Solution

4.1.2 SolidWorks

SolidWorks is a 3D modeling computer-aided design (CAD) program. Each individual component of our speaker was modeled and iterated in SolidWorks. Parameterization of the models was used to easily update the designs. The components were then made into their appropriate assemblies within the program to ensure that all parts would fit together as intended. An example of the realization of our SolidWorks assemblies can be seen below. The files were also used in FEA, CNC programming, and 3D printing. An example of how we converted our CAD files to real parts is shown in Figures 16 and 17 below.

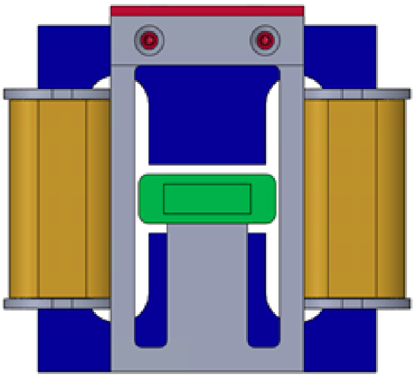


Figure 18: Top View of Moving Magnet CAD Model

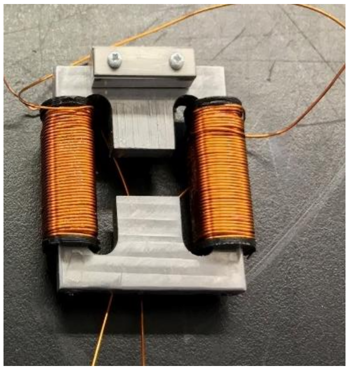


FIGURE 19: TOP VIEW OF MOVING MAGNET

4.1.3 Ansys

The team used Ansys analysis to predict the performance of our speaker. The team utilized Ansys mechanical for structural, harmonic, and modal analysis. The team used Ansys Maxwell for electromagnetic simulations of our speaker.

4.1.3.1 Ansys Mechanical

Models from SolidWorks were imported into Ansys Mechanical. The boundary conditions such as contact regions, fixed supports, displacements, and forces are assigned to the system. Next the solution is specified. Single analyses can be used to determine the values of stress, force, strain, and displacement at a single point. However, if more solution steps are added, charts can be obtained that show the behavior of the system over a broad range of values. The system can then be meshed to create the elements that will be analyzed (Figure 20). After the solution is obtained, graphical animations like the one in Figure 21 can be observed. The results obtained from these analyses show predicted behavior of the system.

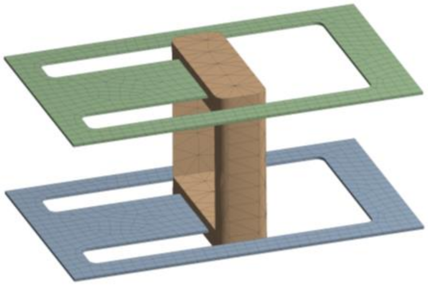


FIGURE 20: MESHED MODEL OF DOUBLE FLEXURE

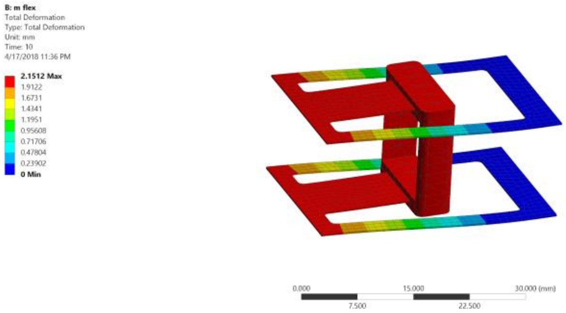


FIGURE 21: GRAPHIC OF DOUBLE FLEXURE SOLUTION

4.1.3.2 Ansys Maxwell

Models cannot be imported into Maxwell. Therefore, they must be built inside the program. The model in Figure 22 below was created as a model of our speaker. The model was parameterized in Maxwell to allow for easy manipulation and faster analysis. Initially, Maxwell was used by the team to determine force output and magnetic field strength (Figure 23). After further investigation, the team began using it to optimize the design of the speaker by using parametric analysis. These analyses compare different parameters in the system as they change. For example, the force output as a function of current in the coils was obtained.

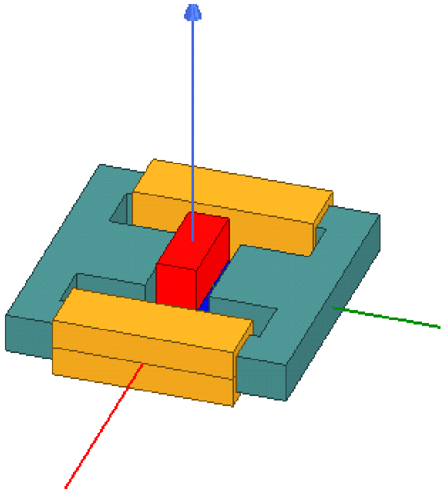


Figure 22: Ansys Maxwell Model

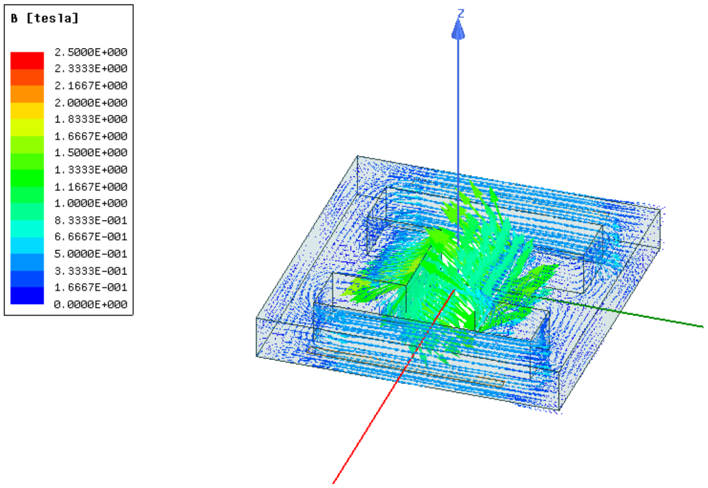


Figure 23: Ansys Maxwell Solution

4.2 Manufacturing

The manufacturing process for our product was done at both WPI and Bose. Everything was manufactured by the group except for the screws we bought to fasten everything together, and the magnets.

4.2.1 Material Sourcing

Our team purchased materials from several different vendors because of convenience factors and availability of stock. Our Neodymium-35 magnets were purchased from MagnetShop.com and were shipped to us from California. The low-carbon steel 1010 stator material was purchased from Peterson Steel in Worcester, Ma. All rigid plastic parts were 3D printed in our rapid prototyping and MQP labs at WPI. The aluminum for our C-blocks was sourced from scrap material in WPI's Washburn Shops. All other miscellaneous materials including screws, adhesives, 1095 spring steel for the flexures, wire for coils, drill bits, and taps were purchased through McMaster-Carr.

FIGURE 24: COMPONENTS OF MOVING MAGNET TRANSDUCER

4.2.2 CNC Machining

Once a finalized design was agreed upon, we began the actual fabrication of the prototype. The computer aided manufacturing program (CAM) we used was ESPRIT. The Esprit program generates a "G-code" that is then read by the CNC machines. The code tells the machine what tools to use and how to perform each individual operation.

The CNC machine used was a HAAS Mini Mill. A picture of the same model machine we used can be seen in Figure X below. We used a .375" end mill to face our parts, a .1875" end mill for pocketing, and two different drill sizes to create the holes for our screws. A .05" drill bit was used to make the holes in the large half of the stator for tapping. A .07" drill was then used to drill the through holes in the small half of the stator so that the two parts could be easily screwed together. After our parts were CNC machined we hand tapped the holes using the taps that corresponded with our screw sizes. A picture of some of the parts half way through the machining process can be seen in Figure 27.

Figure 25: Machining Operation

Figure 26: Haas Mini Mill

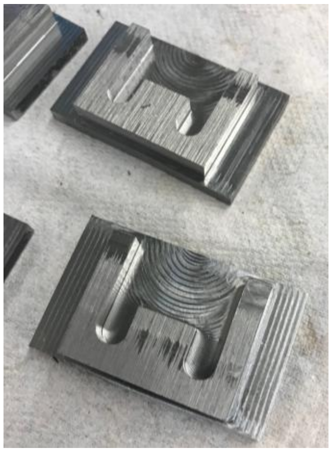


FIGURE 27: STATOR IN BETWEEN MACHINING OPERATIONS

4.2.3 3D Printing and Coil Winding

Our team used 3D printing for several different applications throughout our project. The primary use of 3D printing in our project work was to create the housing for our speaker. We printed the housing in two separate parts for assembly purposes. The bottom half of the housing was made entirely of rigid abs plastic called either Vero Clear or Vero White depending on its color. The top half of the housing was made of both the rigid Vero material and a flexible black material called Tango Black plus. The flexible material acts as our speakers surround and was able to be printed seamlessly with the rigid plastic. The bottom and top of the housings are pictured below.

FIGURE 28: 3D PRINTED HOUSING

Our team also decided to 3D printing to create small sleeves on which we wrapped our coils. After the coils were wrapped, the sleeves were placed onto the two arms of the stators. In addition to the sleeves, our team designed and 3d printed a bobbin which was made to accept the sleeve on one end and insert into a drill on the other end. This allowed us to wrap the coils using a drill instead of entirely by hand like we originally had been doing. The 3D printed setup allowed us to produce much tighter coils in a much more efficient manner. When hand wrapping each coil took about 3 hours to complete but using the sleeve and bobbin we could complete a coil in approximately 10 minutes. Each coil in the final design was made using 4 layers of 50 turns each (200 turns total). Pictures of a hand wrapped coil (left) and a coil made using our 3D printed sleeve and bobbin (right) are shown below. The third picture is an action shot of our team wrapping a coil using the sleeve and bobbin system.

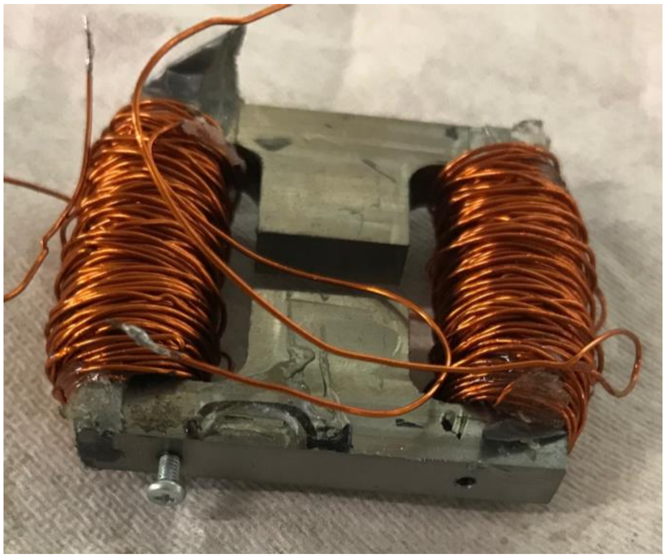


FIGURE 29: ORIGINAL STATOR AND HAND WRAPPED COIL

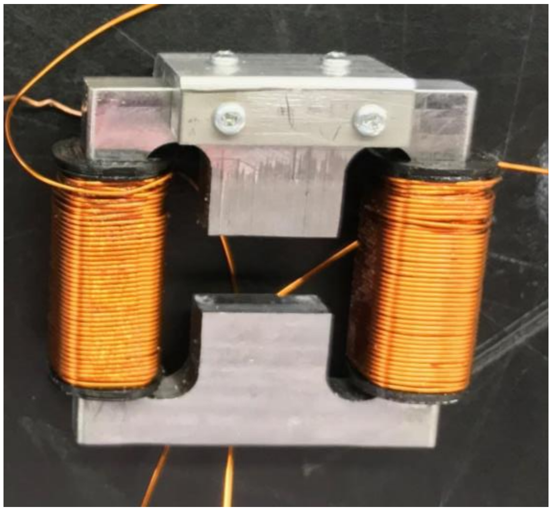


Figure 30: 2 Piece Stator with Machine Wound Coil

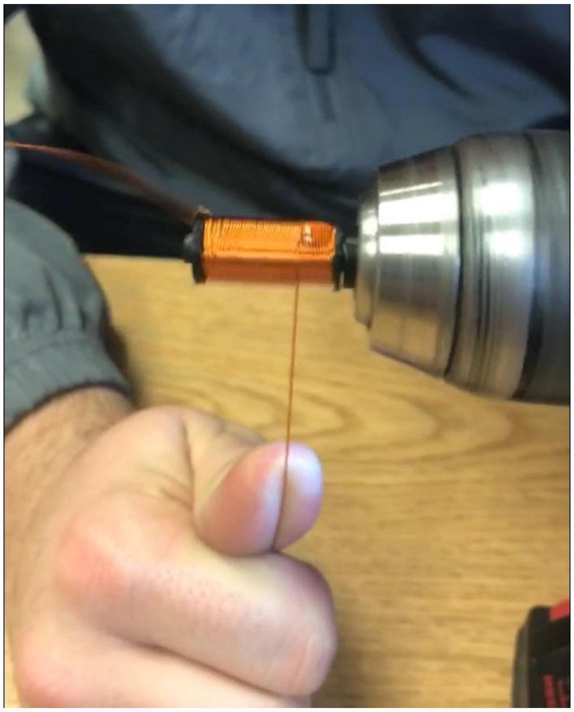


Figure 31: Coil Winding with Drill Motor

4.2.4 Water Jet Cutting

Our team had the opportunity to use the water jet cutting machine at Bose Corporation's maker space in Framingham Ma. We used the water jet cutter to cut our flexures since the material was too thin to CNC mill and our design was too complex for hand machining. The water jet allowed us to cut our 1095 spring steel very quickly and with absolute precision. A picture of two water jet cut flexures is shown below. In addition to the flexures themselves we also cut the small rectangular pieces that fasten the flexures to the C-block with the water jet cutter. This allowed us to produce all we needed plus extra parts quickly.

FIGURE 32: M FLEXURES

FIGURE 33: FLEXURE FASTENERS

4.3 Testing Methods

The Team utilized several different methods of testing throughout the project in order to verify the performance of our speaker.

4.3.1 Listening Test

As simple as it sounds one of our more important ways of testing prototypes was to actually just play music through the device and listen for any notable differences in audio quality. We performed this simple listening test with all of our prototypes to observe any easily noticeable issues or improvements before moving forward with our more advanced methods of testing. To help create a baseline for such an abstract test our team would always listen to “Sail” by AWOLNATION because it has several major bass drops and was a song that our team was already familiar with.

4.3.2 Scanning Laser Vibrometer

The team used the scanning laser vibrometer in WPI dynamics and vibrations lab to verify that our speaker was moving in phase throughout the range of bass frequencies. In addition, the scanning laser vibrometer allowed us to observe the fundamental frequency of our entire model. The results section will further discuss the tests conducted on the vibrometer and our associated findings. Pictures below show the Polytec Scanning Laser Vibrometer that we used for testing and what we saw in the corresponding software. Appendix C contains the procedure for operating the vibrometer.

FIGURE 34: POLYTECH SCANNING LASER VIBROMETER

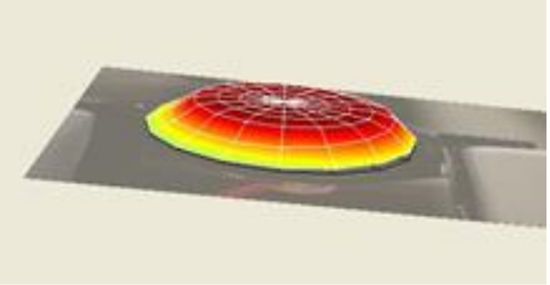


FIGURE 35: VIBRATION ANIMATION FROM VIBROMETER

4.3.3 Instron

An Instron machine is a piece of test equipment designed to evaluate the mechanical properties of materials and components. Our team conducted several tests using the Instron machine in a WPI laboratory to verify spring constants and force outputs of our model. The full detailed procedure that we followed for our Instron testing can be found in Appendix (A).

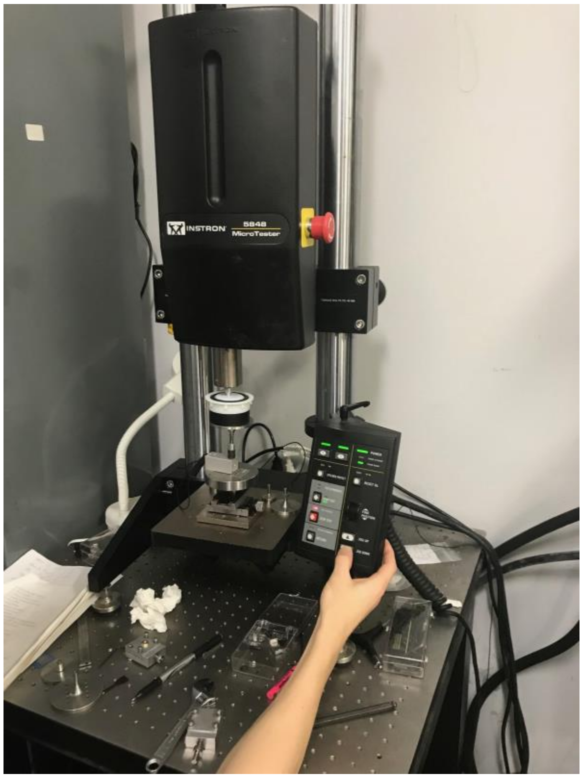


FIGURE 36: INSTRON TEST

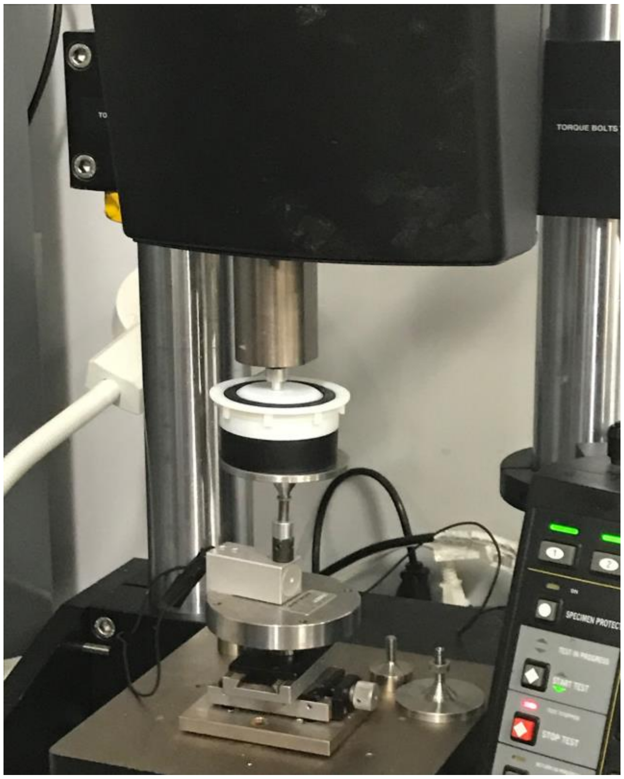


FIGURE 37: INSTRON TEST, CLOSER VIEW

4.4 Iteration

4.4.1 Speaker Housing

Every component in our speaker's housing design was iterated as we saw fit to improve performance and manufacturability of our design. This includes the cone, surround, snap fit, and bottom housing.

Figure 38: Speaker Housing

4.4.1.1 Cone

The cone of the speaker underwent minor iterations as a result of many other changing components. Originally, the cone and magnet holder were designed all as one piece of rigid plastic with a small cutout on the bottom which would accept the rectangular flexure. This design was not stable enough to securely hold the magnets in place and became obsolete as our flexure designs changed. The holder was designed to be its own separate part that would slide into a small raised rectangle shape centered on the underside of the cone. In addition, the original cone was domed but was redesigned to be flat so that it was more easily integrated into the resonant panel design created by one of the groups working alongside us in the MQP.

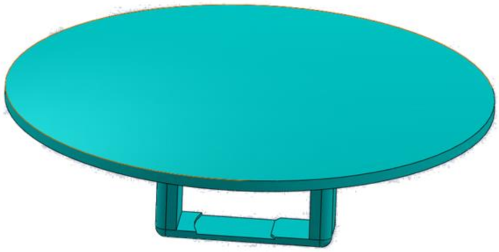


Figure 39: Original Cone Design

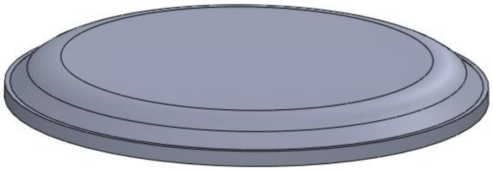


FIGURE 40: FINAL CONE DESIGN

4.4.1.2 Surround

Our team was limited to using Tango Black Plus for our surround material since that was the only available flexible material in WPI's 3D rapid prototyping lab. In our first prints our team discovered that the surround was exhibiting more damping than we would have liked and that it was too stiff. So, we altered the design to allow the surround to move more freely. We kept the thickness the same and simply increased the overall area of the surround and then reprinted our new prototypes. The new surrounds still exhibited some damping but were a dramatic improvement compared to the first model, so we decided to use them in our final design. The top half of the housing including our final version of the surround are pictured below.

FIGURE 41: FINAL SURROUND

4.4.1.3 Snap-Fit

The top half of our speakers' housing connected to the bottom half via our designed snap-fit system. Originally our prototypes only had 4 tabs that snap fit over a ridge on our bottom housing to keep the two-halves secured as one. However, when we tested the first prototype we noticed some rattling and found some of it to be caused by the loose connection between the two halves of the housing. The original 4-tab housing is shown below.

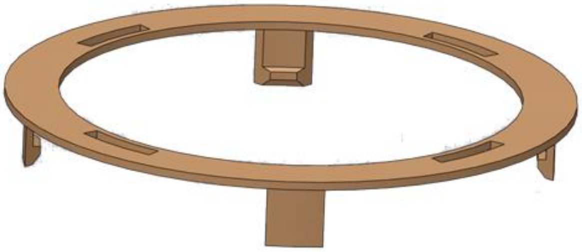


FIGURE 42: ORIGINAL SNAP FIT

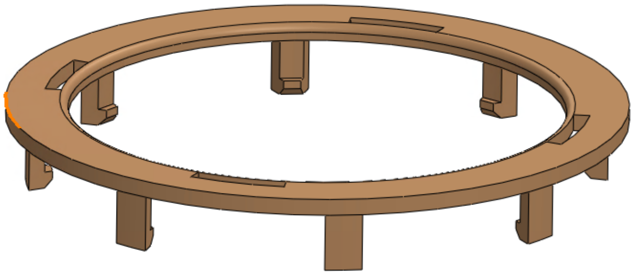


FIGURE 43: FINAL SNAP FIT

As a result, we redesigned the top housing to have 8 tabs instead of the previous 4 in hopes to solidify the connection between the two parts. The thickness of the overall part was also increased to improve rigidity. After the new models were printed we tested them an found that the two halves fit together much more securely and the rattling was gone. A picture of the final housing with 8 tabs are pictured below both in a bottom view and in a side view.

FIGURE 44: FINAL SNAP FIT BOTTOM VIEW

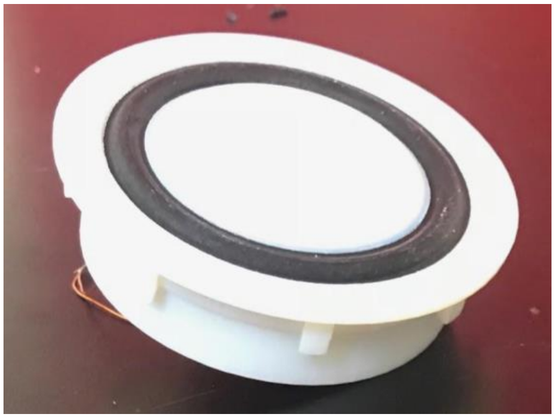


FIGURE 45: FINAL SNAP FIT

4.4.1.4 Bottom Housing

The bottom half of the housing was slightly altered to improve stability in our design. In our first prototype the bottom of the housing used 4 contact points to hold the stator in place. As you can see from the picture on the left the four contact points were rather close together and problems arose as a result. As previously mentioned the first prototype experienced some rattle during activity and one of the actions our group took to fix this was redesigning the bottom housing. We decided to spread the contact points further apart so that they could accept the corners of our stator making the overall design more stable than it was previously. The thickness of the bottom housing also increased in order to improve rigidity.

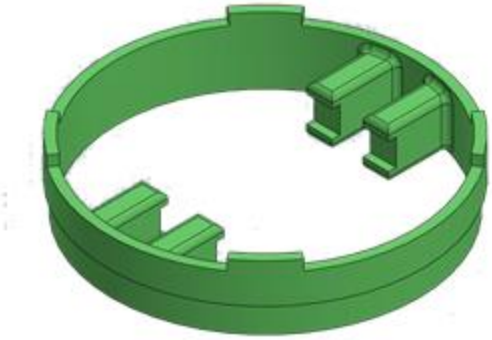


FIGURE 46: ORIGINAL BOTTOM HOUSING

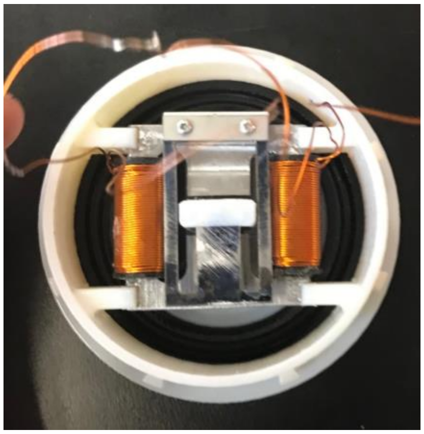


FIGURE 47: FINAL BOTTOM HOUSING

4.4.2 Motor

The motor refers to the actual device within the speaker housing. It includes the magnets, magnet holder, flexure and flexure mounting system, coils, and stator. Almost every part was iterated in some way to max performance along with manufacturability.

4.4.2.1 Stator

The initial design was based off a 3-phase E-core transformer with the middle solenoid being removed. Despite several iterations the shape of the stator remained throughout the design process. We realized the gap between the stator and the magnets could be increased. This iteration was made so that our flexures wouldn't experience as much force caused by the magnetic attraction of the permanent magnets and steel.

The second iteration was one of the most important design alterations in the project. The team decided to change from a one-piece stator to a two-piece stator. This simple modification allowed our team to make several other improvements to the overall design that streamlined manufacturability. The only drawback to the two-piece design was the increased machining time. Our machining process went from a 4-step process to 14 step process. However, the time we saved in the coil wrapping process as well as the quality improvement of the coils as a result of the two-piece design was well worth the extra machining time.

FIGURE 48: ONE PIECE STATOR

FIGURE 49: TWO PIECE STATOR

4.4.2.2 Flexure

Our flexure design underwent what was probably the most significant change of any component in our speaker assembly. Originally our flexures were just simple rectangles attached to our magnets from a 3D printed T-structure.

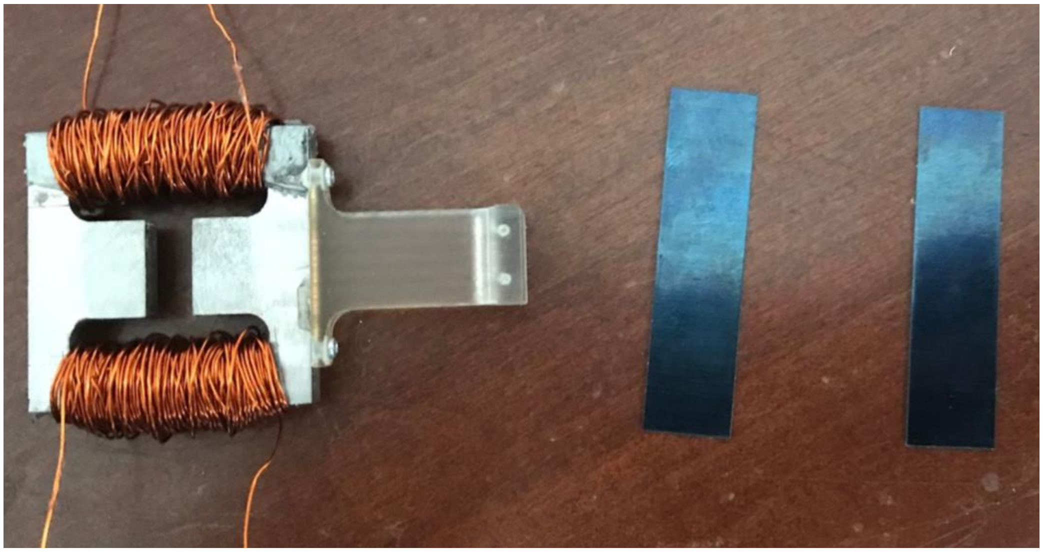


FIGURE 50: RECTANGLE FLEXURE

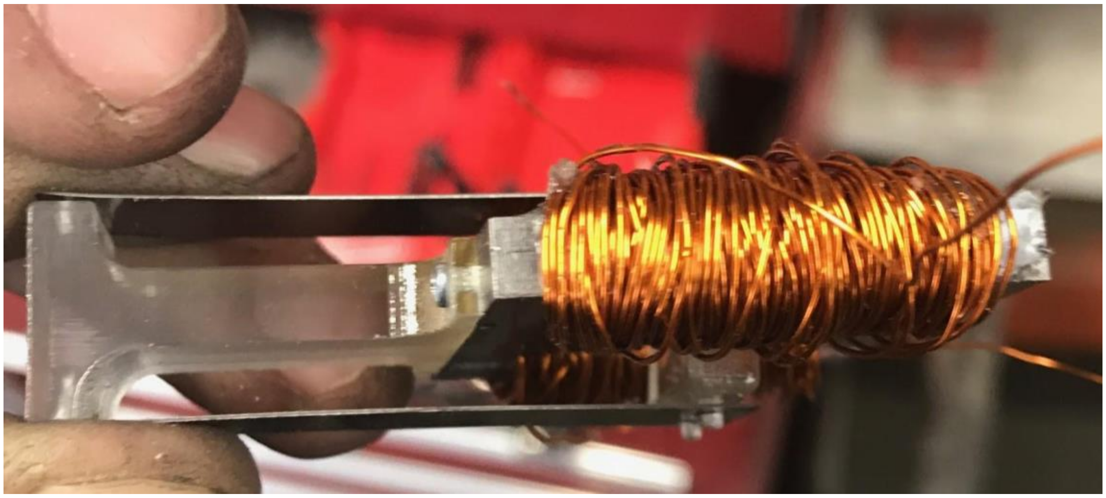


FIGURE 51: RECTANGLE FLEXURE, T- STRUCTURE

After discussing new flexure designs with our advisor, the team decided that a double M-flexure design would offer the most compact geometry while providing stability. The M-Flexures shown below were attached at both the top and bottom of our magnet holder to ensure that the magnet would remain centered in the air despite the attraction to the stator. The M-flexure design allowed us to maximize our cantilever length while also decreasing the overall footprint of our design. Due to the complexity of the flexure shape combined with the thin 1095 spring steel material our team used a water jet cutter in Bose Corporation's maker space to manufacture the parts.

With the new M-Flexure design, came another iteration for the previous T-structure. This flexure support was changed to decrease the diameter of the whole speaker while fixturing the newly designed M-flexure. We called the new support the C-block because it resembles the letter “C” in its shape. It is made of aluminum and also was CNC machined at WPI by the group.

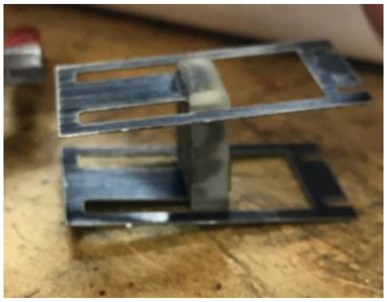


FIGURE 52: FLEXURE AND MAGNET HOLDER

FIGURE 53: M FLEXURE

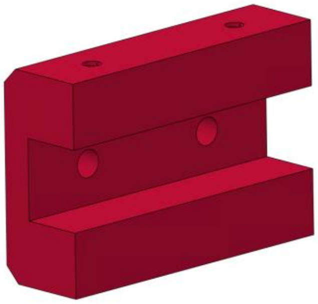


FIGURE 54: C-BLOCK

4.4.2.3 Magnet Holder

As the name implies the "magnet holder" is the small rigid plastic component that holds the magnets and provides the flexures with a surface to connect with. In our first designs using the T-structure the magnet holder had two small pegs on the top and bottom that were aligned with two small cut holes on the rectangular flexures. The pegs slid through the holes and were secured using a strong adhesive. Unfortunately, the T-structure combined with the peg and hole connecting system was not strong enough to stabilize the magnet holder for a long period of time. This design often resulted in the magnets moving and sticking to the sides of the stator deeming the motor useless.

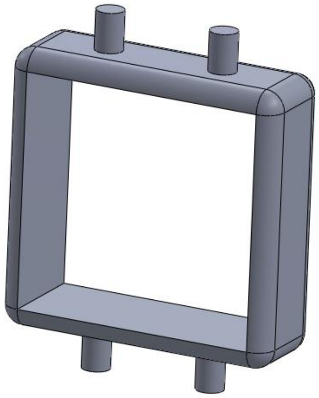


FIGURE 55: ORIGINAL MAGNET HOLDER

When we redesigned the flexures, we felt it was also appropriate to redesign the magnet holder so that we could secure the flexures to the magnet in a more stable manor. The new magnet holder pictured below incorporates two slots where the flexures can slide into and then be further secured with adhesive. We found this design to be much more stable since the flexure is locked into place from all angles and does not allow the magnets to move much at all from the centered plane in the air gap. We also thickened the rigid material on the magnet holder to ensure that it would not fail during extended use and magnet movement.

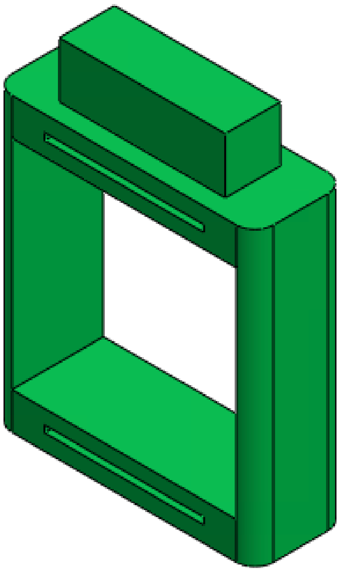
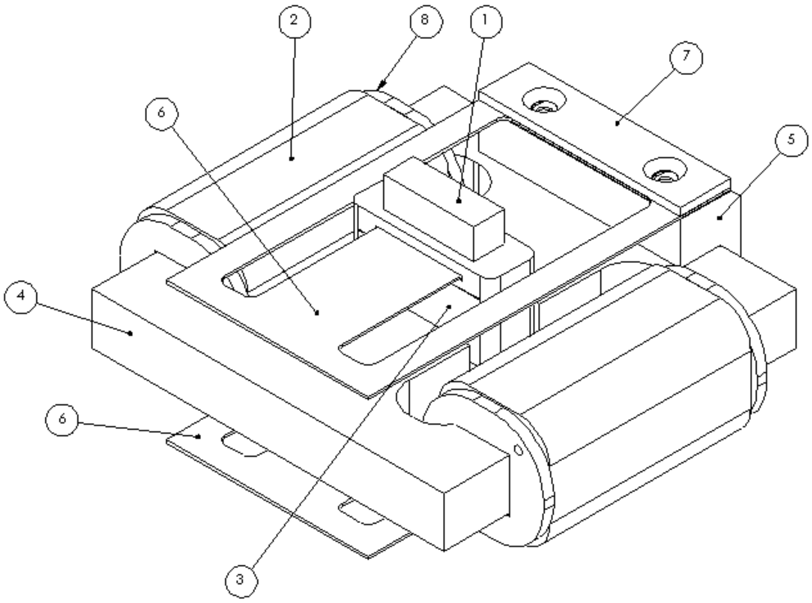


FIGURE 56: FINAL MAGNET HOLDER

5.0 Results

5.1 Final Motor Design

After much iteration, our final SolidWorks and ANSYS design of the motor utilized a two-piece stator, a C-Block coupled with a supporting aluminum piece to hold the two flexures, a magnet holder that would be attached to the cone separately, pre-wound coils on 3D printed sleeves, and multiple screws. The SolidWorks pictures of our motor design can be seen below. The motor's final dimensions consist of a length of 41mm, a width of 37mm, and a thickness of 18.58mm.



ITEM NO.	PART NUMBER	QTY.
1	Magnet Holder	1
2	Coil	2
3	Magnet	2
4	Stator	1
5	C-Block	1
6	M Flexure	2
7	Flexure Fastener	2
8	Coil Holder	2

FIGURE 57: CAD DRAWING WITH CALLOUTS

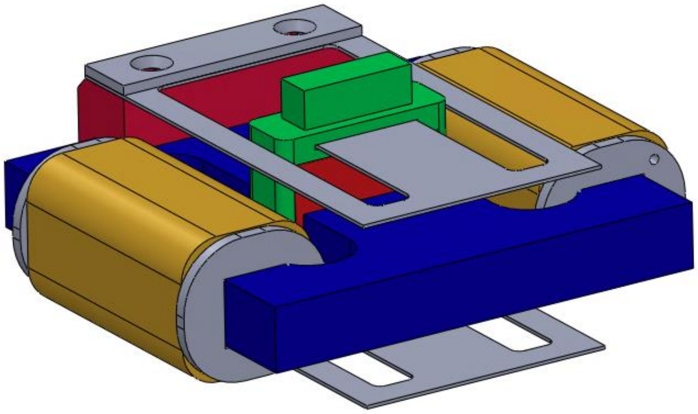


FIGURE 58: CAD MODEL OF MOTOR

5.2 Final Speaker Design

The final speaker housing design was all 3D printed in two separate parts which connect using a snap fit system. The top half of the housing was printed in one piece using Vero Clear for the rid components and Tango Black Plus for the flexible surround. The bottom half of the housing was designed to hold the stator in place using contact points at the four corners of the stator. It was entirely printed using rigid Vero Clear material. Our final 3D printed. The SolidWorks pictures of our speaker design can be seen below. The speaker housing's final dimensions consist of a circumference of 74.82mm and a thickness of 20.38mm.

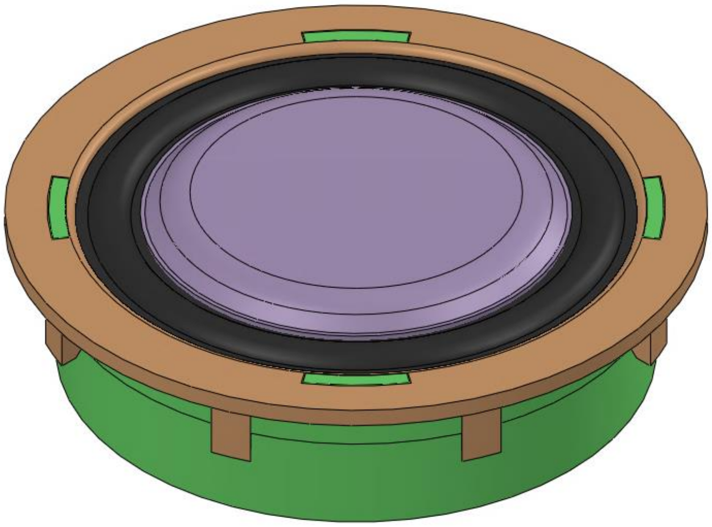
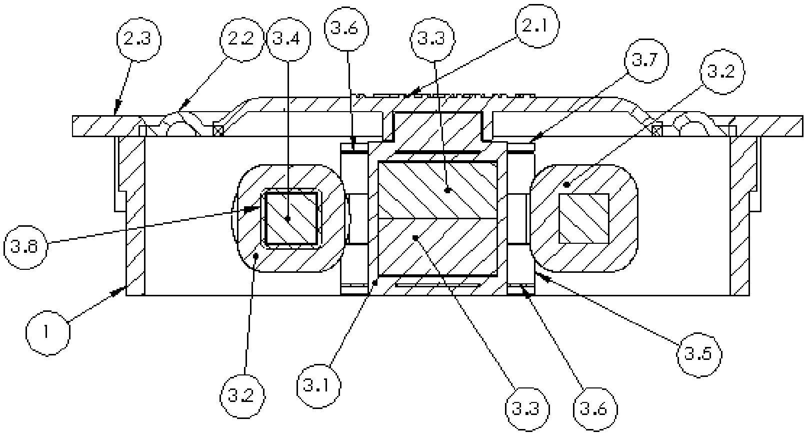


FIGURE 59: FINAL SPEAKER DESIGN



ITEM NO.	PART NUMBER	QTY.
1	Housing Bottom	1
2	Cone and Housing Assembly	1
2.1	Cone	1
2.2	Surround	1
2.3	Housing Top	1
3	Motor Assembly	1
3.1	Magnet Holder	1
3.2	Coil	2
3.3	Magnet	2
3.4	Stator	1
3.5	C-Block	1
3.6	M Flexure	2
3.7	Flexure Fastener	2
3.8	Coil Holder	1

FIGURE 60: CROSS SECTIONAL DRAWING WITH CALLOUTS

5.3 Assembly

Many of the iterations made by the team streamlines the assembly process. The following section provides a step by step procedure for assembling one of our moving magnet speakers.

5.3.1 Step by Step Assembly Process

1. Figure 61 below shows how to wrap coils around the 3D printed coil sleeves using a drill motor as well as numerous finished coils.

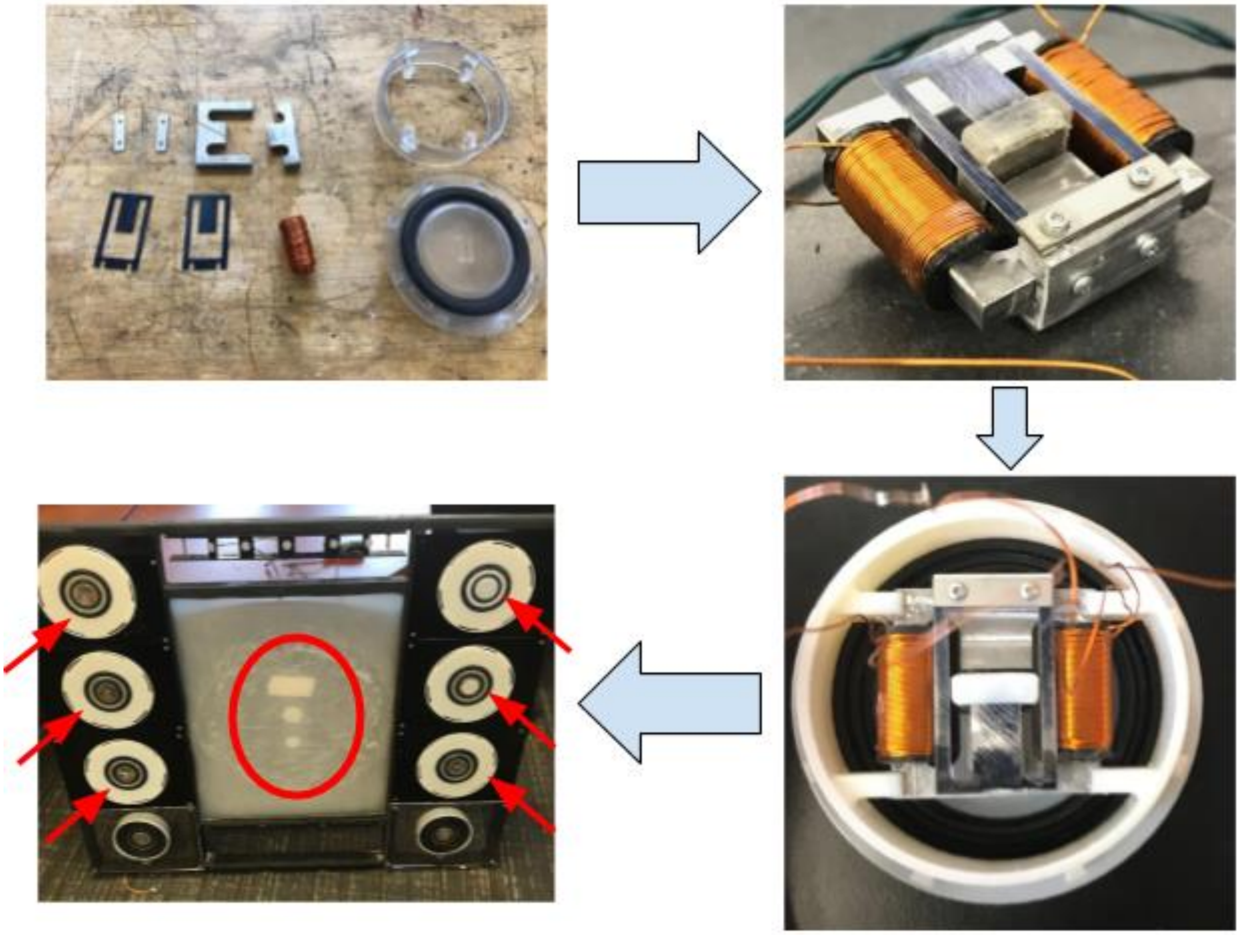


FIGURE 61: ASSEMBLY PROCESS

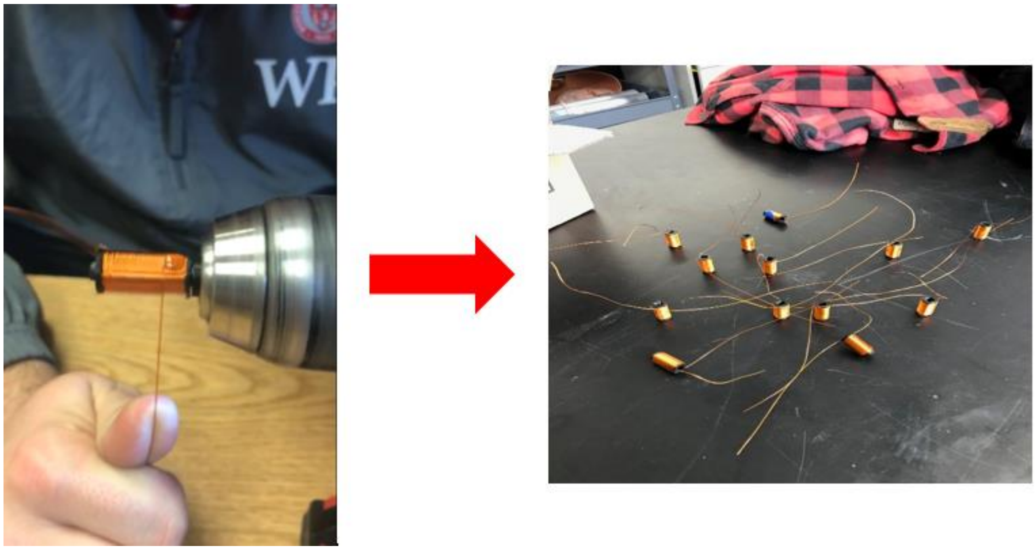


FIGURE 62: COIL MAKING PROCESS

2. Figure below shows how to glue the magnets and flexures into the Magnet Holder.

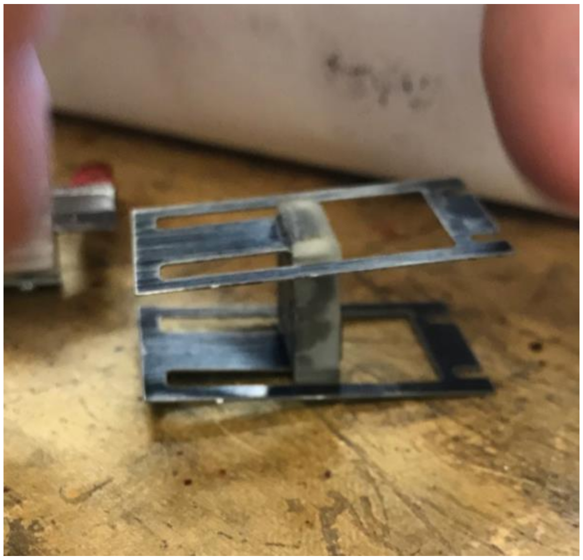


FIGURE 63: FLEXURE AND MAGNET HOLDER ASSEMBLY

3. Figure below shows how to screw the C-Block to the Stator.

FIGURE 64: HALF OF STATOR WITH C-BLOCK

4. Figure below shows how to slide the fully wrapped coils on the arms of the Stator.

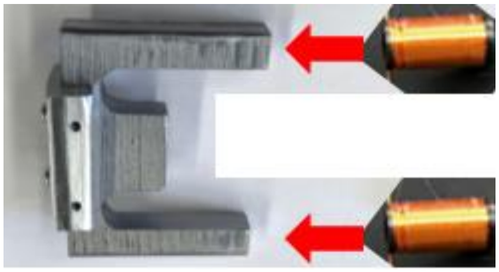


FIGURE 65: COIL SLIDES ON STATOR

5. Screw the Flexure Fasteners to the C-Block, but leave some clearance so you can later slide in the flexures.
6. Take the magnet flexure sub-assembly and maneuver the flexures so that they are concentric with the screws.
7. Fully screw in the Flexure Fasteners.
8. Screw the second part of the stator to this assembly.

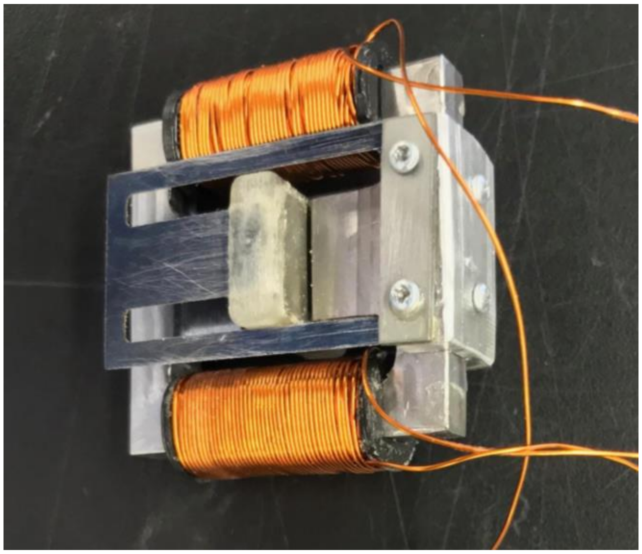


FIGURE 66: MOTOR ASSEMBLY

Figure above shows the result of steps 5-8.

9. Put adhesive on all of the screws to prevent them from falling out due to vibrations and to fully complete the motor part of the moving magnet transducer motor.

10. Figure below shows that once the adhesive is dry, you then insert the motor into the Bottom Housing.

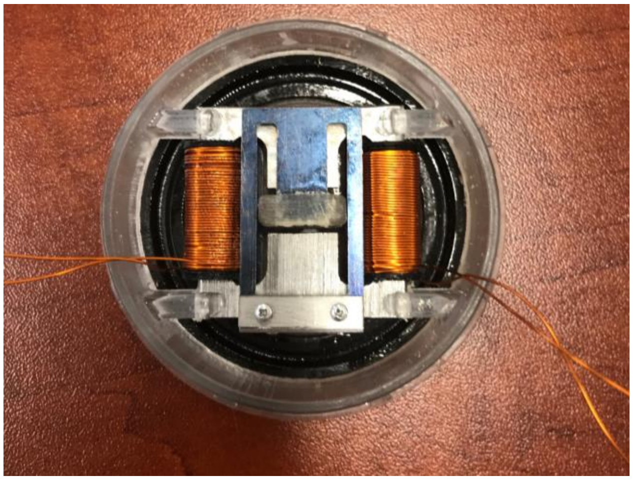


FIGURE 67: MOTOR ASSEMBLED IN BOTTOM HOUSING

11. Finally, Figure below show how you glue the Magnet Holder to the Cone and snap fit the rest of the speaker together.

FIGURE 68: CONNECT TOP HOUSING AND CONE WITH GLUE

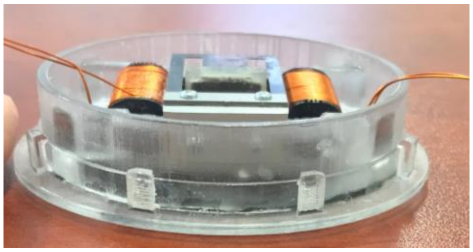


FIGURE 69: SNAP TOP OF HOUSING TO BOTTOM

5.4 Validation and Verification

5.4.1 Ansys

The results of the Ansys simulations for the surround flexure and the full assembly are presented below.

5.4.1.1 Surround

The flexible surround of the speaker was analyzed for stiffness and stress. In the figure below, you can see a graphic of the deformation of the surround after a 2 mm displacement was applied to its inner ring, while its outer right was fixed. The graph below represents ten data points that were analyzed during the displacement of the surround. A force probe measures the required force in order to displace the surround. The slope of this graph at any point is equal to the stiffness of the surround at that displacement. As you can see, the surround behaves non-linearly when displaced.

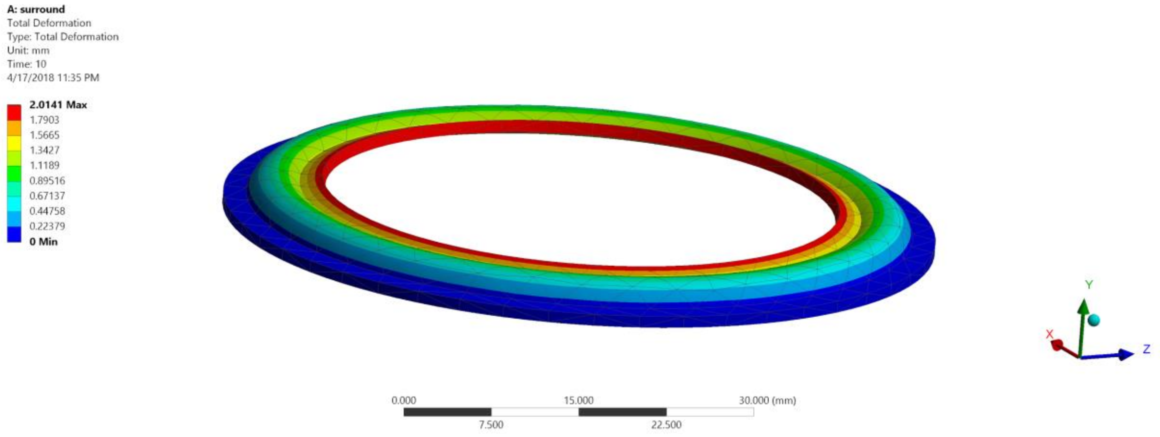


FIGURE 70: SURROUND DEFORMATION GRAPHIC

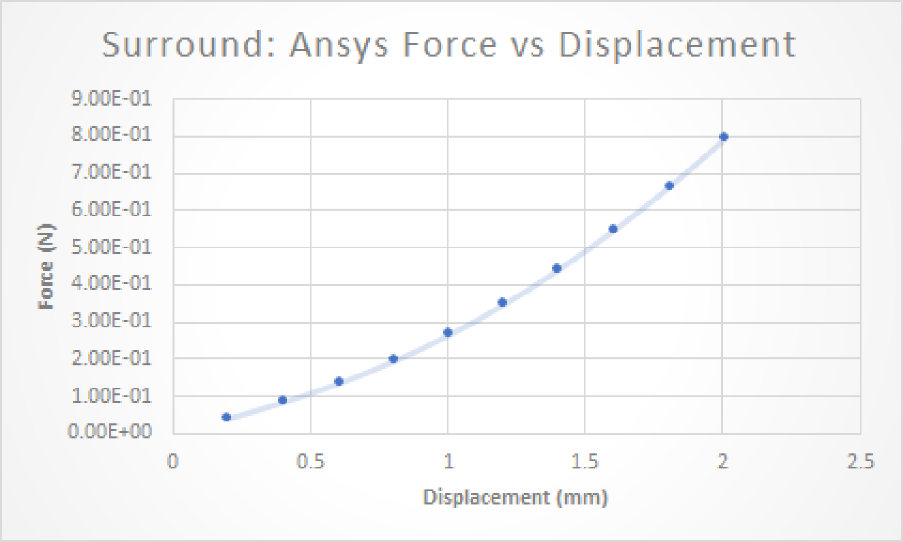


FIGURE 71: SURROUND ANSYS FORCE VS DISPLACEMENT GRAPH

To prevent failure of the surround, the stresses that occur during a 2 mm displacement of the inner ring were found and compared with the yield strength of the material to ensure that the maximum stress stayed within the elastic deformation region.

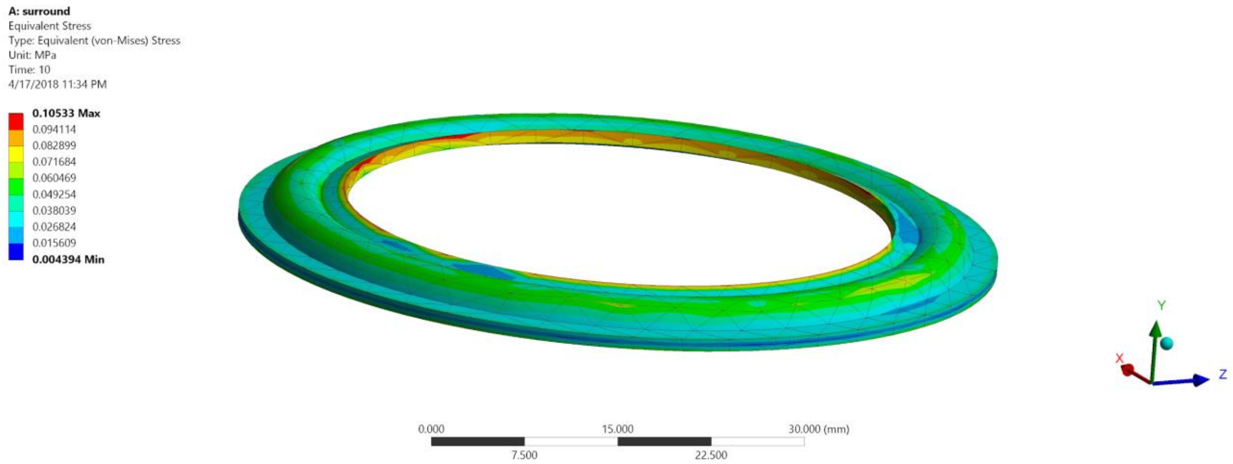


FIGURE 72: SURROUND ANSYS STRESS GRAPHIC

5.4.1.2 Double Flexure

The double flexure of the speaker was analyzed for stiffness and stress. In the figure below, you can see a graphic of the deformation of the double flexure after a 2 mm displacement was applied to the bottom of the magnet holder, while the flexures were fixed by the end connected to the C-block, fastened down by the flexure fasteners. The graph below represents ten data points that were analyzed during the displacement of the double flexure. A force probe measures the required force in order to displace the double flexure. The slope of this graph at any point is equal to the stiffness of the double flexure at that displacement. As you can see, the double flexure behaves linearly when displaced with a stiffness constant of 1.18 N/mm.

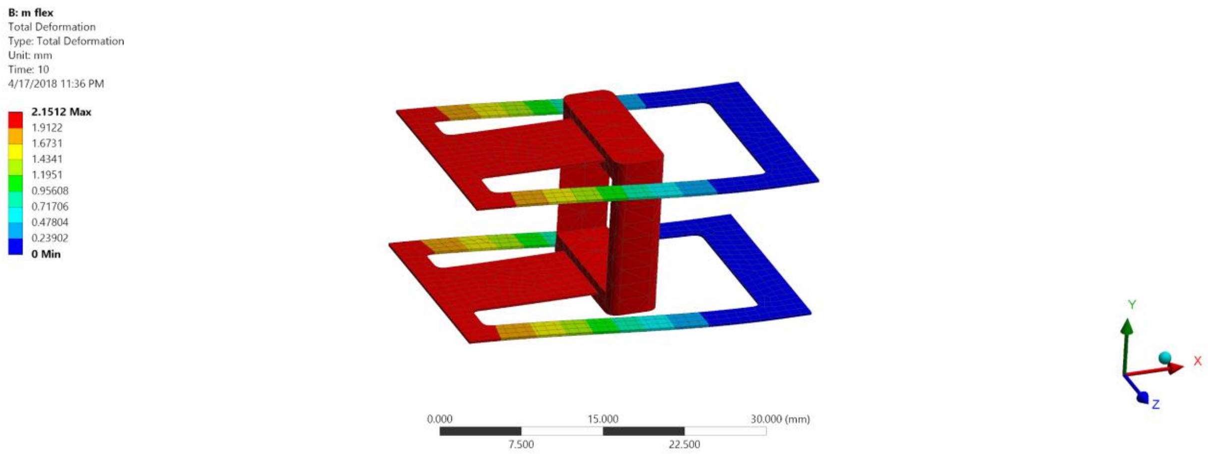


FIGURE 73: DOUBLE FLEXURE ANSYS DEFORMATION GRAPHIC

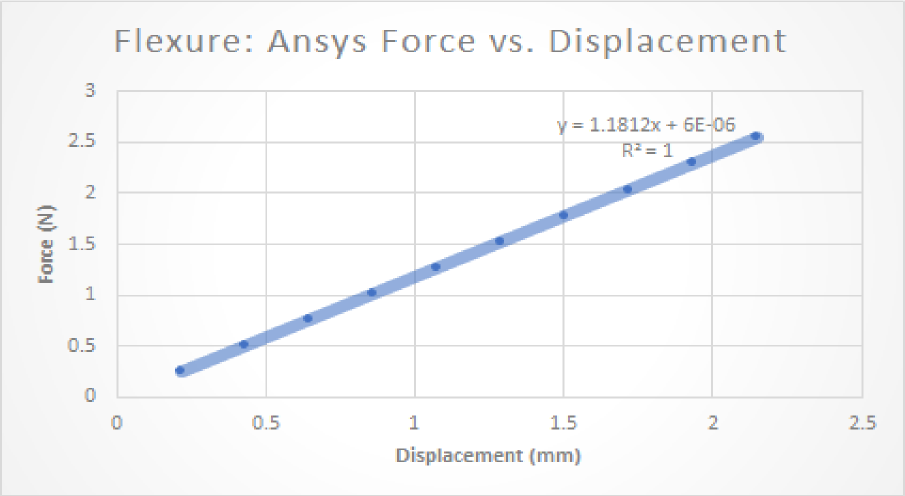


FIGURE 74: DOUBLE FLEXURE ANSYS FORCE VS. DISPLACEMENT GRAPH

To prevent failure of the double flexure, the stresses that occur during a 2 mm displacement of the magnet holder was found and compared with the yield strength of the material to ensure that the maximum stress stayed within the elastic deformation region. As you can see, there are stress concentrations on the inner corners of the flexures. The maximum stress on the flexure is located at the corner closest to where the flexure mounts to the C-Block. The yield strength of the 1095 spring steel is 525 MPa. The maximum stresses on the flexure are between 300-400 MPa except for very small stress concentrations at the corners which do not affect the flexures performance.

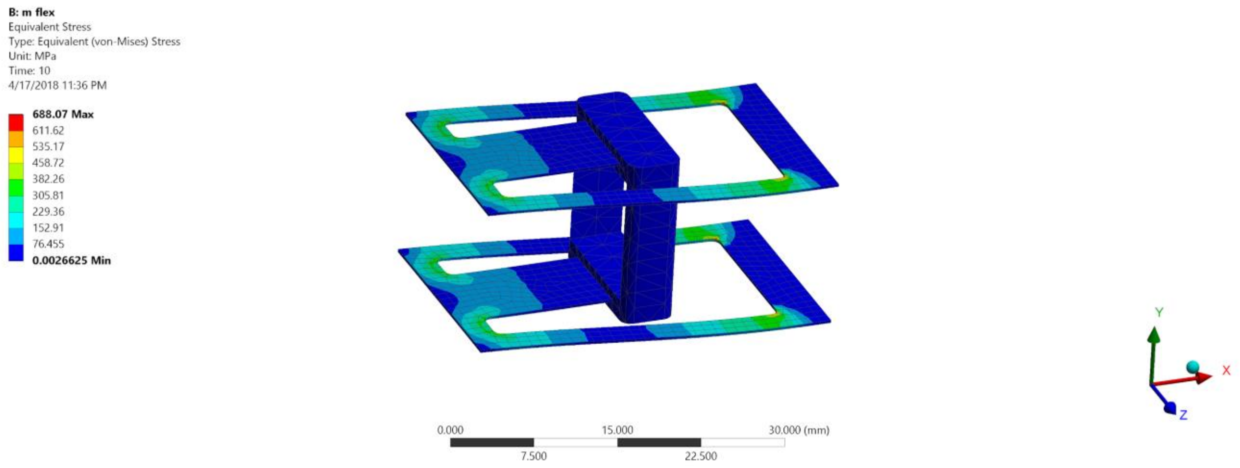


Figure 75: Figure 72: Double Flexure Ansys Stress Graphic

5.4.1.3 Double Flexure and Surround

A modal analysis of the whole assembly was performed. Damping was not considered because we did not have the exact value of the damping constant in the system. The graph below depicts the modal frequencies of the system. As you can see, the fundamental frequency of the system is about 70 Hz. This gives us a good idea of where the speaker will perform at its best. 70 Hz falls into the low to mid frequency range for bass which was one of our goals for this speaker.

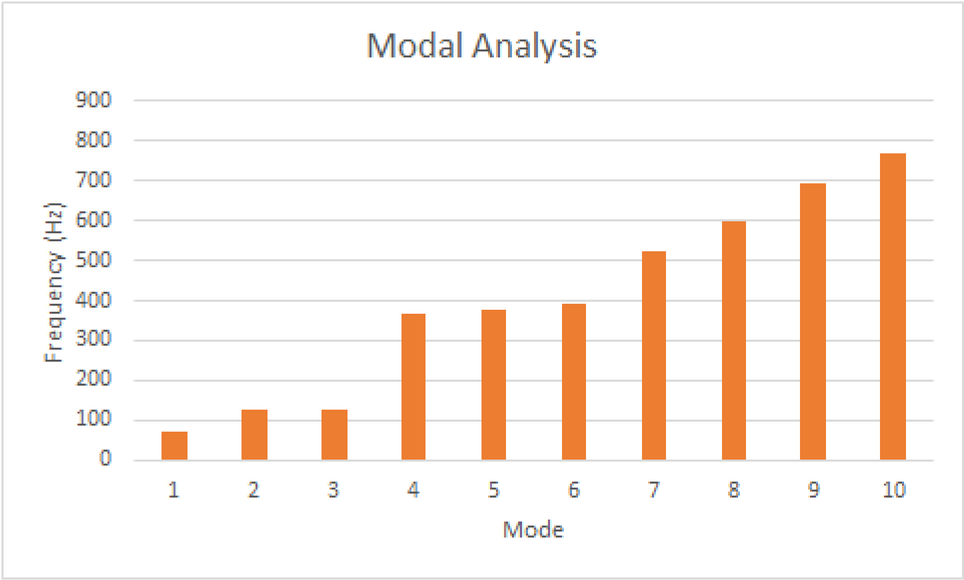


Figure 76: Ansys Modal Analysis

A harmonic response analysis was also performed on the full assembly. This analysis was performed from 0 Hz - 1000 Hz. This allows us to see the response of the system as a function of frequency. If we look at the graph, we can see that the fundamental frequency is at 70 Hz as suggested by the modal analysis above. You can also see that each bar above matches up with a peak from the frequency response.

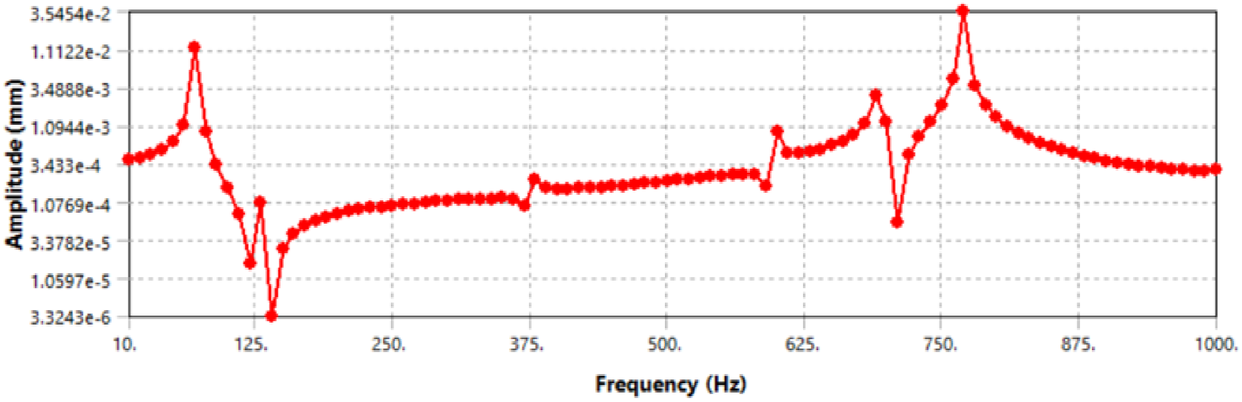
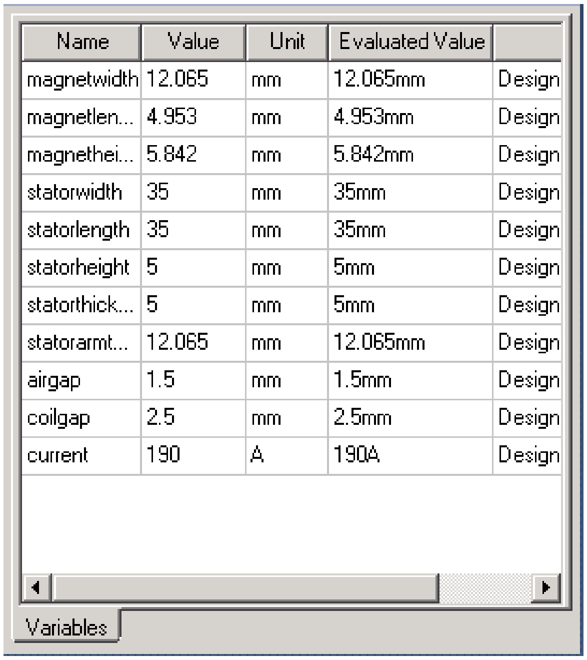


FIGURE 77: ANSYS UNDAMPED FREQUENCY RESPONSE

5.4.1.4 Motor Assembly

Ansys Maxwell was used to determine the magnetic field strength in the stator, as well as the force output of the stator. A parameterized model was created in Maxwell for iteration purposes. The parameters below reflect the final speaker. We can use these parameters to optimize our design by plotting force as a function of each parameter and then determining the ideal value for each.



Name	Value	Unit	Evaluated Value	
magnetwidth	12.065	mm	12.065mm	Design
magnetlen...	4.953	mm	4.953mm	Design
magnethei...	5.842	mm	5.842mm	Design
statorwidth	35	mm	35mm	Design
statorlength	35	mm	35mm	Design
statorheight	5	mm	5mm	Design
statorthick...	5	mm	5mm	Design
statorarmt...	12.065	mm	12.065mm	Design
airgap	1.5	mm	1.5mm	Design
coilgap	2.5	mm	2.5mm	Design
current	190	A	190A	Design

FIGURE 78: MAXWELL MODEL PARAMETERS

The figure below represents the behavior of the magnetic field lines in the stator. It was important to monitor the magnitude of the magnetic field to prevent saturation of the steel. We wanted to keep it below 1 Tesla everywhere except where the magnets are located. The first figure uses arrows to represent the direction of the magnetic field. The second figure represents the magnitude of the magnetic field on the surface of the stator.

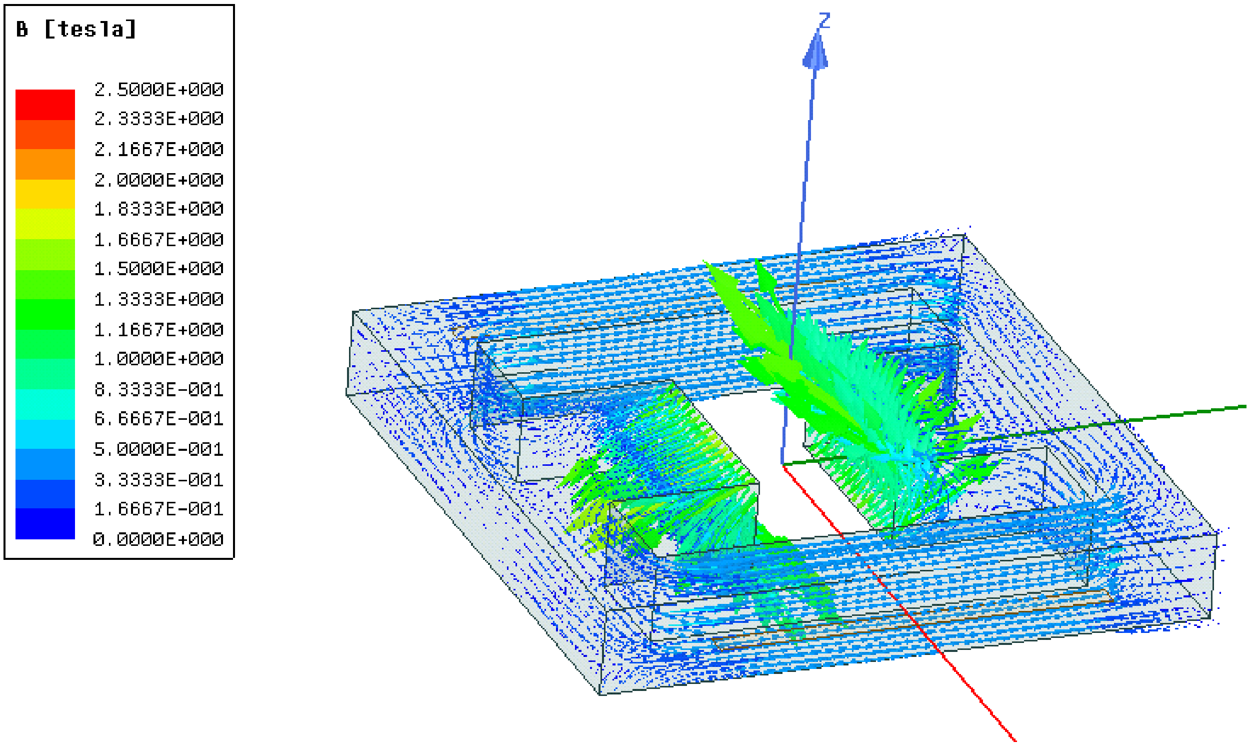


FIGURE 79: MAXWELL MAGNETIC FIELD VECTORS

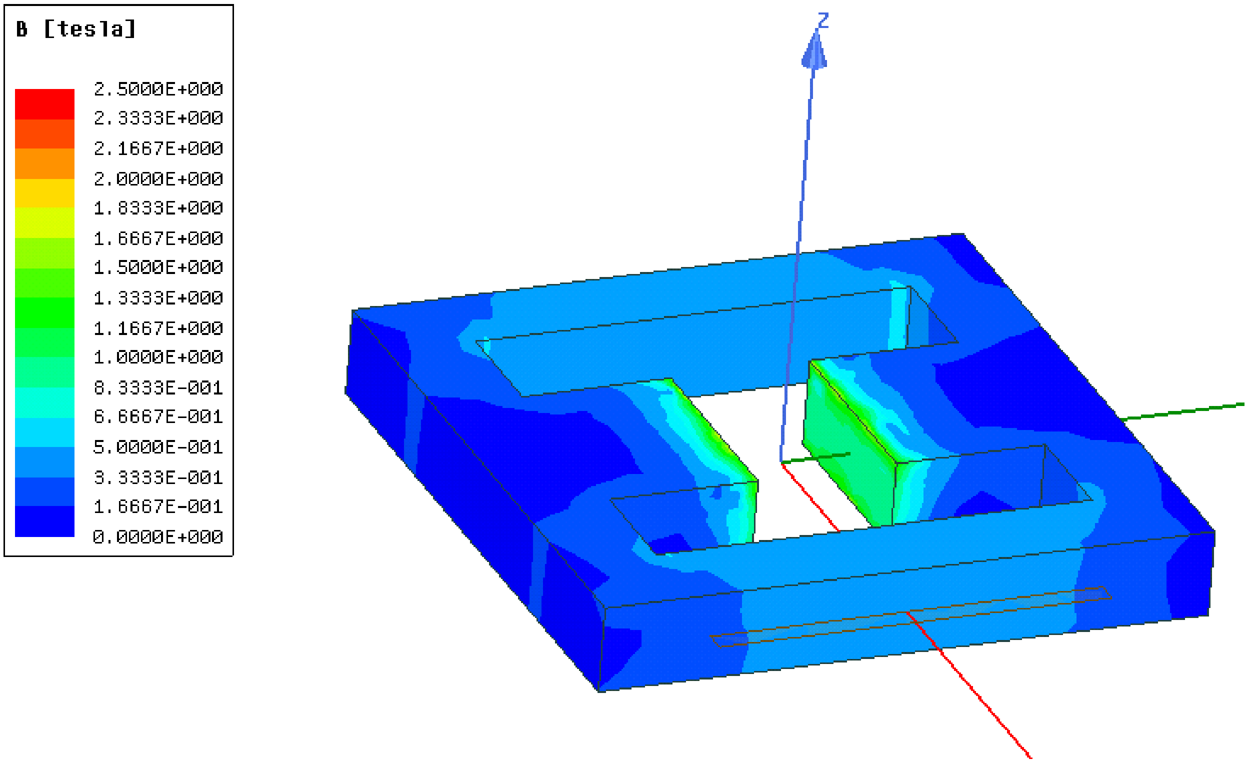


FIGURE 80: MAXWELL MAGNETIC FIELD MAGNITUDE

The relationship between the force output and the current was determined using a parametric study that varied the current in the coils from 0 Amps to 1.6 Amps. The slope of the graph below represents the expected force constant of the speaker. The slope is 1.45 N/Amp.

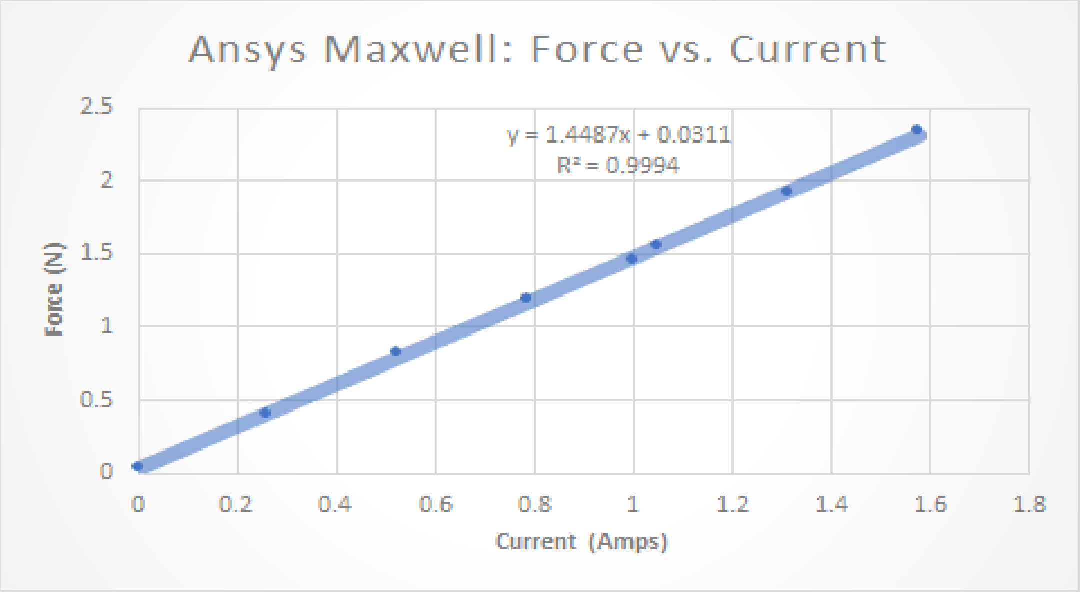


FIGURE 81: MAXWELL PREDICTED FORCE VS. CURRENT

5.4.2 Instron Results

To verify our Ansys results, we used an Instron machine to test the surround, the flexure/magnet holder, and the full assembly of the cone, surround, and flexure/magnet holder. The pictures below illustrate our test setup.

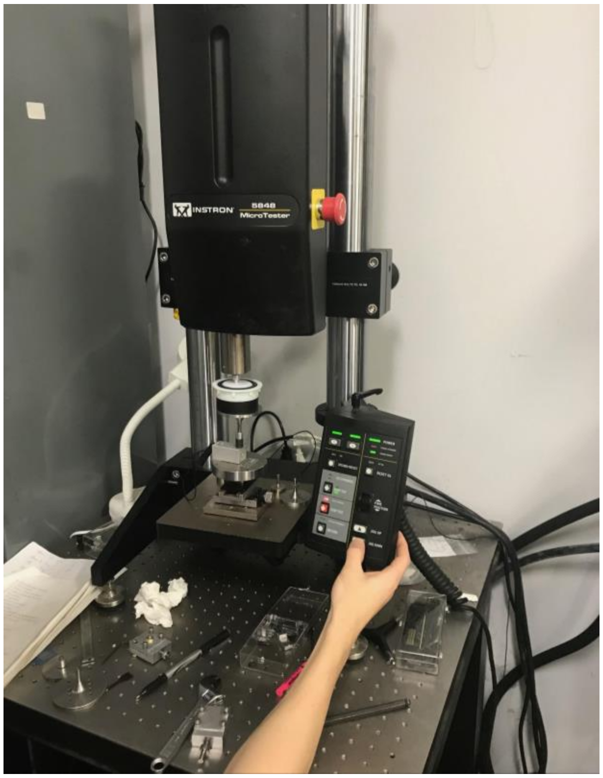


FIGURE 82: INSTRON TEST SETUP

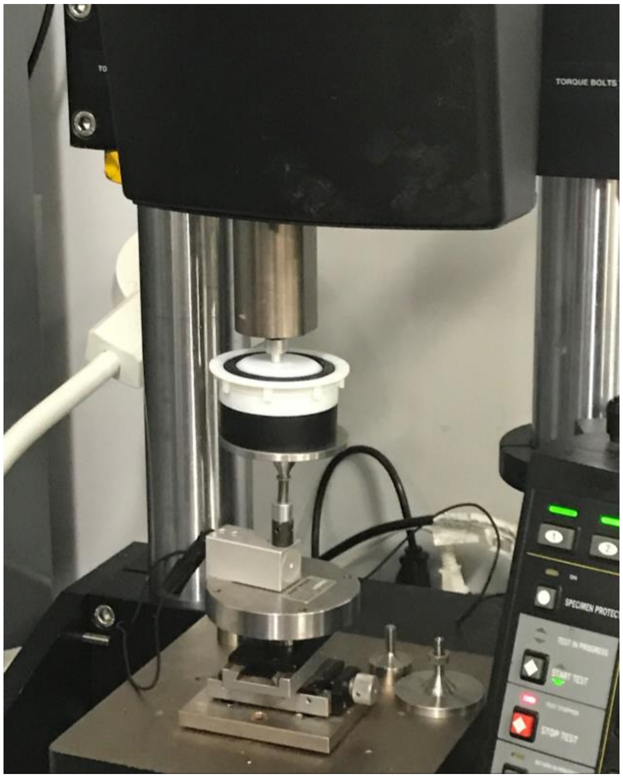


FIGURE 83: INSTRON TEST, ZOOMED IN

5.4.2.1 Surround

To verify the Ansys analysis performed on the surround we measured the relationship between force and displacement with the Instron machine. The graph below shows the data gathered from the test. As you can see, the data closely matches the Ansys expected results.

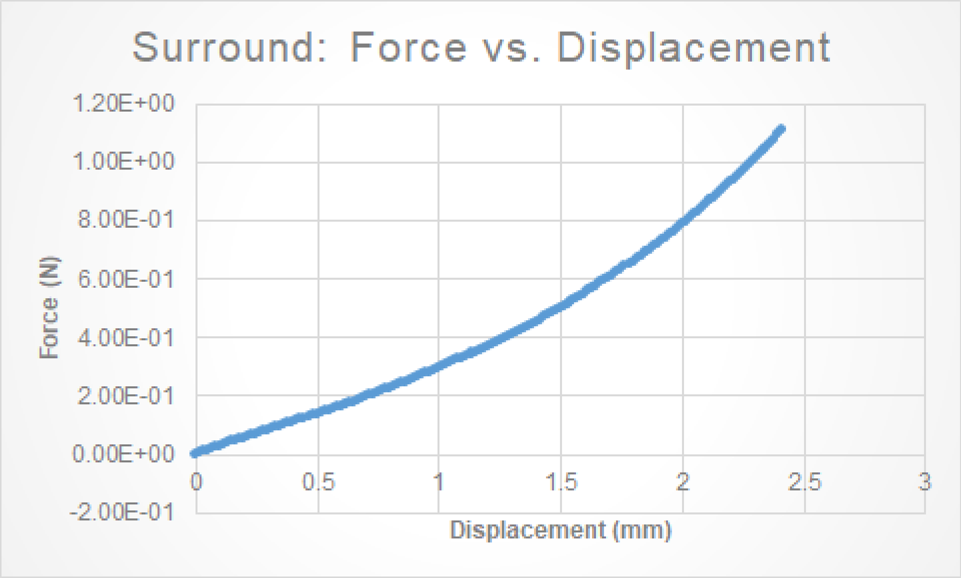


FIGURE 84: MEASURED FORCE VS. DISPLACEMENT OF SURROUND

5.4.2.2 Double Flexure

To verify the Ansys analysis performed on the double flexure we measured the relationship between force and displacement with the Instron machine. The graph below shows the data gathered from the test. As you can see, the data closely matches the results predicted by Ansys. The actual stiffness of the double flexure assembly is 1.12 N/mm.

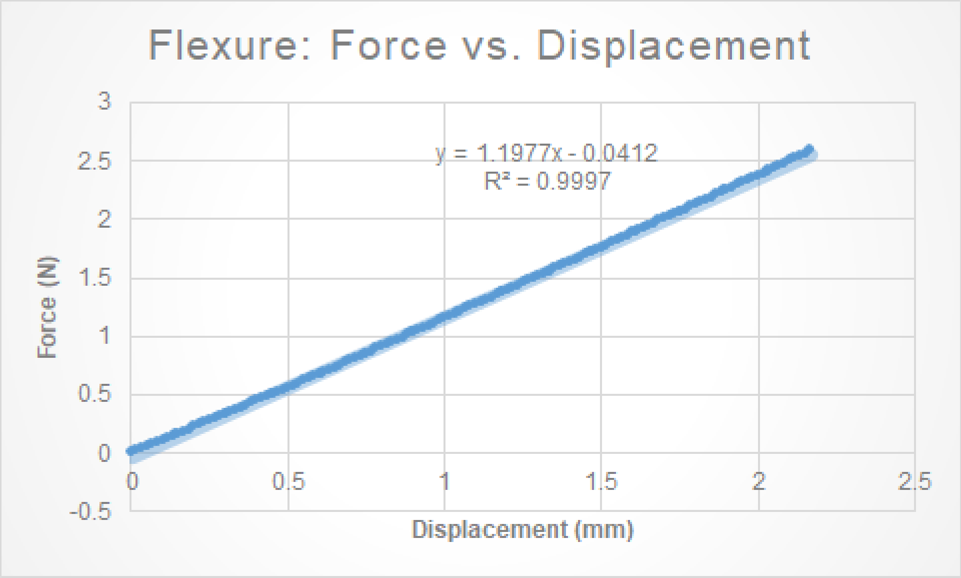


FIGURE 85: MEASURED FORCE VS. DISPLACEMENT OF DOUBLE FLEXURE

5.4.2.3 Double Flexure and Surround

The force vs displacement of the assembly was measured using the Instron machine. The graph below shows the data gathered from the test. As you can see, the stiffness of the full assembly is mostly linear, however due to the non-linearities in the stiffness of the surround, the graph becomes nonlinear at larger displacements.

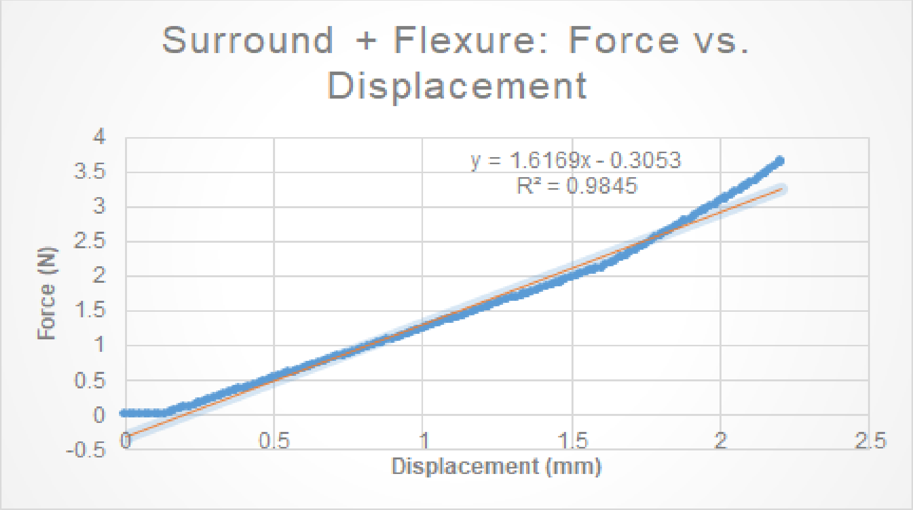


FIGURE 86: MEASURED FORCE VS. DISPLACEMENT OF ASSEMBLY

5.4.2.4 Force Output of Speaker

To verify the Ansys analysis performed on the speaker, the force vs current was measured using the Instron machine and a power supply. In the test set-up, we displaced the cone of the speaker slightly with the Instron machine to apply a pre-load to the system. Next, we incrementally added more and more current to the speaker and measured the force on the Instron machine at each point. A resistor in series was used to verify the current by measure the voltage across and dividing by its resistance. The difference of the pre-load and the force measured on the Instron equaled the force output of the speaker. Below the force vs current is plotted. As you can see, the slope of the line is linear has a value of about 1.24 N/Amp. Our expected result was around 1.48 N/Amp. We believe the discrepancy between the two values is due to manufacturing error.

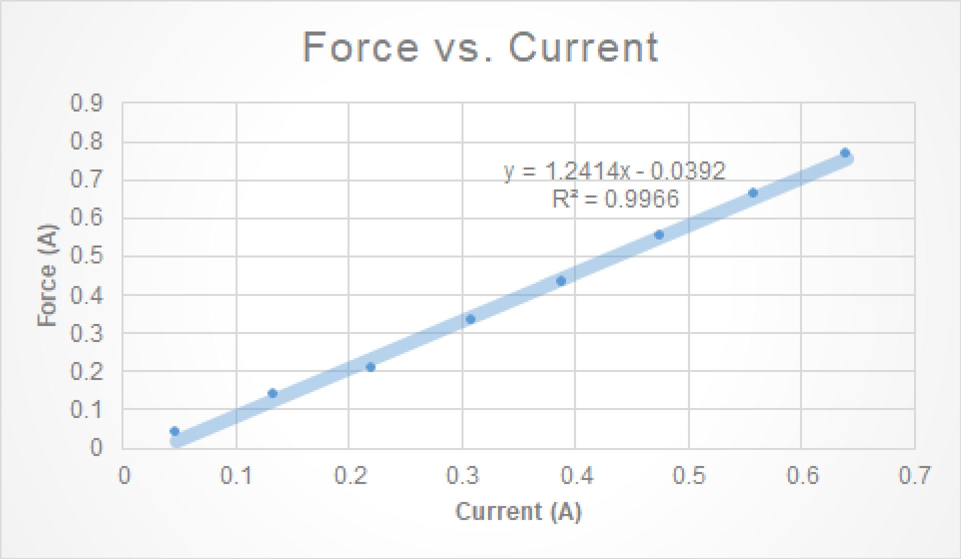


FIGURE 87: MEASURED FORCE VS. CURRENT OF SPEAKER

5.4.3 Laser Vibrometer Results

The Polytec scanning laser vibrometer was used to measure the frequency response of our speaker. This response would tell us the frequency ranges our speaker would perform the best. A frequency sweep and multiple fast scans were both performed on the speaker in order to visualize the performance of the speaker. The speaker was mounted using a laser cut piece of wood that was designed to hold our speaker tightly without allowing extra vibration. The mounting bracket can be seen below.

FIGURE 88: SPEAKER VIBROMETER MOUNT

FIGURE 89: SPEAKER VIBROMETER MOUNT, FRONT VIEW

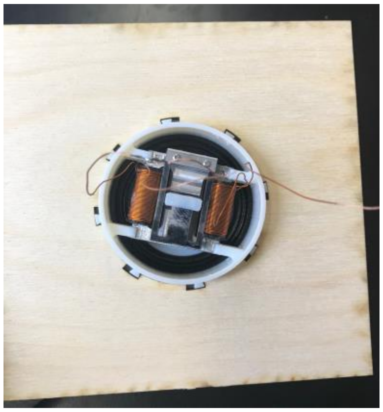


FIGURE 90: SPEAKER VIBROMETER MOUNT, BACK VIEW

The frequency sweep was measured from 20 Hz to 1000 Hz. The plot illustrates the response of the speaker at various frequencies. As you can see, the first fundamental frequency is located at 105 Hz. This means that the speaker is operating in the frequency range we intended.

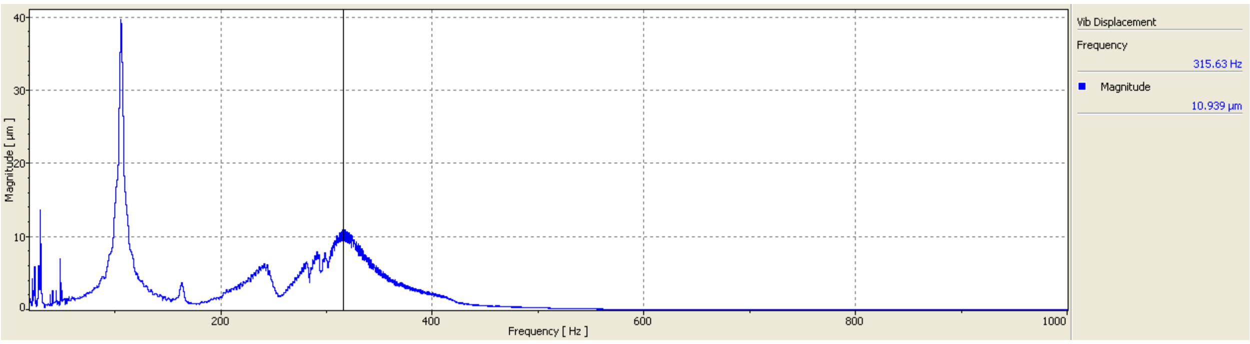


FIGURE 91: LASER VIBROMETER FREQUENCY SCAN

Figure is the Fast Fourier Transform (FFT) graph of our speaker. Our resonance frequency was at 105 Hz, which is the clear large spike in the beginning.

The figure below illustrates an instant in a 3D animation of our speaker moving at 105 Hz. The same tests and animations were produced at both 40 Hz and 200 Hz to ensure that our speaker was operating in phase throughout the entire range of bass frequencies.

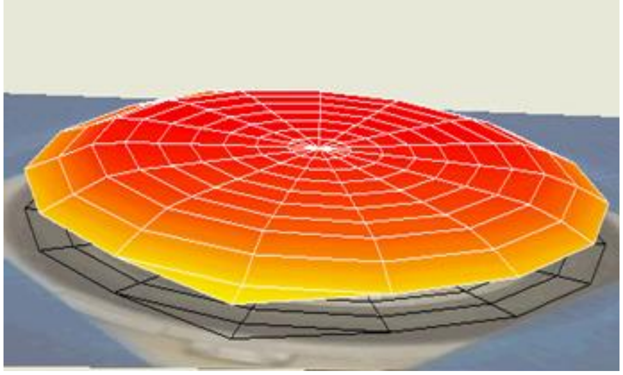


FIGURE 92: VIBROMETER ANIMATION AT 105 HZ

5.5 Low-Profile Home Speaker

The group had to make ten total speakers for this project. Nine of them were used in the Low-Profile Home Speaker and one was used for tests, demonstrations, and presentations. Figure below is a picture of the final design of the Low-Profile Home Speaker. There are three moving magnet transducers attached to the white resonant panel centered in the low-profile home speaker system design. The remaining six other transducers are in the passive radiators on the left and right sides of the overall assembly. Figure 93 is a picture of the Low-Profile Home Speaker. The red arrows denote where our moving magnet transducers are located.

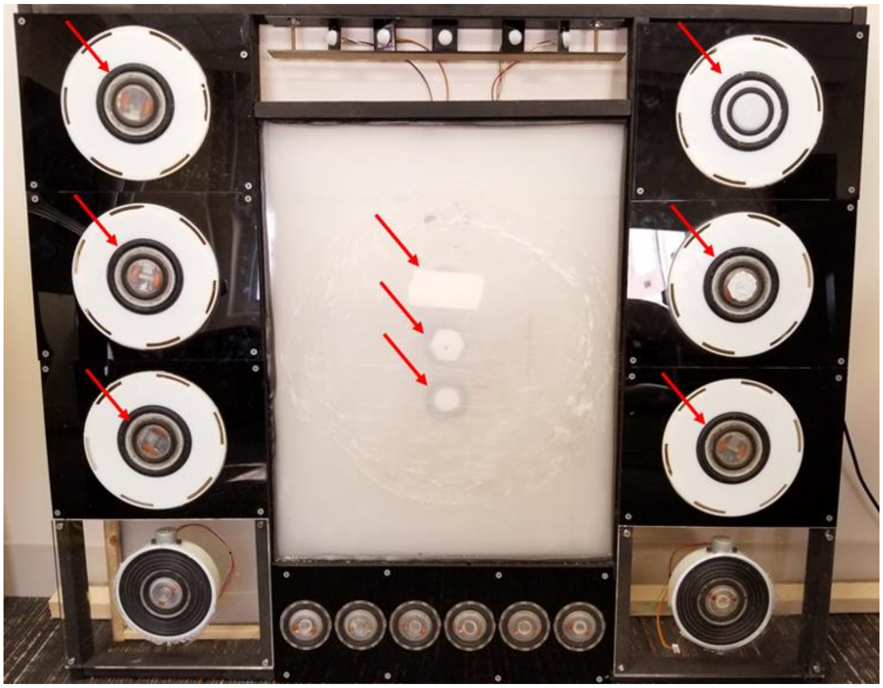


FIGURE 93: FINAL LOW-PROFILE SPEAKER SYSTEM

6.0 Conclusions and Recommendations

The goal of this project was to create a moving magnet transducer capable of generating quality bass while maintaining the slimmest possible profile. Our team was able to produce 10 working prototypes by the end of our project work which included nine for the low-profile speaker system and one extra for demo purposes. While our team did accomplish its goal we feel that the overall performance of our design could be improved by following our three major recommendations:

1. Replace 3D Printed Parts with injection molded components
2. Improve upon the design of the magnet holder
3. Increase length and width of stator while maintaining the same height.

6.1 Injection Molding

Our first recommendation is to fully replace all 3D printing of parts with injection molding. While 3D printing was great for our team in terms of speed and convenience we did notice that the quality of each part would very slightly change print to print. In an ideal situation our team would injection mold all of the rigid plastic components in our design to increase uniformity part to part. Switching away from 3D printing would also have allowed our group to experiment with more materials. Since we used the WPI 3D printing facilities our material options were very limited and Tango Black Plus was actually our only viable option for the speakers' surround. Experimenting with other surround materials such as urethane and santoprene could help us create a final design that experiences even less damping than our current model.

6.2 Magnet Holder Design

Our next major recommendation is to increase the magnet holder design to improve our assembly process and our design reliability. In our final design our team shimmed the magnets into the center of the stators air gap by hand. We used the same method to shim the magnets every time but since we were doing it by hand the magnets were almost never perfectly centered in the air gap after the prototype was fully assembled. We recommend that the design of the magnet holder and the assembly process be altered so that less human error is involved during assembly. The connection of the cone and magnet holder should be iterated so that the design is more robust. Our team explored the idea of a "pocket design" magnet holder that would allow the magnets to slide into a fully enclosed holder printed as part of the cone. Unfortunately, we were only able to print one of these prototype "pocket design" holders before time constraints forced us to use our already proven holder design. We believe that some version of this magnet holder idea would allow overall speaker to be assembled much easier and with more precision with regard to magnet placement in the air gap.

6.3 Increase Size of Stator

Our team's final recommendation is to increase both the length and the width of the stator to allow for a larger magnet and a larger more coil windings. Incorporating the larger magnet and increased number of coil windings would directly increase the force output of our speaker and thereby increase the amount of bass we are able to produce. It should be noted that the increased width and length of the stator would not alter the thickness of the design at all so it would still remain a low profile footprint. Fortunately, our design was created with future work in mind and the current speaker model is very easily scalable. All of our SolidWorks models and Maxwell simulations have been fully parameterized so that any alterations in size would be very easy to perform. Since we were working as just one team in a larger group of teams to create the entire low-profile speaker system we were bound by size constraints for integration purposes. We recommend that a future MQP team increase the scale of our design and test to see how much the force production can be increased using different size combinations of stator, magnet, and coils. A future teams goal may be to achieve 4 N/Amp a scaled-up version of our design.

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Appendices

Appendix A: Instron Testing Procedure

INSTRON TESTING

DO NOT USE GLUE ON FIRST PART

1. Spring Constant of Double Flexure Design
    1. Assemble motor with **empty** magnet holder + flexure (no coils or magnets)
    2. Instron the top of the magnet holder
    3. Measure force vs. displacement (no more than 2 mm displacement)
2. Spring Constant of surround
    1. Insert cone + surround only into laser cut mounting
    2. Fixture
    3. Instron to measure force vs. displacement (no more than 2 mm) displacement)
3. Total Spring constant of surround + double flexure
    1. Assemble motor with **empty** magnet holder + flexure and cone + surround **(NO GLUE)**
    2. Mount in laser cut mount
    3. Instron force vs displacement

MAKE SURE PREVIOUS TESTS ARE DONE CORRECT AND YOU HAVE SAVED AND LABELED ALL OF THE DATA SO WE CAN TELL THEM APART.

4. Force output of speaker
    a. Assemble motor with magnet and flexures. Insert motor into housing and cone **(WITH GLUE)**
    b. Mount speaker in laser cut mount
    c. Preload speaker with instron
    d. Resistance of speaker is 1.7 Ohms
    e. Use a power source to increment the voltage

Test Results for Fully Assembled Speaker:

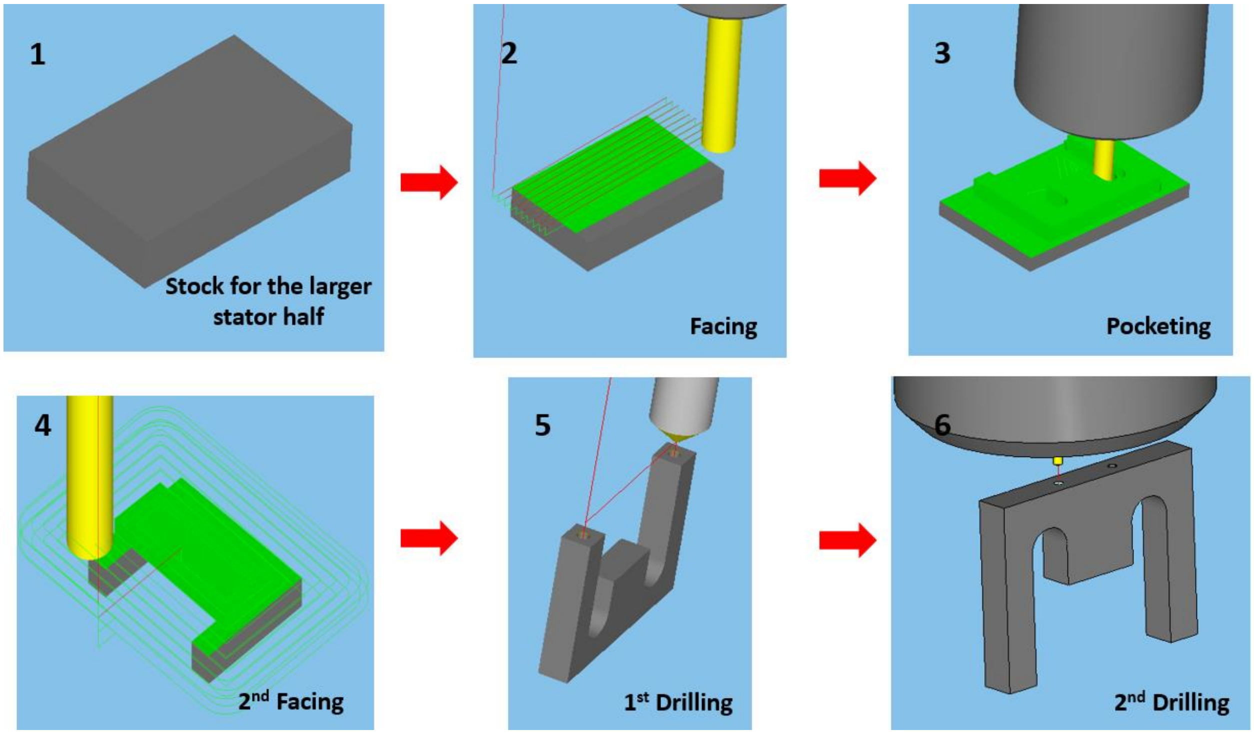
Voltage Source (V)	Current Source (A) (measured by power supply)	Voltage of Resistor (V)	Calculated Current (A)	Preloaded Force (N)	Measured Force (N)	Delta Force (N)
0.5	.05	.47	0.047	.11	.137	.027
1.5	.138	1.34	0.134	.11	.21	.1

2.5	.228	2.2	0.22	.178	.328	.15
3.5	.325	3.09	0.309	.162	.40	.238
4.5	.414	3.88	0.388	.15	.46	.31
5.5	.517	4.75	0.475	.146	.544	.398
6.5	.615	5.58	0.558	.143	.619	.476
7.5	.714	6.4	0.64	.14	.69	.55

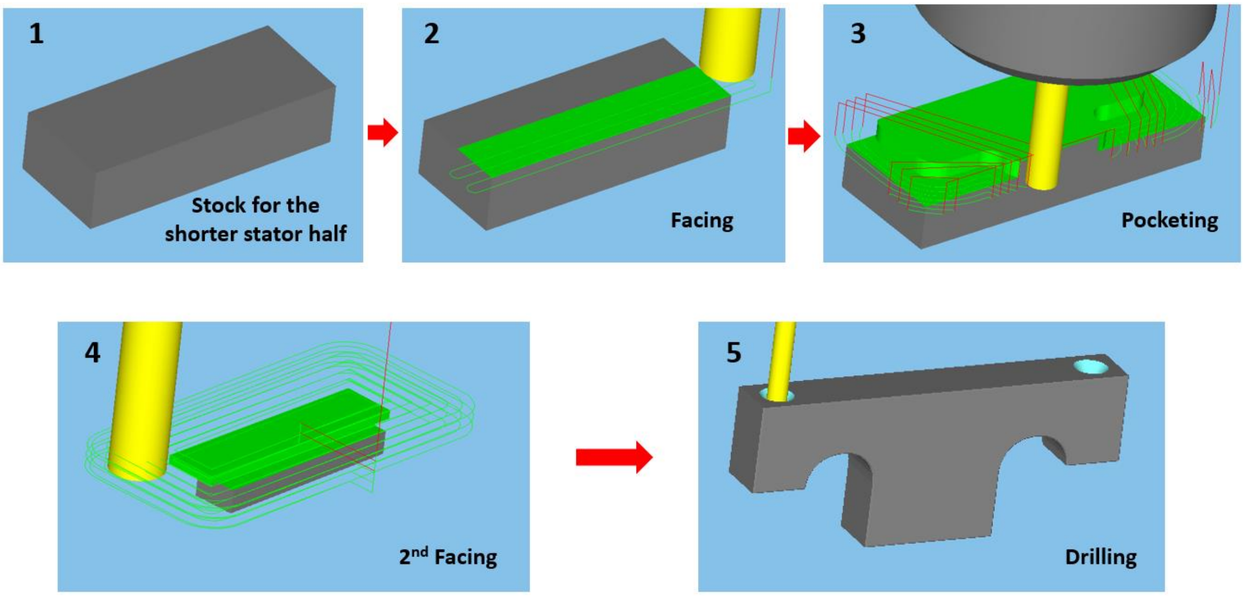
Tests were performed using portable power supply from the office.

Resistor used was 10 ohms

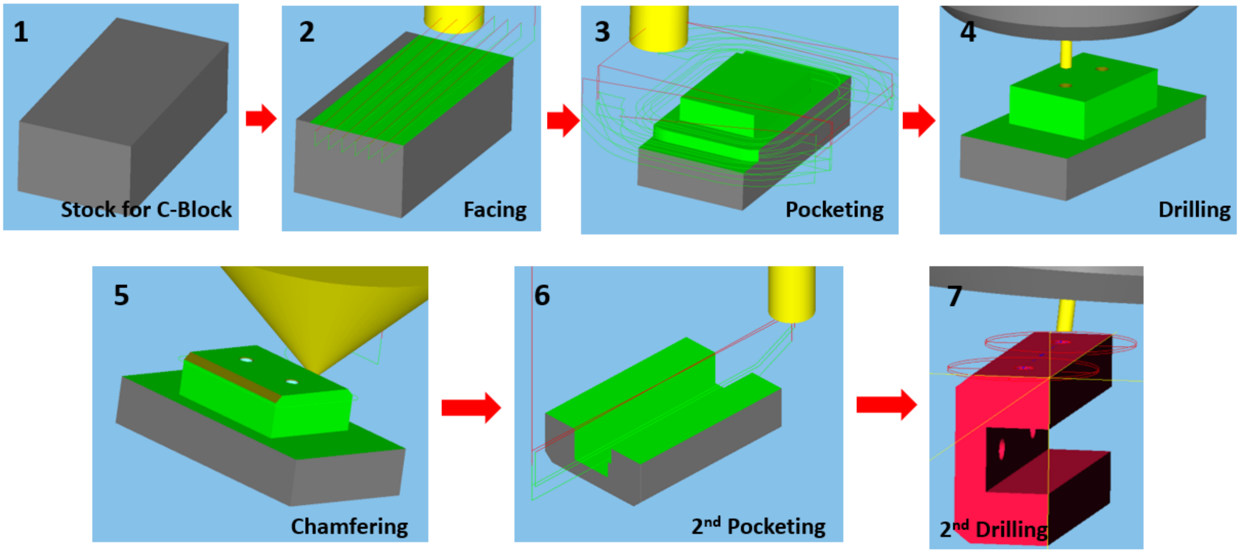
Appendix B: Machining Operations



The six step process for machining the larger stator half



The five step process for machining the shorter stator half



The seven-step process for machining the C-Block

Appendix C: Scanning Laser Vibrometer Procedure

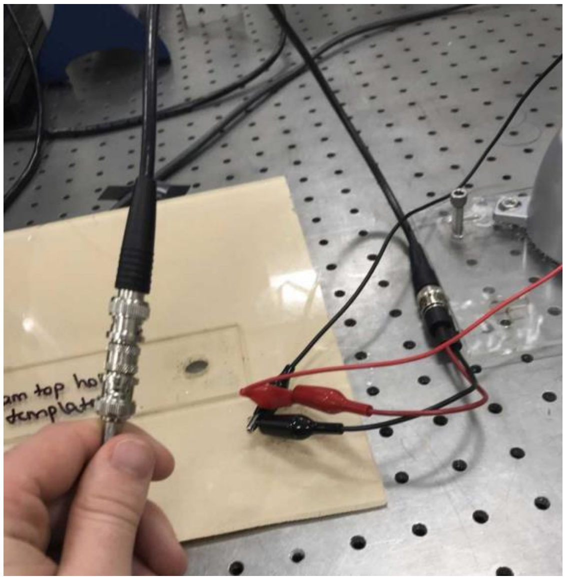
Scanning Laser Vibrometer Procedure

Before starting ensuring that your speaker has been properly secured with the clamps and is square to the vibrometer head. If you are ever unsure of what to do, stop and ask any of the lab assistants for help.

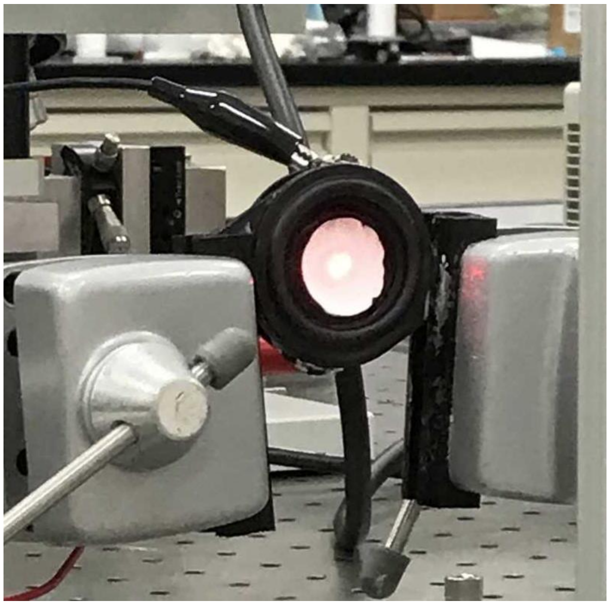
1. Turn the machine on by turning the key to the on position and then pressing the power button.

2. Turn the beam shutter from “Off” to “On” on the vibrometer head.

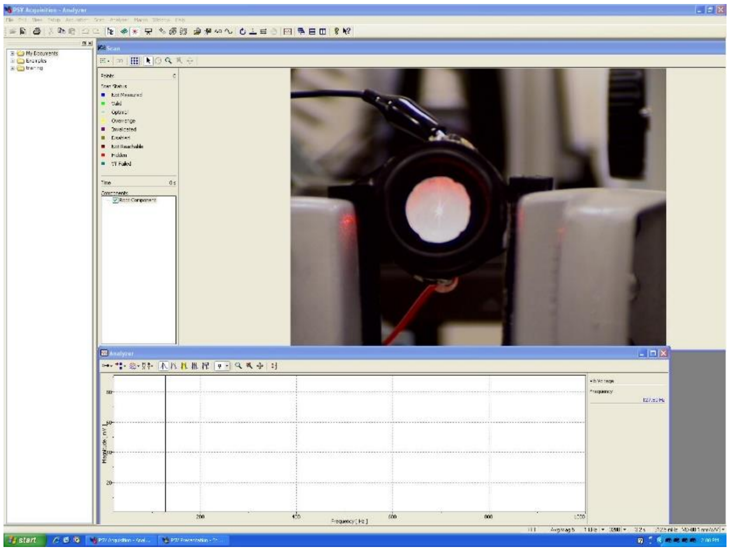
3. Hook your speaker up to the BNC cable, completing the circuit from the machine to your speaker.



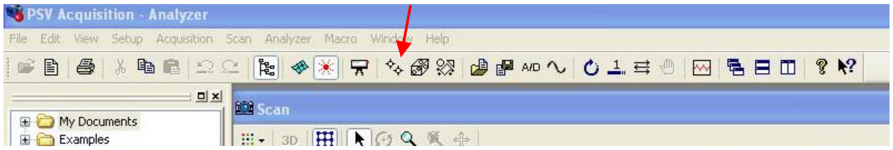
4. Make sure the speaker if painted white with either white out or white spray paint so the vibrometer head can achieve a more accurate reading.



5. Adjust the laser vibrometer head so that the speaker appears in the viewing window on the screen. You can also adjust the zoom and focus of the vibrometer using the Camera sliders on the right edge of the screen

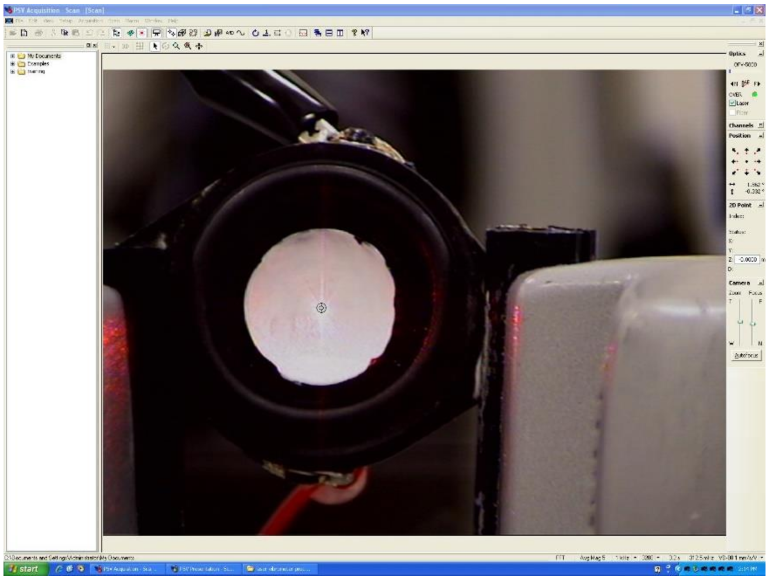


6. Now, select “2d alignment” in the top toolbar indicated by the two small stars.

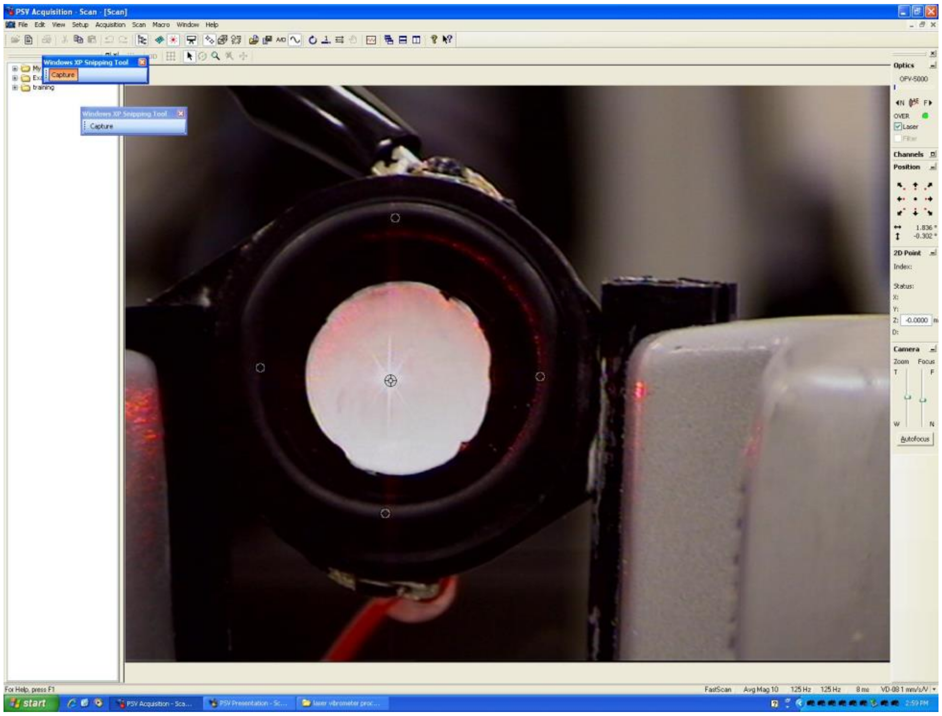


7. If there are any reference points from previous testing right click in open space and select “delete all”.
8. Click the roller on the mouse to drag the laser to the center of the speaker.
9. Click “autofocus” in the top right portion of your screen indicated by the “AF” icon.

10. Put the mouse over the laser in the center of the speaker and left click to insert a reference point. Drag the laser to another position on the speaker and then left click to insert another reference point. Try to place your reference points along the surround of the speaker.



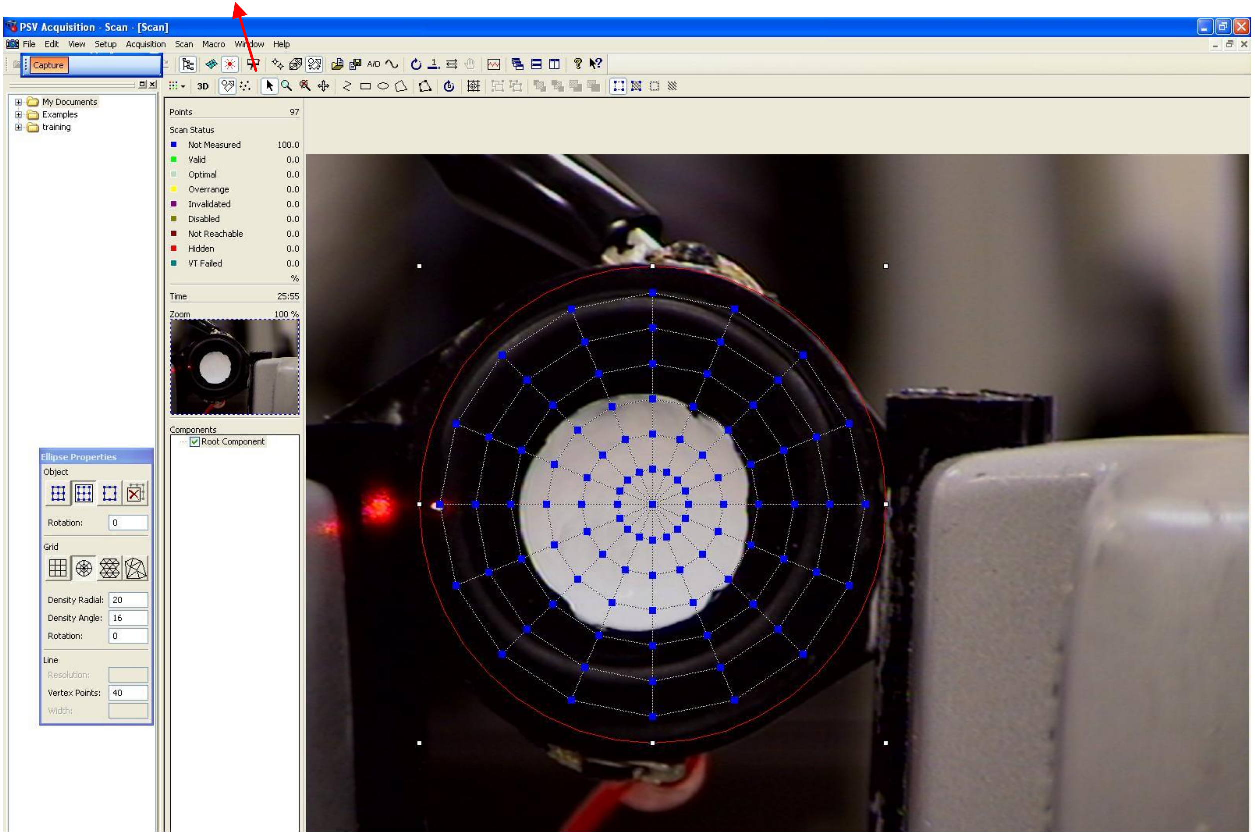
ONE REFERENCE POINT AT CENTER OF SPEAKER



SEVERAL REFERENCE POINTS ALONG SURROUND OF SPEAKER

11. Click on the "define scan points" icon in the top toolbar. (check with Harrison)

12. Select "create ellipse" or whichever shape best fits your speaker. The create shape buttons are located in the lower of the two toolbars at the top of your screen. Adjust the shape's boundaries so that the blue points cover the entirety of your speaker. A "shape properties" pop up menu will appear so that you can adjust the grid characteristics to best fit your speaker. Once you are satisfied with your grid unclick "define scan points" in the top toolbar.



Points	97
Scan Status	
🟦 Not Measured	100.0
🟩 Valid	0.0
▨ Optimal	0.0
🟨 Overrange	0.0
🟪 Invalidated	0.0
▨ Disabled	0.0
🟫 Not Reachable	0.0
🟥 Hidden	0.0
▨ VT Failed	0.0
	%
Time	25:55
Zoom	100 %

Rotation: 0

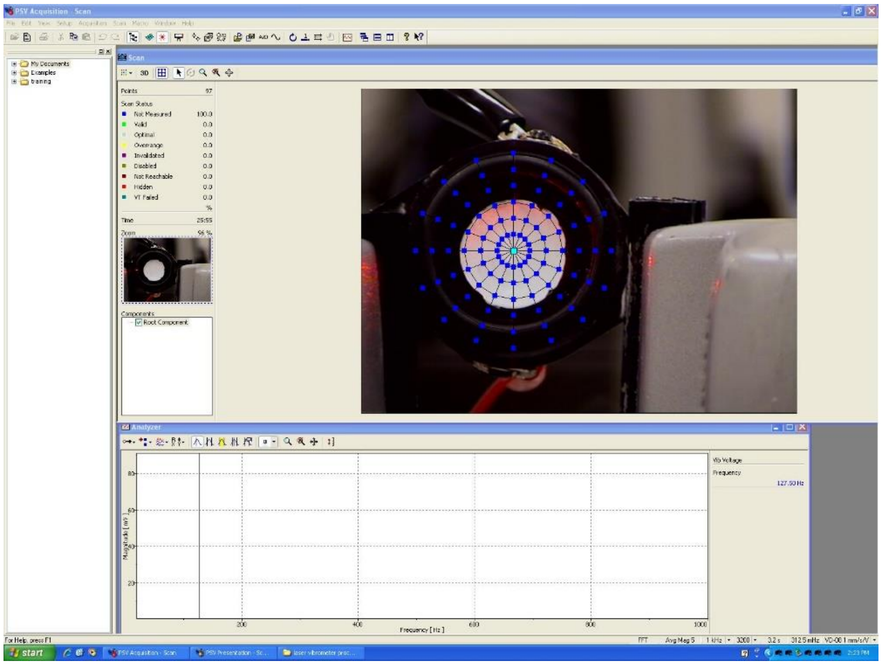
Density Radial: 20

Density Angle: 16

Rotation: 0

Vertex Points: 40

13. Test the quality of your reference points by clicking on the blue nodes and making sure that the laser follows along. Once you have confirmed that the machine is appropriately calibrated leave the laser on the center of your speaker or wherever you wish to perform the testing.



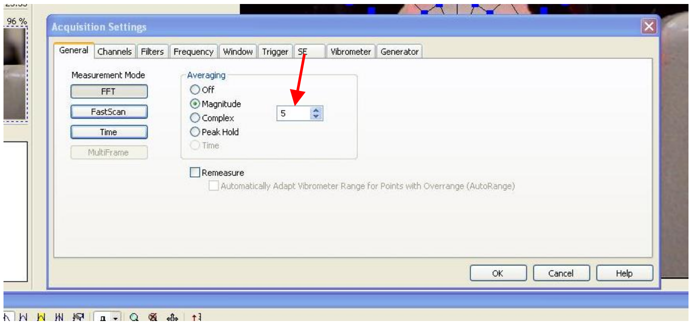
PSV Acquisition - Scan

Points	97
Scan Status	
Not Measured	100.0
Valid	0.0
Optimal	0.0
Overrange	0.0
Invalidated	0.0
Disabled	0.0
Not Reachable	0.0
Hidden	0.0
VT Failed	0.0
	%
Time	25:55
Zoom	96 %

Components

☑ Root Component

14. A. Click the "A/D" icon in the top toolbar which will bring you to the general tab of the acquisition settings. Once there select the "FFT" option for measurement mode. Then enter 5 as the magnitude averaging.



Acquisition Settings

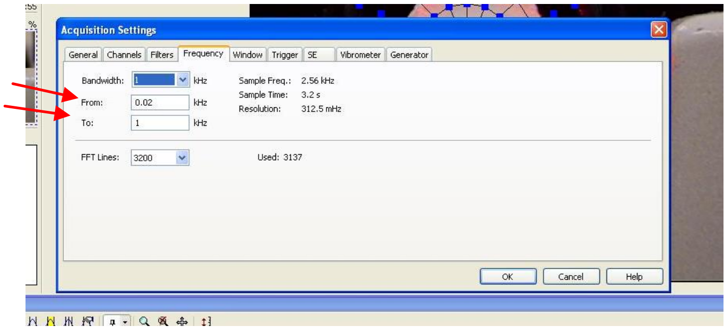
Measurement Mode

Averaging

○ Off
● Magnitude 5
○ Complex
○ Peak Hold
○ Time

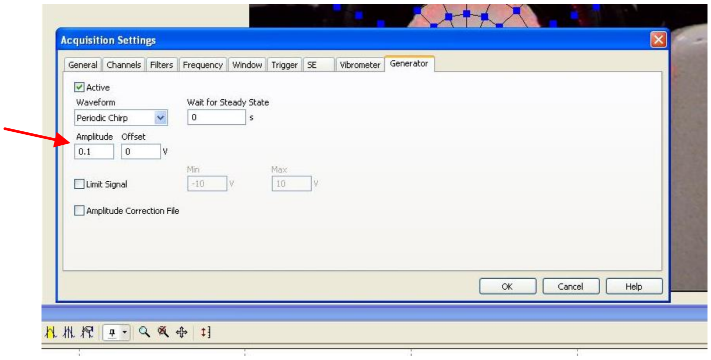
☐ Remeasure
☐ Automatically Adapt Vibrometer Range for Points with Overrange (AutoRange)

B. Now select the frequency tab and enter your range to be from .02 kHz to 1 kHz(for bass testing) or whatever your desired testing range is.



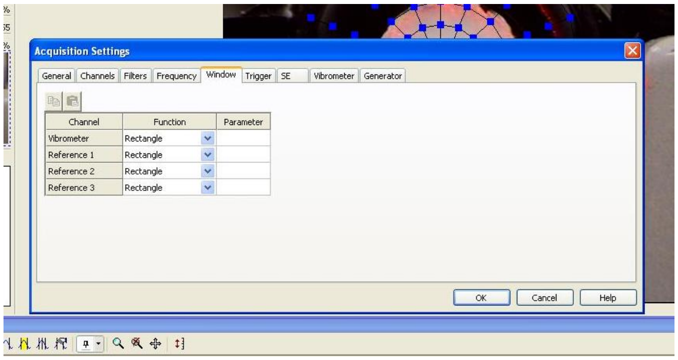
Bandwidth: 1 kHz
From: 0.02 kHz
To: 1 kHz
Sample Freq.: 2.56 kHz
Sample Time: 3.2 s
Resolution: 312.5 mHz
FFT Lines: 3200
Used: 3137

C. Now select the generator tab and select periodic chirp in the drop-down menu under waveform. Set the amplitude to 0.1 Volts



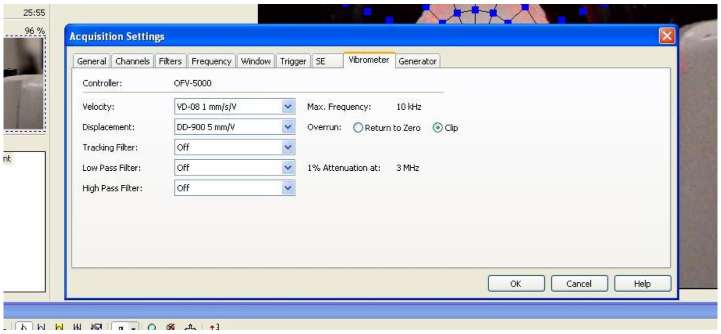
☑ Active
Waveform: Periodic Chirp
Wait for Steady State: 0 s
Amplitude: 0.1 V
Offset: 0 V
☐ Limit Signal
Min: -10 V
Max: 10 V
☐ Amplitude Correction File

D. now select the Window tab and select the vibrometer function to rectangle. (always use rectangle when using periodic chirp).



Channel	Function	Parameter
Vibrometer	Rectangle	
Reference 1	Rectangle	
Reference 2	Rectangle	
Reference 3	Rectangle	

E. Now select the Vibrometer tab and leave the settings alone until you have tried running the scan. If you are receiving an over ranging error increasing your level of precision by adjusting the velocity setting will be your best bet at fixing the issue.



Controller: OFV-5000

Velocity: VD-08 1 mm/s/V

Max. Frequency: 10 kHz

Displacement: DD-900 5 mm/V

Overrun: ○ Return to Zero ● Clip

Tracking Filter: Off

Low Pass Filter: Off

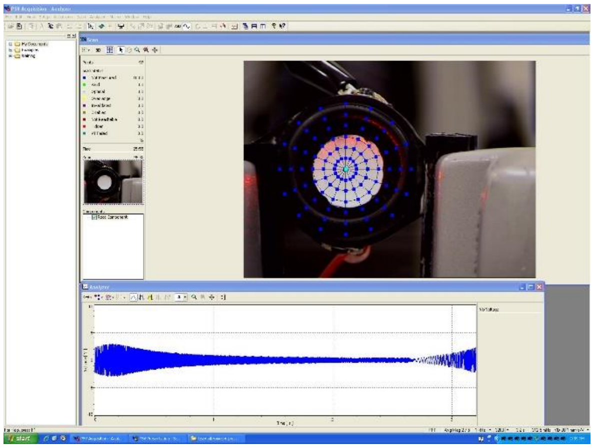
1% Attenuation at: 3 MHz

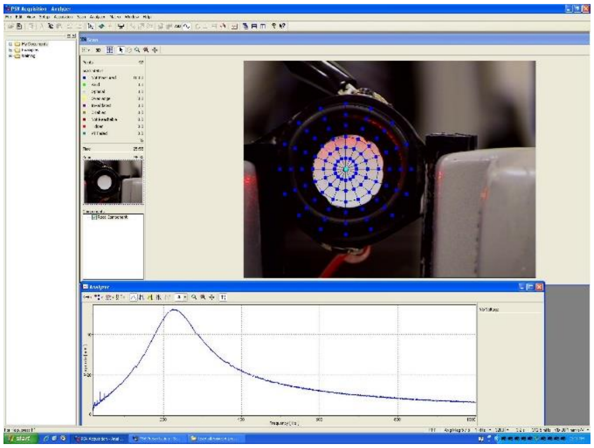
High Pass Filter: Off

F. When done press "OK" at the bottom of the pop up menu.

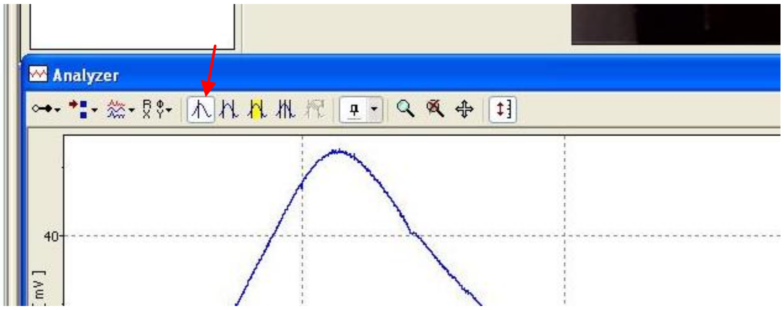
15. Click "Generator on" in the top toolbar (sine wave icon). Then click "continuous" in the top toolbar (circular arrow icon).

16. Once your graph has been filled with data and there is no over ranging error message select "FFT" in the drop-down menu located at the top left corner of your Analyzer window. Then click auto scale. (the rightmost button in the analyzer toolbar). Let the machine process the data for a few seconds and observe how the graph smooths out as it takes more and more averages.

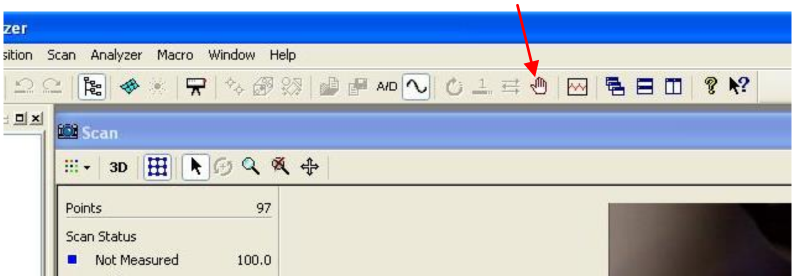




17. Select "cursor" in the analyzer toolbar to pinpoint frequencies of interest indicted by spikes in the FFT graph. The corresponding frequency will appear in the right side of the analyzer window.



18. select the red hand icon in the top toolbar to stop the machine from gathering any further information.

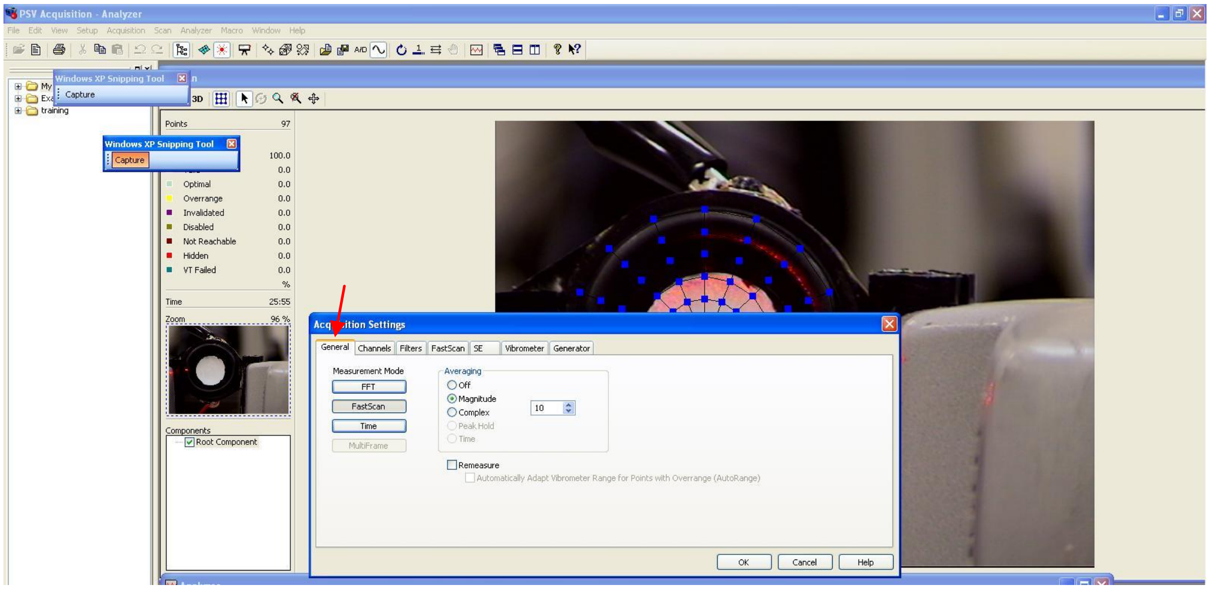


Points 97

Scan Status

Not Measured 100.0

19. A. Select the "A/D" settings button in the top toolbar and then select "Fastscan" under the general tab. Increase your magnitude averaging to 10.



Points 97
100.0
0.0
Optimal 0.0
Overrange 0.0
Invalidated 0.0
Disabled 0.0
Not Reachable 0.0
Hidden 0.0
VT Failed 0.0
%
Time 25:55
Zoom 96 %

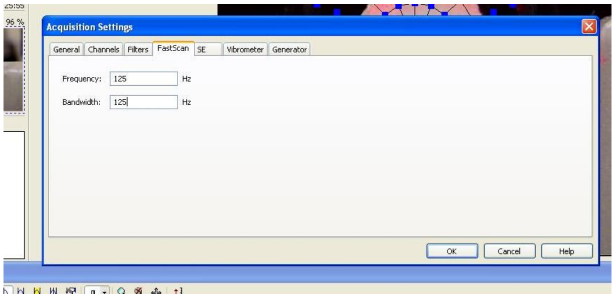
Acquisition Settings

Measurement Mode

Averaging
○ Off
● Magnitude 10
○ Complex
○ Peak Hold
○ Time

☐ Remeasure
☐ Automatically Adapt Vibrometer Range for Points with Overrange (AutoRange)

B. select the "Fastscan" tab and enter the frequency of interest you found from the FFT graph into both the frequency and bandwidth settings. Press "ok"



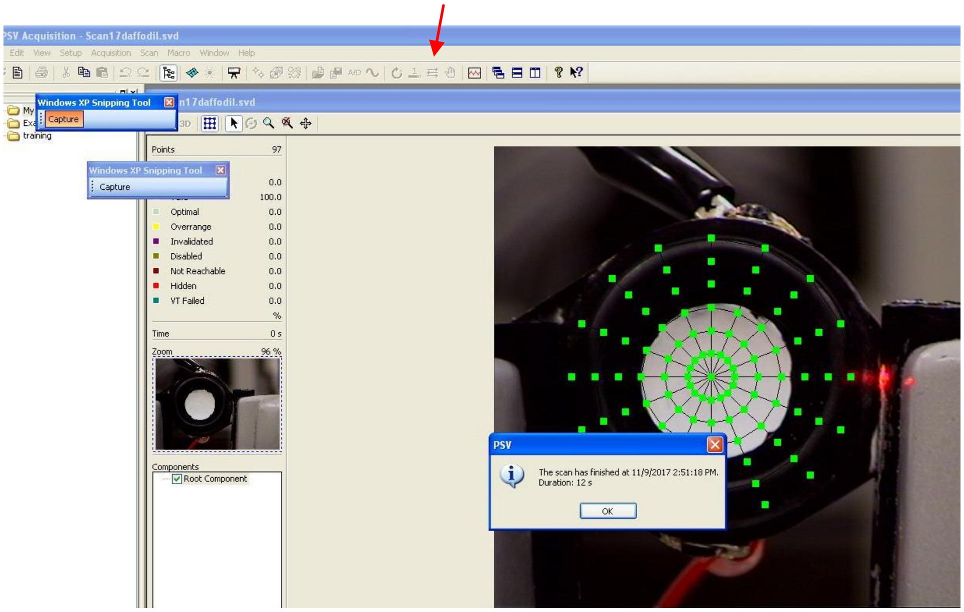
Acquisition Settings

Frequency: 125 Hz

Bandwidth: 125 Hz

20. Now select "scan" in the top toolbar and save the file to your desired location. Once you save your file the "fastscan" will run and the nodes form your grid will reappear on your speaker.

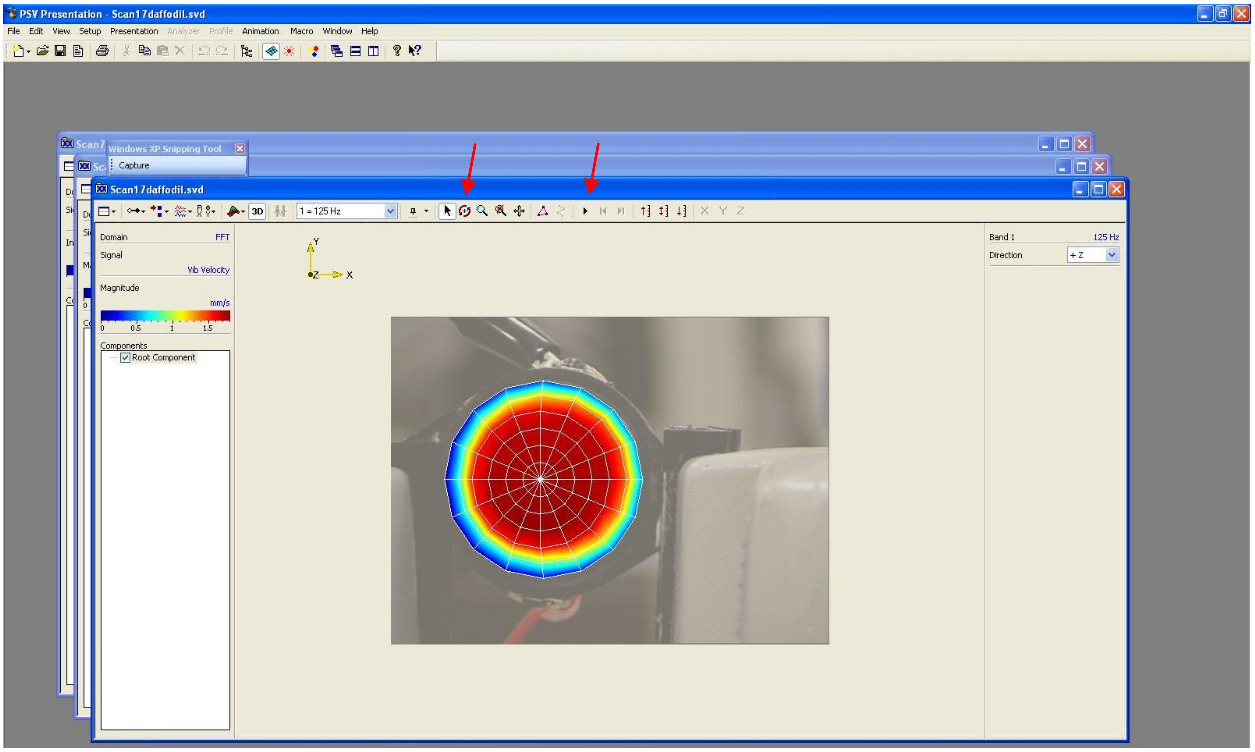
Green nodes indicate high quality and yellow nodes indicate poor quality. Yellow nodes may result in holes or undefined areas in your simulation.



Points	97
	0.0
	100.0
Optimal	0.0
Overrange	0.0
Invalidated	0.0
Disabled	0.0
Not Reachable	0.0
Hidden	0.0
VT Failed	0.0
	%

The scan has finished at 11/9/2017 2:51:18 PM.
Duration: 12 s

21. Select “presentation” in the top toolbar and select “Yes” in the pop up prompt. Now you will see a still image of your speaker in a new window. Press start/stop animation in the toolbar indicated by the play button. Your image will become animated and will show how the speaker is acting at your entered frequency of interest. Use the rotate button to rotate the animation and view it from different perspectives. You can save your animation using “file”, “save animation”.



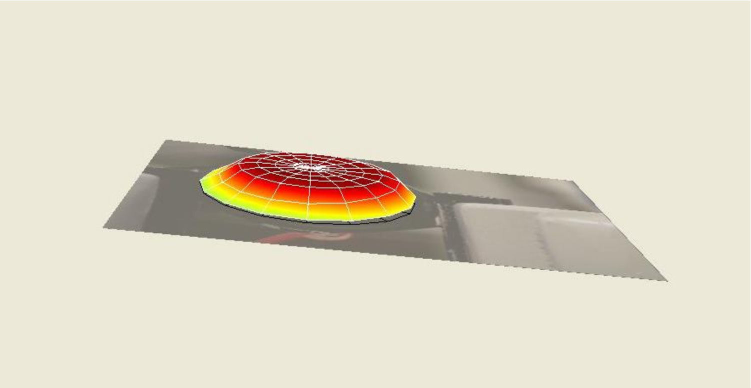
1 = 125 Hz

Domain FFT

Signal Vib Velocity

Band 1 125 Hz

Direction +Z



ROTATED VIEW OF ANIMATION

22. Be sure to shut down the machine once finished and clean your workspace.

Notes:

In the acquisition window you can save your settings after you have finished testing so that you can reuse them in future tests.