Low-Profile Speaker System: Optimization of Passive Radiator Design

A Major Qualifying Project Submitted to the
Faculty of *Worcester Polytechnic Institute* in partial
fulfillment of the requirements for the Degree of
Bachelor of Science in Mechanical Engineering

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Abstract

The goal of this Major Qualifying Project (MQP) is to create a low-profile, wall-mounted home speaker system with a focus on an improved passive radiator design. This design is classified as a low-profile, force-balanced, sealed passive radiator bass box with a low frequency response. A continuation of projects from previous years, this project helps idealize passive radiator injection molding techniques as well as material selection. This is done through extensive online research, contact with acoustic professionals, software simulation, 3D modeling, 3D printing, and injection molding. Previous projects were tested using vibrometer technology and later optimized to obtain ideal resonant frequencies. Multiple injection molding techniques were used to create silicone surrounds for the passive radiator system using 3D printed molds. Improvements were made to the passive radiator SolidWorks model to achieve an ideal resonant frequency and secure the material to the 3D printed parts using different geometrical configurations.

Executive Summary

Speaker systems have a wide range of applications, both small and large. Small speaker systems are used in devices such as phones, televisions, and computers. Larger speakers are typically used for music and sound reinforcement and are often used in theaters, concert venues, sporting arenas, and public address (PA) systems. While large speakers have the ability to produce high quality bass, small speakers typically struggle to do this. The goal of this Major Qualifying Project (MQP) is to create a low-profile, wall-mounted home speaker system with a focus on an improved passive radiator design. This design is classified as a low-profile, force-balanced, sealed passive radiator bass box with a low frequency response. A continuation of projects from previous years, this project helps idealize passive radiator injection molding techniques as well as material selection.

Research was conducted on speaker systems, including passive radiators. Once the project team had an understanding for speakers, several project objectives were formed. To complete these objectives, the team first used 3D scanning vibrometry to determine resonant frequencies of existing speaker systems. These systems were modeled in various ways using SolidWorks and later simulated and analyzed using Simscape and ANSYS. Software simulation was used to represent the real life systems and compare to experimental results. Once the simulations properly represented a real world speaker system, the project team moved to manufacturing the low-profile sealed passive speaker system. This process first began by modeling the system using CAD and making a number of improvements to the previous passive radiator design to both secure the speaker connections and obtain a desired resonant frequency. Once the low-profile system was modeled, 3D printing was utilized to create the rigid components, while a new method was introduced to create the silicone surrounds. Injection molding was researched and a number of different molding procedures were tested and analyzed. In addition to manufacturing the outer components of the speaker assembly, the team designed conical surrounds and an enclosure for a lever system within the moving magnet transducer assembly.

1. Introduction

Speaker systems have a wide range of applications, both small and large. Small speaker systems are used in devices such as phones, televisions, and computers. Larger speakers are typically used for music and sound reinforcement and are often used in theaters, concert venues, sporting arenas, and public address (PA) systems. While large speakers have the ability to produce high quality bass, small speakers typically struggle to do this. To combat this problem, a Major Qualify Project (MQP) was created to develop a small speaker system that could produce higher quality bass outputs. This year, three teams of mechanical engineers were tasked with improving upon previous designs, each responsible for a specific component of the speaker system. Our team focused mainly on the passive radiator, with the goal to optimize the passive radiator design for a low-profile, wall-mounted speaker system. Another sub focus of the project was to develop surrounds and an enclosure for a moving magnet transducer driven speaker system. Unfortunately, due to the COVID-19 pandemic cutting the year short and shutting down campus, the project team was not able to achieve the final objective for the project. If regulations had permitted, the project team would have been able to finish the entirety of the speaker system.

2. Background

2.1 Speaker System

Despite being invented in the early 1920s by Edward Kellogg and Chester Rice, dynamic speaker systems have not become significantly popular until the 2010s. Though they have grown in popularity, the speaker systems have lacked low-profile designs while maintaining a powerful low-frequency response.

A dynamic speaker (see below) is defined as a speaker that uses a magnetic field to drive the cone shaped surround attached to it. As a result of an audio input being played into the speaker, the magnetic field forces the surround to vibrate, which moves air through the speaker which produces sound. Compared to an electrostatic driven system, a dynamic speaker system can produce a higher quality sound. Due to this reason, dynamic speakers are being produced more commonly.

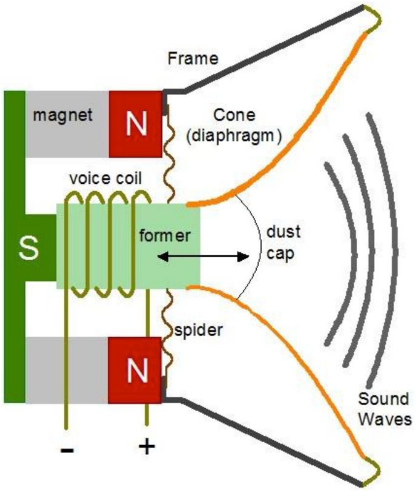


Figure 1. Dynamic Speaker System

Looking at the image below, the different parts of the dynamic speaker system all work together in order to produce sound.

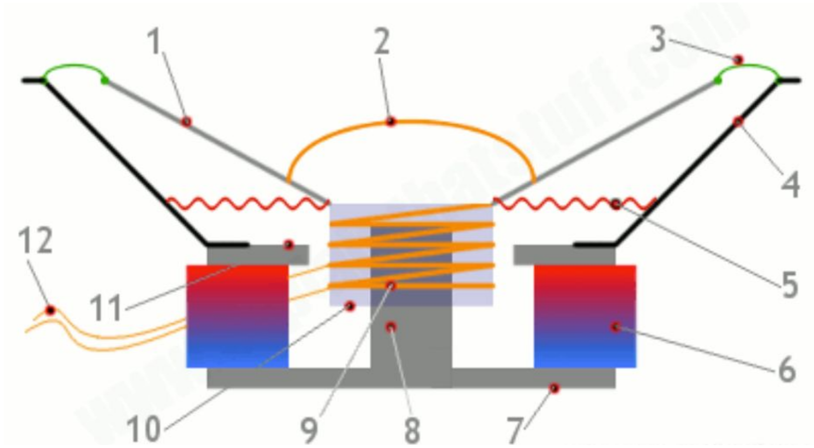


Figure 2. Dynamic Speaker System Parts

1. Is the diaphragm of the speaker. It is pushed by air in and out to produce sound.

2. Is the dust cap for the speaker; it protects against dust and debris from getting inside of the speaker.

3. Is the surround, which is a specific material made most commonly out of foam or rubber that connects the diaphragm (**1**) to the basket (**4**).

4. Is the basket; the basket is the sturdy metal material that makes up the frame for the speaker system.

5. Is the suspension for the speaker system, it allows the voice coil to move freely while suspended in place.

6. Is the magnet, which helps produce the magnetic current that drives the speaker.

7. Is the bottom plate of the speaker, it helps support the speaker system and keep everything in place.

8. Is the pole piece which helps to contain the magnetic current that is generated by the voice coil.

9. Is the voice coil, which pushes on the diaphragm.

10. Is the former, which the coil is wound onto.

11. Is the top plate which helps maintain the structural integrity of the speaker.

12. Are the cables that connect the stereo amplifier to the coil.

What lacks in the current market however is a low profile speaker system. Essentially a low profile speaker system would have considerably less volume to work with in producing noise. This factor has pushed many developers away from creating low profile systems like the group intends to build.

2.2 Passive Radiator

Passive radiators are components of a speaker system that create more power and resonance in the acoustic experience of the speaker. Passive radiators are commonly used in most speaker systems in order to improve bass quality without having to sacrifice bass. The speakers are called passive because they aren't being driven by a current or power. Instead they are driven by air pressure inside of a surround. Smaller speaker cones that are connected to electrical current drive the passive radiator creating sound.

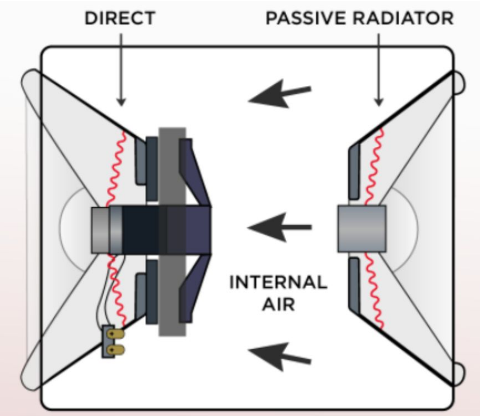


Figure 3. Passive Radiator Driven by Active Speaker

Due to the benefits that passive radiators offer, they are going to prove to be incredibly useful in our design process. Essentially, they will enable us to keep a smaller, more compact and low profile design while not having to sacrifice for rich sound quality.

2.3 3D Printing

3D printing, also known as additive manufacturing, is the process of digitally creating 3D models of objects and printing them into 3D solid parts. 3D printers utilize additive processes, where objects are created by laying down successive layers of material. The 3D printing process starts with a digital file of an object, which can be created using 3D modeling software programs such as SolidWorks or AUTOCAD.

Figure 4. LulzBot 3D Printer

Once a CAD file is introduced into the printing software, it is split into thousands of horizontal layers that it then maps for later use during the printing process. Typically, 3D printed parts do take several hours to finish printing. However, its versatility has made it a very successful and ingenious invention. 3D printed materials are being used in numerous industries around the world including dental products, prosthetics and the tool industry.

Using 3D printers, the team will be able to take parts modeling using modeling software and print parts for the speaker system. This will increase the productivity of the team, as custom parts can be printed very quickly and used for assembly.

2.4 Injection Molding

Injection molding is a process commonly used to obtain a mold of an area by heating a plastic material to a liquid, injecting it into said area, and then allowing it to cool and solidify to capture a mold. Injection molding allows the user to capture a mold of a complex shape in order to produce more of that object on a larger scale.

The most common type of injection molding materials are called thermoplastics. Thermoplastics are classified as polymers, and have the ability to continuously switch between a physical state of liquid and solid. Depending on the application of your mold however, some types of molding materials are better to use than others. For example, looking at one of the more common types of injection molding materials, Celcon (Acetal) is a material that is well lubricated on its surface, and also chemical resistant. LDPE, low density polyethylene, is another commonly used material that has high impact strength and is moisture-resistant.

Injection molding material commonly comes in separate parts that need to be mixed together in order to create required mixing material. There are two common ways of mixing the injection mold material, by hand or by using a mixing head. Mixing my hand is very straightforward. The two part mold is mixed together in a container and stirred continuously until it reaches the intended viscosity. However, this process can prove to be difficult and time consuming. Another common method of mixing material is using a mixing head.

Figure 5. MixPac Mixing Head

A mixing head helps to mix the material together to a desired consistency, and makes the process much less difficult. This option is commonly used due to its effectiveness in mixing together the injection molding material both quickly and properly.

Once the injection molding material is mixed, it needs to be somehow placed inside of the mold before it begins to solidify. There are several different commonly used methods in the pouring process of injection molding. One method is to pour by hand; using this method, a person would physically pour the molding material into the mold and allow it to sit and solidify to capture the mold. However, this method can only be used in some applications. If the pouring hole was small in size or the mold itself was not very large, pouring by hand is not the best method to use. In this case it would be more practical to utilize either a dispensing kit or a syringe. For example, the MixPax Dispensing kit offers a multi barrel syringe that can be filled with molding material and dispensed through one small port where the tips of the two syringes meet.

Figure 6. MixPac Dispensing Gun

The Mixpac dispensing gun increases the productivity of the pouring process, as it delivers the injection molding material to a precise location and avoids spillage or missing during the pouring process. Another technique, similar to the MixPac mixing gun, would be to use a syringe. Placing the injection molding material into the syringe allows the user to deliver the material to a precise location on the mold, and also allows the user to force material into the mold using pressure generated by the hand. Forcing the material down into the mold will ensure that no part of the mold is missed during the pouring process, and will positively affect the outcome of the mold.

Once the injection molding material is poured into the mold, it may need to be degassed depending on the situation. If there are no pockets of air trapped inside of the mold after the pouring process, then degassing is not required. However, it is extremely important that all pockets of air are removed from the mold as this will negatively affect the outcome of the mold. If pockets of air are trapped in the mold, then the mold will need to be degassed. One way to properly degass a mold after pouring would be to create a vacuum chamber. It is possible to create a vacuum chamber out of household materials that could be used in the degassing process.

Figure 7. DIY Vacuum Chamber

The Vacuum chamber can be created out of a mason jar, a length of pneumatic hose, and either a syringe or hand pump. If the mold was placed inside of this DIY vacuum chamber and a pressure was created and held for an extended period of time, it would properly degas the mold. However, a much more effective way of degassing a mold is to use a vacuum chamber.

Figure 8. Vacuum Degassing Oven

A freshly poured mold would be placed into the vacuum chamber and after the hatch was sealed air tight and a vacuum was induced for an extended period of time, the mold would be properly degassed. This tool is the most effective in degassing a mold because it is essentially effortless to do and will consistently hold a vacuum during the entire degassing process.

2.5 Previous Projects

The project team utilized previous years' MQP projects in order to optimize the passive radiator design and manufacturing process. Previous years started this MQP, creating the original design for the low-profile speaker system with a passive radiator system.

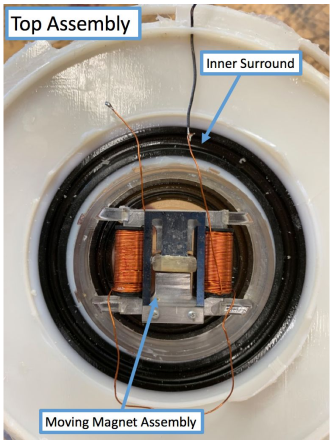


Figure 9. Previous Design Top Assembly

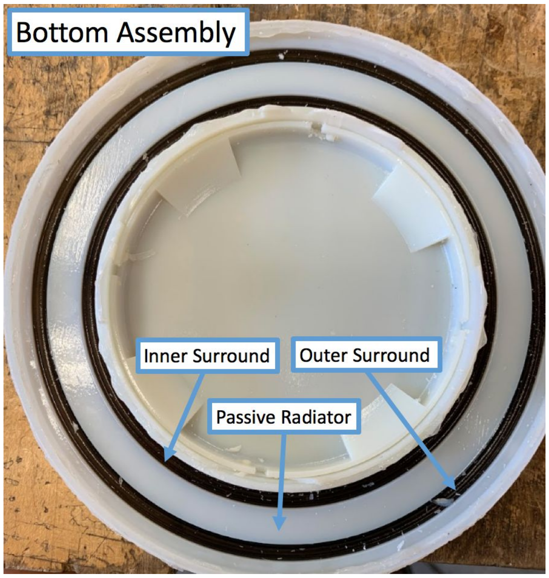


Figure 10. Previous Design Bottom Assembly

In 2018, the previous project team created the low-profile speaker with the passive radiator system, as shown in Figures 9 and 10. SolidWorks was used to 3D model the entire system, and the Rapid Prototyping Lab was used to manufacture the system. Then in 2019, the project team used this design to 3D model and manufacture the passive radiator system at half the size. This project team also utilized SolidWorks for the 3D model and the Rapid Prototyping Lab for manufacturing. By utilizing these previous projects, this years' project team was able to optimize the 3D model and the manufacturing process of the passive radiator system. Better understanding previous years' projects is discussed in more detail in Methodology section 3.2.

3. Methodology

The goal of this project was to improve upon the passive radiator design for a low-profile, wall mounted speaker. The passive radiator needs to be designed in conjunction with the moving magnet transducer that was designed by another team. This goal will be achieved through the following objectives:

1. Gain a better understanding of speaker systems, with a focus on the passive radiator design.
2. Gain a better understanding of previous projects and analyze them for further improvement upon the design.
3. Test previous MQP's passive radiator and other existing systems to determine resonant frequencies.
4. Create simulations of passive radiators to predict the performance of the physical models.
5. Model passive radiator design, with improvements from previous years' design.
6. Manufacture an optimized, functional passive radiator with a specified resonant frequency.

The objectives of the project will be achieved through the following methods:

Objective	Method(s)
1	● Conduct extensive online research on speakers and passive radiator systems.
2	● Read previous final project reports to get an understanding of the methods that were followed, final results, and conclusions.
3	● Perform scanning vibrometer testing on the previous passive radiator design and a small Bose speaker. ● Perform calculations on moving masses and internal volumes of the passive radiator system.
4	● Create models in Simscape to simulate physical speaker and passive radiator systems. ● Utilize finite element analysis (FEA) software program ANSYS to create 3D simulations of passive radiator systems in order to predict resonant frequencies.
5	● Analyze previous passive radiator design in SolidWorks. ● Make changes to passive radiator design in SolidWorks.
6	● Utilize 3D printing to manufacture rigid passive radiator parts. ● Create molds using SolidWorks and 3D printing. ● Determine the best practice for injection molding through extensive testing.

Table 1. Objectives and Methods

3.1 Objective 1: Understanding Speaker Systems and Passive Radiators

The project team gained a better understanding of speaker systems and passive radiators through online research and contact with industry professionals. The group felt that this was the best decision to proceed because in order to improve on last year's project, the team first needed an in-depth understanding of the system that would be improved upon.

3.1.1 Online Research

We began this objective by going online and researching what a passive radiator system is as well as it’s function in making the speaker produce noise. Essentially, the passive radiator helps increase the low frequency response (i.e. bass) of a speaker system. The passive radiator helps improve the efficiency of the system by allowing downsized speakers to produce richer and louder responses.

Figure 11. Simple Passive Radiator

The passive radiator system is made up of three main components: a cone, suspension, and frame. As shown in the image above, the passive radiator system looks similar to an active speaker despite some minor differences. The passive radiator is mounted to a speaker enclosure and needs to be completely air tight in order for the passive radiator to begin moving. The movement of the driving speaker causes pressure to be unequal on either side of the passive radiator cone, and as a result fluctuation begins to occur. The cone of the passive radiator begins moving forwards and backwards, replicating the motion of the driving speaker. The figure below shows an example of this process.

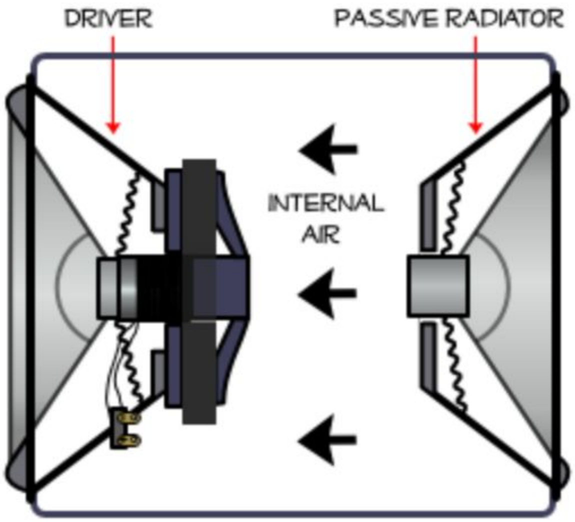


Figure 12. Sealed Passive Bass Box

Since the main design requirements of the speaker system are to be low profile and wall mountable, a passive radiator system was crucial to incorporate into our speaker system assembly. Without a proper passive radiator system in place to help boost the bass that a larger speaker would be able to produce, the sound quality would be reduced.

Through this online research the group gained a better understanding of how the system works and felt comfortable with improving on last year's project. The group felt at this point it would be necessary to contact industry professionals for advice on design on the system.

3.1.2 Contact Industry Professionals

With a thorough understanding of how speaker systems and passive radiators work, the team felt it was time to reach out to industry professionals who could provide additional knowledge on speaker systems and passive radiator design methods. A useful contact was Binu Oommen, an advanced materials engineer for Bose. Though the team understood the overall design of passive radiators, speaker components, and their respective functions, it was unclear what material provides the best performance. A team member reached out to Bose and asked what designers look for when selecting material for speaker surrounds. The team learned that stiffness is the primary material property that affects the performance of the surrounds and consequently the overall speaker performance. This information allowed the team to narrow the scope of material selection and focus on one property, helping to select and test different materials for the flexible speaker surrounds.

3.2 Objective 2: Previous Project Research

The project team gained a better understanding of the previous passive radiator projects by reading through the final reports and the data collected to further improve the design of the passive radiator within the low-profile speaker system. By analyzing the data they collected and the manufacturing methods they used, the project team was able to use similar data collection methods and manufacturing methods, as well as optimize certain parts of the process.

3.2.1 The Synthesis and Improvement of a Force Balanced, Sealed Double Passive Radiator Bass Box for a Low Profile Home Speaker System (2018)

The previous passive radiator was manufactured primarily using 3D printing. The passive radiator was created using two different materials. VeroWhite, a white Polyjet resin, was used for the rigid parts of the passive radiator. The second material used was TengoBlackPlus, a flexible elastomer that is similar to rubber. This material was used for the surrounds of the passive radiator. Using the 3D printers in the Rapid Prototyping Lab allowed the previous years' project team to print the entire system together. The printer connects the rigid parts with the silicone parts, and the project team connected the top and bottom of the system with a light layer of adhesive.

The previous team's design (shown below) was made up of 2 main parts, a top and bottom piece. The moving magnet assembly was mounted into the center of the top assembly and was connected two a dual surround system.

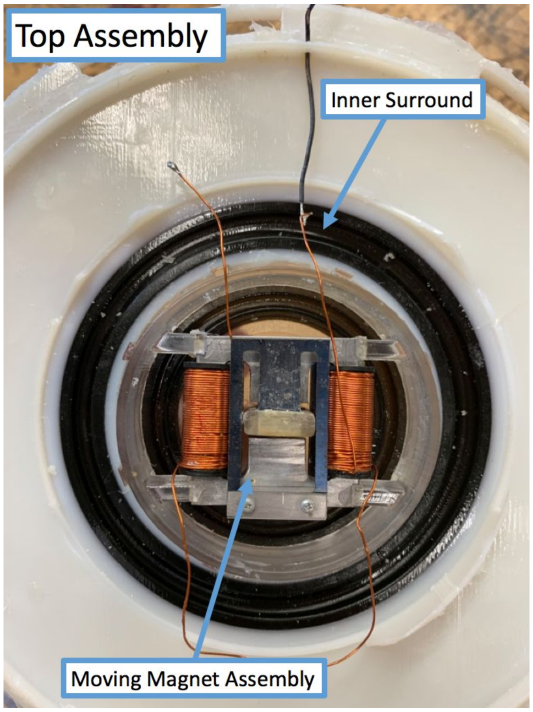


Figure 13. Previous Design Top Assembly

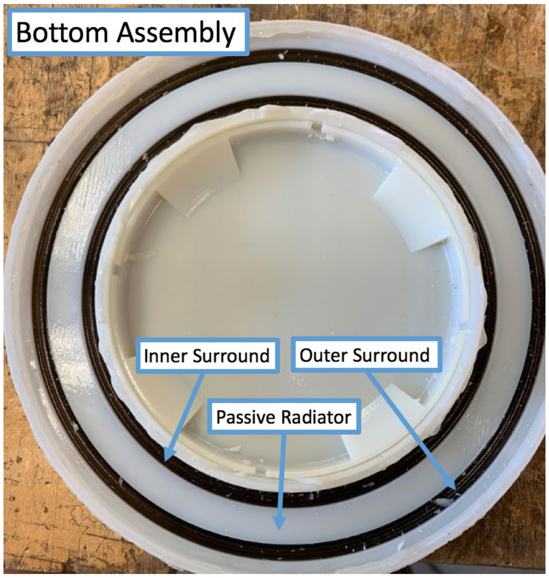


Figure 14. Previous Design Bottom Assembly

The previous years team had done tremendous research on dual passive radiator systems in the background portion of the report. This research was helpful in guiding the team through the process of understanding what a passive radiator system is as well as sources we could use to learn more information. From there, the group first needed to understand how the current modeled system operates so that we could improve upon it.

The group felt the next necessary step would be to utilize the laser lab to scan the previous team's design using 3D laser vibrometry. The laser scan showed the group that there were some improvements that needed to be made to the current system to boost the overall performance.

3.3 Objective 3: Determining Resonant Frequencies

Resonant frequency is defined as the frequency at which an object vibrates. Resonant frequencies can be determined using 3D scanning vibrometry. Scanning vibrometry is used to measure the mechanical vibrations on objects. Precise vibrometers measure the vibrations and noise of singular components as well as full assemblies. These machines are used in many industries, including automotive, aerospace, and manufacturing.

3.3.1 Scanning Vibrometer Testing

Worcester Polytechnic Institute provided access to a Polytec PSV-400 Scanning Vibrometer. Figure 15 below represents the Polytec PSV-400 Scanning Vibrometer.

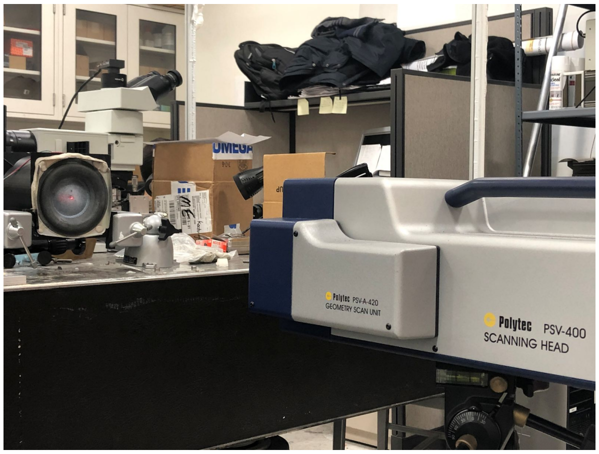


Figure 15. Polytec PSV-400 Scanning Vibrometer

This specific vibrometer is classified as a Polytec Doppler Laser Vibrometer and can measure the mechanical vibrations on objects. The Polytec PSV-400 was used to determine the resonant frequencies of various speakers and passive radiators. An instruction manual for use of the PSV-400 Scanning Vibrometer can be found in Appendix B (8.2.3). To get an understanding of the scanning vibrometer, the first test conducted was on a small Bose speaker, represented in Figure 16 below.

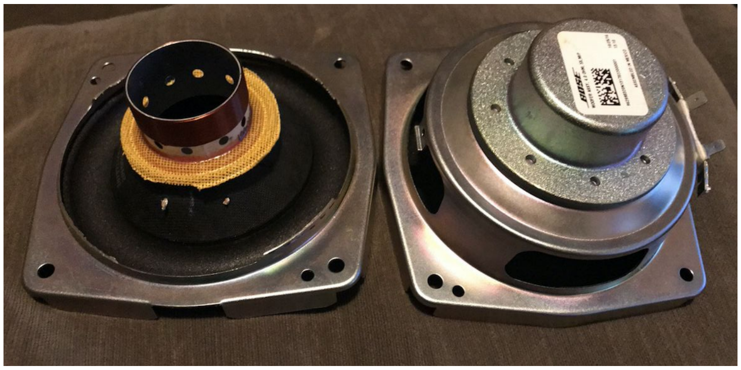


Figure 16. Passive Radiator and Active Bose Speaker

As passive radiators are simply a speaker without the magnet or electrical components, the internal components must be disconnected. What is left is the cone and surround. To compare the effects of air volume on resonant frequencies, three tests were conducted. For these tests, a 3D printed enclosure needed to be manufactured, shown in Figure 17 below.

Figure 17. Bose Speaker 3D Printed Enclosure

The enclosure was designed to create an airtight seal with the speaker. To ensure this seal, the active speaker and passive radiator were fixed to the enclosure with screws at the corners and the connections were lined with Mortite caulking. Figures 18, 19, and 20 below show the final Bose speaker assembly used for the scanner vibrometer testing.

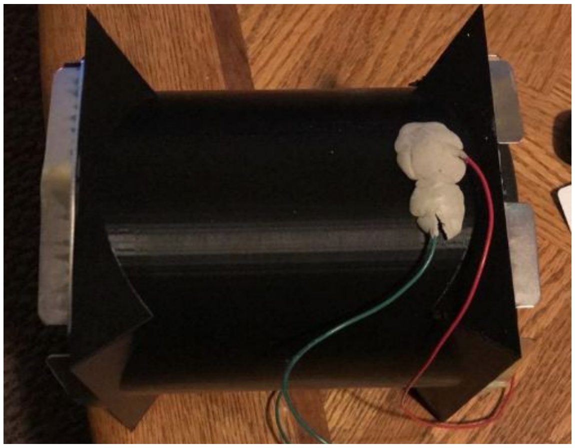


Figure 18. Bose Speaker Assembly - Top View

Figure 19. Bose Speaker Assembly - Active Speaker

Figure 20. Bose Speaker Assembly - Passive Radiator

The first test conducted was on the speaker and enclosure assembly in free air, eliminating the effects of air volume. Free air refers to the speaker being fixed to one end of the enclosure while the other is open. The second test analyzed the resonant frequency of this assembly with the addition of an acrylic plate fixed to the open end, sealing the enclosure. The last vibrometer test was conducted on a dual-speaker assembly. This assembly is defined by the Bose speaker on one end of the enclosure to serve as the passive radiator and a fully operational speaker on the opposite end, functioning as the active speaker. The testing apparatus for the Bose speaker assembly is shown in Figure 21 below.

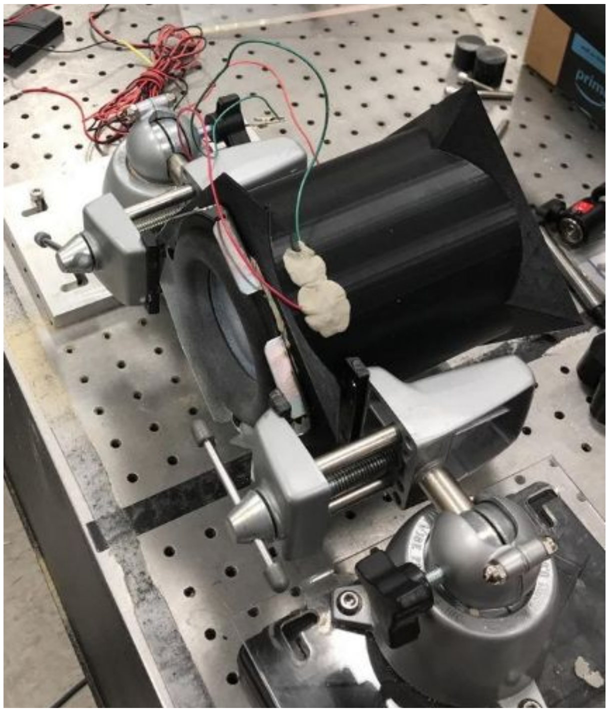


Figure 21. Bose Speaker Testing Apparatus

After testing the Bose speaker, the previous low-profile sealed passive speaker assembly was scanned. A section view of the sealed passive is shown in Figure 22 below.

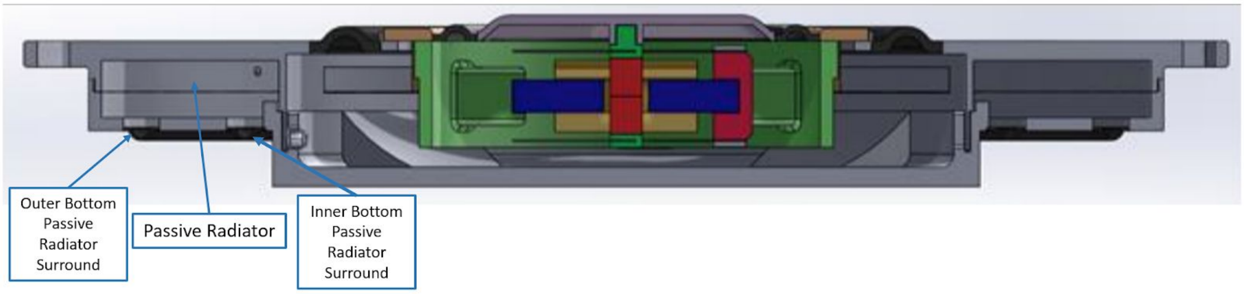


Figure 22. Low-Profile Sealed Passive Speaker Cross Section

A small aluminum ring was also machined in Washburn Shops and attached to the front of the passive radiator. The aluminum ring acted as an additional weight for the front passive radiator.

This was used to distinguish between the passive radiator resonance and the speaker resonance. The testing apparatus was similar to that of the Bose speaker, and is represented in Figure 23 below.

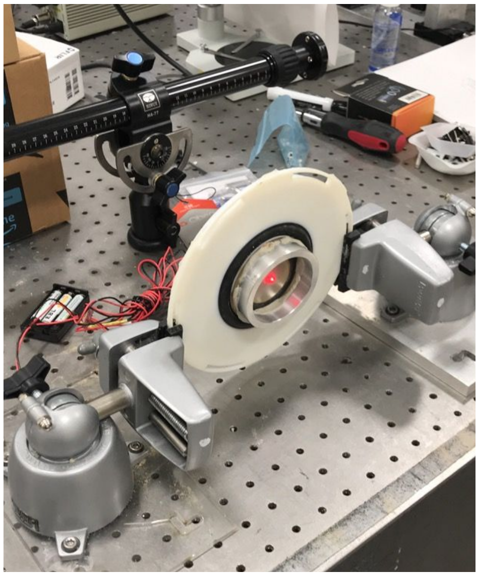


Figure 23. Previous Passive Radiator Testing Apparatus

The results of these tests will then be used to compare with various software simulations. This will help assess the validity of the various simulations that are conducted on the models.

3.3.2 Calculations

In order to determine the theoretical resonant frequency of the final speaker model, calculations were done on the areas, moving masses and internal volumes. In order to calculate the resonant frequency of the system, first the moving masses were defined. Next, the air volume within the speaker was obtained. The air stiffness was then obtained for the moving magnet and the passive radiator. Using these values, a resonant frequency was calculated for the system using the equations shown in Figure 24 and Figure 25.

$$\boxed{k = \frac{\rho_{air} c^2 A^2}{V}}$$

Figure 24. Equation to Calculate Air Stiffness

$$\boxed{f_{res} = \frac{1}{2\pi} * \sqrt{\frac{k}{m}}}$$

Figure 25. Equation to Calculate Resonant Frequency

The values that were obtained for the final design can be found in the results and Appendix B (8.2.2).

3.4 Objective 4: Software Simulation

In the design process, utilizing software to perform simulations and analyzing results is critical to optimization. Performing software simulations allows an engineer to determine the feasibility and performance of the design prior to manufacturing, allotting more time to make improvements and less to tangible construction. These simulations help visualize errors prior to making them. The project team focused on two softwares to model and analyze the passive radiator designs, Simscape and ANSYS. In the software, the speaker system can be modeled as a spring-mass system. This is due to the moving mass of the cone and magnet assembly along with the stiffness of enclosed air, replicating a spring.

3.4.1 Simscape

Developed by MathWorks, Simscape is a software that allows a user to create models of physical systems within MATLAB. Using a visual user interface, Simscape represents a physical system through the connection of block diagrams and a directory of real-world model systems, such as electrical, mechanical, thermal, magnetic, or hydraulic. This program also can estimate the frequency response of a system modeled in Simscape. The team attempted to utilize this program to model various systems. The first model created was a spring-mass-damper system, which replicates a simple speaker. This model was then updated to create a simple speaker and passive radiator. These simulations can be used to determine resonant frequencies given input values for properties such as mass, internal air pressure, internal volume, or spring constants. The effects of each property on resonant frequency can be evaluated by changing a specific variable and the others remaining constant.

3.4.2 ANSYS

ANSYS has developed a number of simulation software for engineers to use throughout the product life cycle. This project focused on the use of ANSYS Workbench, a finite element analysis (FEA) software that can be used to solve problems of stresses, deformations, heat transfer, fluid flow, and other common engineering elements. To perform a simulation in ANSYS, a geometry must first be generated through a SolidWorks model and be properly imported for analysis.

The first model imported into ANSYS was a spring-mass system. Composed of multiple springs and two flat plates, this model simulated the dual speaker assembly that was tested on the scanning vibrometer. The springs for the passive radiator and active speaker are fixed at the ends to represent their attachment to the lab references frame. Figure 26 below represents the spring-mass assembly.

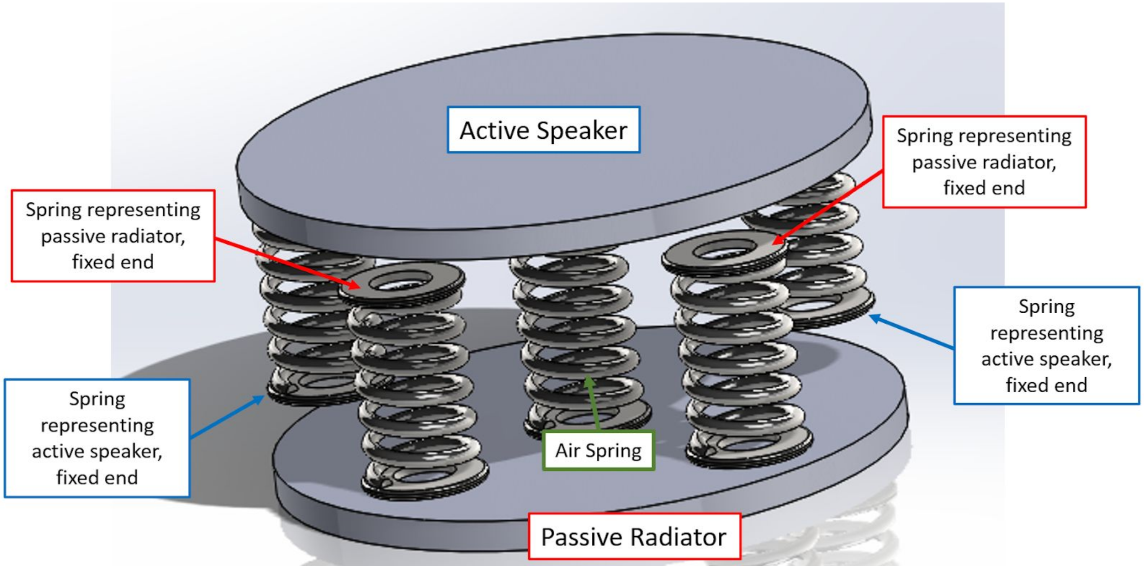


Figure 26. D Model of Spring-Mass System

Upon completion of this model, the team transitioned to built-in ANSYS features to potentially provide more accurate simulations. The next step in simulating a speaker system in ANSYS was to create a simple speaker assembly based off of the Bose speaker created for the scanner vibrometer testing. SolidWorks was utilized to create the Bose speaker assembly. The main purpose of creating this speaker assembly in SolidWorks and simulating the system in ANSYS was to compare results with the scanner vibrometer testing. Similar to the scanner vibrometer testing, three different models were created in SolidWorks; free air, sealed box and an active and passive assembly. Pictured below are the SolidWorks models created.

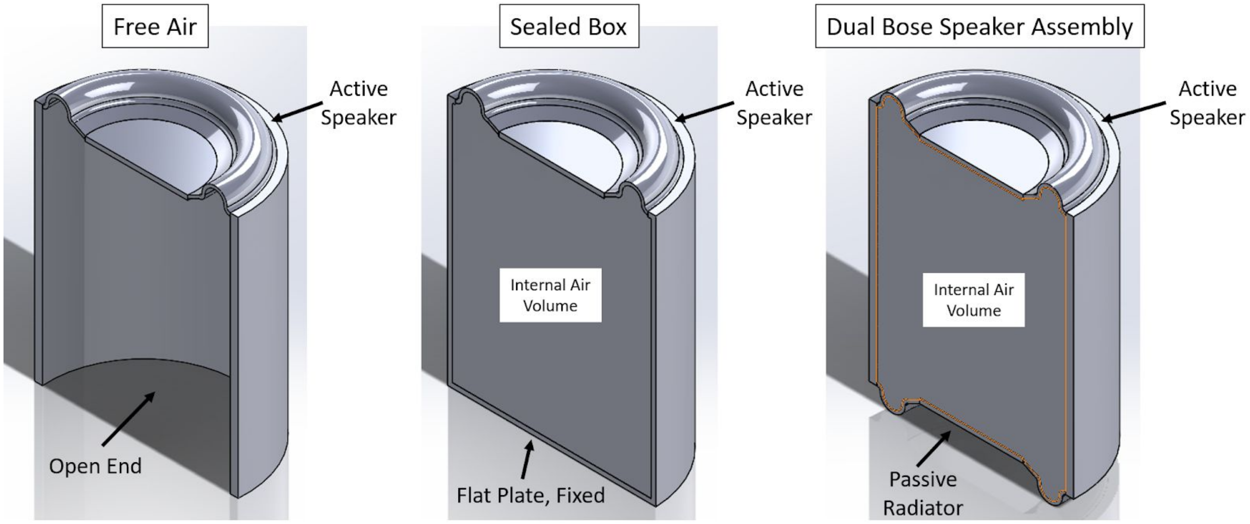


Figure 27. Section Views of Free Air, Sealed Box and Active/Passive SolidWorks Models

The free air model has an active speaker on one side, and is open on the other side. The sealed box model has an active speaker on one side, and is closed off on the other side, which creates a sealed box. The inside of the speaker is the internal air of the system, which is created in SolidWorks using the internal volume feature. Appendix B (8.2.1) details how to create an internal volume in SolidWorks. The active and passive speaker assembly has an active speaker on one side, and a passive radiator on the other side. This model also has an internal air volume. These three models were then used to import into ANSYS to simulate total deformation and resonant frequency. ANSYS static acoustics and harmonic acoustics were used to test for resonant frequencies. By utilizing this software simulation, the project team was able to predict resonant frequencies for the passive radiator system.

3.5 Objective 5: Model Passive Radiator Design

3D modeling using computer-aided design (CAD) is an essential step in the design process. CAD software provides the ability to create, analyze, and improve designs prior to creating a physical prototype. Computer-aided design can also be used to easily produce 3D printed parts. The project team utilized SolidWorks to make modeling changes to the previous passive radiator design.

3.5.1 Previous Passive Radiator Design

To improve the passive radiator model, the team referenced the previous model developed by prior MQP teams. The assembly consisted of three sub-assemblies: top, bottom, and moving magnet. A cross-sectional view of the previous design is shown in Figure 28 below.

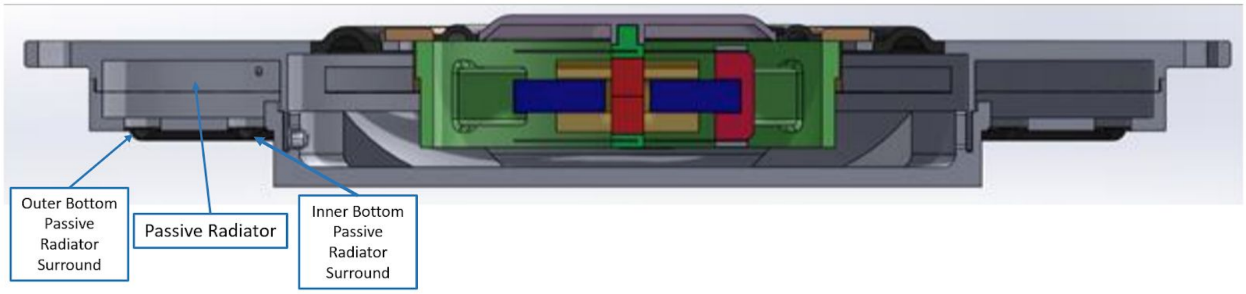


Figure 28. Low-Profile Sealed Passive Speaker Cross Section

Each sub-assembly was analyzed to determine potential improvements. The key features of the previous model that were inspected were its deflection room, connection of the surrounds, connection of top and bottom sub-assemblies, and its overall size and mass.

3.5.2 Improving the Passive Radiator Design

Upon identifying potential improvements, a new 3D model was created. This model worked to provide additional deflection room, improved material attachment for the surround and 3D printed parts, and improved sub-assembly connection. The final CAD model and its internal volume will be used to determine the moving mass required to obtain a resonant frequency of 50 Hz. Finally, the SolidWorks components can be converted to .stl files to 3D print the parts and begin the manufacturing process.

3.6 Objective 6: Manufacture an Optimized, Functional Passive Radiator

The project team started the manufacturing process by researching the methods used in the previous project. With guidance from project advisor Joe Stabile, the methods that we selected to produce the passive radiator included 3D printing of rigid components and injection molding for the surrounds. By utilizing injection molding techniques, key components of the passive radiator system would be molded and secured to the 3D printed parts. This project was the first of its kind to use injection molding as a manufacturing method, therefore extensive research needed to be conducted. All information gathered in this research phase can be found in background section 2.4.

3.6.1 3D Printing of Rigid Speaker Parts

For the passive radiator design, the rigid components were created in SolidWorks and then sent to 3D printers in the Foisie Innovation Studio on campus. The diaphragm (cone) of the system was first printed based on the design of the 2018 model to test the printing quality. Previous project teams used a different machine to manufacture the system in the rapid prototyping lab, therefore our team needed to determine feasibility with standard 3D printed parts. The team started the printing process with a focus on the moving magnet assembly. The piece used to connect the moving magnet assembly and passive radiator was printed as well as the cone. The prints were assessed and continuously improved upon using SolidWorks and the Foisie Innovation Studio Makerspace. 3D printed parts are printed using PLA, which is a thermoplastic aliphatic polyester.

3.6.2 Injection Molding

The previous project team utilized rapid prototyping for the entire passive radiator assembly, including the silicone surrounds. Despite their functionality, the surrounds were susceptible to ripping and often did not provide an air-tight seal. In addition to improving the strength of the passive radiator, the project team aimed to implement a new method to create surrounds in an effort to improve quality. Injection molding was used to manufacture the passive radiator surrounds. Injection molding is a manufacturing technique for producing parts that involves injecting material into a solid mold. The mold can be made out of any material, and there can also be different types of molds. The mold can be a hollow piece, or it can have a top and bottom (two part mold) that is clamped together. The material is then injected into the hole or space and eventually the material is cured into the desired part. The project team utilized many different molds and many different injection molding techniques when creating the surrounds.

3.6.2.1 Creating Molds for Surrounds

The first step in the injection molding process is to create custom molds to produce a given shape. The molds were created for the passive radiator surrounds using SolidWorks. These molds typically consisted of a top and bottom assembly, made based on the shape of the surround and its location within the speaker system. Due to the precision of the geometries within the moving magnet assembly, with dimensions in the millimeter range, numerous iterations needed to be modeled, printed, and tested. Further description of the molds and their respective results can be found in results sections 4.4.3 and 4.5.2. Each mold was manufactured using 3D printing and made of PLA. The final iterations made for the molds that create the surrounds are designed so the cured material latches to the 3D printed parts.

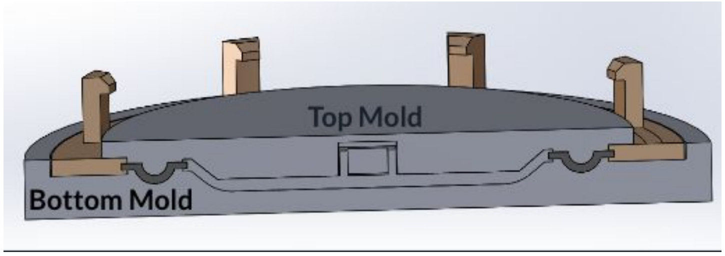


Figure 29. Section View of MMT Molds

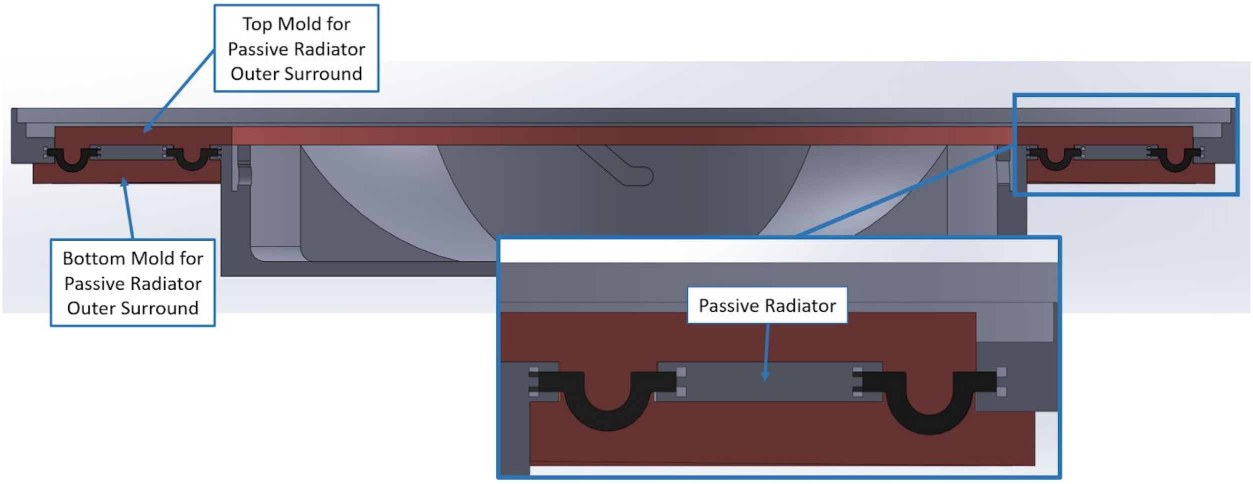


Figure 30. Section View of Molds for Bottom Passive Radiator Surrounds

Figure 31. Section View of Molds for Top Outer Surrounds

3.6.2.2 Testing Different Injection Molding Techniques

In addition to the molds used, numerous other factors affect the resulting part in the injection molding process. To determine the best method for injection molding, the project team used many different procedures. To better understand the injection molding process, the project team started by creating a two part mold that did not correlate with the final passive radiator surround design, which included a top part and a bottom part. Using this two part mold, the project team utilized Smooth-On Mold Max 14NV as the silicone injection material. Mold Max 14NV includes silicone and a mixing agent, which need to be mixed at a 10:1 rate prior to injection. The material was hand mixed in a cup and then poured into the bottom part of the mold using a spoon. The top part of the mold was then clamped onto the bottom part, and the material was cured within 4 hours of pouring. Vents were utilized on the side of the mold in order to release air pockets inside the mold. Next, the project team drilled a hole into the top of the mold, and injected the material into the mold using a syringe. The material was still hand mixed in a cup and then poured into the syringe. To expand on the vents on the side, a hole was drilled into the top as well.

With a better understanding of injection molding, the next iteration of injection molding was to create a mold for the moving magnet surround. The 3D printed moving magnet parts were placed inside the mold so the material would latch onto the parts after injection. The injection molding technique we moved on to was obtaining a mixing gun and shooting the material in. The mixing gun contains a dual sided cartridge, with the silicone on one end and the mixing agent on the other. The mixing gun mixes two materials (part A and part B) that have a 10:l ratio, allowing the material to cure properly. For this stage, we moved on to using Mold Max 40, which gave the project team a better modulus of elasticity. The material is mixed in the gun through a nozzle, and then shot into the injection hole. As shown in Figure 33, the nozzle is injecting the material into the mold as the mold is clamped down.

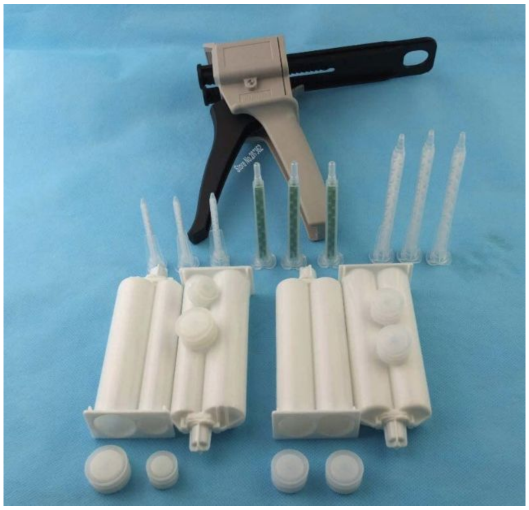


Figure 32. Mixing Gun Parts

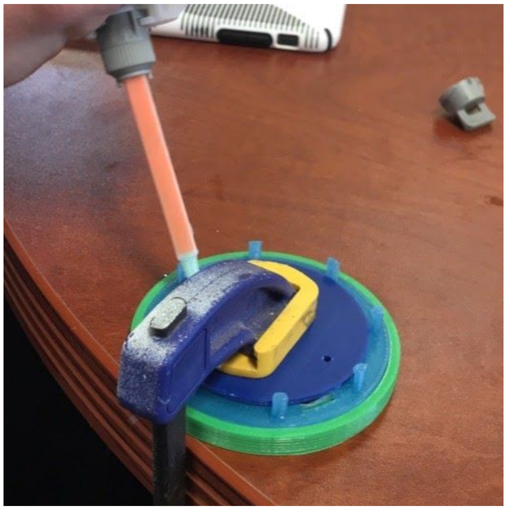


Figure 33: Project Team Using Mixing Gun

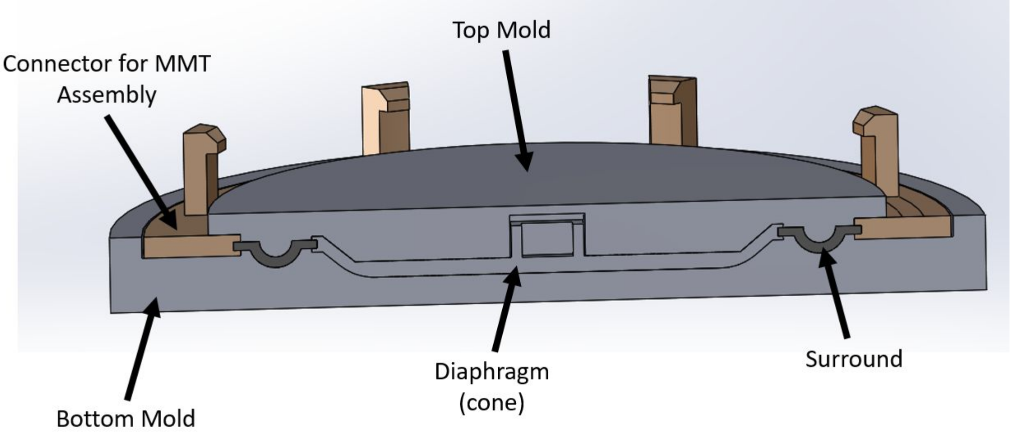


Figure 34: Section View of Molds, Moving Magnet Parts and Surround

In Figure 34, a section view of the molds, moving magnet parts and surround are shown. The surround, which is located in the middle, was the part that was injection molded. The main advantage and improvement to injection molding the surround is the silicone material molded to the 3D printed parts. The latch feature created on the rigid parts allows the material to cure inside the parts. The injection molding technique the project team utilized was to overmold, which results in material molded over the parts for improved attachment.

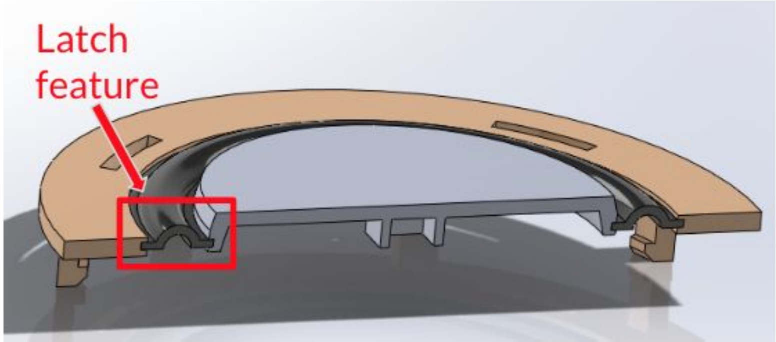


Figure 35. Latch Feature - Injection Molding Surround

Due to air bubbles in the molded surrounds, which is discussed more in the results section, the project team needed to find a way to degas the material. At first, this was done by making a vacuum chamber from household objects. A vacuum chamber is used to remove air bubbles from hard setting materials. As shown in Figure 36, the vacuum chamber was made from a Mason jar, a brake bleeder and vacuum pump kit, sealed with silicone. The tubing is attached to a hole in the top of the Mason jar and silicone is used for an airtight seal. To achieve even better results, the project team used a vacuum oven in Professor Panchapakesan's lab. The vacuum oven works as a pressurized vacuum chamber. The final injection molding technique we used was to degas the material using the vacuum oven and inject the material using a small syringe. The material was hand mixed in a cup, and then put into the vacuum oven for 45 minutes. Then, once the material is rid of air bubbles, it is poured into the syringe, and then shot into the mold. We mainly used Smooth-on Mold Max 40, but had planned on using Wacker Elastosil LR 3003/70 silicone.

Figure 36. DIY Vacuum Chamber

Figure 37: Vacuum Oven

4. Results

4.1 Scanning Vibrometer

4.1.1 Bose Active Speaker in Free Air

The first tests that were performed using 3D scanning vibrometry were on the Bose active speaker from Figure 19. The speaker was first scanned in free air across frequencies ranging from 0 to 1000 Hz. Figure 38 belows shows the results of the first vibrometer testing.

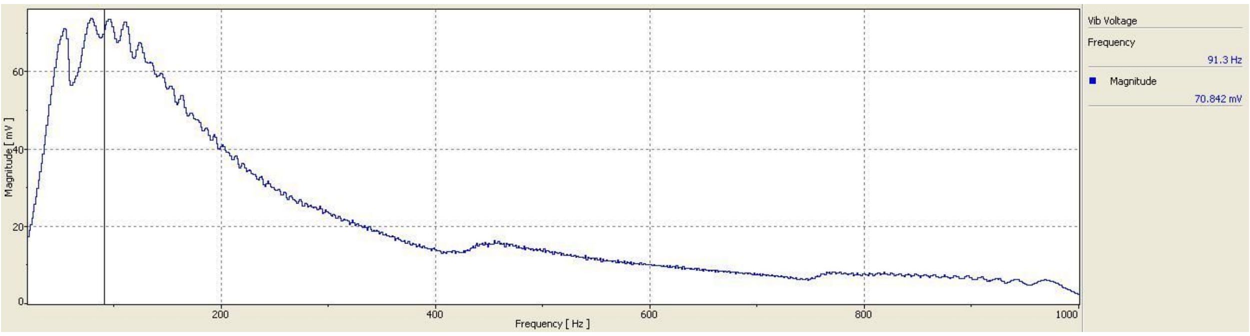
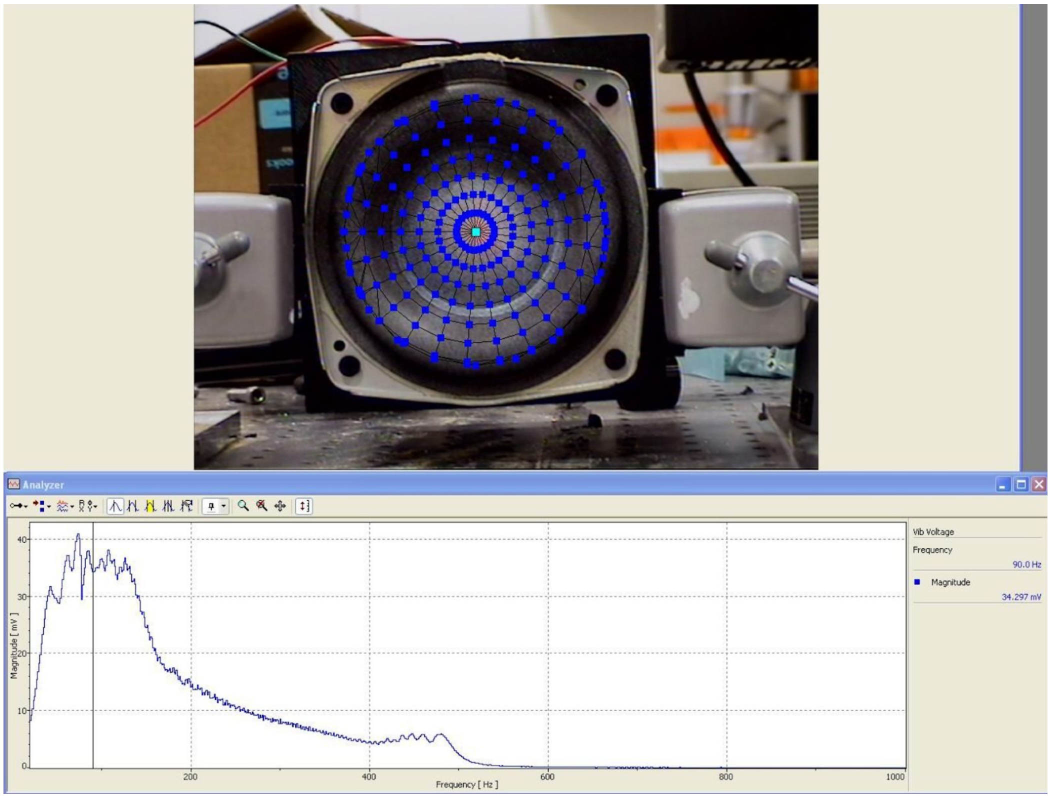


Figure 38. Bose Active Speaker in Free Air, First Scan

The peak of this graph contains noise that makes it difficult to determine a precise resonant frequency. The middle of this peak was measured at approximately 91.3 Hz. To confirm this data, an additional scan was conducted. Figure 39 below represents the results of the second vibrometer test on the Bose speaker in free air.



Vib Voltage
Frequency
90.0 Hz
■ Magnitude
34.297 mV

Figure 39. Bose Active Speaker in Free Air, Second Scan

The results of this scan correlated with those of the first scan, with the middle of the frequency peak taken to be approximately 90 Hz. The results from these two tests indicate that the speaker, without any effects from the internal air of the enclosure, resonates at roughly 90 Hz. This frequency was then used as a reference for the sealed and dual speaker assembly testing, helping to differentiate the resonant frequencies of the active speaker and passive radiator. This data was also used to visualize the effects of internal air.

4.1.2 Bose Active Speaker in Sealed Enclosure

The second speaker configuration that was tested was the Bose active speaker in a sealed enclosure. This included an acrylic plate attached to the end of the enclosure with an air-tight seal. By adding the plate and therefore increasing the vibrations within the enclosure, it is expected that the tests provide results of an increased resonant frequency. The same initial parameters as the Bose speaker in free air were used for these tests. The results of the first scan for the speaker and sealed enclosure are shown in Figure 40 below.

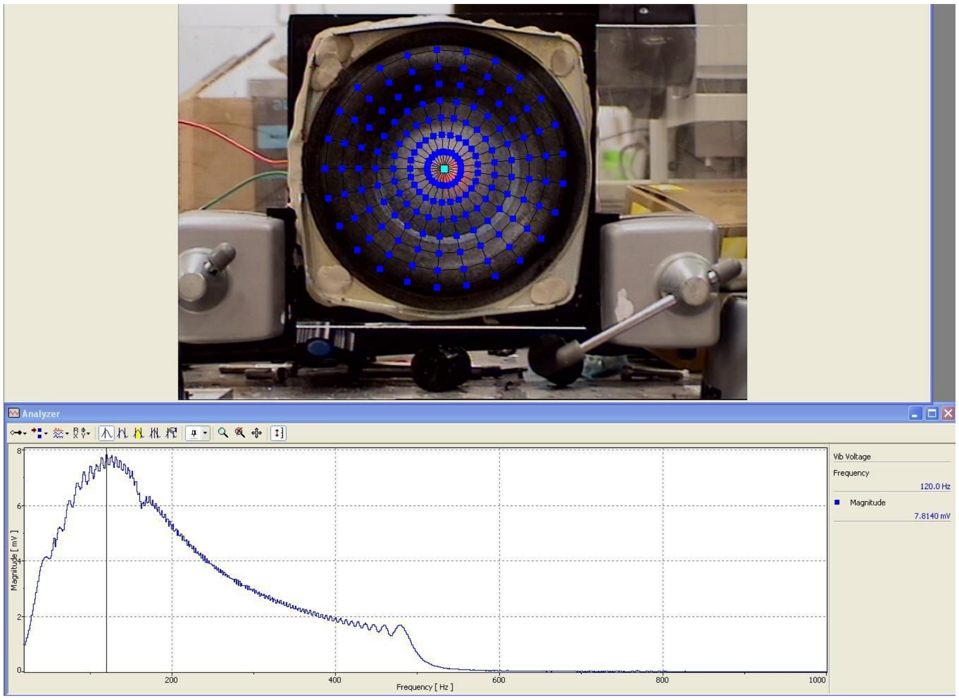
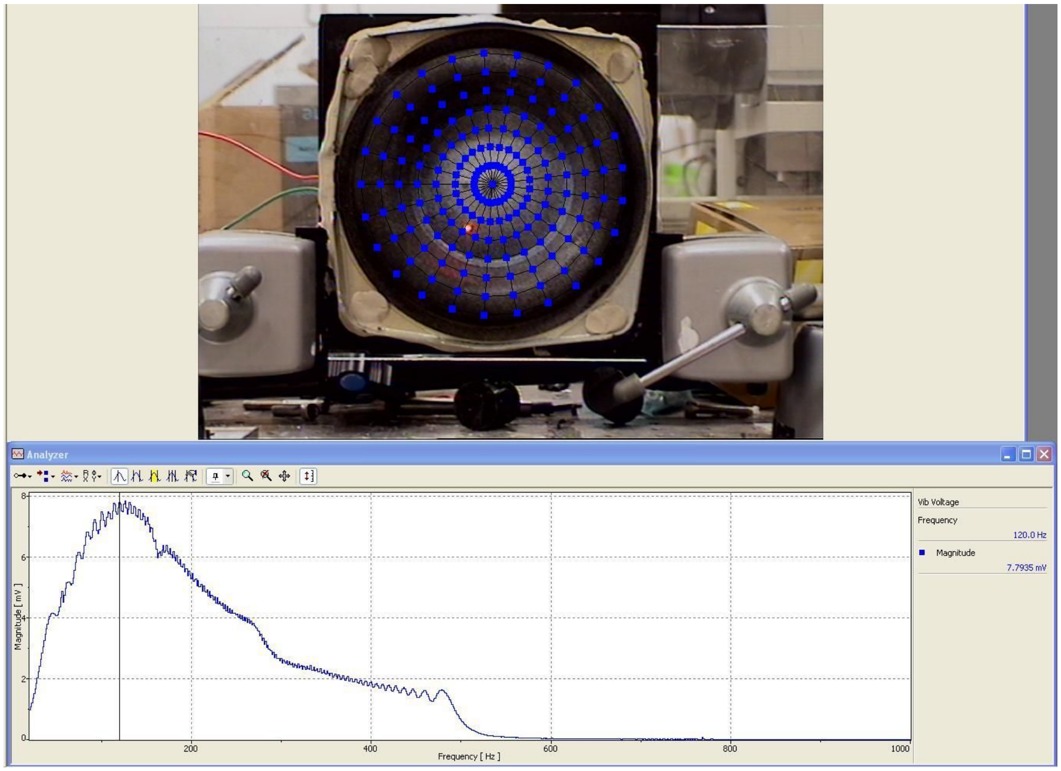


Figure 40. Bose Active Speaker in Sealed Enclosure, First Scan

This scan produced less noise and cleaner data compared to the free air testing. The frequency of the speaker is shown to peak at approximately 120 Hz. This data aligns with the project team’s hypothesis that the resonant frequency would increase with the addition of an acrylic plate. To confirm this data, a second test was conducted. Figure 41 below shows the test results for the second scan.



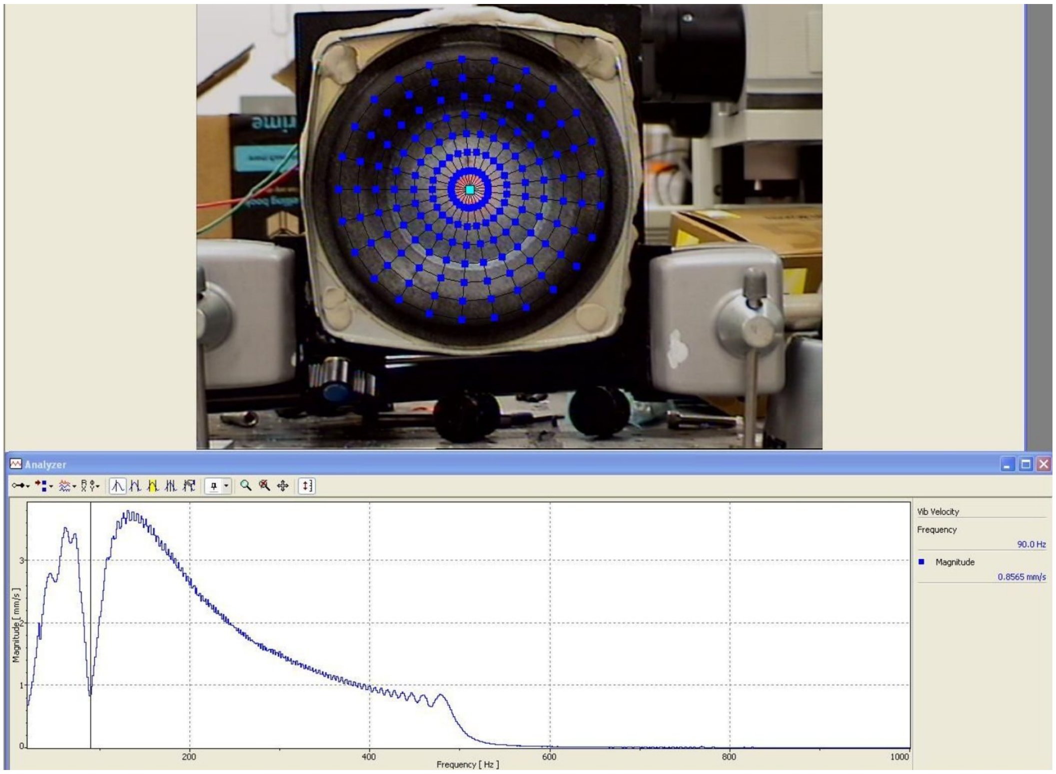
Vib Voltage
Frequency 120.0 Hz
Magnitude 7.7935 mV

Figure 41. Bose Active Speaker in Sealed Enclosure, Second Scan

The two sets of results were nearly identical, as the second scan confirmed that the active speaker in a sealed box resonated at an increased frequency of 120 Hz. This test provided a better understanding of the effects of internal air on resonant frequency. The project team then tested the dual speaker assembly, adding a passive radiator to the enclosure. It was expected that the frequencies in this test would be lower than those of the sealed box due to the fluctuating passive radiator.

4.1.3 Dual Bose Speaker Assembly

The third configuration that was tested was the dual Bose speaker assembly, consisting of an active speaker and passive radiator. This assembly was created by attaching the Bose passive radiator to the enclosure using Mortite caulking. The team first tested the frequency response of the active speaker, with the scan results shown in Figure 42 below.



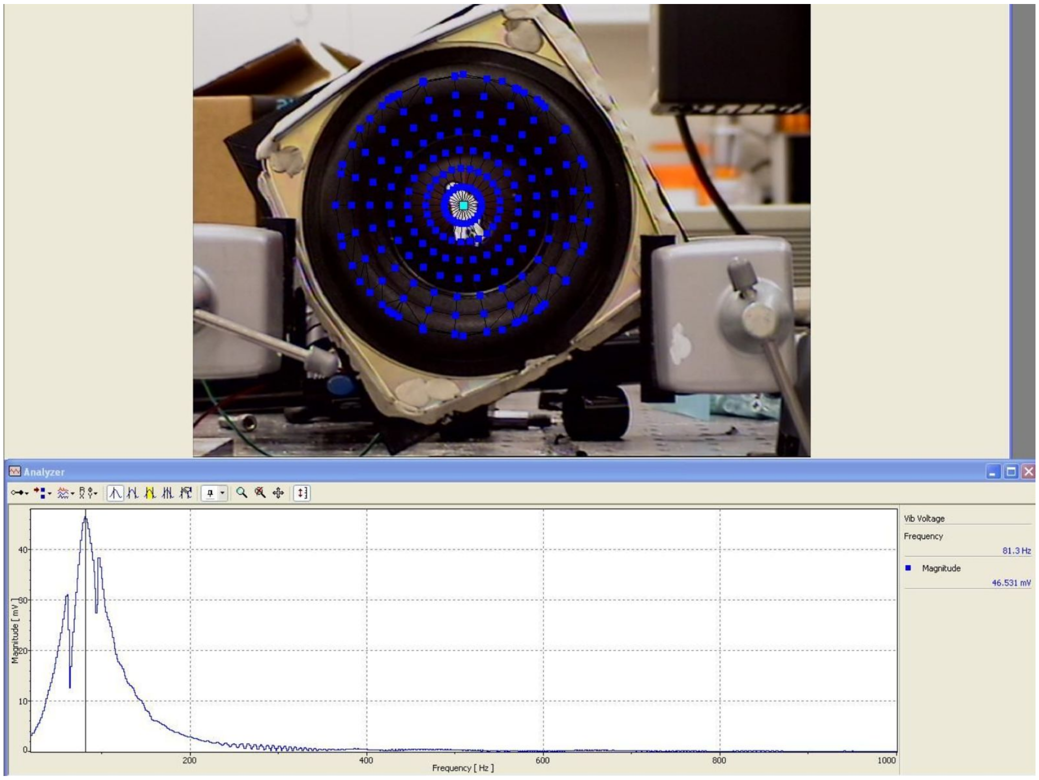
Vib Velocity

Frequency 90.0 Hz

Magnitude 0.8565 mm/s

Figure 42. Dual Bose Speaker Assembly, Active Speaker, First Scan

Figure 42. displays a dip at 90 Hz and a peak at approximately 120 Hz. In a dual speaker system, a sharp decrease in response is expected at the passive radiator's resonant frequency. The first active speaker test results indicate that the resonant frequency of the passive radiator is 90 Hz. The peak of the scan is at roughly 120 Hz, indicating that the active speaker resonates at about 120 Hz. To confirm the passive radiator's resonant frequency, the speaker assembly was flipped and the passive radiator was scanned. Based on the data in Figure 42 above, a peak is expected at 90 Hz. Figure 43 below represents the results of the first scan performed on the passive radiator.



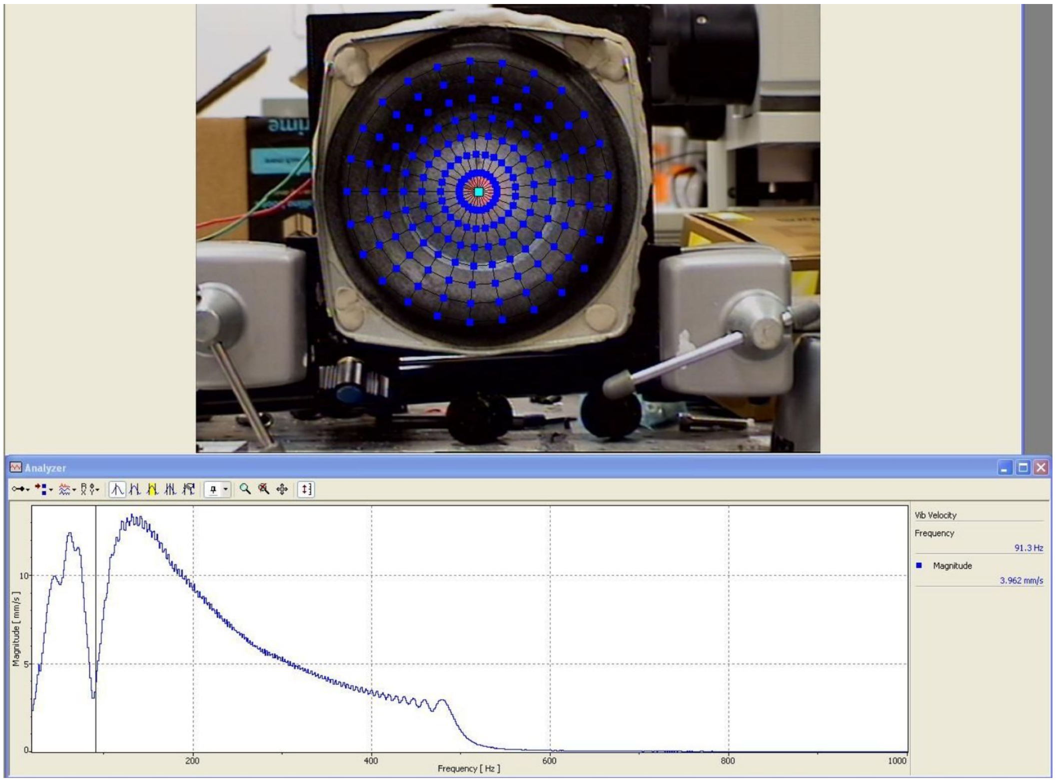
Vib Voltage

Frequency 81.3 Hz

Magnitude 46.531 mV

Figure 43: Dual Bose Speaker Assembly, Passive Radiator, First Scan

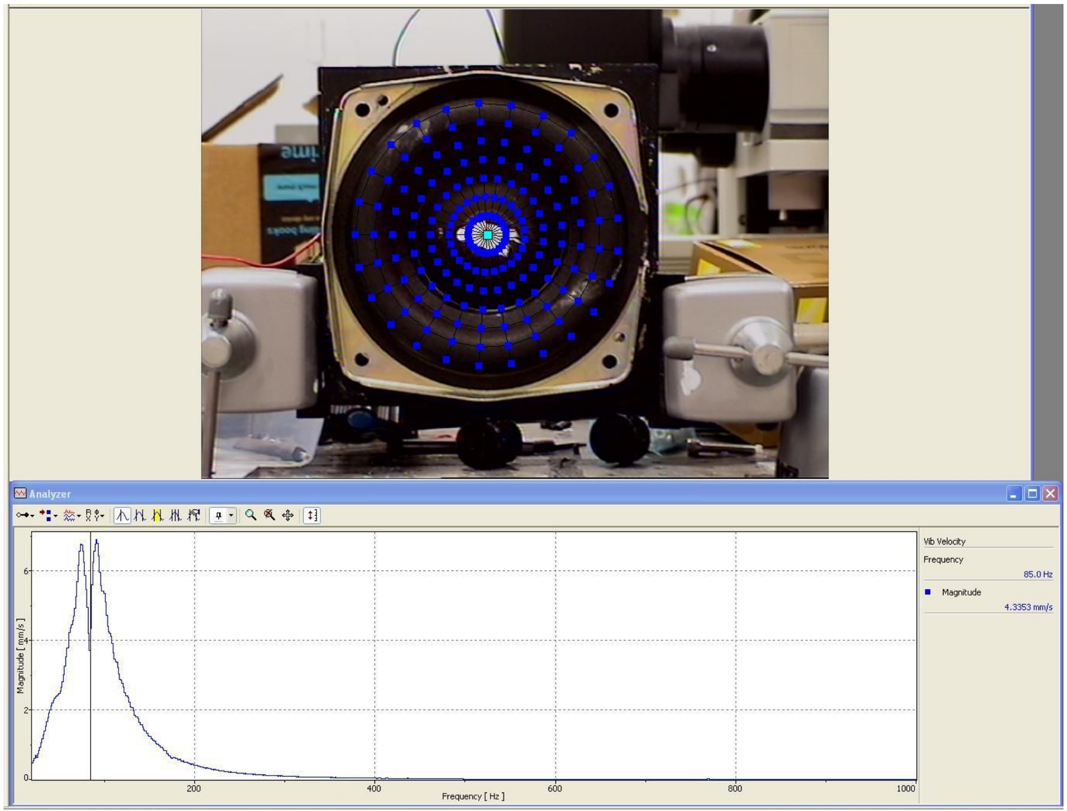
The results indicate that the passive radiator in the dual speaker enclosure resonates at approximately 81 Hz. The passive resonated at a slightly lower frequency than the data in Figure 43 above suggests. This may be due to the lack of repeatability of mounting the dual speaker assembly to the lab reference frame, as the assembly would need to be fixed in the same positions as the active speaker test. The passive radiator does not use a power source and resonates due to the active speaker fluctuating internal air. There is a lone peak in the results with no clear trough from the active speaker at 120 Hz because the passive radiator, without any power input, resonates only at around 81 Hz. A second test of both ends of the enclosure was performed to compare to the previous results.



Vib Velocity
Frequency 91.3 Hz
Magnitude 3.962 mm/s

Figure 44. Dual Bose Speaker Assembly, Active Speaker, Second Scan

The results of the second scan of the active speaker were similar to those of the first test. The scan displayed a dip at approximately 91 Hz and a peak at 120 Hz. The dip corresponds to the resonance of the passive radiator while the peak corresponds to the active speaker's resonance. The results from the first passive radiator test were lower than expected and an additional scan was performed to validate the data. Figure 46 below represents the results from the second test of the passive radiator for the dual Bose speaker assembly.



Vib Velocity

Frequency: 85.0 Hz

■ Magnitude: 4.3353 mm/s

Figure 45. Dual Bose Speaker Assembly, Passive Radiator, Second Scan

The results of the second passive radiator scan indicate that there is a resonant frequency of approximately 85 Hz. This is slightly higher than the recorded frequency from the first test. Though the data does not align perfectly, it can be concluded that the passive radiator resonates at a range of 80-90 Hz. Additional scans for the dual Bose speaker assembly can be found in Appendix A (8.1).

4.1.4 Low-Profile Sealed Passive Speaker (2018)

The 2018 low-profile speaker system then needed to be tested to determine its resonant frequency. Results of the scan helped to model and improve upon the design. Figure 46 below displays the resonance of the speaker across a range of frequencies.

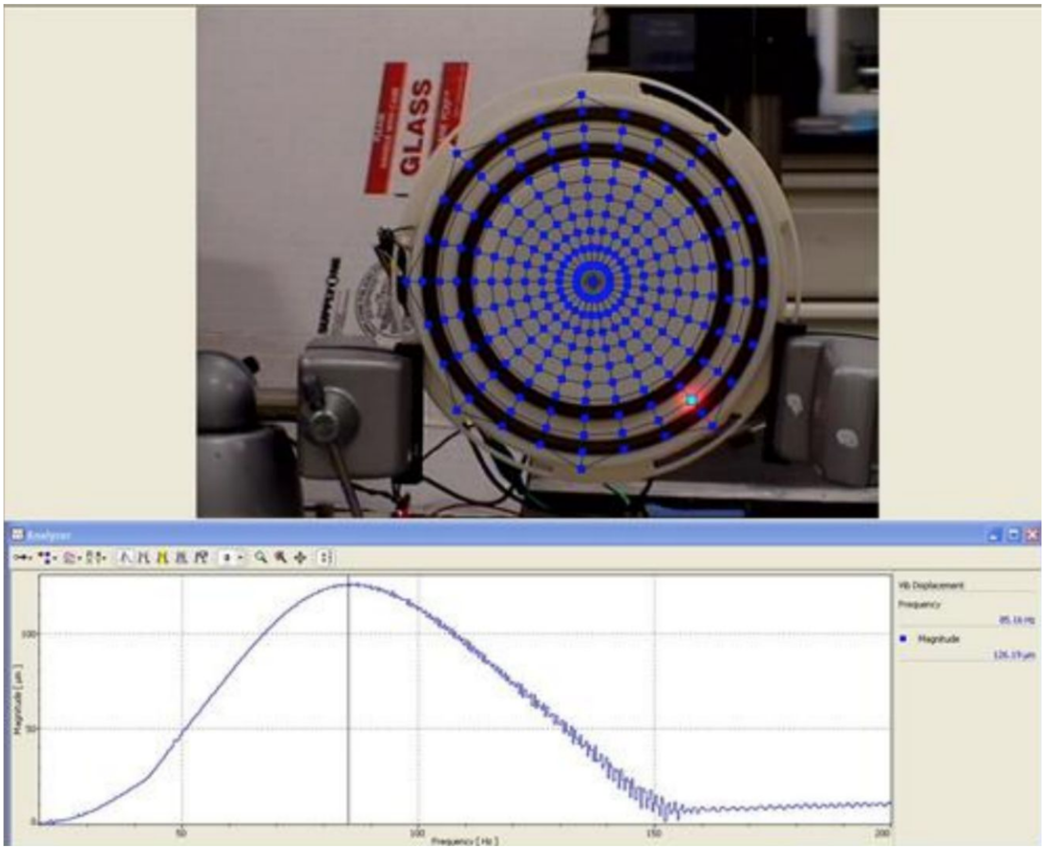


Figure 46. Previous Passive Radiator Scan

The peak of the graph is located at approximately 90 Hz. This is the resonant frequency of the previous passive radiator design.

Results from the numerous 3D scanning vibrometry tests can be used to understand the different speaker configurations and compare with the results from software simulations.

4.2 Calculating Resonant Frequency

Calculations were done on the final passive radiator design to determine the resonant frequency of the system. Taking into account moving areas and internal volumes, internal air stiffness for the MMT and passive radiator can be determined. Following the steps outlined in Appendix B (8.2.2), the air stiffness for the moving magnet assembly was determined to be 21,141 N/m. The air stiffness for the passive radiator was calculated to be 22,146 N/m. These stiffnesses were then used to calculate the resonant frequencies of both speaker parts. Using the resonant frequency equation, the resonance of the MMT was calculated to be at 90.767 Hz. The same equation was used for the passive radiator, resulting in a resonant frequency of 233.42 Hz. Due to the frequency being significantly higher than desired, additional mass must be attached to the passive radiator to obtain a lower frequency of 50 Hz. Solving for mass in the resonant frequency equation to get 50 Hz, an additional 0.2141 kg must be added to the passive radiator.

4.3 Software Simulation

Prior to using software to simulate the system, the assembly needed to be represented and understood as a spring-mass system. Each surround can be represented through a spring and a respective spring constant, compressing and decompressing to allow for movement and vibrations. The fluctuating internal air can also be modeled as a spring connected to the rigid components of the system, with its stiffness affecting the speaker resonance. A simple schematic of this system is shown in Figure 47 below.

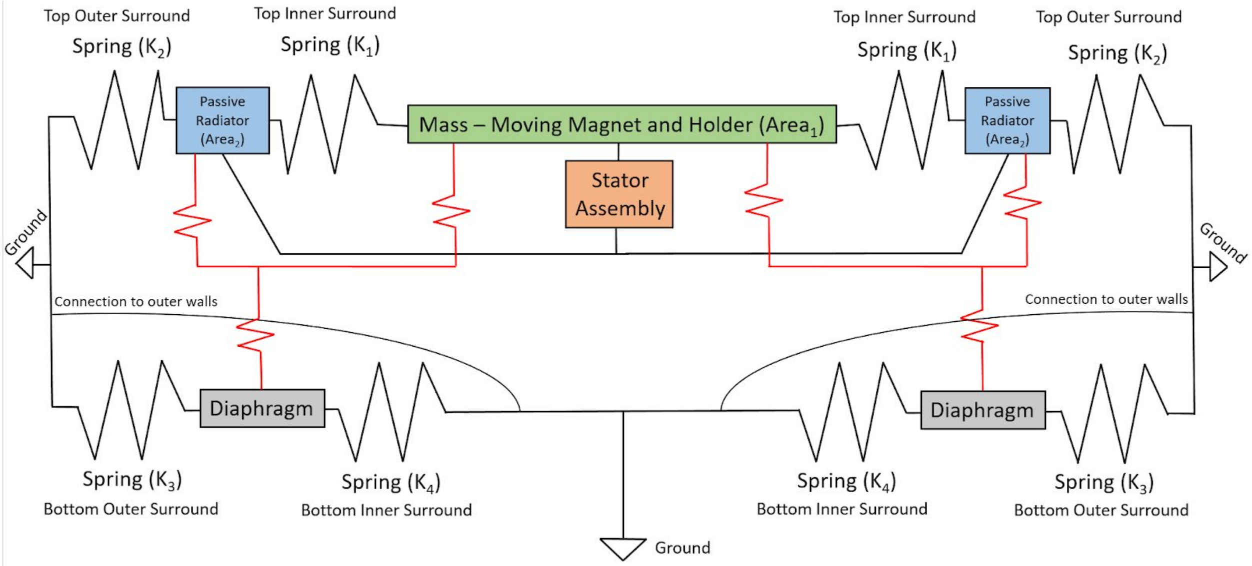


Figure 47. Schematic of Dual Speaker Assembly with Active Speaker and Passive Radiator

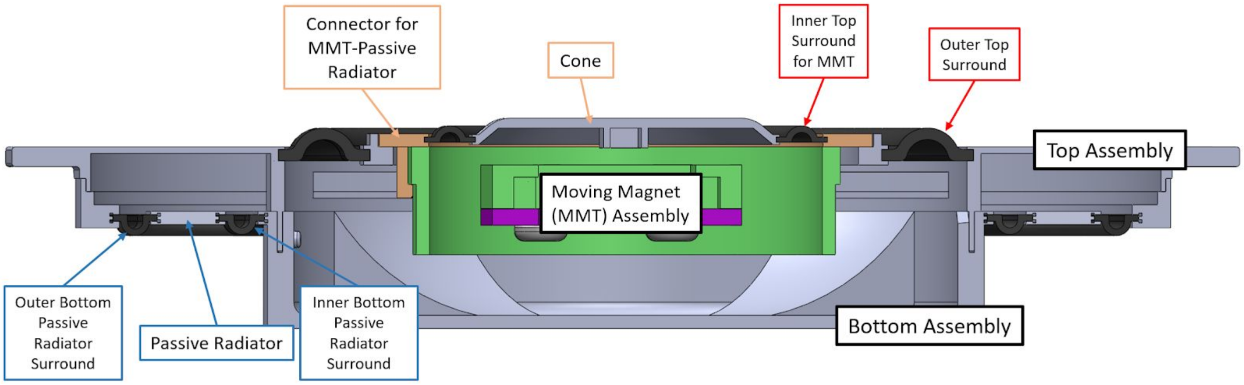


Figure 48. Low-Profile Sealed Passive Speaker Cross Section

4.3.1 Simscape

A Simscape model was created to simulate a speaker and passive radiator system. One reference that was used to complete the model was the 2018 final project report, which discussed the software in the background section. Additional resources included MATLAB tutorial videos and sample Simscape models. A speaker and passive radiator Simscape model is represented in Figure 49 below.

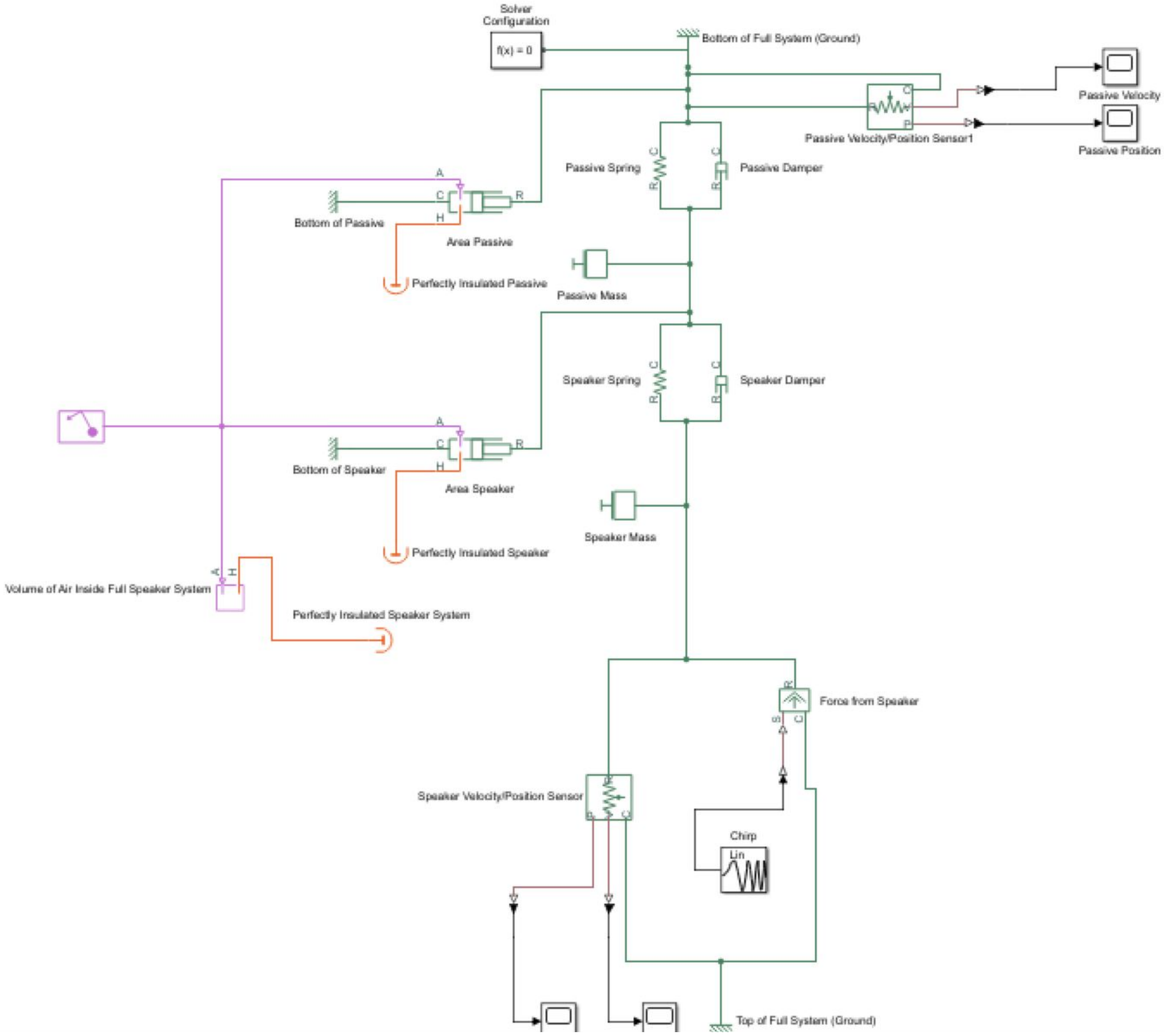


Figure 49. Speaker and Passive Radiator Simscape Model

The model starts at the bottom of the figure, which represents the top of the assembly. The model starts with a ground reference and a chirp signal. The chirp signal runs the simulation at a range of specified frequencies. The ground and chirp signal connect to a force from the speaker, which is caused by the change in air pressure due to vibrations. To the left of the chirp signal is a sensor that tracks the velocity and position of the speaker during the simulation. The next section of the model represents the speaker and passive radiator. The speaker and passive are both treated as spring-mass-damper systems. The components' respective spring constants and masses needed to be entered to accurately model the systems. The areas of these two components are represented on the left side of Figure 49 above. Area in Simscape requires four inputs, including the area of the component, the air properties inside the component, how it is insulated, and a ground reference. For this system, we considered the speaker and passive radiator as perfectly insulated and used standard air properties for the internal air. The volume of air inside the entire system was also required and was treated as a perfectly insulated assembly. An additional velocity and position sensor was included for the passive radiator.

Despite making numerous assumptions for the systems, the project team determined that this simulation method proved ineffective. This was mainly due to many unknown variables as well as overall software complexity. Simscape lacked any visual representation of how the system was resonating and made it difficult to understand the model. The team discussed with advisor Joe Stabile alternative simulation methods that were user-friendly, and decided to move to ANSYS.

4.3.2 ANSYS

ANSYS was utilized to create a simulation of moving masses and resonant frequencies of speaker systems. The project team started by creating a spring-mass system ANSYS model. By using this simple model, a Bose speaker assembly was created to simulate a more complex system. The Bose speaker assembly, consisting of three different configurations of free air, sealed box and active/passive, yielded resonant frequencies for the system.

The spring-mass system consists of two plates, with a spring connecting the two. The middle spring represents the air moving inside the system. On each plate, there are two springs which represent the moving mass of each speaker. In ANSYS, the end of each spring connected to the plates is fixed. A force of 10 N is applied to both the top and the bottom of the plate. Shown in Figure 50, the blue region indicates where it is fixed with no deformation. The red region indicates the highest level of deformation. The spring constant (k) for this spring was valued at 4,543.74 N/m and the modulus of elasticity is valued at $7.22\ x\ 10^{10}\ Pa$. The spring constants for these springs are valued at 3,702.10 N/m and the modulus of elasticity is valued at $4.39\ x\ 10^{10}\ Pa$.

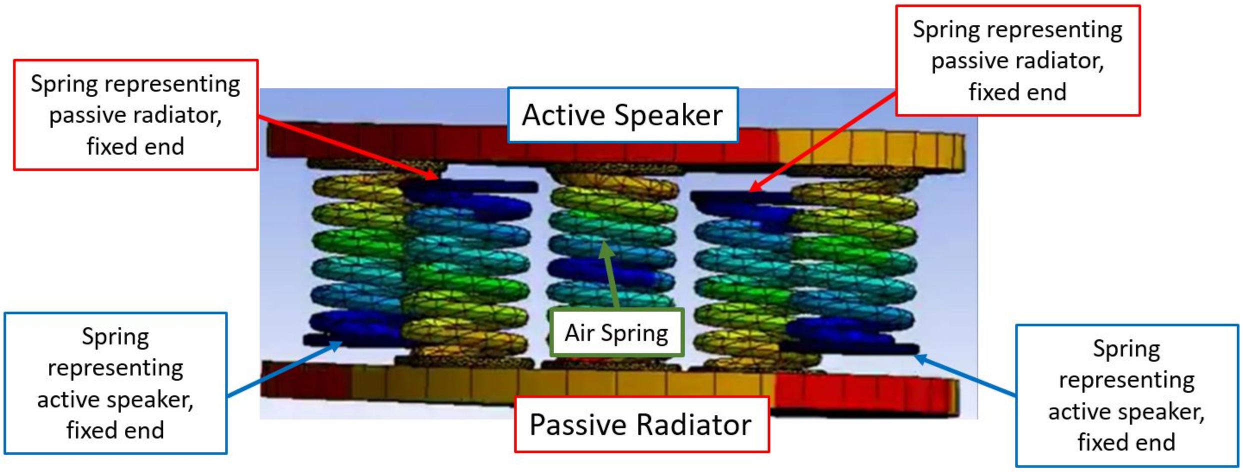


Figure 50. Spring-Mass System ANSYS Model - Total Deformation

Simulating this simple spring-mass system by obtaining modulus of elasticity enabled the project team to simulate a more complex speaker system. Simulating ANSYS models after the Bose speaker assembly, which is shown in previous sections, allowed the project team to predict resonant frequencies. First, the free air assembly was imported into ANSYS and a simple model was created. The bottom of the assembly was fixed, and a force of 3 N was applied to the active speaker. This force represents the air that is being forced from inside the assembly to the active speaker. By utilizing ANSYS acoustics and simulating the model, a frequency response is achieved. Figure 51 shows the frequency response of the system, with a resonant frequency of 120 Hz.

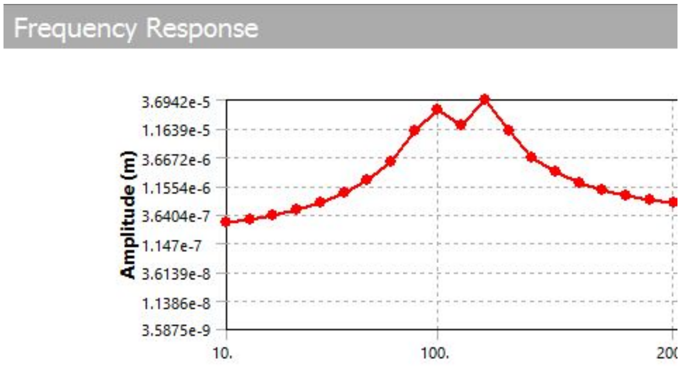


Figure 51. Frequency Response of Free Air Assembly

Next, the sealed box assembly was created and imported into ANSYS. Similar to the free air model, the sealed box side is fixed, while there is a 3 N force being applied to the active speaker side. The spring rate of the speaker is valued at 7,404.19 N/m, and the modulus of elasticity is valued at 13.965 MPa. This model differs from the free air model because the sealed box creates an internal volume, along with the external air that surrounds the assembly. The internal volume exerts a force onto the active speaker In ANSYS, the internal volume and the external air must be defined. After simulating the model, a frequency response is recorded. Figure 52 shows resonant frequencies at 100 and 120 Hz. The project team believes ANSYS acoustics is not properly modeling the air sealed inside the bass box.

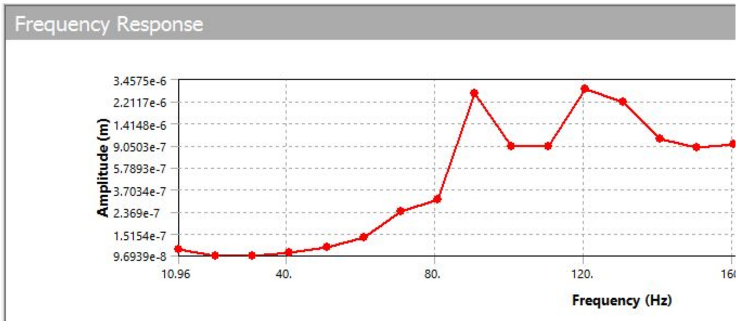


Figure 52: Frequency Response of Sealed Box Assembly

Next, the active and passive speaker assembly was created and imported into ANSYS. This assembly consists of an active speaker on one end, and a passive radiator on the other. Similar to the sealed box, this assembly is enclosed and has an internal volume and external air that acts on the system. In ANSYS, the passive side is fixed along the edge, and a 3 N force is applied to the center of each side, which represents the fluctuating internal air pressure between the active speaker and the passive radiator. After simulating the model, a frequency response is recorded. Figure 53 shows a resonant frequency at 120 Hz.

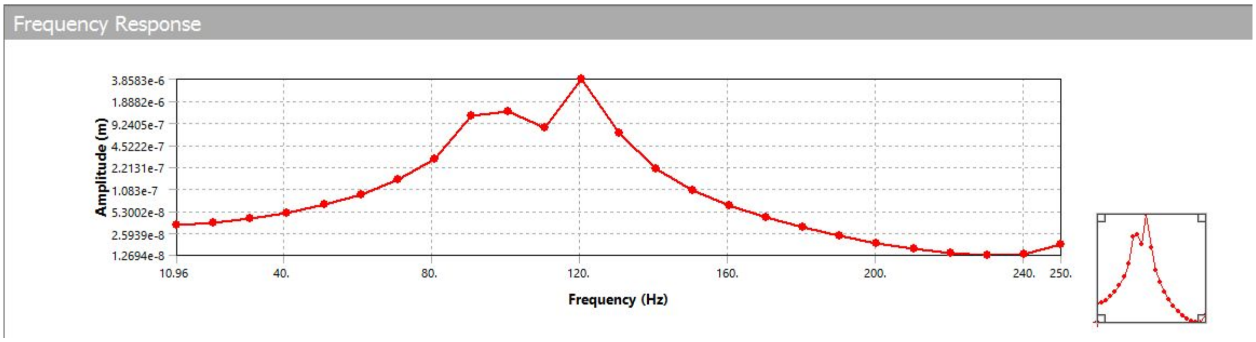


Figure 53: Frequency Response of Active and Passive Assembly

ANSYS acoustics simulated the speaker systems that were created to obtain resonant frequencies. When comparing the results with the results from the scanning vibrometer testing, the resonant frequencies of each assembly do not match up as expected. The scanning vibrometer testing yields more accurate results than ANSYS acoustics, as ANSYS was not properly modeling the internal volume of air.

4.4 3D Modeling

The passive radiator design for the low-profile, wall mounted speaker was 3D modeled using SolidWorks. The project team 3D modeled the passive radiator design utilizing a combination of previous years' designs and improvements made that optimized the system. SolidWorks allowed the project team to create new and improved features for the design. Many iterations of the design were created in SolidWorks and a final optimized passive radiator design was completed.

4.4.1 Previous Passive Radiator Design

The previous sealed passive radiator design was analyzed and discussed in sections 2.5 and 3.2. To both understand and look for potential improvements, the physical model was taken apart. The design was broken down into two parts, the top assembly and bottom assembly. This project mainly focused on the design of the passive radiator system, which includes the passive radiator and surrounds. While separating the top and bottom assemblies, a flaw was discovered in the rigid sections of the design. Figure 54 below shows this connection failure.

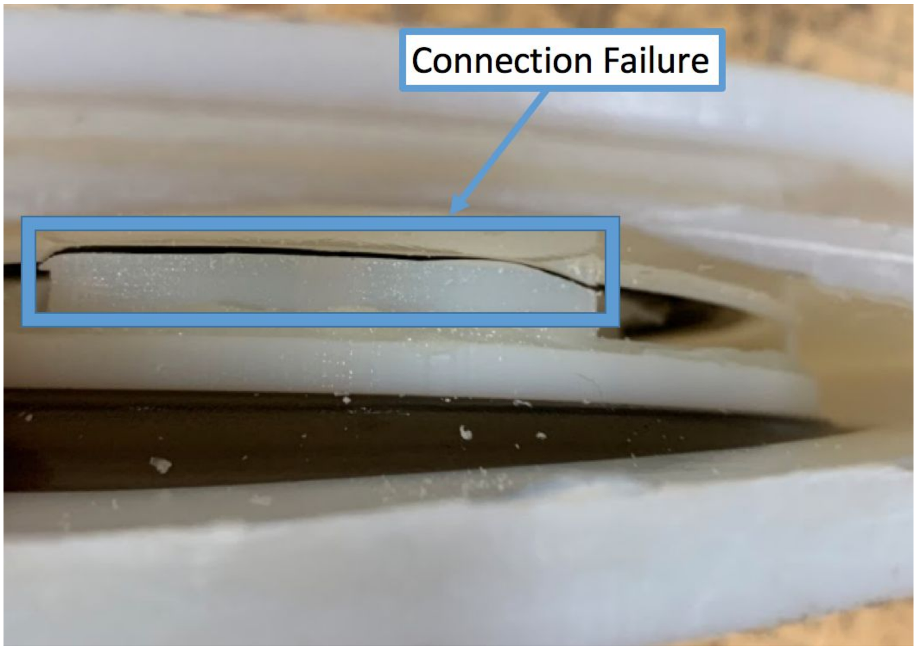


Figure 54. Previous Design Connection Failure

While the intended design used a slot and pin mechanism to connect the two sub-assemblies, the previous project team used glue to secure the assemblies. This crack was a result of excess glue used to connect the two sub-assemblies, as significant force was required to separate the two components. Once the system was disconnected, the attachment mechanism was exposed and is represented in Figure 55 below.

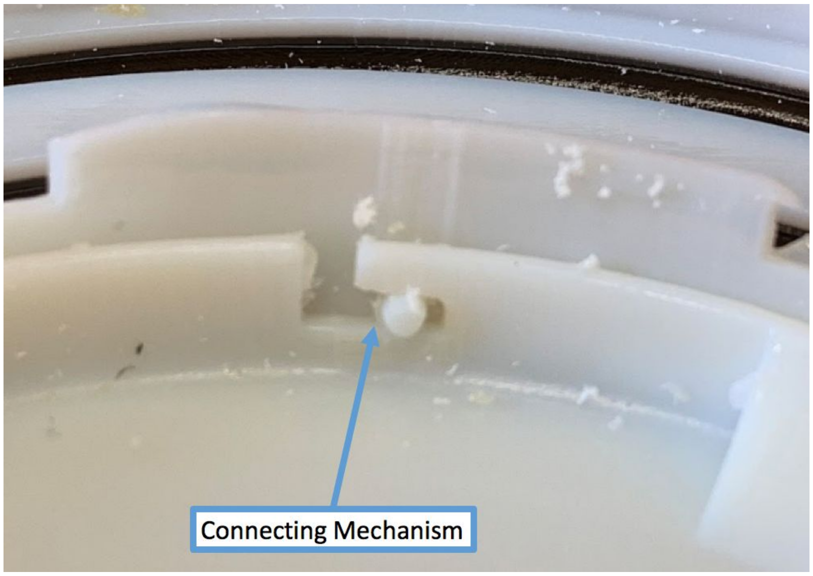


Figure 55. Previous Design Connecting Mechanism

The top assembly includes the pin, while the bottom assembly contains the slot. The top section drops into the slot and is turned to lock the two assemblies in place. Despite being a common mechanism to connect two parts, glue was still required to secure the two assemblies and provide an airtight seal. This is an area of the design that the project team will improve upon to provide a more effective connection.

An additional area of concern in the previous design was the passive radiator surrounds. Flaws in the sections of the surrounds where the rigid and flexible components meet were discovered, and are represented in Figure 56 below.

Figure 56. Previous Design Tear in Surround

The tear above was found on the inner surround of the bottom assembly. The tear was a result of sensitive material and poor attachment to the rigid parts. With a gap in the surround, the full system did not have an airtight seal and resulted in a defective model. The process of creating surrounds along with their attachment to the rigid parts will be improved upon to ensure an airtight seal.

4.4.2 Optimized Passive Radiator Design

The team made a number of design changes to optimize the performance of the previous low-profile sealed passive speaker system. The final design and its changes are shown in the figures below.

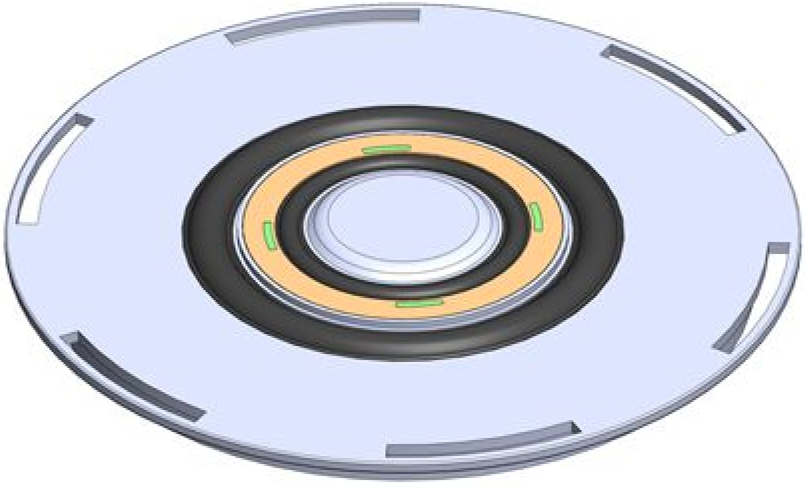


Figure 57. Final Passive Radiator Design

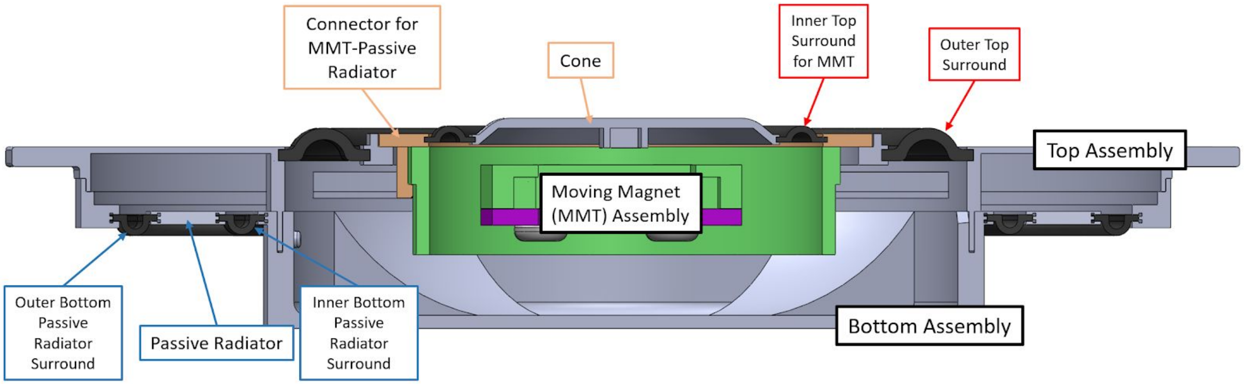


Figure 58. Final Passive Radiator Design Cross Section

Figure 59. Final Passive Radiator Design Side View - Increased Deflection Room

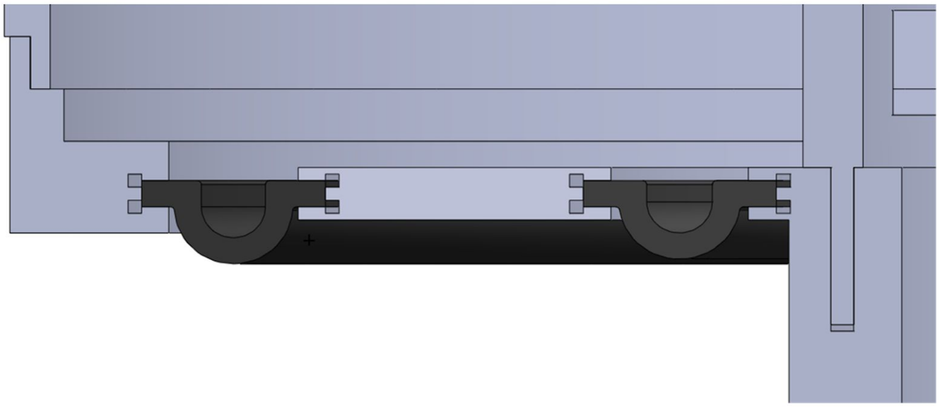


Figure 60. Final Passive Radiator Design - Notches for Material Attachment

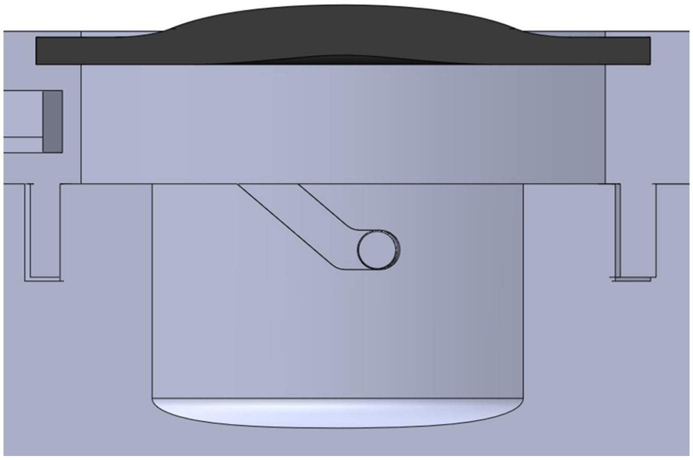


Figure 61. Angled Slots for Improved Top and Bottom Assembly Connection

4.4.3 3D Modeled Molds

The project team 3D modeled molds for the surrounds of the passive radiator design. The molds that were modeled for the moving magnet surround were manufactured and the surround was also manufactured. All of the molds were created in SolidWorks using the geometry of the existing parts. The molds that were 3D modeled for the top surround and the bottom surrounds were only 3D modeled and did not make it to the manufacturing stage.

A top and bottom part of the mold were created for the top surround utilizing SolidWorks. As shown in Figure 62, the red components are the top and bottom molds, which create the shape of the top outer surround, shown in black.

Figure 62. Section View of Molds for Top Passive Radiator Surround

Similar to the top surround mold, a top and bottom mold were created for the two bottom surrounds utilizing SolidWorks. As shown in Figure 63, the red components are the top and bottom pieces, which creates a mold for the two black surrounds.

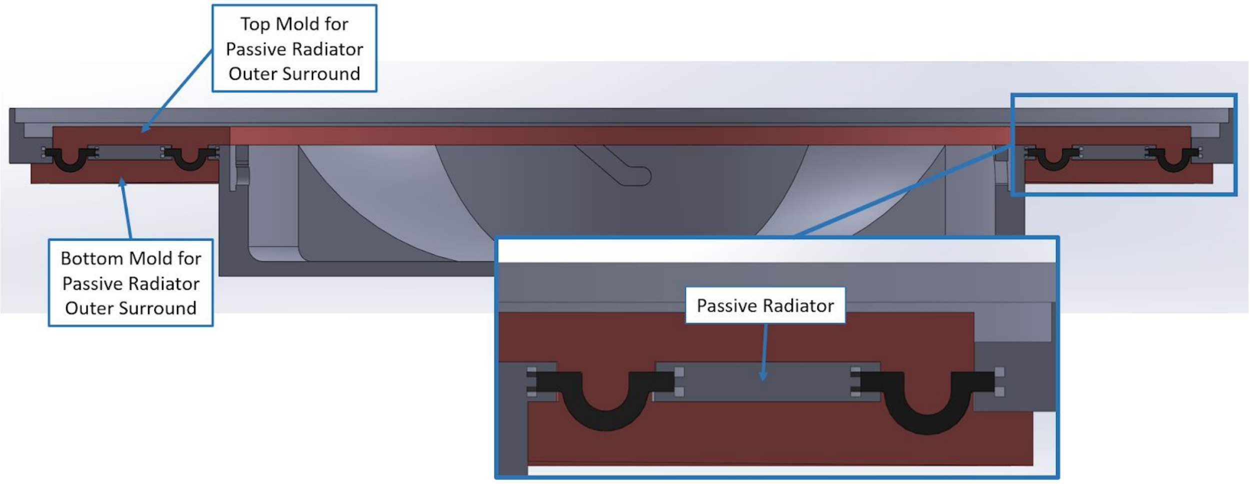


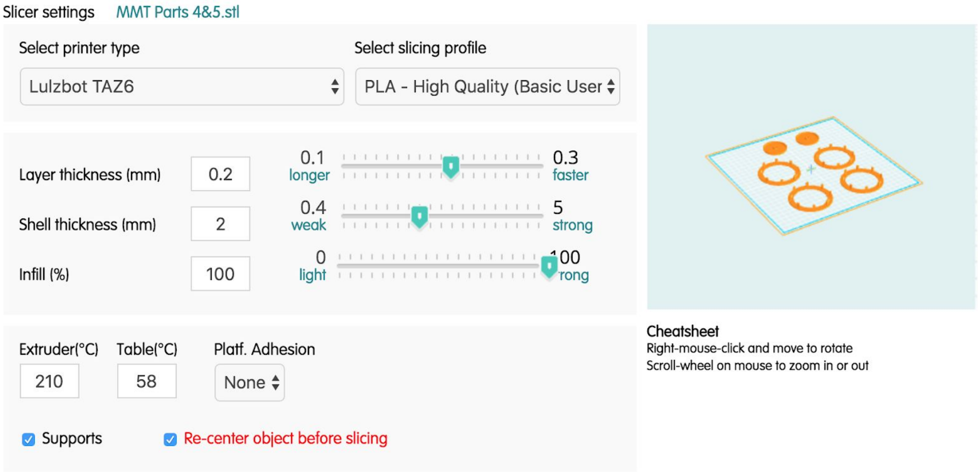
Figure 63. Section View of Molds for Bottom Passive Radiator Surrounds

4.5 Manufacturing

The project team manufactured components of the passive radiator design using both 3D printed parts and injection molded surrounds. Many iterations of the moving magnet components were 3D printed. These parts, as well as the molds that were created, were used to manufacture the surrounds through injection molding techniques. Many iterations of the surrounds were created through injection molding. Unfortunately, due to the COVID-19 pandemic that occured, the project team was not able to complete the manufacturing process of the passive radiator design.

4.5.1 3D Printed Passive Radiator Parts

The project team utilized 3D printers for the rigid components of the passive radiator design. Most of the 3D printed parts that were manufactured were for the moving magnet assembly at the top of the passive radiator design. The Foisie 3D printing software allowed our project team to select the layer thickness at 0.2mm, the shell thickness at 2mm and the infill rate at 100%. Utilizing these properties ensured the 3D printed parts were rigid and were printed with the correct tolerances.



Slicer settings MMT Parts 4&5.stl

Select printer type: Lulzbot TAZ6

Select slicing profile: PLA - High Quality (Basic User

Layer thickness (mm): 0.2

Shell thickness (mm): 2

Infill (%): 100

Extruder(°C): 210

Table(°C): 58

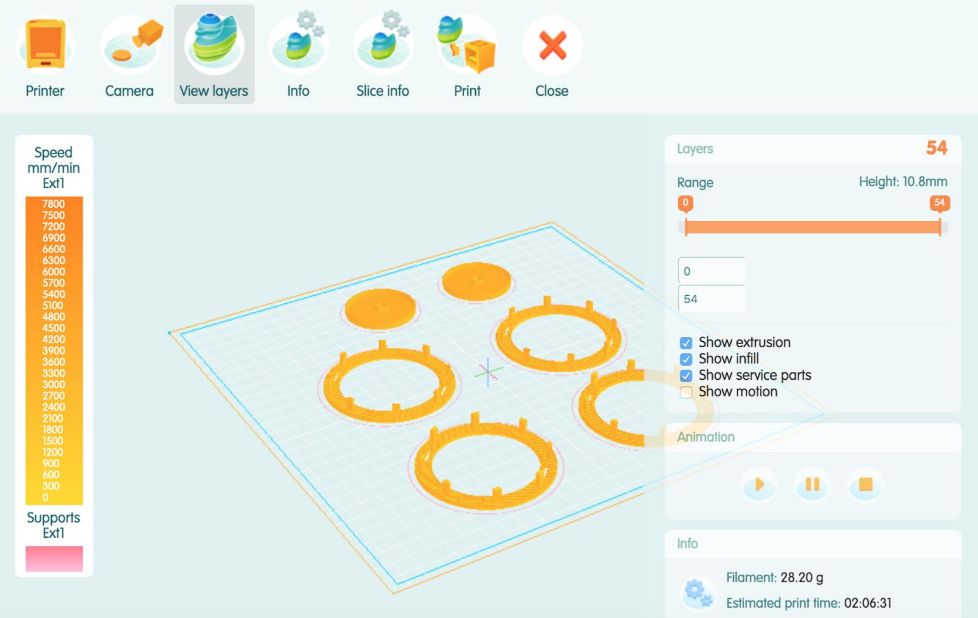
Platf. Adhesion: None

☑ Supports

☑ Re-center object before slicing

Cheatsheet
Right-mouse-click and move to rotate
Scroll-wheel on mouse to zoom in or out

Figure 64. D Printing Software (3DPrinterOS) Slicer Settings for 3D Printing Parts



Layers 54

Range Height: 10.8mm

0

54

☑ Show extrusion
☑ Show infill
☑ Show service parts
☐ Show motion

Info

Filament: 28.20 g

Estimated print time: 02:06:31

Figure 65. DPrinterOS Print Preview

Many iterations of the cone for the moving magnet assembly were 3D printed. The project team started by 3D printing the cone design from the previous years' model to test the 3D printer feasibility. The previous design is shown in Figures 66 and 67.

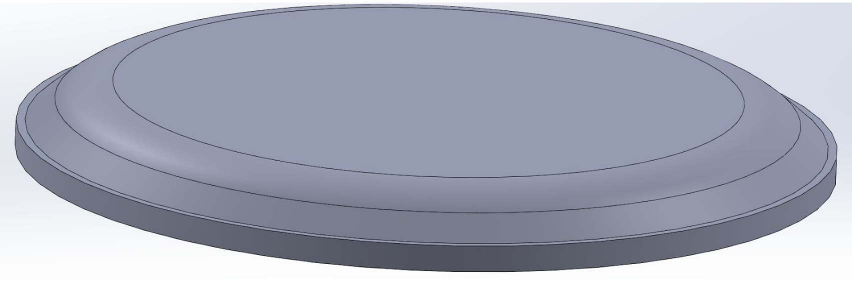


Figure 66. Previous Cone Design

Figure 67. Previous Cone Design - Front View

Due to the part being small and the limitations of the 3D printers, the part was not printed properly, which would have led to insufficient molded surrounds. Improvements were made to the cone design, including an indent for material attachment and an increased angle for better 3D printing results, as shown in Figures 68 and 69, and were reprinted.

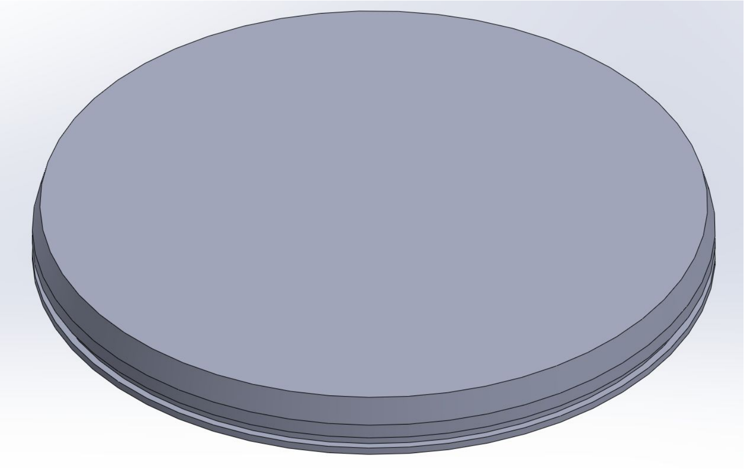


Figure 68. Updated Cone Design

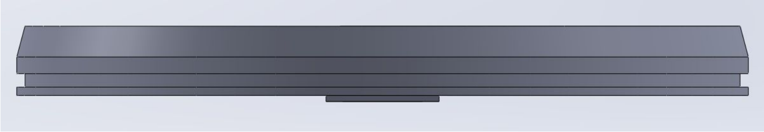


Figure 69. Updated Cone Design - Front View

Figures 67 and 68 show the first iteration of the 3D printed moving magnet cone, which as mentioned above did not print as expected. Pictured below in Figure 71 is the final iteration for the 3D printed moving magnet components.

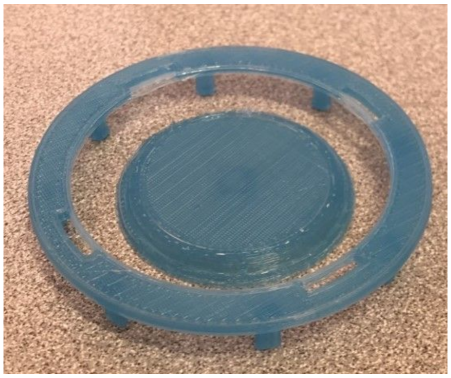


Figure 70. D Printed Parts for Moving Magnet Assembly - First Iteration

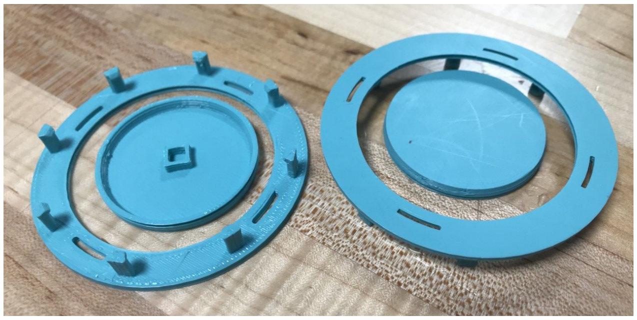


Figure 71. D Printed Parts for Moving Magnet Assembly - Final Iteration

4.5.2 Injection Molding

Many iterations of the surround were molded using injection molding techniques that were continually improved on throughout the project. The first iterations of molds that were manufactured were injection molding tests, as discussed in Background Section 3.6.2.2. The SolidWorks model for initial testing is represented in Figure 72 below.

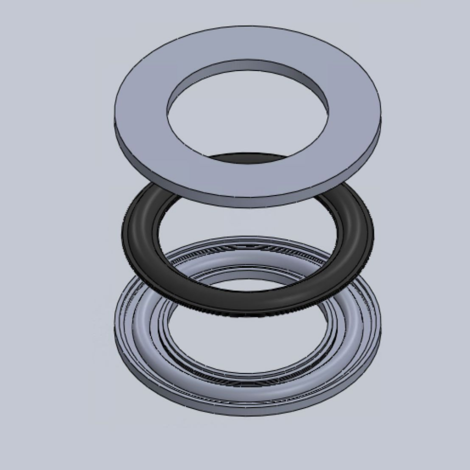


Figure 72. Initial CAD Model for Injection Molding Testing

This design consisted of two parts, a top mold and bottom mold. The theory behind this was simple, the material is poured into the bottom mold and the top mold is clamped down on top, creating a cavity inside of the two molds. The material used for initial testing was MoldMax 14NV, and it was hand-mixed prior to pouring. The result of the first molding test is represented in Figure 73 below.

Figure 73. First Injection Molding Results

The quality of the first molded material was poor, as there were many tears throughout. The results from initial testing clearly indicated that more material needed to be dispersed through the mold. Using the same 3D printed mold and material as above, a second test was conducted. The results of the second test are shown in Figure 74 below.

Figure 74. Second Injection Molding Results

With an increased amount of material poured, the quality of the mold was much greater and there was little to no tears throughout the material.

Once initial molds were tested, the project team created molds specific to the passive radiator design. The second iteration of surrounds that were manufactured were made using the mold shown in Figure 75. This mold featured a small ring and middle plate that the material could latch onto.

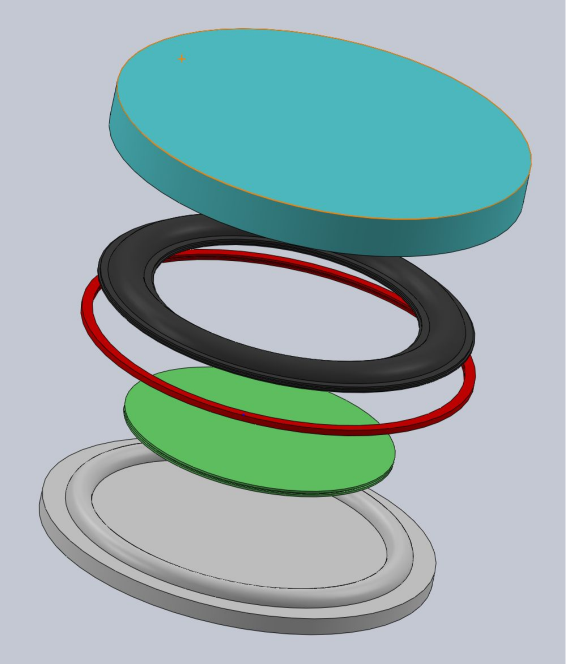


Figure 75. Second Iteration of CAD Model for Injection Molding

Multiple molds were 3D printed and tested. Similar to our initial testing, the material used was MoldMax 14NV and it was hand mixed prior to testing. The material was poured into the mold cavity and clamped for 24 hours. The results of using this mold are represented in Figures 76 and 77 below.

Figure 76. Third Injection Molding Results

Figure 77. Fourth Injection Molding Results

The molds above are of much higher quality compared to the ones from initial testing. Once the material was cured, the ends that connected to the small ring and middle plate were disconnected. The molds shown above had small air bubbles scattered throughout the material. To combat this problem, a new method of injection molding was introduced. Instead of pouring the material, a small hole was added to the top mold that a syringe could fit into. The material used was MoldMax 14NV and was mixed by hand and poured into the syringe. The tip of the syringe was pushed into the hole and the material was forced into the open cavity of the mold. Figure 78 below represents the 3D printed mold and the results from this method.

Figure 78. Injection Molding using Syringe Results

The same mold was used for this testing, except a small hole was drilled into the top plate. The results of this mold were promising, as there were only a small amount of air bubbles in the material. This method of injection molding proved to be a better option compared to pouring material directly into the cavity of the mold. The next tests that were conducted used a mixing gun. The mixing gun is a more efficient method compared to using a syringe, as you do not need to mix the material by hand prior to putting it into the gun. The team also wanted to test different materials that had a higher durometer hardness than the MoldMax 14NV. The material used for the following tests was MoldMax 40NV, which had a higher durometer hardness and modulus of elasticity. Figure 79 below shows the results from injection molding using the mixing gun with MoldMax 40NV.

Figure 79. Injection Molding using Mixing Gun Results

The two-part material that was used did not mix properly, shown by the difference in color. Therefore, the material did not cure completely. The mold also had some air bubbles and tears throughout. This test was promising, but slight procedure changes needed to be made to get a higher quality surround mold. The next and final injection molding procedure consisted of vacuum degassing and continued use of the MixPac mixing gun. The result of the degassing and dispensing is shown in the figure below.

Figure 80. Final Injection Molding Result

The material showed strong adhesiveness to the 3D printed parts through edited geometry and over-molding. The material on the connector (orange piece) can be cleaned up using an X-Acto knife, as it has structural function. Though the project team could not advance with injection molding, this mold was of high quality and the process would be repeated for the other surrounds of the passive radiator system.

4.6 Design of Conical Surround and Speaker Enclosure

The moving magnet transducer assembly needed both a speaker enclosure as well as dual conical surrounds to functionally work with the previously designed lever assembly done by another MQP team from this year. The requirements for the design were to be air tight and to house the existing design.

4.6.1 Design of the Conical Surrounds

The team first needed to design the conical surrounds that would be driven by the lever assembly (shown below):

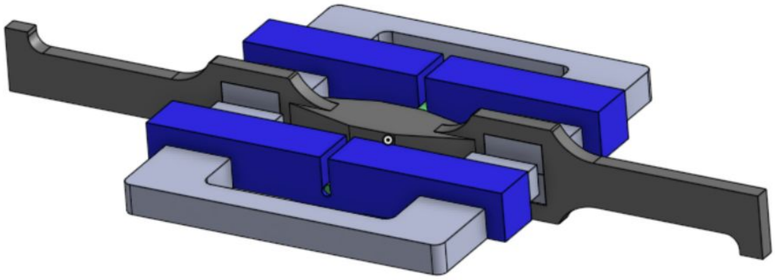


Figure 81. Lever Assembly

The lever assembly would be driven by the moving magnet transducer and begin driving the lever (shown in the image below) either up or down, which in turn would press on specific parts of the surround.

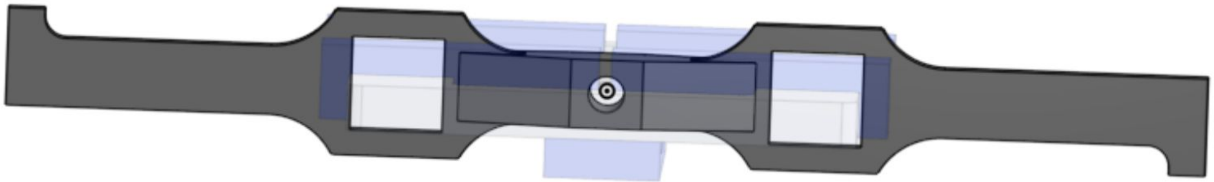
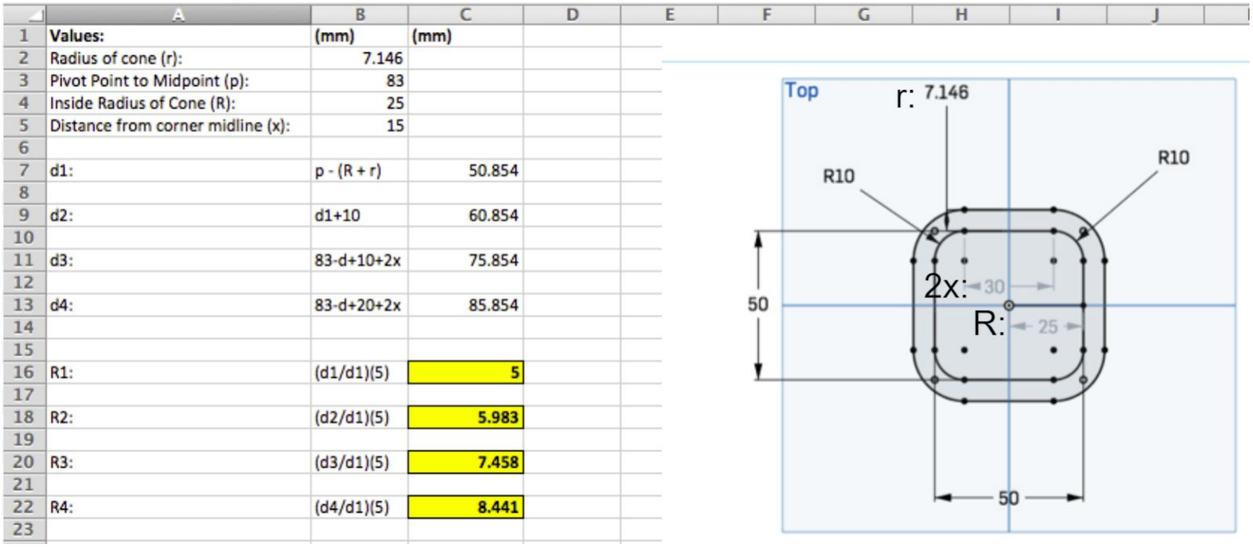


Figure 82. Lever

Due to the fact that the lever needed to press on specific portions of the surround, it needed to be specifically shaped in a way that would fit the profile of the lever. Using scaling, the group was able to determine the required radii at specific locations of the surround in order to account for how far the location was from the center of the pivot.



	A	B	C
1	**Values:**	**(mm)**	**(mm)**
2	Radius of cone (r):	7.146	
3	Pivot Point to Midpoint (p):	83	
4	Inside Radius of Cone (R):	25	
5	Distance from corner midline (x):	15	
6			
7	d1:	p - (R + r)	50.854
8			
9	d2:	d1+10	60.854
10			
11	d3:	83-d+10+2x	75.854
12			
13	d4:	83-d+20+2x	85.854
14			
15			
16	R1:	(d1/d1)(5)	**5**
17			
18	R2:	(d2/d1)(5)	**5.983**
19			
20	R3:	(d3/d1)(5)	**7.458**
21			
22	R4:	(d4/d1)(5)	**8.441**
23			

Figure 83. R Value Calculations for Conical Surround

Using these derived R values, the team developed a surround that fulfilled both the required R values as well as a 50 mm x 50 mm inside diameter (flat cone) that made sense for the scope of the design. The 3D model as well as a sketch of the final conical surround are shown below.

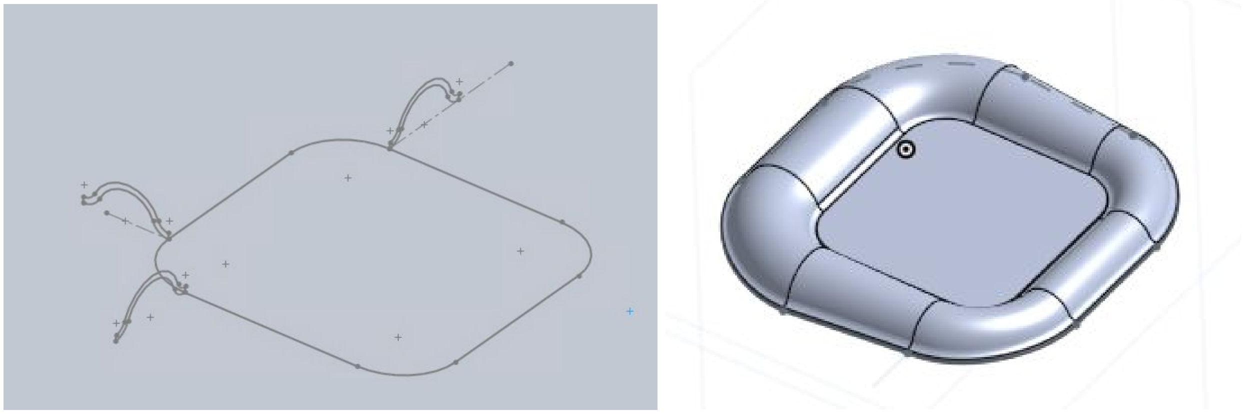


Figure 84. Conical Surround 3D Design

The arch like features seen in the sketch in the image above depict the two corners of a loft. Based on the radius calculations the team derived earlier, the team applied the values to the radii of the arches, and lofted during the design of the surround.

4.6.2 Design of the Speaker Enclosure

Using the dimensions of the lever assembly created by another MQP team working on creating the low profile speaker system, the team developed a speaker enclosure that needed to be airtight, house the lever assembly, and house two of the conical surrounds (one on either side of the exterior of the surround). Using this information, a basic idea was formed by the team to develop a two-piece enclosure that would allow the lever assembly to be mounted on the inside of the enclosure, and would allow two conical surrounds to be mounted to the exterior of the enclosure.

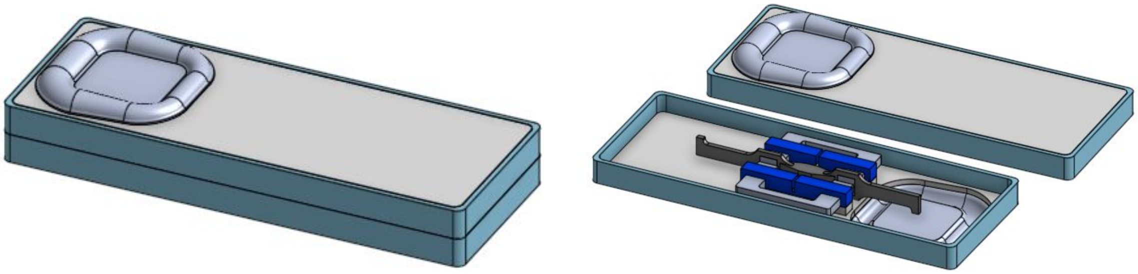


Figure 85. Enclosure for Lever Assembly

The lever assembly mounts into two raised channels inside of the surround (see image below) so that the lever is free to move up and down on its fixed axis. As depicted in the image above, when the two piece surround is mated together and sealed, the surround satisfies the requirements of being airtight, housing two conical surrounds, and the lever assembly.

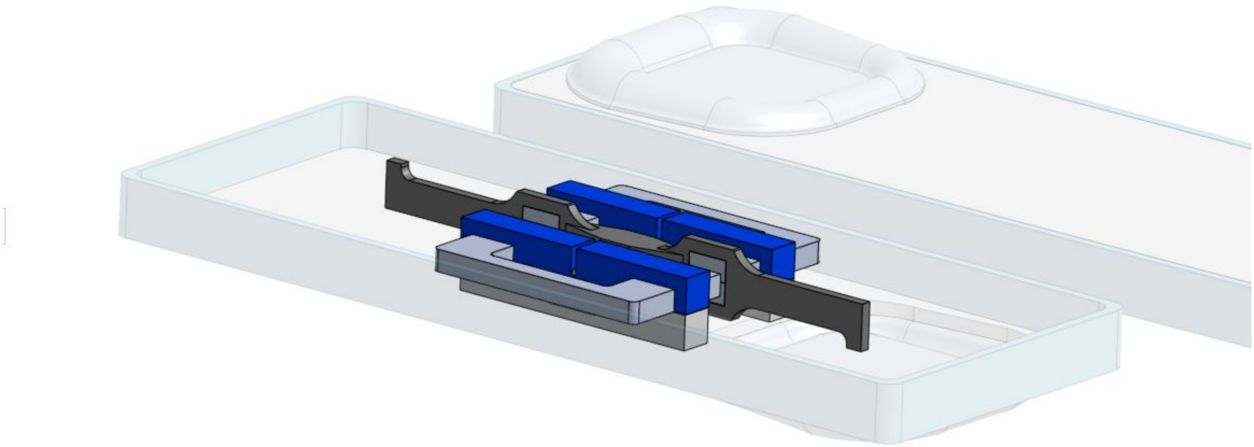


Figure 86: Lever Assembly Mounted to Raised Channels

5. Conclusion

The goal of this MQP was to create a low-profile, wall-mounted home speaker system with a focus on an improved passive radiator design. This design is classified as a low-profile, force-balanced, sealed passive radiator bass box with a low frequency response. Through extensive research, software simulation, 3D modeling, 3D printing, and injection molding, the project team was able to work towards the main goal of manufacturing a speaker system with an improved passive radiator design. The project team was not able to complete the project due to the COVID-19 pandemic closing down campus. Utilizing SolidWorks, a complete 3D model of the passive radiator system was created, with improvements from the design made from previous years. Improvements in the 3D model were angled slots for improved attachment, increased internal volume for improved bass sound, and latches for improved attachment to molded surrounds. Many iterations of injection molding techniques were utilized for the manufacturing of the moving magnet surround. The final iteration of injection molding yielded a functional surround for the moving magnet assembly. 3D modeled molds were created for the other surrounds, and injection molding techniques would have yielded functional parts for the entirety of the system. The desired resonant frequency of the project teams' passive radiator system is calculated to be 50 Hz. This desired resonant frequency allows for the optimal acoustic experience. By utilizing resources from previous MQP's, the project team was able to 3D model an optimized passive radiator system for a low-profile speaker system.

6. Future Work and Recommendations

Based on these conclusions, the project team has developed many recommendations for future work regarding this speaker system and passive radiator design. If the academic year did not get cut short due to the COVID-19 pandemic, the project team would have continued to injection mold the moving magnet surround, the top surround and the bottom surrounds for the passive radiator system. Along with manufacturing the surrounds, testing would have been done on the passive radiators to test for stiffness using the Instron machine. The project team would have been able to 3D print the remaining parts for the system. After 3D printing the rigid parts and injection molding surrounds, the final assembly would be constructed. Testing on the laser scanner would be done, in order to test for the desired resonant frequency of the system. Testing the system for resonant frequency would determine if the system needs material changes and/or changes to the moving mass of the system.

7. Acknowledgements

The project team would like to thank Professor Joseph Stabile for his guidance, knowledge and constructive criticism throughout the project. Professor Stabile has devoted countless time and effort towards the low-profile speaker system and the passive radiator design. His experience working for Bose on complex speaker systems and the extensive research he conducts was extremely useful in the guidance he provided throughout the course of the project.

8. Appendices

8.1 Appendix A: Scanning Tests

Figures 87 and 88 show two of the first tests that were done on the laser scanner using the Bose speaker assembly. These frequency graphs did not yield smooth results and the project team continued to improve the scanning process in order to achieve better results. Changing the trigger of the laser scanner yielded more accurate frequency responses for the speaker systems.

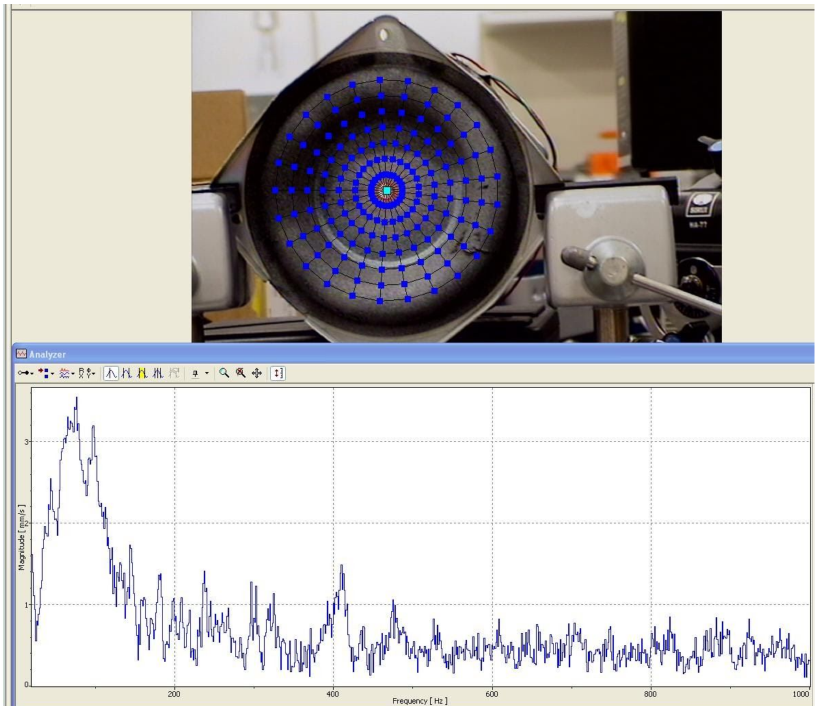


Figure 87. Dual Speaker Passive Side Test

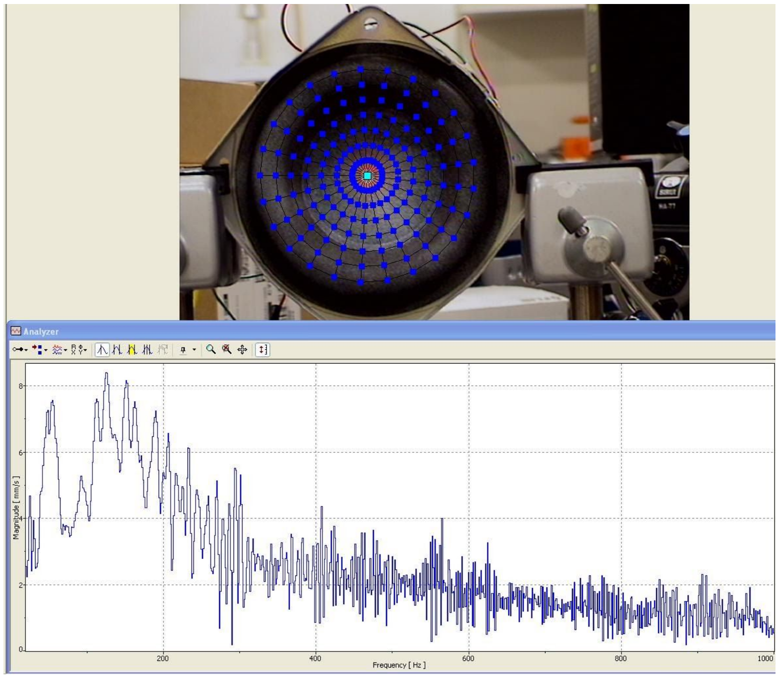
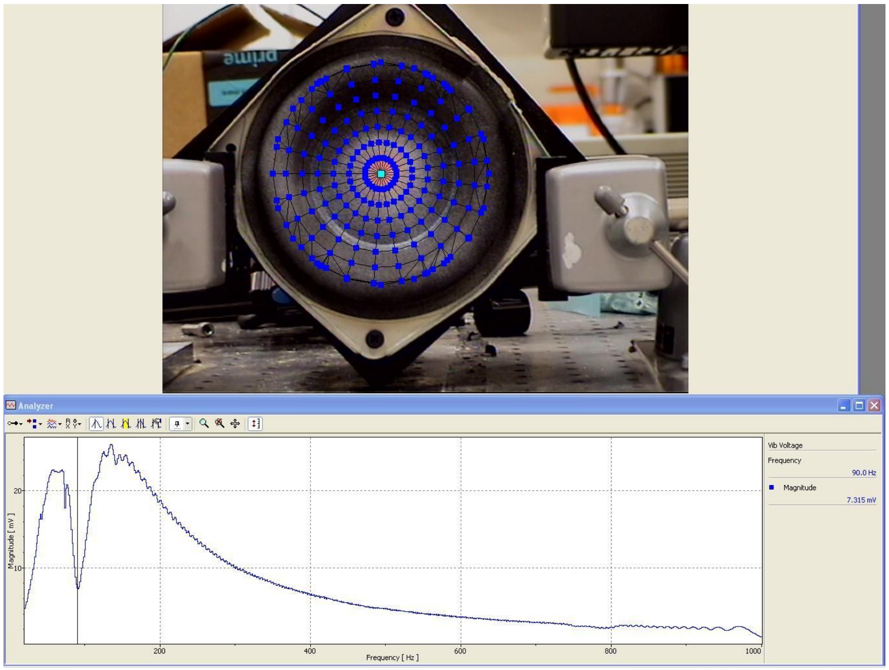


Figure 88. Dual Speaker Active Side Test



Vib Voltage
Frequency 90.0 Hz
■ Magnitude 7.315 mV

Figure 89. Active Speaker Additional Results

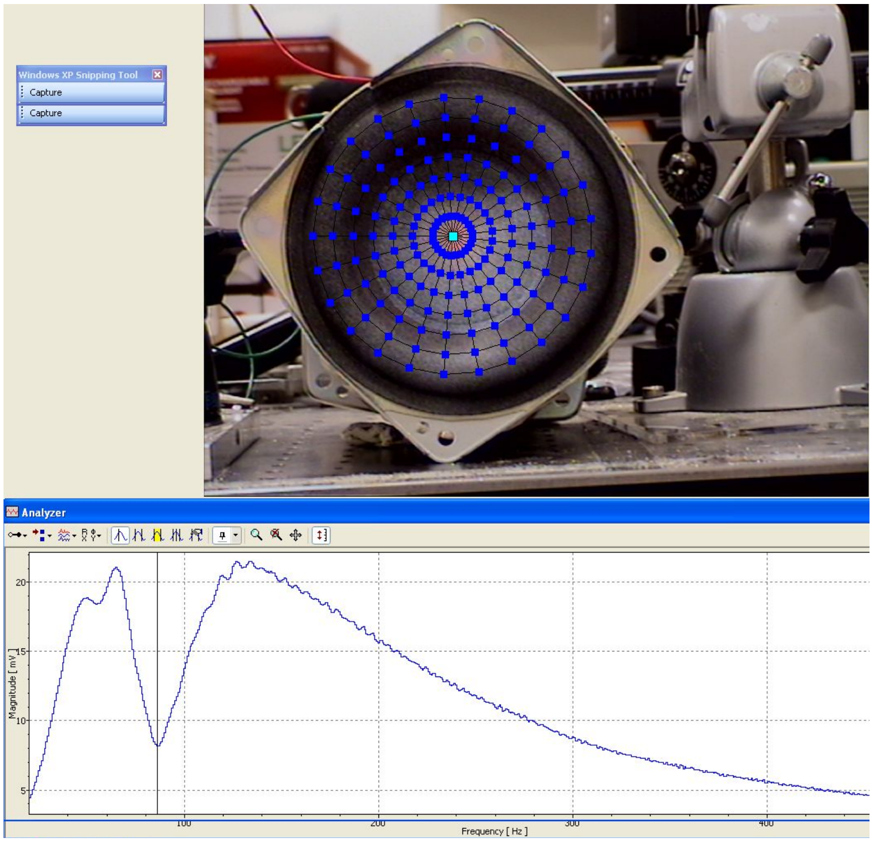
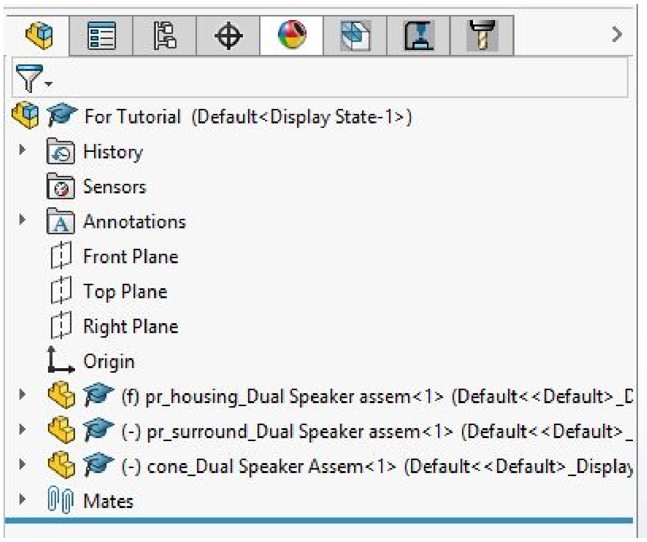


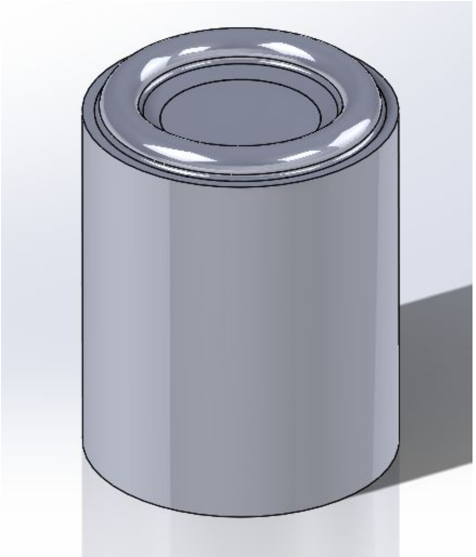
Figure 90. Active Speaker Clean Results

8.2 Appendix B: Instruction Manuals

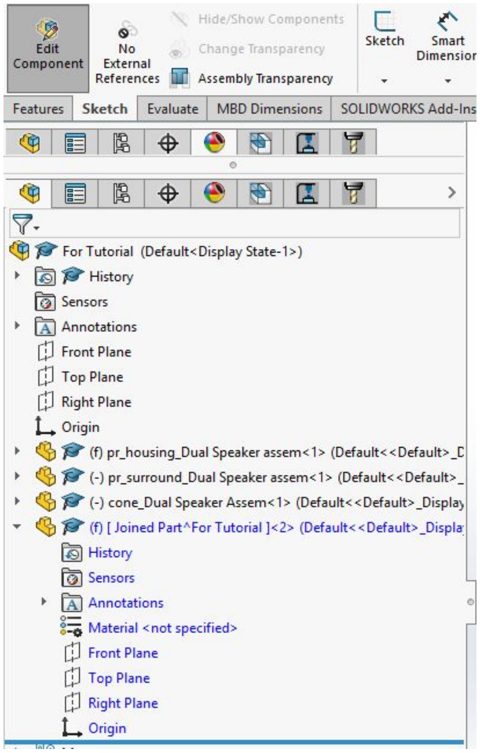
8.2.1 How to Add Internal Volume in SolidWorks

Step 1: Open up SOLIDWORKS assembly



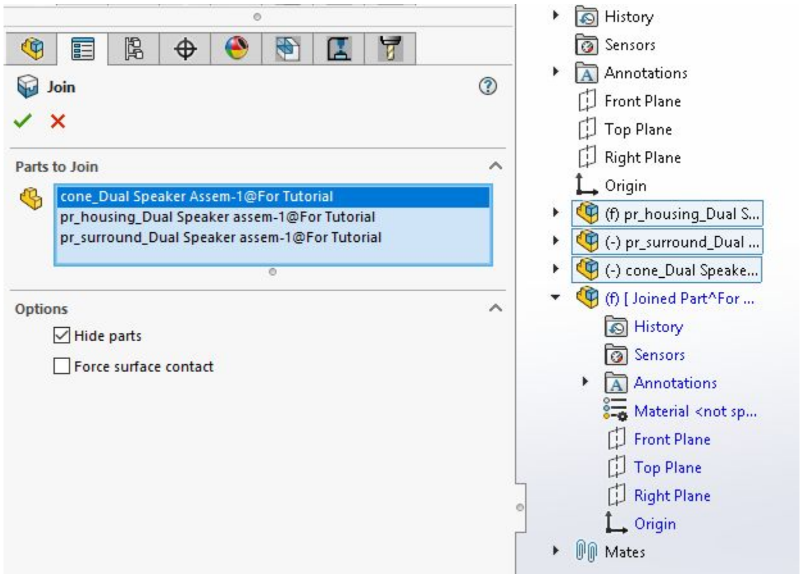


Step 2: Add a new part until the insert components button.
Step 3: Rename new part “Joined Part” and edit component.



Step 4: Under Insert > Features, click on the Join Feature.

Step 5: Select all the parts of the assembly. Click OK. Unclick Edit Component.



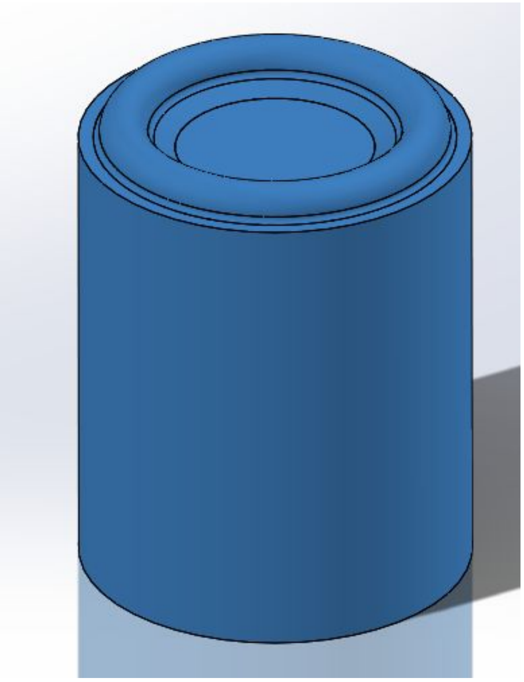
Join

Parts to Join

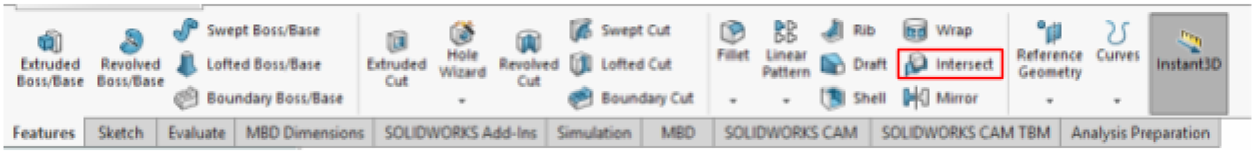
cone_Dual Speaker Assem-1@For Tutorial
pr_housing_Dual Speaker assem-1@For Tutorial
pr_surround_Dual Speaker assem-1@For Tutorial

Options

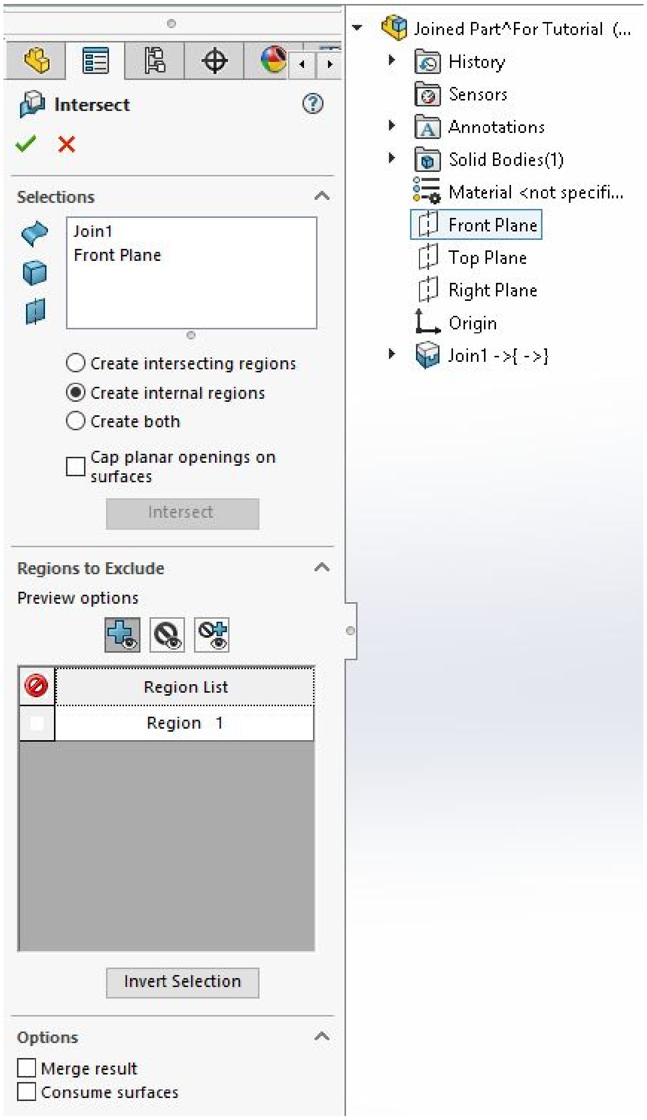
☑ Hide parts
☐ Force surface contact



Step 6: Open Joined Part. Once inside the part, select the Intersect Feature in the Features tab.



Step 7: For selections, select the part and the front plane. Also select create internal regions.



Intersect

Selections

Join1
Front Plane

○ Create intersecting regions
● Create internal regions
○ Create both

☐ Cap planar openings on surfaces

Intersect

Regions to Exclude

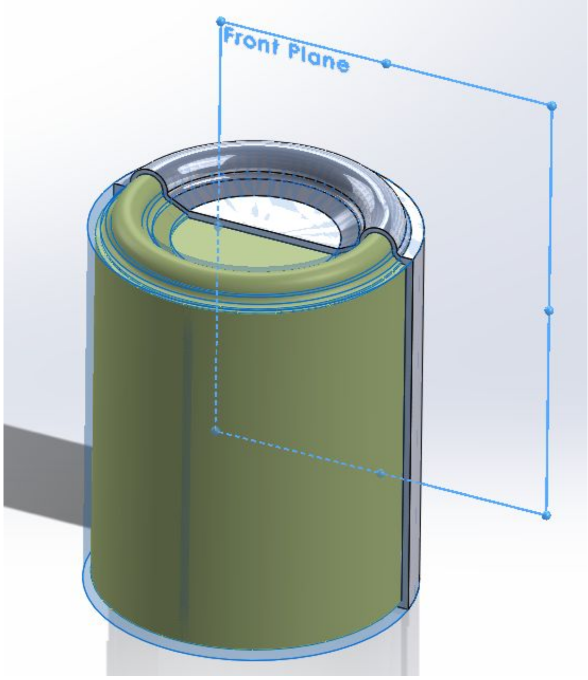
Preview options

	Region List
☐	Region 1

Invert Selection

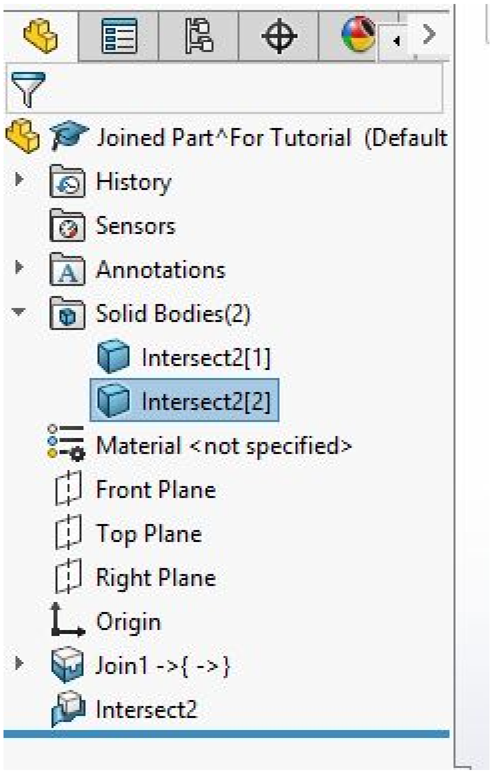
Options

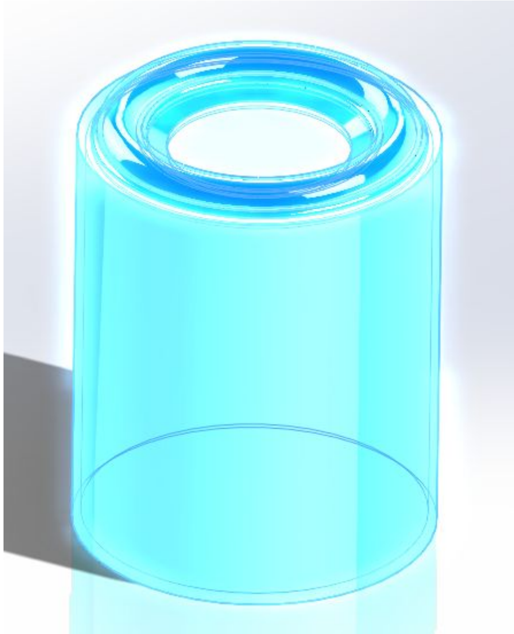
☐ Merge result
☐ Consume surfaces



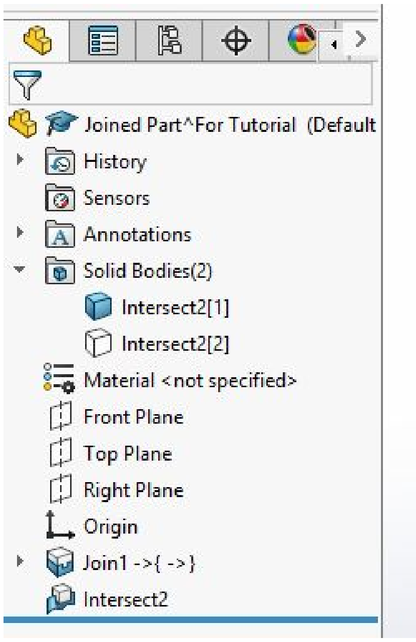
Select OK.

Step 8: Hide the Solid body that when selected, shows this. In this case, it’s Intersect2[2].





When hidden, it should look like this.



Joined Part^For Tutorial (Default

History

Sensors

Annotations

Solid Bodies(2)

Intersect2[1]

Intersect2[2]

Material <not specified>

Front Plane

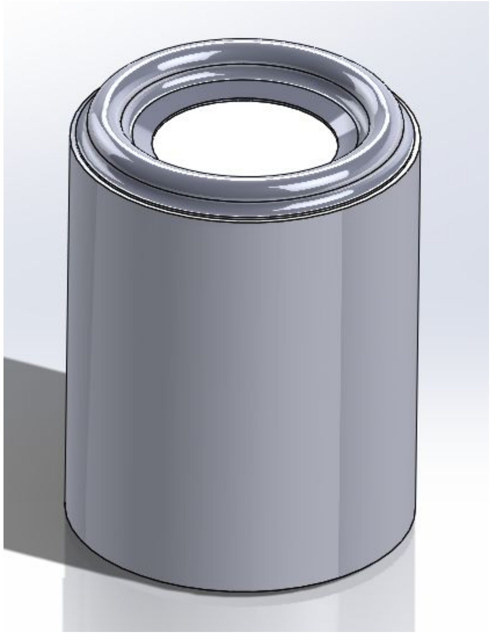
Top Plane

Right Plane

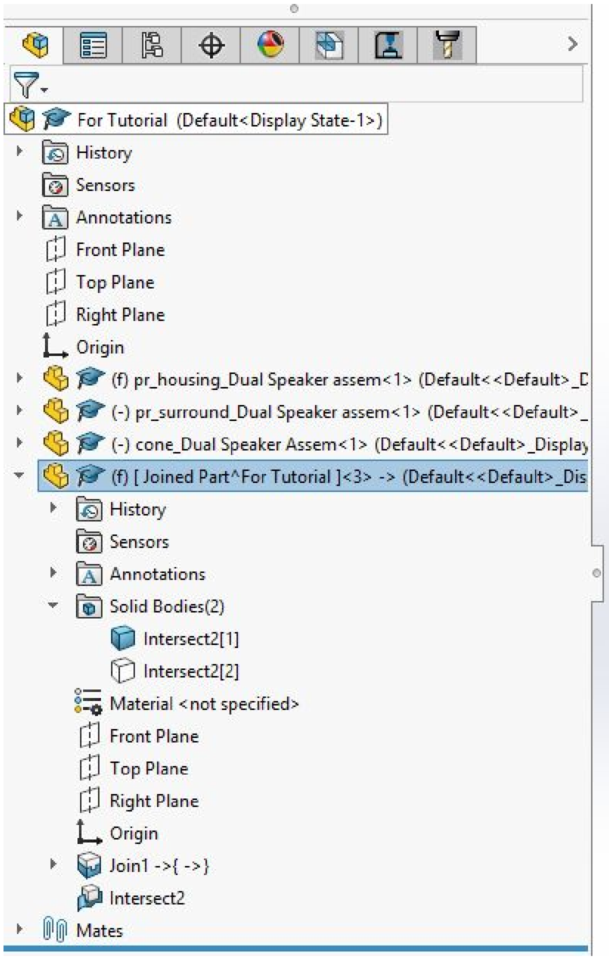
Origin

Join1 ->{ ->}

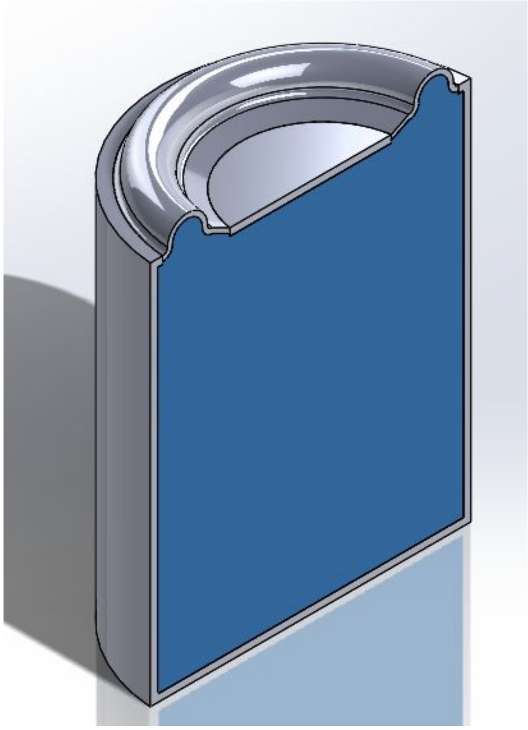
Intersect2



Step 9: Save part and go back into assembly. It should look like this in a section view.

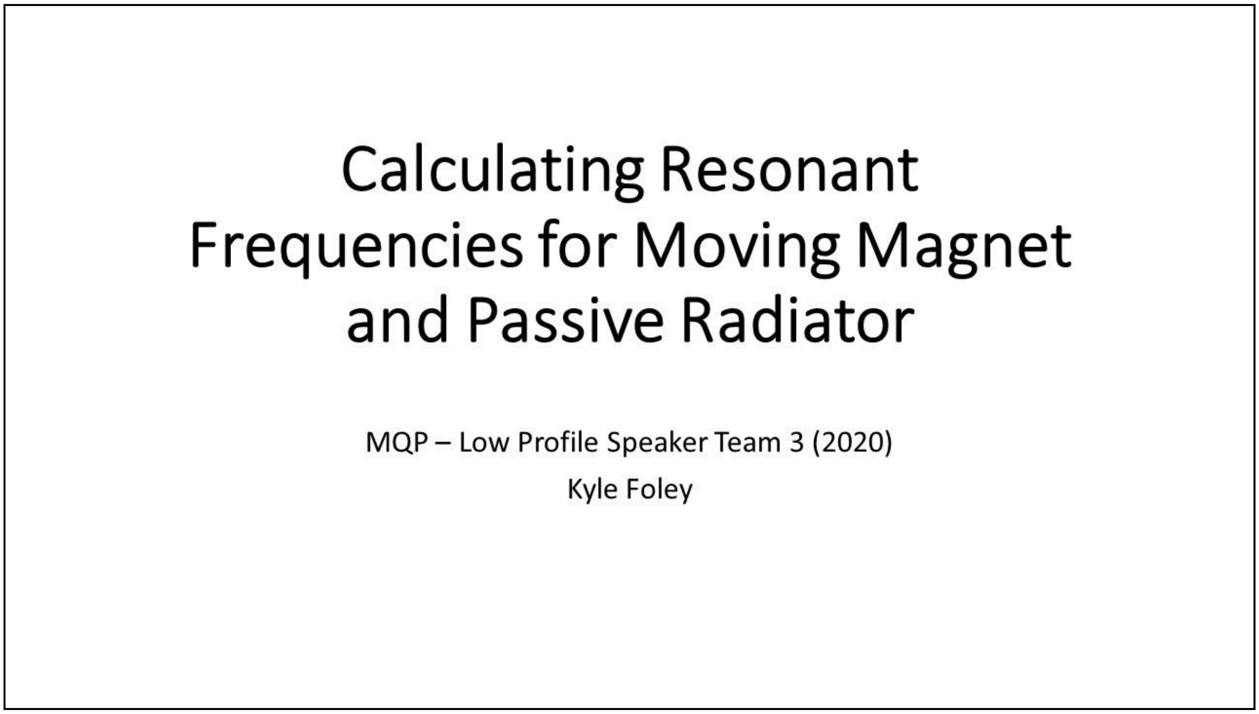


For Tutorial (Default<Display State-1>)
- History
- Sensors
- Annotations
- Front Plane
- Top Plane
- Right Plane
- Origin
- (f) pr_housing_Dual Speaker assem<1> (Default<<Default>_D
- (-) pr_surround_Dual Speaker assem<1> (Default<<Default>_
- (-) cone_Dual Speaker Assem<1> (Default<<Default>_Display
- (f) [Joined Part^For Tutorial]<3> -> (Default<<Default>_Dis
  - History
  - Sensors
  - Annotations
  - Solid Bodies(2)
    - Intersect2[1]
    - Intersect2[2]
  - Material <not specified>
  - Front Plane
  - Top Plane
  - Right Plane
  - Origin
  - Join1 ->{ ->}
  - Intersect2
- Mates



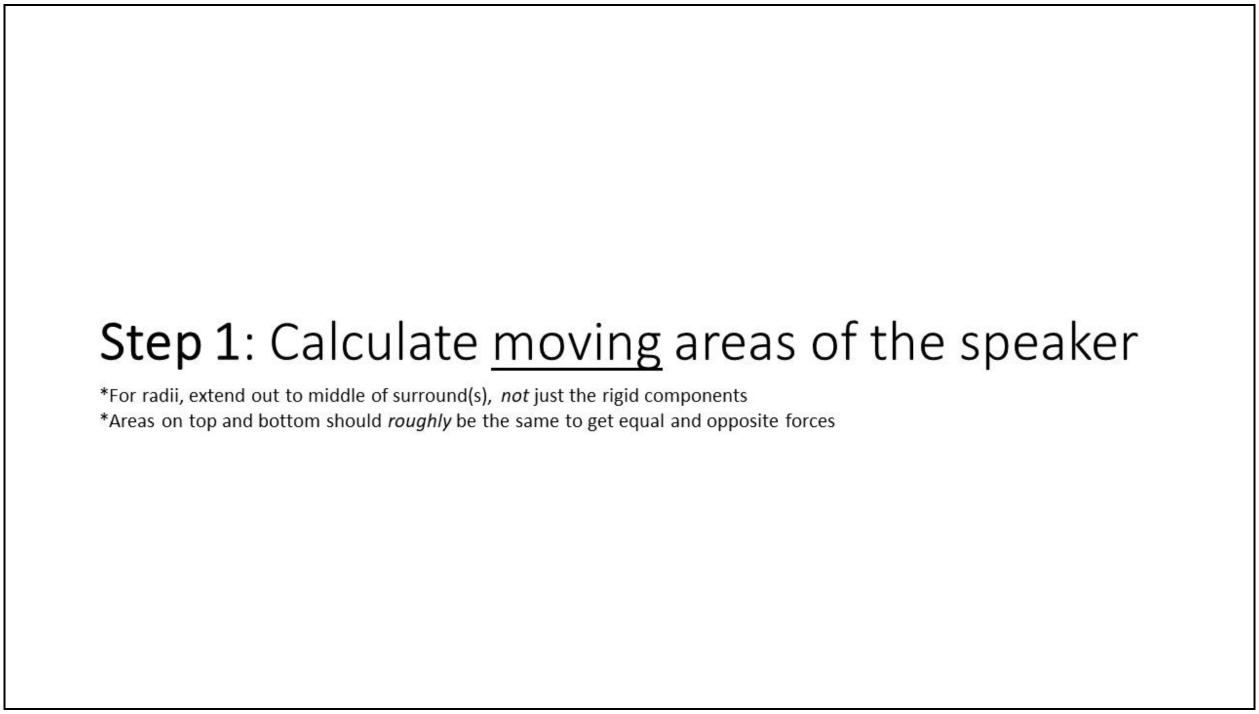
Step 10: Save assembly and use for acoustic modeling in ANSYS.

8.2.2 How to Calculate Resonant Frequencies



Calculating Resonant Frequencies for Moving Magnet and Passive Radiator

MQP – Low Profile Speaker Team 3 (2020)
Kyle Foley

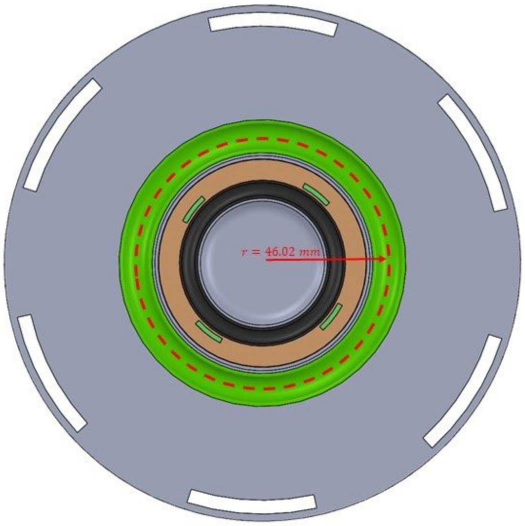


Step 1: Calculate moving areas of the speaker

*For radii, extend out to middle of surround(s), *not* just the rigid components
*Areas on top and bottom should *roughly* be the same to get equal and opposite forces

Calculating MMT (top) area

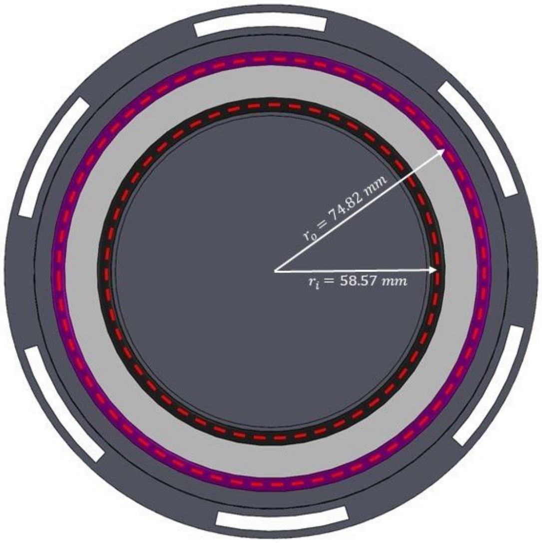
*Area within the middle of the top outer surround (shown in green)



$$A_{MMT} = \pi r^2 = \pi(46.02\ mm)^2 = 6653.392\ mm^2$$

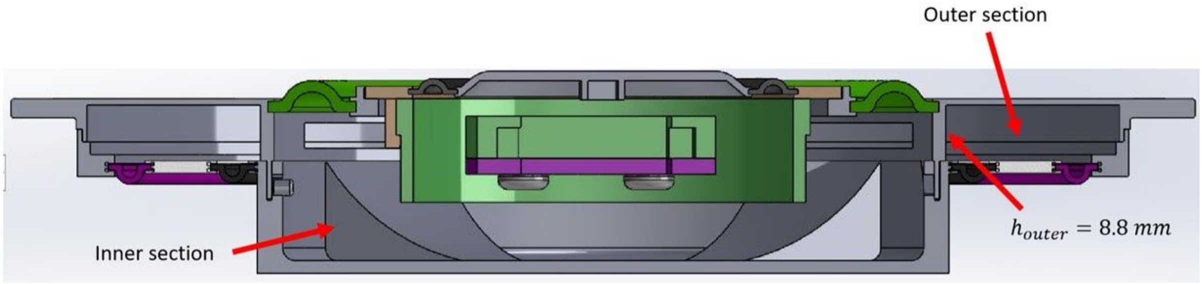
Calculating passive radiator (bottom) area

*Area between bottom outer surround (purple) and bottom inner surround (black)



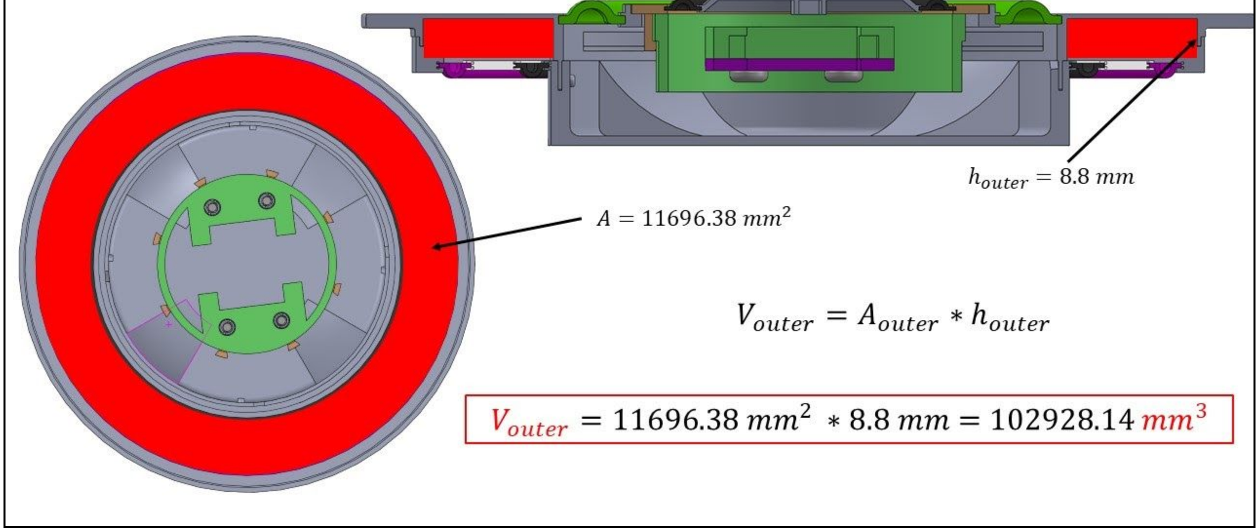
$$A_{PR} = \pi\left(r_o^2 - r_i^2\right)$$
$$= \pi[(74.82\ mm)^2 - (58.57\ mm)^2]$$
$$= 6809.677\ mm^2$$

Step 2: Calculate air volume(s) within the speaker



Calculating air volume of outer section

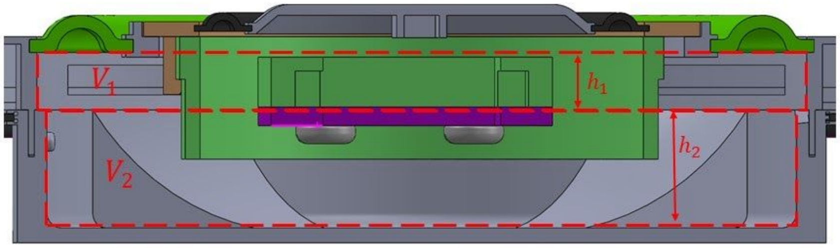
*the air enclosed by the passive radiator (shown in red)



$$V_{outer} = A_{outer} * h_{outer}$$

$$\boxed{V_{outer} = 11696.38\ mm^2 * 8.8\ mm = 102928.14\ mm^3}$$

Calculating air volume of inner section



Heights:

$h_1 = 7.67\ mm$

$h_2 = 15.78\ mm$

Radii:

$r_1 = 51.59\ mm$

$r_2 = 50.62\ mm$

$$V_1 = \pi r_1^2 h = \pi (51.59\ mm)^2 * 7.67\ mm = 64132.22\ mm^3$$

$$V_2 = \pi r_2^2 h = \pi (50.62\ mm)^2 * 15.62\ mm = 127028.50\ mm^3$$

$$\boxed{V_{inner} = V_1 + V_2 = 64132.22\ mm^3 + 127028.50\ mm^3 = 191160.72\ mm^3}$$

Total air volume in the assembly: $\boldsymbol{V_{net}} = V_{inner} + V_{outer} = 191160.72\ mm^3 + 102928.14\ mm^3 = \mathbf{294088.86\ mm^3}$

Step 3: Calculate air stiffness for the MMT and passive radiator

Equation to calculate stiffness: $k = \dfrac{\rho_{air} c^2 A^2}{V}$

Calculating air stiffness for the MMT

*NET volume of air was used in calculation

$\rho_{air} = 1.18 \; {}^{kg}/_{m^3}$

$c = 345 \; {}^{m}/_{s}$

$A_{MMT} = 6653.392 \; mm^2 = 0.006653392 \; m^2$

$V_{net} = 294088.86 \; mm^3 = 0.00029408886 \; m^3$

$$k_{MMT} = \frac{\rho_{air} c^2 {A_{MMT}}^2}{V_{net}} = \frac{(1.18 \; {}^{kg}/_{m^3})(345 \; {}^{m}/_{s})^2 (0.006653392 \; m^2)^2}{0.00029408886 \; m^3} = 21141 \; {}^{N}/_{m}$$

Calculating air stiffness for the passive radiator

*NET volume of air was used in calculation

$\rho_{air} = 1.18 \; {}^{kg}/_{m^3}$

$c = 345 \; {}^{m}/_{s}$

$A_{PR} = 6809.677 \; mm^2 = 0.006809677 \; m^2$

$V_{net} = 294088.86 \; mm^3 = 0.00029408886 \; m^3$

$$k_{PR} = \frac{\rho_{air} c^2 {A_{PR}}^2}{V_{net}} = \frac{(1.18 \; {}^{kg}/_{m^3})(345 \; {}^{m}/_{s})^2 (0.006809677 \; m^2)^2}{0.00029408886 \; m^3} = 22146 \; {}^{N}/_{m}$$

Step 4: Calculate resonant frequencies of the MMT and passive radiator

*stiffness and mass of both components must be known

Equation to calculate resonant frequency: $f_{res} = \frac{1}{2\pi} * \sqrt{\frac{k}{m}}$

Calculating resonant frequency of the MMT

Mass of MMT (using scale): $m_{MMT} = 65\ g = 0.065\ kg$

$$f_{res,MMT} = \frac{1}{2\pi} * \sqrt{\frac{k_{MMT}}{m_{MMT}}} = \frac{1}{2\pi} * \sqrt{\frac{21141\ {}^{N}/_{m}}{0.065\ kg}} = 90.767\ Hz$$

Calculating resonant frequency of the passive radiator

Volume of passive radiator: $V_{PR} = 8302.93\ mm^3$

Density of PLA (material used for passive radiator): $\rho_{PLA} = 1.24\ {}^{g}/_{cm^3}$

Mass of passive radiator: $m_{PR} = V_{PR} * \rho_{PLA} = (8.30293\ cm^3)\left(1.24\ {}^{g}/_{cm^3}\right) = 10.296\ g = 0.010296\ kg$

$$f_{res,PR} = \frac{1}{2\pi} * \sqrt{\frac{k_{PR}}{m_{PR}}} = \frac{1}{2\pi} * \sqrt{\frac{22146\ {}^{N}/_{m}}{0.010296\ kg}} = 233.42\ Hz$$

Step 5 (if necessary): Change mass to obtain desired resonant frequency

*If a lower resonant frequency is desired, material such as steel can be added to a section of the speaker

Changing mass to get desired frequency

For the passive radiator, a resonant frequency of 50 Hz is desired (currently at 233.42 Hz)

$$f_{res,PR} = \frac{1}{2\pi} * \sqrt{\frac{k_{PR}}{m_{PR}}} = \frac{1}{2\pi} * \sqrt{\frac{22146\ {}^{N}/_{m}}{m_{PR,new}}} = 50\ Hz$$

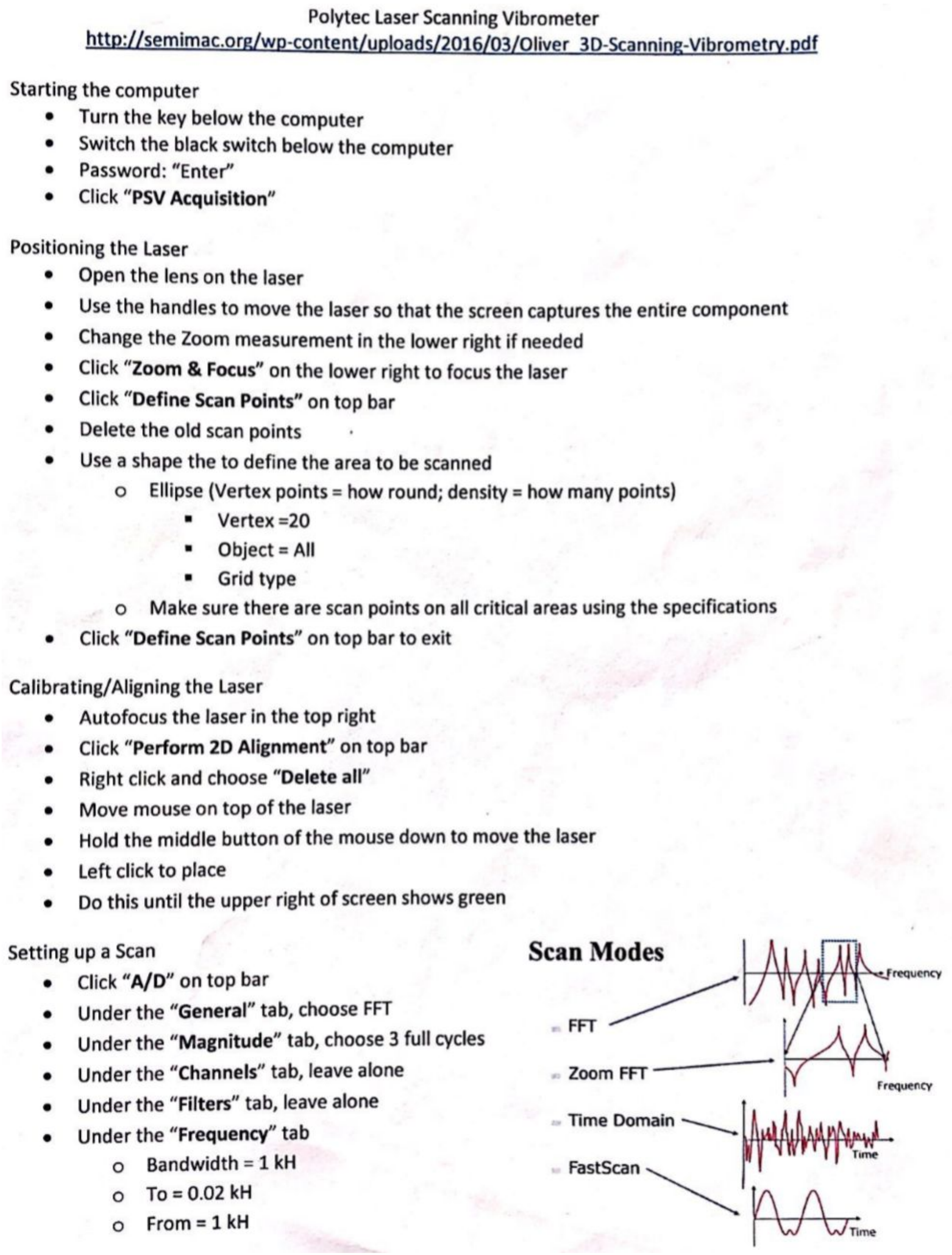
To obtain 50 Hz, a passive radiator mass of 0.22438 kg is required

The passive radiator has a current mass of $0.010296\ kg$, so an additional **0.2141 kg** is needed

Density of steel: $\rho_{steel} = 8.05\ {}^{g}/_{cm^3}$

Volume of steel needed: $V_{steel} = \frac{m_{steel}}{\rho_{steel}} = \frac{0.2141\ kg}{0.00805\ {}^{kg}/_{cm^3}} = 26.596\ cm^3$ ⟶ Adjust geometry to get proper volume and fit into respective assembly

8.2.3 How to Use the Polytec Scanning Vibrometer



Polytec Laser Scanning Vibrometer

http://semimac.org/wp-content/uploads/2016/03/Oliver_3D-Scanning-Vibrometry.pdf

Starting the computer

- Turn the key below the computer
- Switch the black switch below the computer
- Password: "Enter"
- Click "**PSV Acquisition**"

Positioning the Laser

- Open the lens on the laser
- Use the handles to move the laser so that the screen captures the entire component
- Change the Zoom measurement in the lower right if needed
- Click "**Zoom & Focus**" on the lower right to focus the laser
- Click "**Define Scan Points**" on top bar
- Delete the old scan points
- Use a shape the to define the area to be scanned
    - Ellipse (Vertex points = how round; density = how many points)
        - Vertex =20
        - Object = All
        - Grid type
    - Make sure there are scan points on all critical areas using the specifications
- Click "**Define Scan Points**" on top bar to exit

Calibrating/Aligning the Laser

- Autofocus the laser in the top right
- Click "**Perform 2D Alignment**" on top bar
- Right click and choose "**Delete all**"
- Move mouse on top of the laser
- Hold the middle button of the mouse down to move the laser
- Left click to place
- Do this until the upper right of screen shows green

Setting up a Scan

- Click "**A/D**" on top bar
- Under the "**General**" tab, choose FFT
- Under the "**Magnitude**" tab, choose 3 full cycles
- Under the "**Channels**" tab, leave alone
- Under the "**Filters**" tab, leave alone
- Under the "**Frequency**" tab
    - Bandwidth = 1 kH
    - To = 0.02 kH
    - From = 1 kH

- Under the "**Trigger**" tab, make sure Ref 1 is chosen
- Under the "**Generator**" tab, choose Waveform, Sweep, Sweep-time
    - Sweep-time should mirror the Sample-time (0.8s)

Performing a Scan

- Click on the scan point at which you want to scan
- Click "**Generator On/Off**" or "**Continuous**"
- On the graph at the bottom of the screen, on the bar to the right, click "**Autoscale**"
- On the graph at the bottom of the screen, on the bar to the left, one can changes the axis (Time or Amplitude, Frequency)
- Take a screenshot of the graph
- Take note of the different frequency peaks as you can later do a scan at those frequencies

Perform a Fast Scan

- Click "**A/D**" on top bar
- Under the "**General**" tab, choose Fast Scan
- Put the frequency that you want to scan in both boxes
- Scan
- Save the scan with the name to the component and frequency
- Click "**Presentation**" on the top bar
- Click "**Play**" to animate
- Click "**File**", "**Save Animation**", and name to the component and frequency