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Anthony Taibi

APRIL 2019
KENNESAW STATE UNIVERSITY
Honors Capstone

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Honors Capstone Creative Project

22 February 2019

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1. Abstract

This creative capstone project involves the conception, design, and creation of a less-than-lethal self defense device with an integrated sound board to control the acoustic element. Theoretically, this device is capable of deterring potential threats without causing any serious harm or any long-term damage. When starting this project, I was very focused on sonic warfare, and how to harness the power of ultrasonic and infrasonic sound waves to subdue to target; however, I concluded that using resonant frequencies to deter a human being is too dangerous, expensive, and can have negative effects for the user of the device if used incorrectly. After extensive research on acoustical properties, harmonic/resonant frequencies, and the science behind directing sound waves, I have created an efficient, effective, and safe way to add an acoustic element to my Senior Design project. I have accomplished this by adding a small Arduino Sound FX Board and two 1.5-inch drivers to an embedded horn on the underside of the device. The sound board and drivers will produce the needed frequencies while the embedded horn will direct the sound waves toward the threat and minimize reflections back towards the user of the device.

2. Background/Research

Before going in depth on my project and its functions, I feel it necessary to give some background knowledge on acoustics to fully understand this system. Sound waves are simply acoustic (pressure) waves which carry vibrational energy through a medium. Sound waves are longitudinal waves which are transferred through the vibration of particles in a given medium. The most common medium used by humans is air, which is responsible for the transmission of auditory sound in our everyday lives. Similar to electromagnetic waves, acoustic waves have a quantifiable speed, frequency, and wavelength. The higher the frequency (or shorter the wavelength), the higher the pitch will be. Humans are capable of hearing sound with a frequency between from 20 Hz to 20 kHz; however, this is only a small portion of the entire frequency spectrum which ranges from infrasound (less than 20 Hz) to ultrasound (greater than 20kHz). Frequencies above 20 kHz are inaudible to humans and are classified as ultrasonic waves. Ultrasonic waves are used by many animals including dolphins, bats, and rats, and commonly used in the medical industry as an imaging/cleaning tool. On the opposite side of the spectrum, with frequencies below 20 Hz, these extremely low frequency waves (infrasound) are inaudible rumbles that humans can feel rather than hear. Volcanic eruptions, earthquakes, and severe storms are examples of infrasound as they can only be felt, not audibly heard. Animals such as giraffes and elephants use infrasound to communicate over long distances. The denser the medium, the faster sound travels which is why animals such as whales and elephants can communicate with each other from many miles away (using the ocean/ground respectively). Infrasound has a very long wavelength, allowing them to easily traverse through many obstacles/boundaries over very long distances.

While sound is most commonly used with good intentions for exploration, communication, and imaging, humans have begun to utilize the potential applications to use sound waves as a weapon. From stories in holy texts such as the battle of Jericho, to World War II, audible sound has been utilized to destroy and disorient. Using specific frequencies within the auditory spectrum can have interesting effects on people; however, using ultrasound and infrasound have many different uses that humans have only just begun to uncover. Devices such as LRAD (Long Rand Acoustic Device) are starting to become commonly used 'weapons' in various situations that do not involve traditional firepower. LRAD, a relatively new device which is now used by police and military forces around the world, utilizes ultrasonic waves in combination with auditory waves to create discomfort and unease for those who stand in its way. If standing in the way of LRAD, you may become nauseous and have reduced sensory-motor functions. In Robert Brenner's publication on sound weapons, he states that LRAD "…emits a 2.5 kHz warning tone at 146 dB… with a maximum range of 300 meters. This can cause nausea, discomfort, disorientation, reduced sensory-motor functions, or severe pain." (Brenner, 1).

The reason why I cannot use a long-range acoustic device like LRAD for this project, is because of its size, cost, and power (extremely dangerous). Despite this, with adequate funding and electrical-engineering knowledge, it is possible to supply enough power to a compact device like LRAD that utilizes infrasonic frequencies to impair the enemy. Resonant frequencies can be used to cause damage to the object, such as a wine glass breaking when the right frequency is made. Reproducing the resonant frequency of a certain human body part could cause temporary, or permanent damage to the persons affected. The approximate resonant frequency of the human eye is 19 Hz, which, if played loud enough can cause the persons extreme discomfort and temporary vision impairment. Since the human eyeball is a fluid-filled ovoid, when subjected to an external force (pressure wave at its resonant frequency), the membrane will stretch and shrink in tandem with the infrasonic vibrations of the molecules found within. Needless to say, the stretching and shrinking of one’s eyeballs will cause extreme discomfort and can impair their vision. Theoretically, when the membrane is subjected to enough power, the amplitude of the vibrations will be so great that it will cause the eyeballs to burst. In order to cause such drastic effects, the produced frequency would need to be extremely loud – over 150 dB. Even though 150 dB is louder than a jet taking off, most human body parts (such as the eyes and heart) have resonant frequencies outside of the range of human hearing, which would be inaudible to humans and most animals as it is outside of the audible spectrum. In Seth S. Horowitz’s article on sonic weapons, it is stated that a “…researcher named Vladmir Gavreau… launched a series of experiments on the effects of infrasound on human subjects, with results ranging from subjects needing to be saved from a ‘infrasonic envelopment of death’ that damaged their internal organs to people having their organs ‘converted to jelly’ by exposure to an infrasonic whistle.” (Horowitz, 1).

This principle of resonant frequency can be applied to any object comprised of matter, specifically almost any body part. This phenomenon widely known as the ‘wine glass shattering’ effect is when someone sings the glass’s resonant frequency loud enough causing it to fracture. The major issue with testing these resonant frequencies and their effectiveness on humans/animals is that they are mostly infrasonic waves which are well below the spectrum of human hearing. That being said, one would not hear the tone being directed at them, rather feel the vibrations as molecules vibrate within them. As this practice has serious implications and can be fatal, I have not conducted any experiments utilizing this technology. Given the right circumstances, an acoustic device capable of producing infrasonic frequencies could be tuned in such a way as to not cause serious or permanent harm.

With increased public attention to gun safety and regulation, sonic (sound) weapons may be an answer that will allow people to protect themselves without worrying about inflicting long-term damage or fatal wounds. Although sound has the potential to be lethal, given specific requirements, the sound waves will have a certain threshold for which they must stay under resulting in controlled use. Although I am staying out of the range of human organ's resonant frequencies, implementing a sound-based deterrent into my Senior Design team's less-than-lethal self-defense device will open new doors for future products to utilize sound waves.

3. LTL Device Design Criteria

The device my senior design group and I have created is modeled after the body of an AR-15 rifle. With a re-designed firing mechanism, clip, buttstock, barrel, and grip, the less-than-lethal self defense device will be capable of firing plastic or rubber rounds up to 300 ft/s. The exterior of the device is 3-D printed, while the inner workings are assembled from parts bought online and from different hardware stores. The Arduino Uno which is responsible for the opening and closing of the solenoid valve will also output a signal to the Arduino Sound FX Board, triggering the audio file to play from the two 1.5-inch drivers. While different resonant frequencies could potentially be used as discussed earlier in this paper, a gunshot sound will be played simultaneously with the firing of the round. The loud gunshot sound accompanied by a projectile impact will deter the threat without causing any harm to the user. A normal gunshot, which is over 140 dB, will cause hearing damage if ear protection is not worn – especially if fired in an enclosed space. As this product will mostly be used in indoor scenarios, I do not want the sound to cause permanent damage to either the user's or the threat's hearing. With both drivers playing at once, the goal is to produce a sound around 100dB, which will be loud enough to be perceived as a real gunshot while not causing hearing loss. Being that I am only using a 2-Watt amplifier, it is highly unlikely

I will get results close to this; however, the directivity and amplification of the horn-driver assembly will be tested for effectiveness assuming a more powerful amplifier would be used.

The Sound FX Board 2 x 2.2 will be embedded next to the magazine, directly above both drivers. The battery pack will sit alongside the Arduino underneath the barrel. The horn will extend from the drivers all the way to the end of the barrel and will be concealed inside the ergonomic grip as displayed in the conceptual image below. Given the design parameters of the device body, there is approximately 7 inches of length underneath the barrel and in front of the magazine to effectively integrate the sound module and horn set-up. The goal is to not make this part intrusive and add the horn and drivers into the design of the body while being ergonomically compliant.

Figure (1)

In my experiment, the Arduino Sound FX Board 2x2.2 was powered by a 5V = 4.8A rechargeable battery, while in the final design the board will be powered by the 5.5V output from the Arduino Uno embedded in the trigger assembly of the device. This will supply enough power to the two 1.5-inch drivers via a compact breadboard. Although experimental data was collected using the 5V rechargeable battery, the directivity and amplification can still be unbiasedly compared. Note that the closed circuit being made by the orange jumper wire is triggering the audio file to play; however, when fully integrated into the LTL device, an output signal will be generated when the trigger is compressed, and sent from the Arduino Uno to the Arduino Sound FX Board 2 x 2.2, causing the audio file to play. The Arduino and driver set-up is displayed in Figure (2) below.

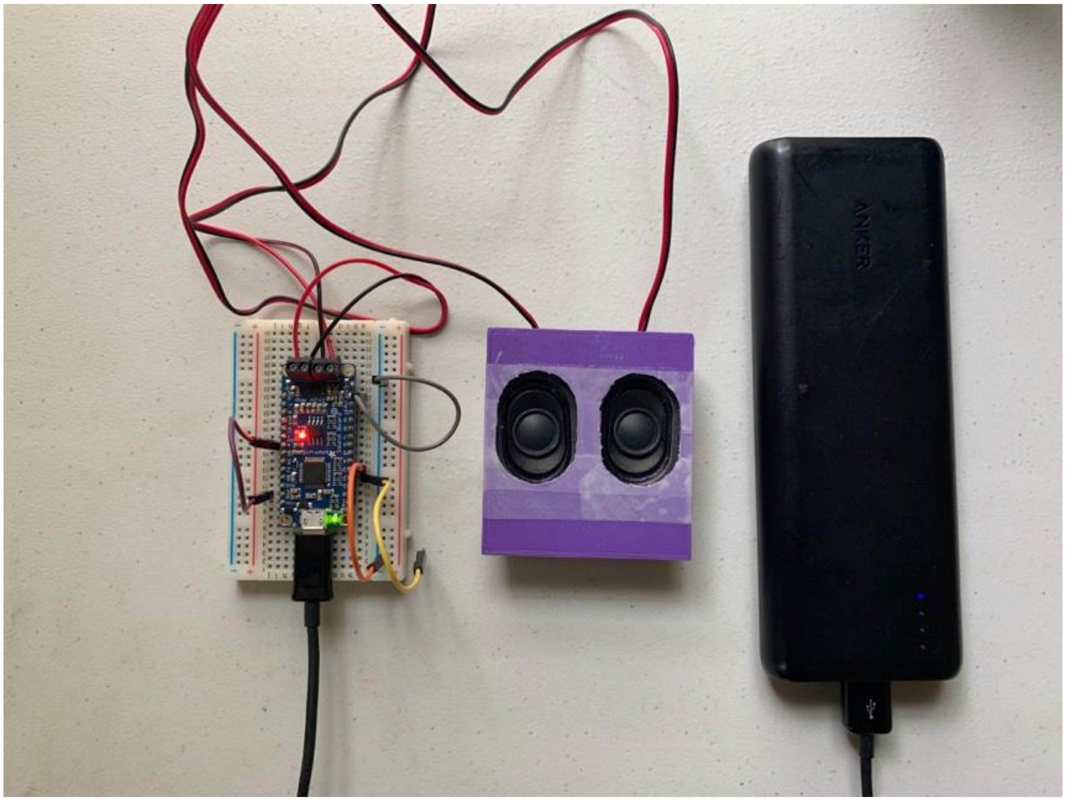


Figure (2)

4. Acoustic Design

The speaker housing for the Arduino drivers was designed in Solidworks and printed on my Monoprice Maker Select V2 3-D Printer. For my experimental research regarding this project, three different horns were also modeled in Solidworks 2018 and then 3-D printed. The first and second horns had a perfectly conical shape, doubling in size from the throat (base of horn) to the mouth (opening of horn). Both of these conical horns had an initial diameter of 2.5 inches (1.5625 in^2 throat area), and a final diameter of 5 inches (6.25 in^2 mouth area). The only difference between the first and second horn design is the inner funnel system that further directs and amplifies the sound. This funnel system is very similar to those that are used in common day 'megaphones'; forcing the pressure waves through a smaller diameter tube and then reflecting off the base of the horn and thus being directed outward with a greater velocity. Figure (3) below shows the 3-D model of the 'open conical horn' and Figure (4) shows the cross-sectional 3-D model of the 'funneled conical horn.'

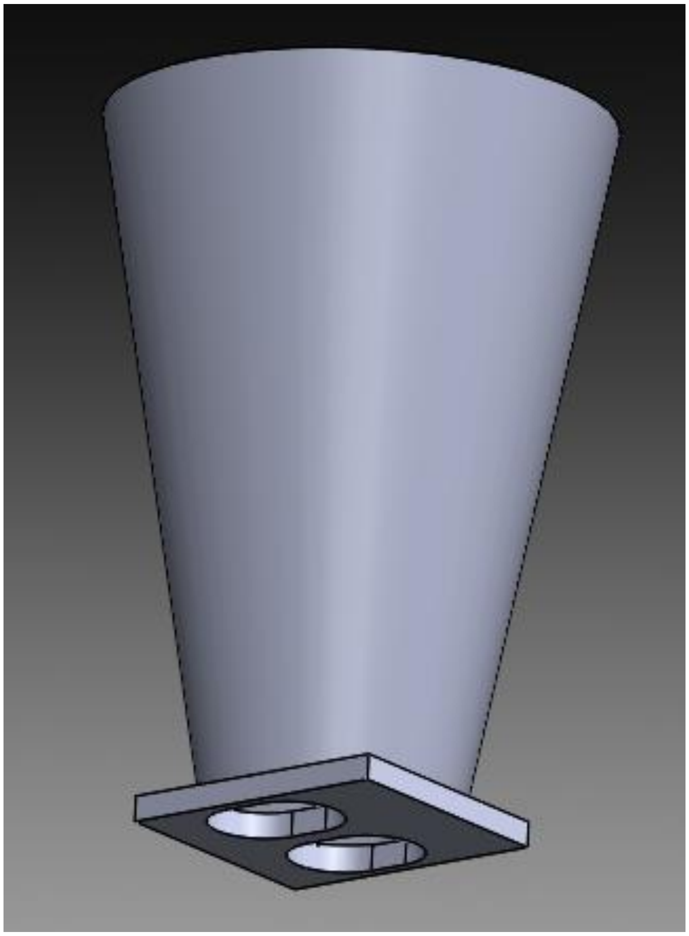


Figure (3)

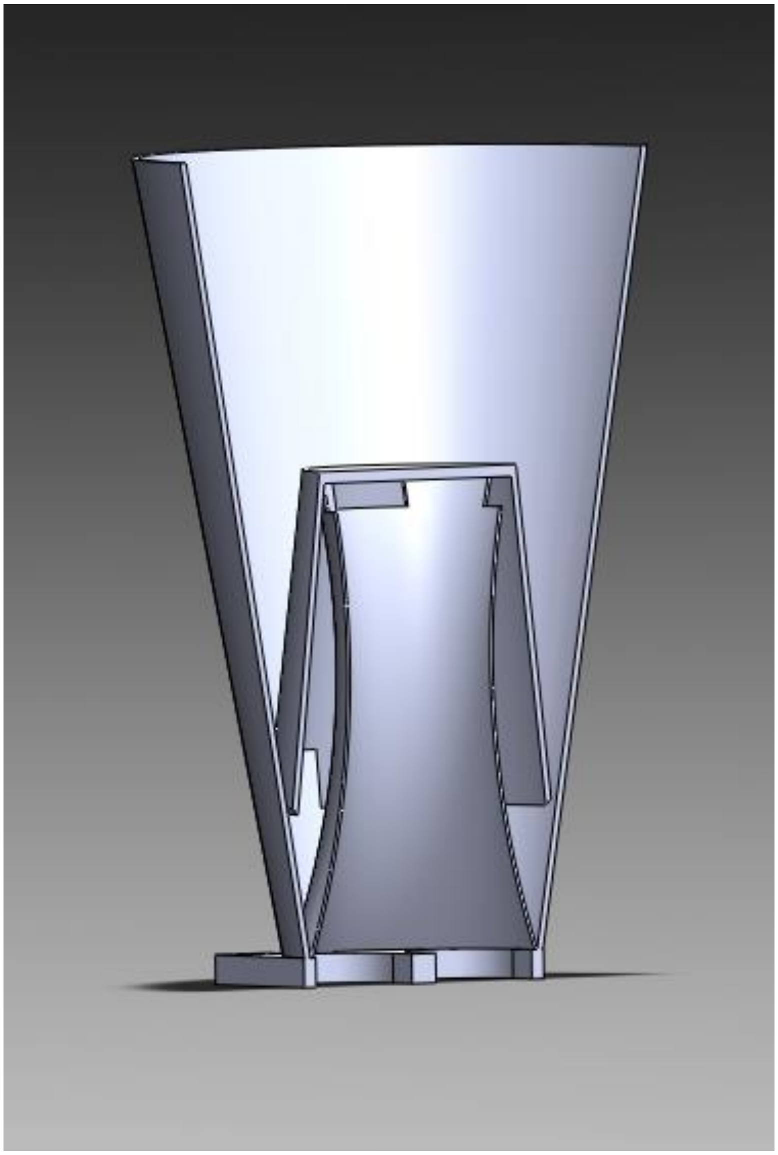


Figure (4)

Unlike the first two horns, the third horn was modeled as an ‘exponential horn’ with rectangular geometry. Based on Martin J. King’s publication on ‘Horn Theory,’ exponential horns are very effective at amplifying and directing sound waves. King specifies that his “First pass through the derivation of the one dimensional exponential horn has wave equation has been completed, and… There is a lot more work to be done and documented.” (Martin J. King, Conclusion Page 1). King's final derivation for the one dimensional exponential horn wave equation as a function of displacement (x) and time (t), is shown in Equation (1) below, where $m = \text{flare constant } (\mathrm{m}^{-1})$, $c = \text{speed of sound } (\frac{\mathrm{m}}{\mathrm{s}})$, $\xi = \text{displacement variable}$, $\rho = \text{density } (\frac{\mathrm{kg}}{\mathrm{m}^3})$. From King's one dimensional wave equation for exponential horns, Equations (2), (3), and (4) are found where $f_c = \text{critical frequency (Hz)}$, $S_O = \text{throat cross} - \text{sectional area } (m^2)$, and $S_L = \text{mouth cross} - \text{sectional area } (m^2)$.

Equation (1):

$$c^2\left[\left(\frac{\partial^2}{\partial x^2}\xi(x,t)\right) + m\left(\frac{\partial}{\partial x}\xi(x,t)\right)\right] - \left(\frac{\frac{\partial}{\partial t}\xi(x,t)}{\rho}\right) = \frac{\partial^2}{\partial t^2}\xi(x,t)$$

Equation (2):

$$m = \frac{4\pi f_c}{c}$$

Equation (3):

$$S_L = \frac{(\frac{c}{2f_c})^2}{\pi}$$

Equation (4):

$$m = \frac{ln(\frac{S_L}{S_o})}{L}$$

Since the length (L) of the exponential horn is constrained by the LTL design specifications, the equations below are used to solve for the flare constant, throat cross-sectional area, and mouth cross-sectional area. Given the design parameters, the total length underneath the barrel subtracted from the length of the speaker housing gives approximately 5.5 inches (or 0.14 meters) for L, the length of the horn. For the following calculations, the critical frequency (f_c) is assumed to be 1000 Hz, which was solved for by averaging the peak frequency from both audio files (shown in Figures (7) and (8)). Also, the speed of light (c) is assumed to be 343 (m/s).

$$\boldsymbol{m = \frac{(4)\pi(1000Hz)}{(343m/s)} = 36.64\,m^{-1} = 0.9304\,in^{-1}}$$

$$\boldsymbol{S_L = \frac{(\frac{343m/s}{2(1000Hz)})^2}{\pi} = 0.00936\,m^2 = 14.51\,in^2}$$

$$\boldsymbol{S_O = \frac{S_L}{e^{mL}} = \frac{(0.00936\,m^2)}{e^{(36.64\,m^{-1})*(0.14\,m)}} = 0.0000554\,m^2 = 0.0859\,in^2}$$

Based on my hand calculations using equations (2), (3), and (4), the flare constant (m) is equal to $0.9304\,in^{-1}$, the throat cross-sectional area (S_L) is equal to $14.51\,in^2$, and the mouth cross-sectional area (S_O) is equal to $0.0859\,in^2$. To verify my calculations and further conceptualize the design of the exponential horn, I used Edward Zechmann's MATLAB code 'exp_horn.m' which was free to download online. With very little modification, Zechmann's code is capable of calculating the overall length and mouth radius, and also displays flat sheet fabrication plots and outputs position and radius design vectors, which can be used for manufacturing. The R2018b version of MATLAB was used to execute this program. Shown in Figures (5) and (6) below, the profile of the exponential horn matches almost exactly based on my hand calculations with an overall length equal to approximately 0.15 meters (5.9 inches), and a mouth radius of approximately 0.05 meters (1.97 inches), giving an approximate mouth cross-sectional area equal to 15.5 in^2. The derived mouth cross-sectional area from MATLAB was slightly larger than the hand-calculated area which is in part because the program required the mouth radius to be greater than one wavelength of the critical frequency. Despite the differences between hand calculations and MATLAB calculations, all calculated values can be considered accurate, as they were approximately the same. Figure (5) and (6) below displays two of the output plots from the MATLAB code; the side profile plot, and a 3-D plot of the exponential horn respectively.

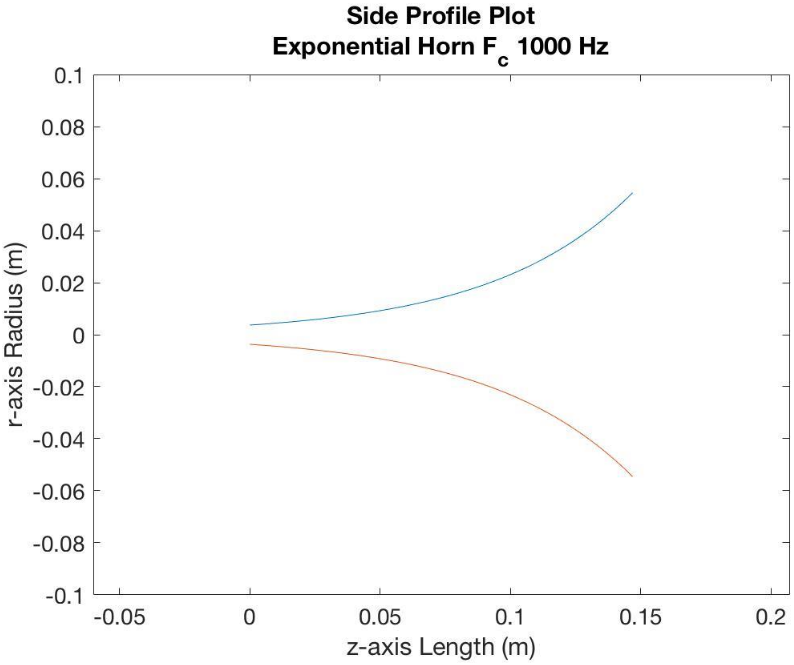


Figure (5)

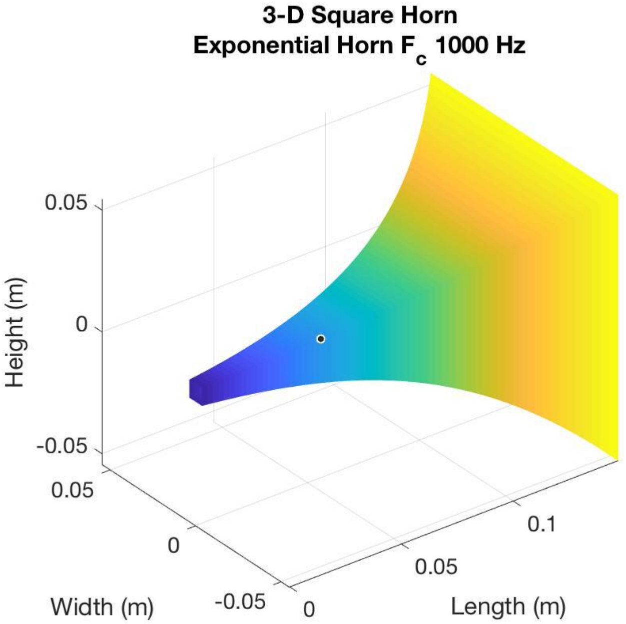


Figure (6)

Based on the above hand calculations and MATLAB models, I designed an exponential horn with similar design specifications. Since the speaker housing was significantly larger than the throat, I needed to add a larger connection to fully encase the speaker housing and minimize the unwanted escape of sound. The speaker housing is to fit snugly at the base of the horn and be 'funneled' to the throat of the horn which is approximately 1.75 inches above the housing. Based on the MATLAB models, the width and height of the mouth were identical. To comply with the LTL design specifications, the horn could not be wider than 2.75 inches. To create the same cross-sectional area as my calculations, the height of the horn was increased to 5.8 inches. This was done to keep the width the same as the width of the LTL device while still keeping the same S_L. The 3-D model from Solidworks is shown in Figure (7) below. Refer to the Appendix/CAD for additional 3-D images of the horns and housing.

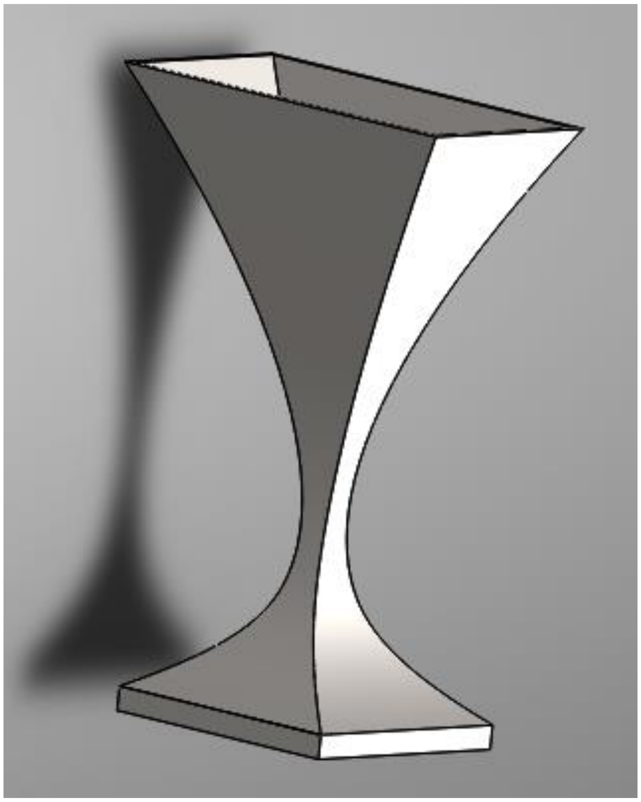
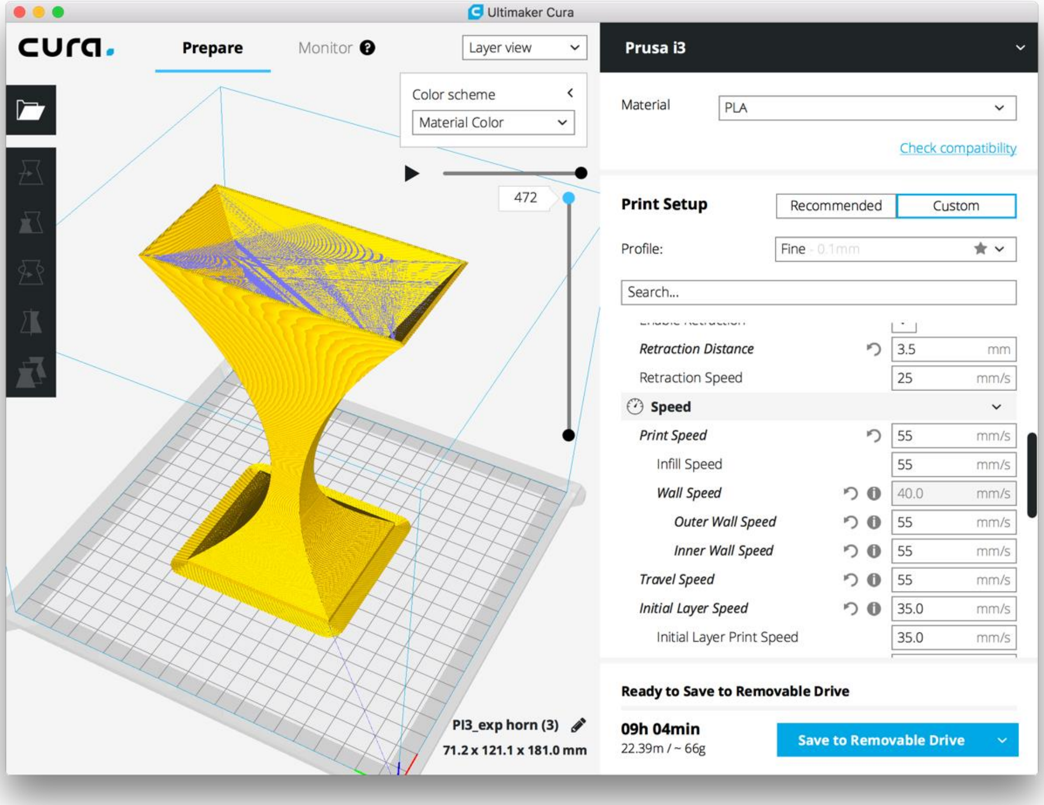


Figure (7)

5. Prototyping

The 3-D Solidworks for each horn file was converted into a STL file and imported into ‘Ultimaker Cura,’ which is an advanced 3-D printing software. After optimizing the print settings to match my Monoprice Maker Select V2 printer, each piece was printed. The ‘open conical horn’ took approximately 14 hours to print, the ‘funneled conical horn’ took almost 24 hours, and the ‘exponential horn’ took approximately 9 hours. A 20% infill density was used for the horns (and speaker housing), with a print speed of 55 m/s. Support material was only needed when printing the exponential horn, as the conical horns had no cantilevering edges. Figure (8) below shows a screenshot of the 3-D printing software used in this project, given the dimensions of my printer.



Material: PLA
Print Setup: Custom
Profile: Fine - 0.1mm
Retraction Distance 3.5 mm
Retraction Speed 25 mm/s
Speed
Print Speed 55 mm/s
Infill Speed 55 mm/s
Wall Speed 40.0 mm/s
Outer Wall Speed 55 mm/s
Inner Wall Speed 55 mm/s
Travel Speed 55 mm/s
Initial Layer Speed 35.0 mm/s
Initial Layer Print Speed 35.0 mm/s
Ready to Save to Removable Drive
09h 04min
22.39m / ~ 66g
PI3_exp horn (3)
71.2 x 121.1 x 181.0 mm

Figure (8)

The ‘open conical horn’ is shown on the print bed in Figure (9) below. As the printer dimensions are 200mm x200mm x 180mm, the z axis had to be slightly adjusted to fit the printer specifications. Moving the whole part down approximately 3 mm gave enough clearance for the part to print seamlessly, without any support material. As seen in the figure below, the surface finish is very smooth both on the inside and outside of the horn.

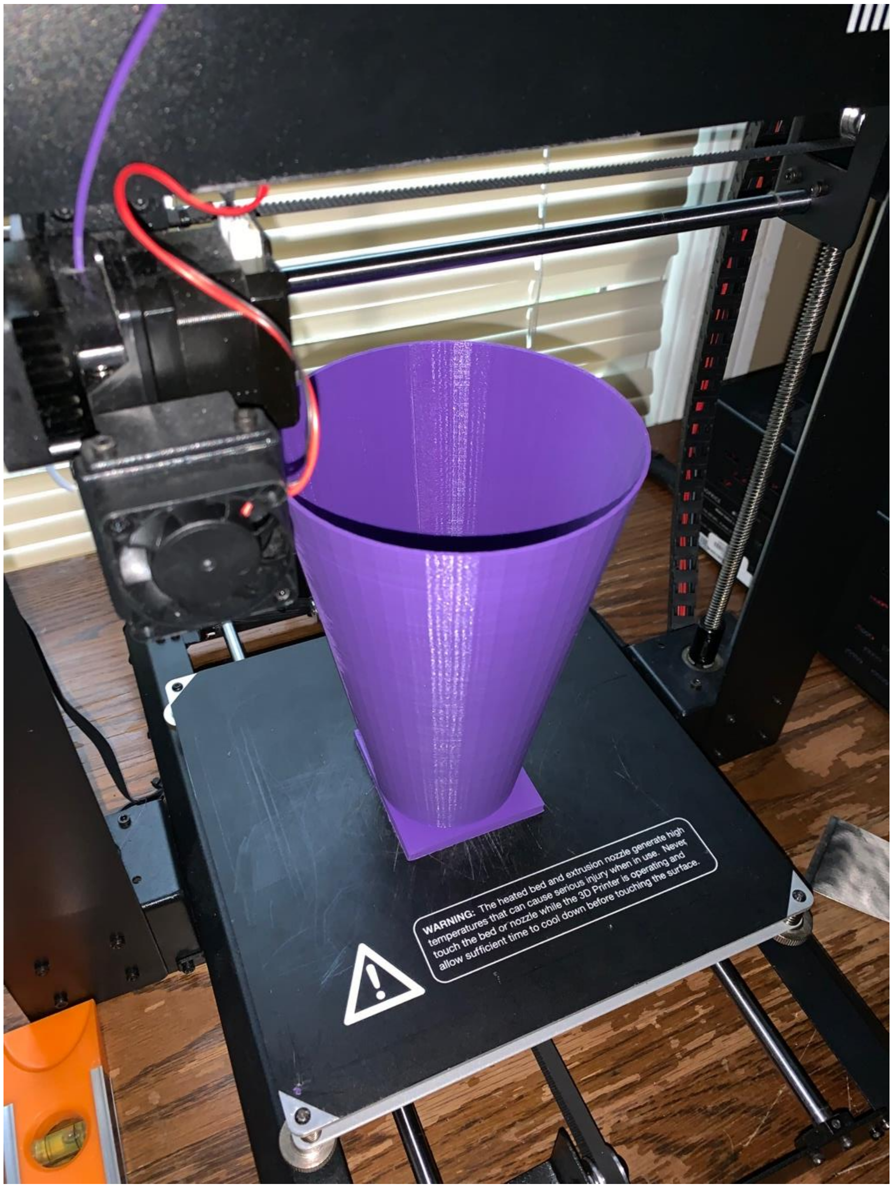


Figure (9)

Displayed in the image below, Figure (10), is the ‘funneled conical horn’ which has an equally smooth surface finish as the ‘open conical horn.’ Since both of these conical horns share the same dimensions, it also had to be offset by approximately 3mm down the z axis to print.

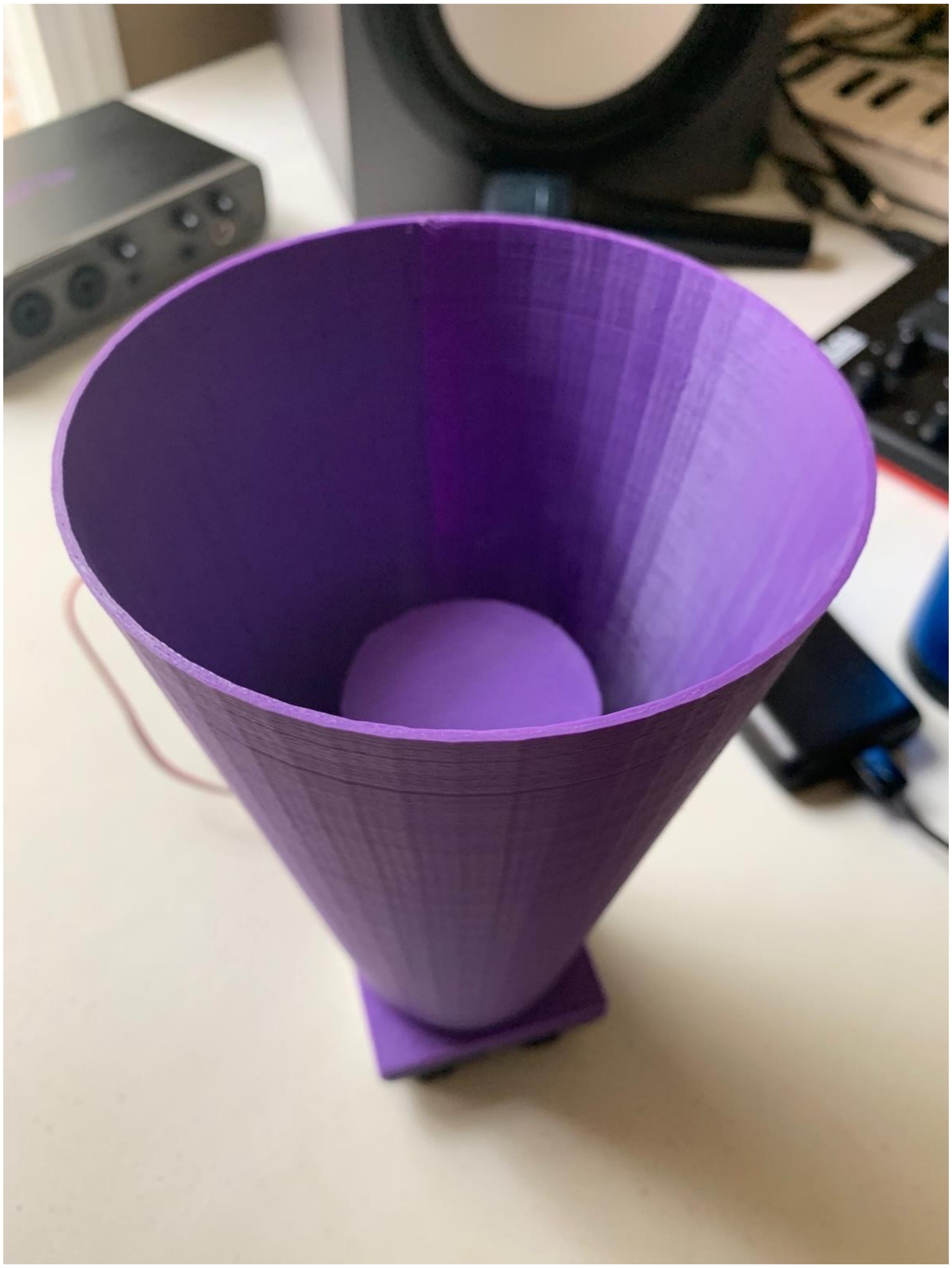


Figure (10)

An image of the 3-D printed ‘exponential horn’ is shown in Figure (11) below. Compared to the first two horns, the ‘exponential horn’ has a significantly more abrasive surface finish as shown in Figure (12) and (13). This is most likely caused by the more complex (curved) geometry of the object. If a more precise (expensive) 3-D printer was used, then the surface finish would be smooth regardless of the complex geometry.

Figure (11)

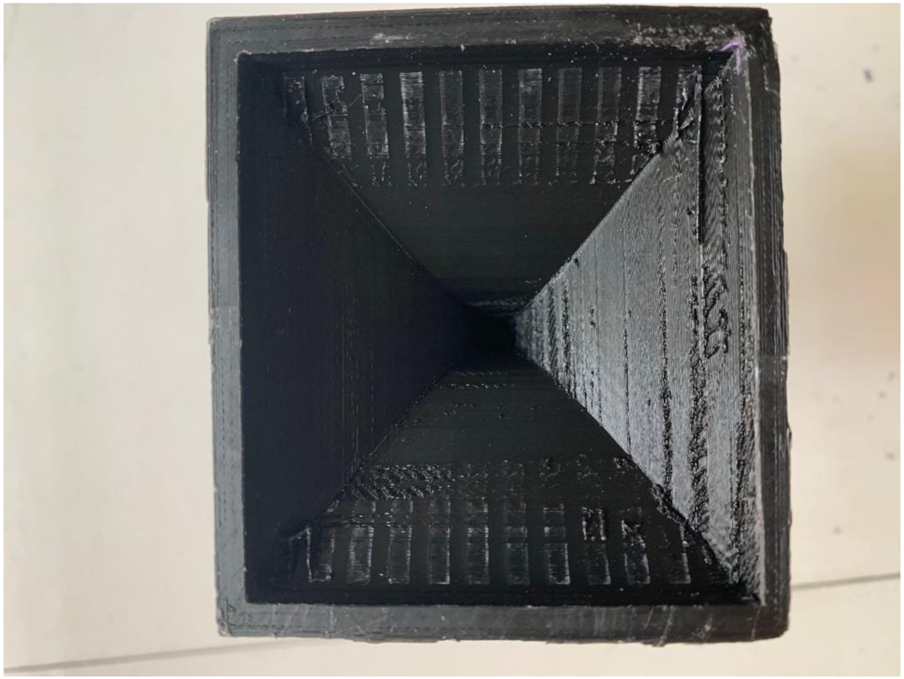


Figure (12)

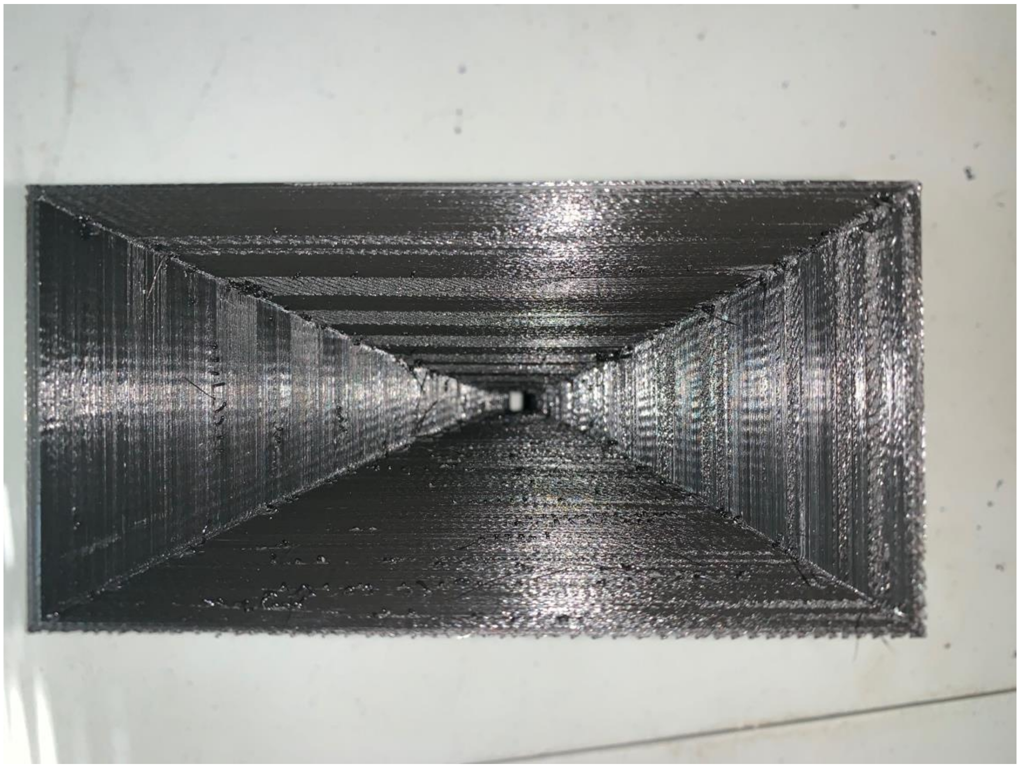


Figure (13)

6. Experiment

Data was collected comparing the sound pressure level made by two different speakers (in decibels) at variable distances, using the three 3-D printed horns. The distance, audio files, and sound sources remained constant throughout the experiment as to properly record data that would demonstrate the different effects that different horns have to amplify and direct the sound. Two different gunshot mp3 files were used as the audio clips in this experiment. A digitally-derived frequency spectrum analyzer (using Logic Pro X) was used to visualize the frequency response of each sound, which is shown in Figures (14) and (15) below.

Figure (14)

Figure (15)

It is necessary to note that since these sounds were digitally analyzed, there is no low frequency roll-off and in reality, the lower frequencies (below 600 Hz) will be considerably less than displayed in the analyzer. Using the built-in microphone on an iPhone XR in conjunction with the ‘Audio Spectrum Analyzer dB RTA’ application, both sounds were recorded and analyzed when played through the Arduino speaker drivers used in the experiment. These figures below show the response of both audio files in the 6 ft. x 9 ft. control room where the experiment was done. Notice that the lower frequencies are significantly lower than in the previous spectrographs derived from Logic Pro X. This is in part because of the microphone used; however, the frequency response of the Arduino drivers play a much more crucial role in this. Generally speaking, low frequencies require very large drivers to be accurately reproduced. In my experiment, the speakers used were 1.5 inches in diameter which is quite small. The peak frequencies of both audio files are shown in Figures (16) and (17), with the first sound having a peak of 1295 Hz and the second sound with a peak of 793 Hz. The average value of both peak frequencies were calculated as $\frac{1259Hz + 793\ Hz}{2} = 1026\ Hz$, and was used as the desired cutoff frequency $(f_c \approx 1000\ Hz)$.

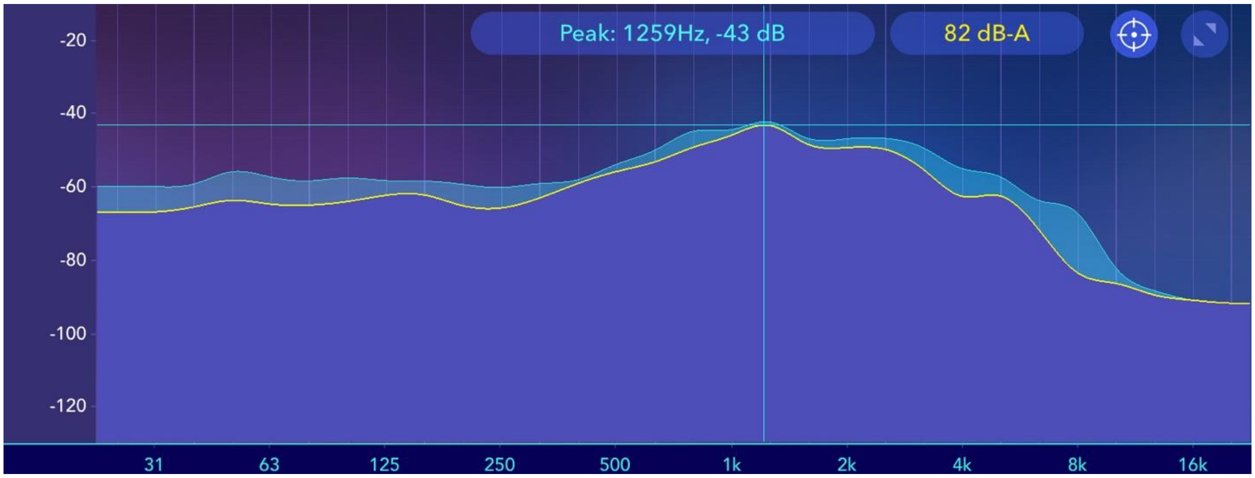


Figure (16)

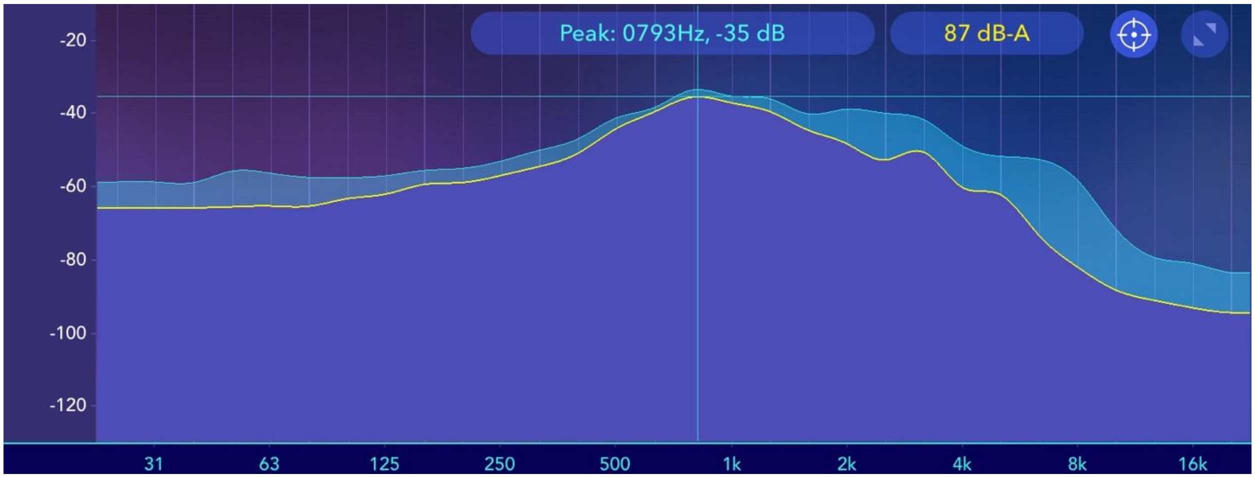


Figure (17)

As described earlier, the experiment took place inside of a 6 ft. x 9 ft. room. As shown in Figure (18), the microphone stayed stationary throughout the experiment while the speaker was recorded at two different locations – the full length of the room and half-length of the room.

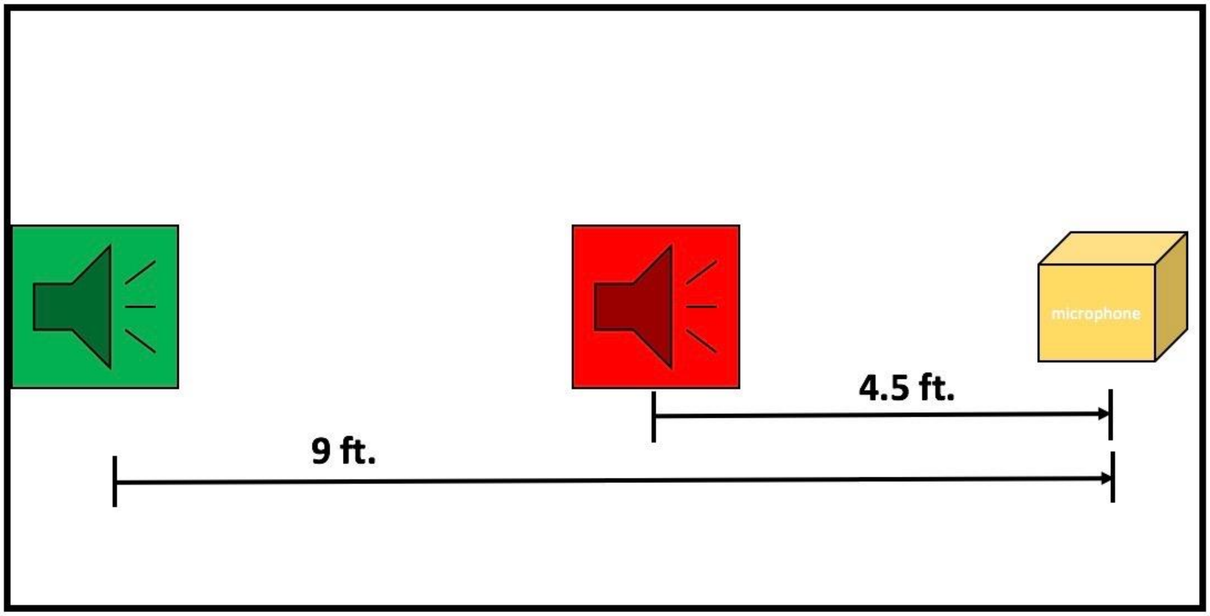


Figure (18)

For each speaker location, both audio files were played and the SPL (sound pressure level in decibels) was recorded using the 'Google Science Journal' application. To gain more data relevant to the horn functionality, two different sound sources were used; the dual 1.5 inch Arduino drivers shown earlier in this report, and an '808 Canz 2' speaker shown in figure (19) below. The '808 Canz 2' speaker has a single driver unlike the dual Arduino drivers. A total of 32 data entries were taken – 8 data entries for each different horn type. For each data entry, the sound file was played a total of 5 times to ensure accurate data and account for any outliers. An example of one raw data entry directly from 'Google Science Journal' is shown in Figure (20) below.

Figure (19)

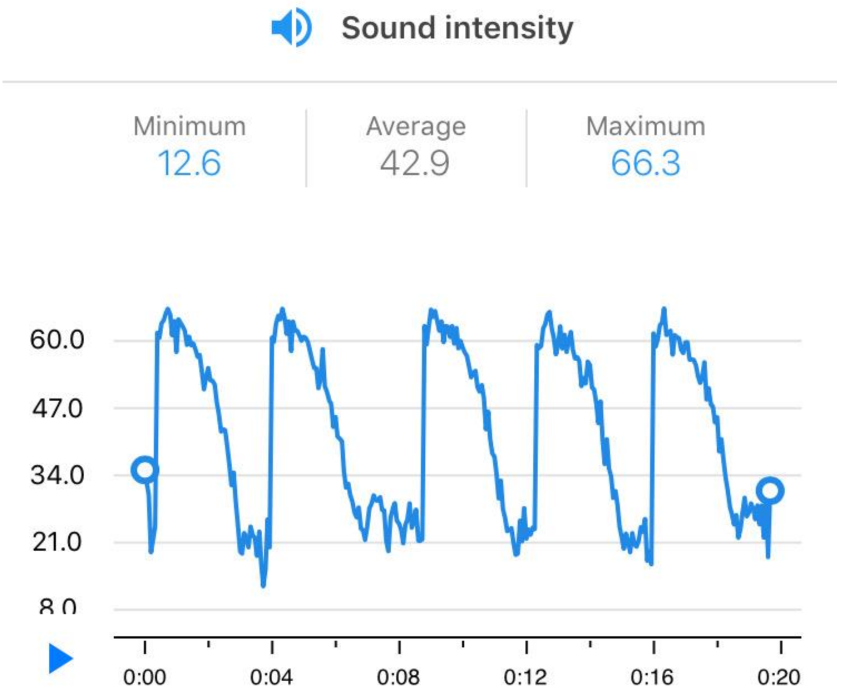
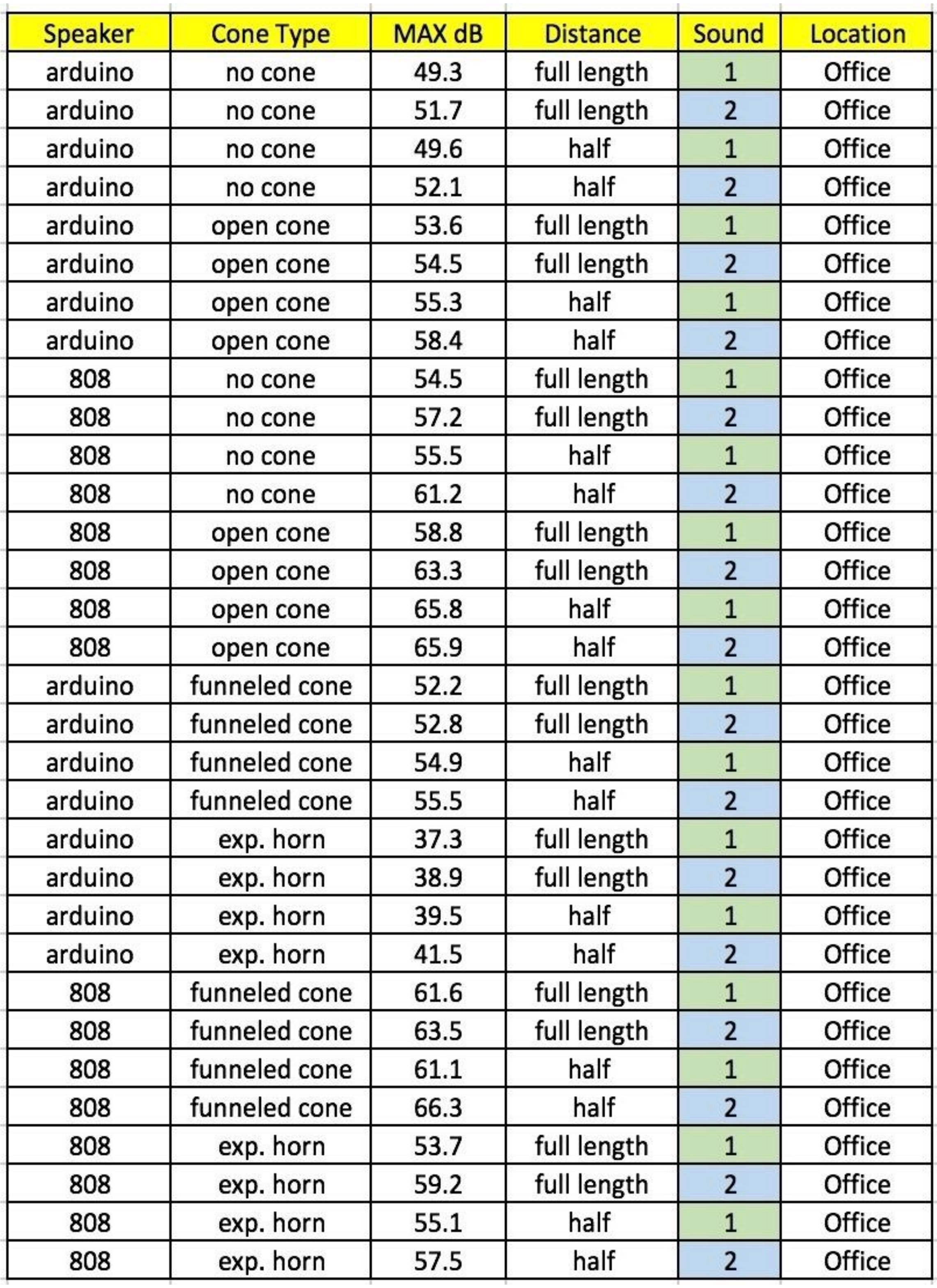


Figure (20)

7. Experimental Data and Analysis



Speaker	Cone Type	MAX dB	Distance	Sound	Location
arduino	no cone	49.3	full length	1	Office
arduino	no cone	51.7	full length	2	Office
arduino	no cone	49.6	half	1	Office
arduino	no cone	52.1	half	2	Office
arduino	open cone	53.6	full length	1	Office
arduino	open cone	54.5	full length	2	Office
arduino	open cone	55.3	half	1	Office
arduino	open cone	58.4	half	2	Office
808	no cone	54.5	full length	1	Office
808	no cone	57.2	full length	2	Office
808	no cone	55.5	half	1	Office
808	no cone	61.2	half	2	Office
808	open cone	58.8	full length	1	Office
808	open cone	63.3	full length	2	Office
808	open cone	65.8	half	1	Office
808	open cone	65.9	half	2	Office
arduino	funneled cone	52.2	full length	1	Office
arduino	funneled cone	52.8	full length	2	Office
arduino	funneled cone	54.9	half	1	Office
arduino	funneled cone	55.5	half	2	Office
arduino	exp. horn	37.3	full length	1	Office
arduino	exp. horn	38.9	full length	2	Office
arduino	exp. horn	39.5	half	1	Office
arduino	exp. horn	41.5	half	2	Office
808	funneled cone	61.6	full length	1	Office
808	funneled cone	63.5	full length	2	Office
808	funneled cone	61.1	half	1	Office
808	funneled cone	66.3	half	2	Office
808	exp. horn	53.7	full length	1	Office
808	exp. horn	59.2	full length	2	Office
808	exp. horn	55.1	half	1	Office
808	exp. horn	57.5	half	2	Office

Figure (21)

The data captured in ‘Google Science Journal’ was transferred into an excel spreadsheet as shown in Figure (21) above. The data was split into 4 subsets, each subset observing a single sound file at a certain distance (full or half length). Graphical representations of the raw data subsets (shown in Figures (22-25)) were made in order to better comprehend the overall trends from the experiment and the effects that the different horn types made on the perceived loudness. These graphs compare both speakers when attached to different horn types with the Arduino dual driver represented in blue and 808 driver represented in orange.

The highest peak values in the data occurred when the horn was pointed directly at the microphone. While only a few decibels increase was seen when pointing the horn directly at the microphone, this proves the horns’ capability of directing the sound in a specific direction. The exponential horn proved to be the best at directing the sound compared to the conical horns, while the conical horns proved most effective at amplifying the sound.

As expected, both conical horns (with and without the inner funnel) increased the sound pressure level for almost every experiment when compared to values taken without any horn attachment (no cone). The conical horns performed very well at amplifying the sound, while the exponential horn performed poorly even though the exponential horn directed the sound efficiently. The very poor performance of the exponential horn has not to do with its design, but has much more to do with its rough surface finish. The many striations and uneven surfaces that make up the inside surface of the horn causes friction against the vibrating air molecules when the pressure waves pass, which results in the dampening of sound. If an exponential horn with the same geometry as the one calculated earlier in the report was made out of a glossy/smooth material (or printed with a high-quality printer capable of printing complex geometry while maintaining a smooth surface finish), the results would be much different. According to my research on horn theory (and calculations from Martin J. King's Horn Theory), the exponential horn should increase the output of the driver at f_c; however, experimental data did not reflect this as the object was too coarse to effectively reflect and direct the sound waves.

The 'funneled conical horn' performed better than the 'open conical horn' when being operated by the 808 driver at the full distance of the room, whereas it performed worse, equal, or just marginally better when its distance was 4.5 feet (half length). This phenomenon is most likely because the reflections off the inner workings of the funnel caused the sound waves to be more 'directional', thus making it more effective at long distances as opposed to close range.

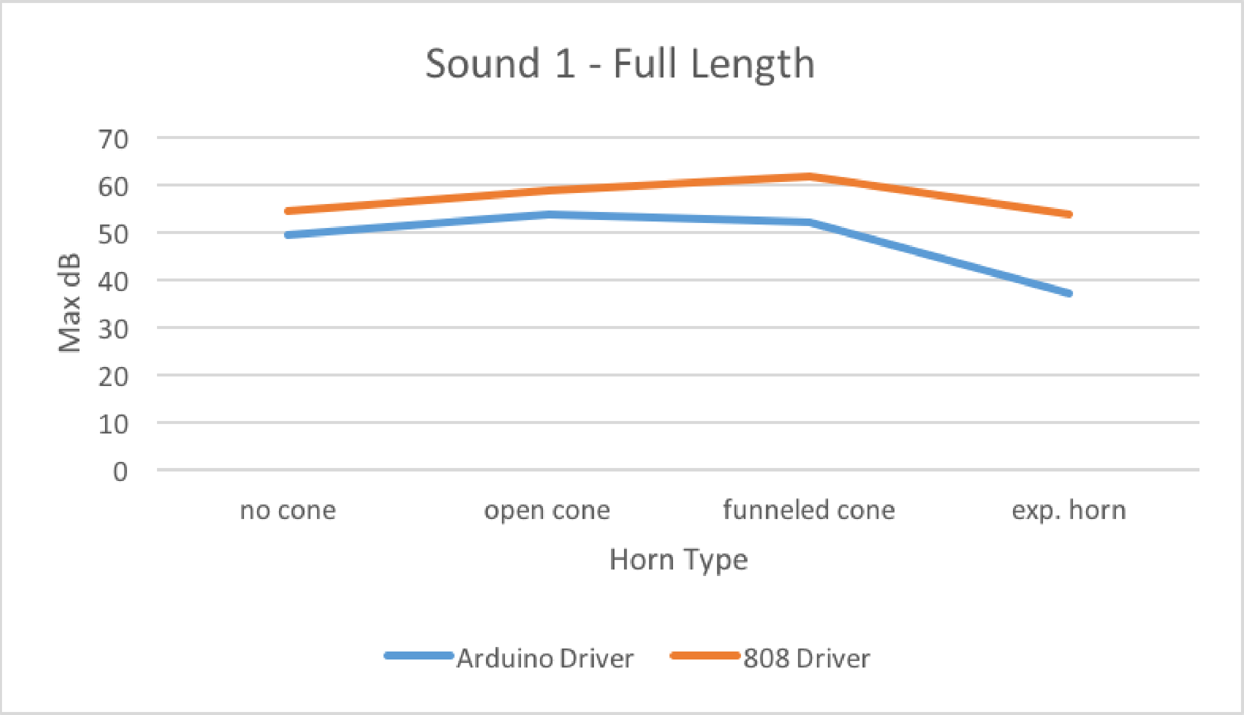


Figure (22)

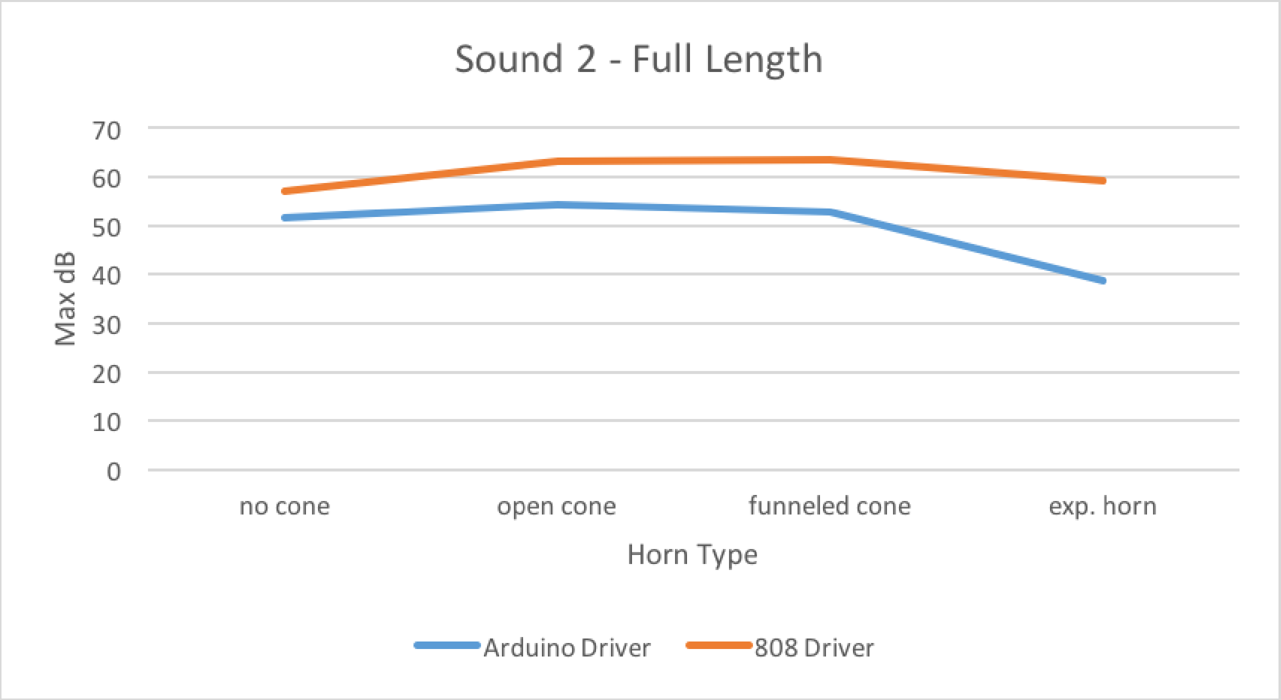
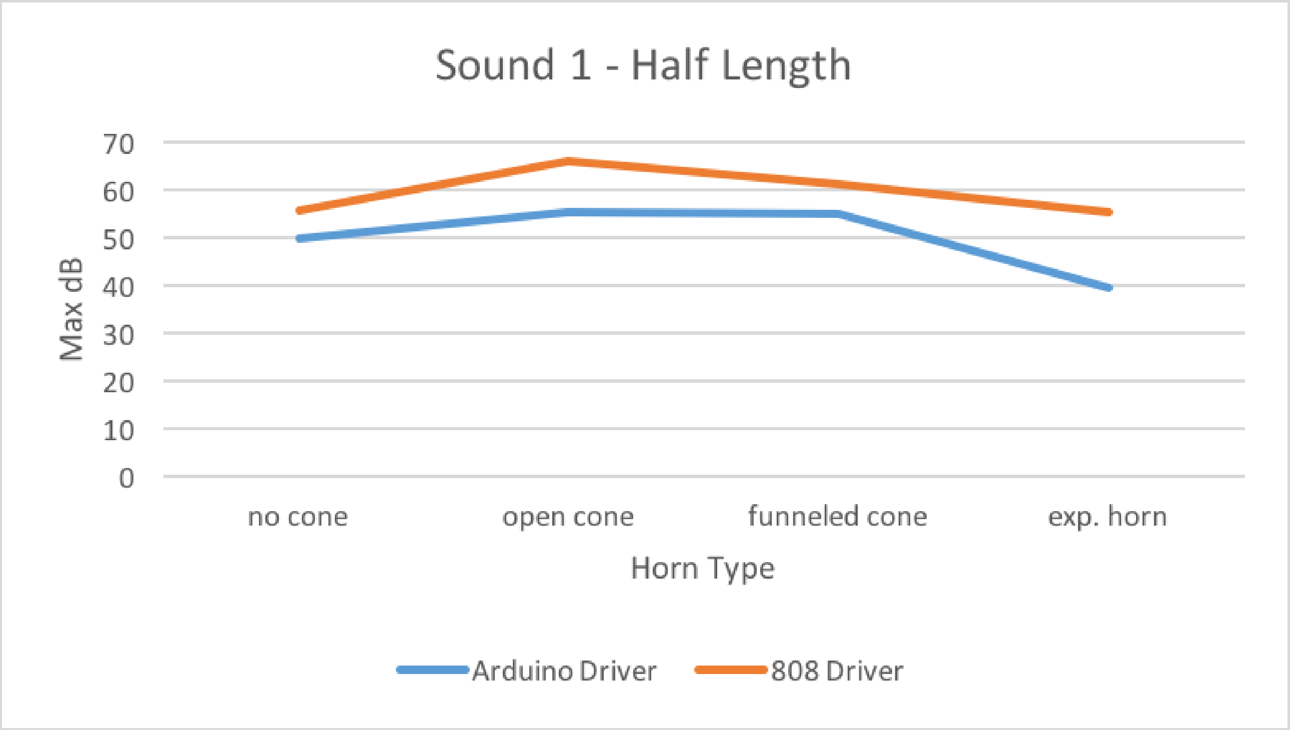


Figure (23)



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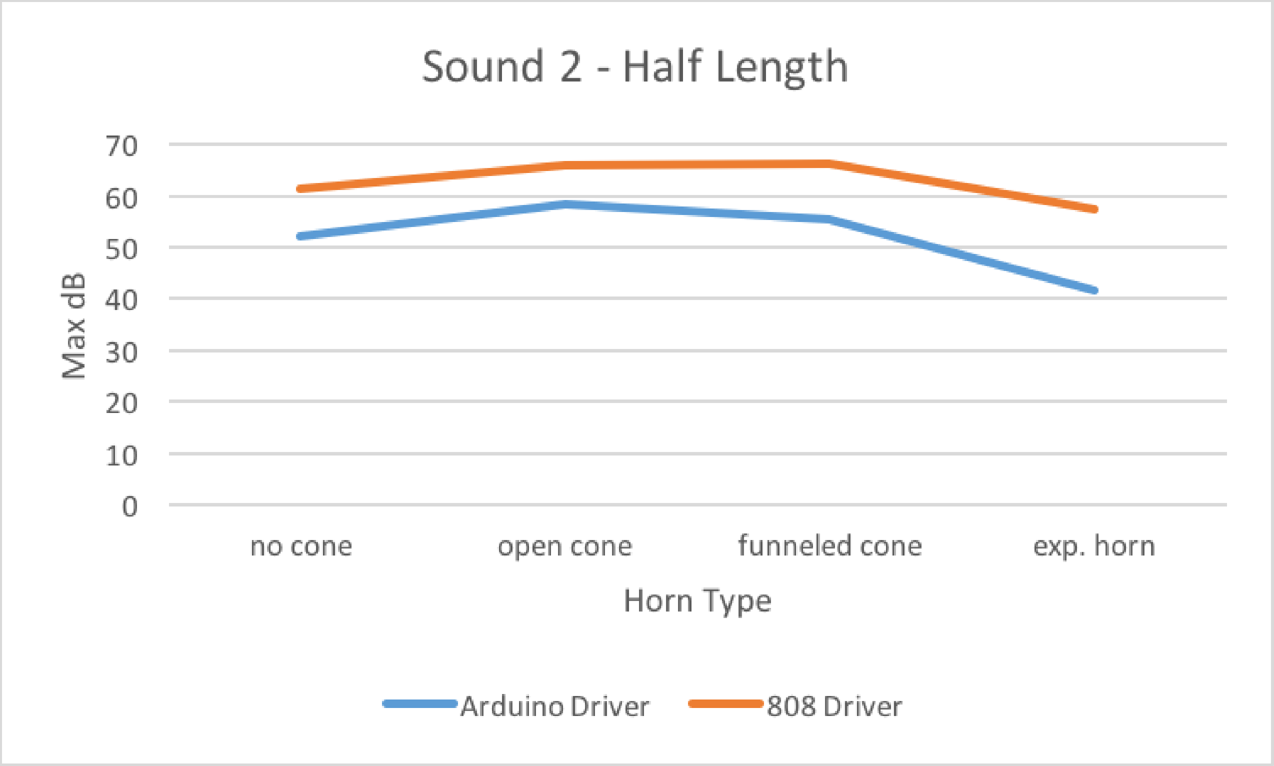

Figure (25)

8. Conclusion

The design process, manufacturing, and experimental testing of the acoustical properties of horns gave me invaluable experience that will be applied in my future work. The conical horns and exponential horn were both effective at directing sound, although the exponential horn was more effective at directivity. Despite the poor functionality of the 3-D printed exponential horn, I am confident that the same horn with a smoother surface finish would produce drastically different results. Because of its directivity, an exponential horn will be used in the final prototype of my team's senior design project. Having the same horn manufactured with a more accurate/precise 3-

D printer is something that my senior design team and I are pursuing before submitting our final prototype.

In hindsight, a much more powerful amplifier should be used in conjunction with the horns (both conical and exponential) to produce a sound almost loud enough to an actual gunshot. While the Arduino drivers and horn assembly produced less than half the sound pressure level of an actual gunshot, increasing the power of the amplifier would make reaching this threshold attainable. The 2-Watt amplifier powering the Arduino 1.5 inch drivers is very low considering the average loudspeaker is well over 1000 watts. The Arduino Sound Fx board is a very compact design that was effective as a prototype that shows proof of concept. Although the actual product would require an amplifier with much more power to replicate the loudness of a gunshot, this prototype allowed me to research, perform design analysis, and collect experimental data on the different horns modeled and manufactured on my Monoprice Maker Select V2 3-D printer. Overall, I learned a lot about acoustical design, manufacturing (3-D printing), and prototyping from the initial stages of conception to the final stages of manufacturing and testing.

The exponential horn and speaker housing assembly needed to be integrated into the LTL device without causing too much bulk as well as be aesthetically pleasing. An encasing was added around the horn and outfitted with an ergonomic design on the underside to account for a human grip. The sound module and horn assembly is detachable and is mounted using the built-in rail system on the LTL device. For the final prototype used by my senior design team, we will be using an exponential horn 3-D printed by a better-quality printer. Refer to the Appendix to see a cross-sectional view of the full sound module and encasement as well as other CAD files from the experiment. Figures (26) and (27) show the completed Less-Than-Lethal Self Defense Device with the added acoustic element.

Final CAD Model

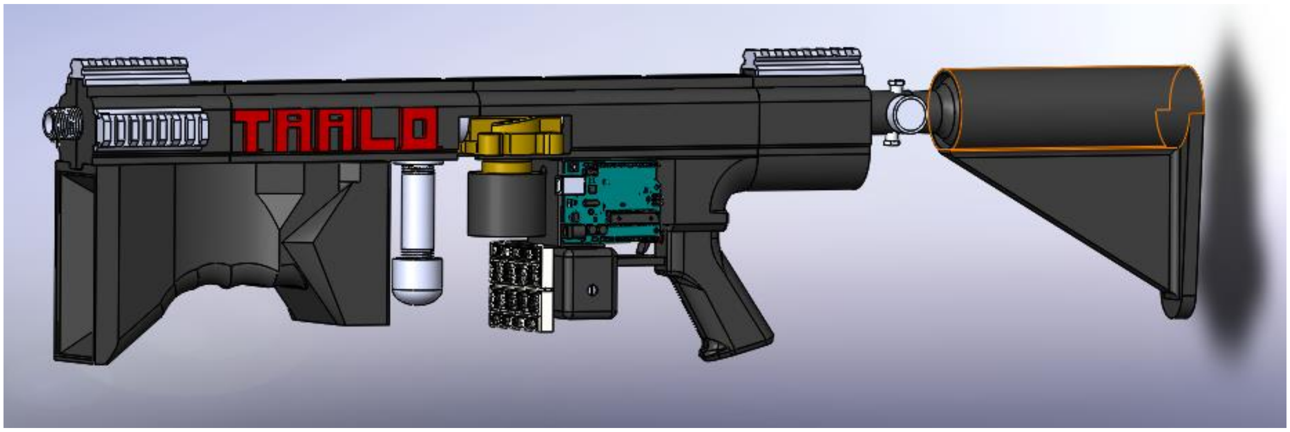

Figure (26)

Figure (27)

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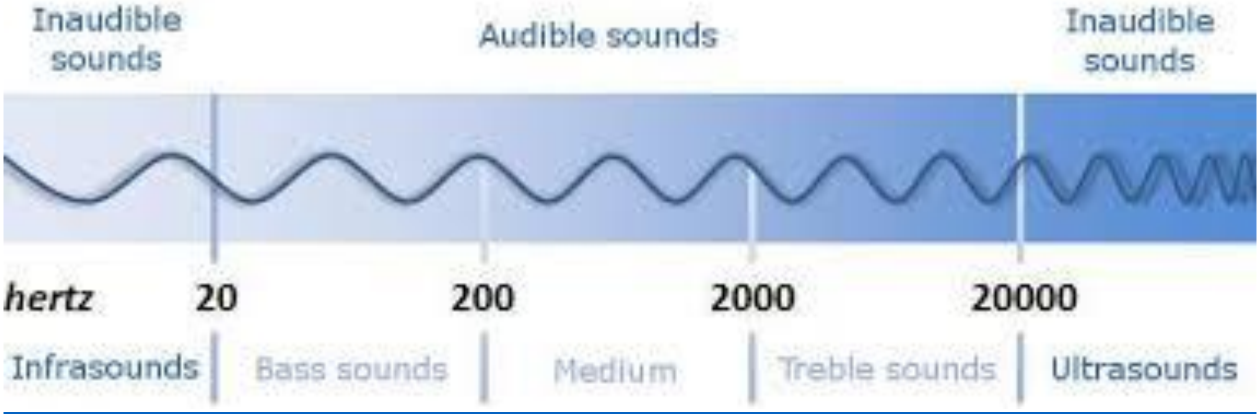
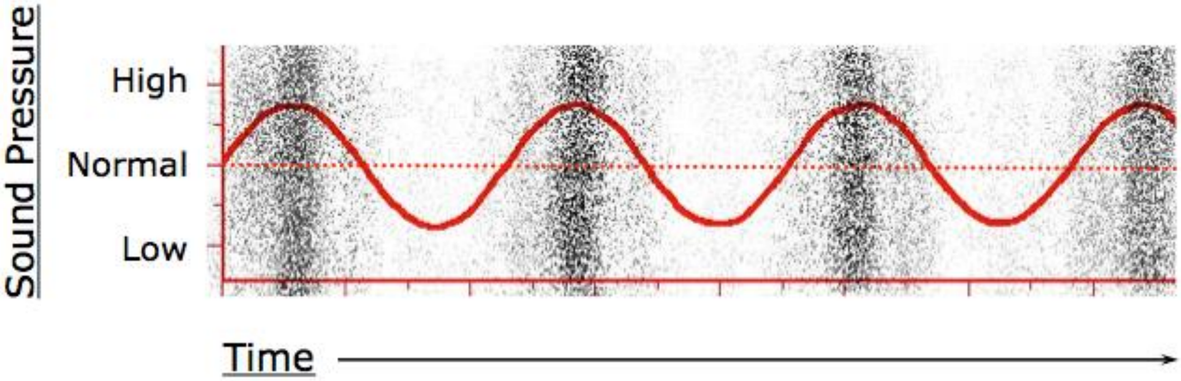
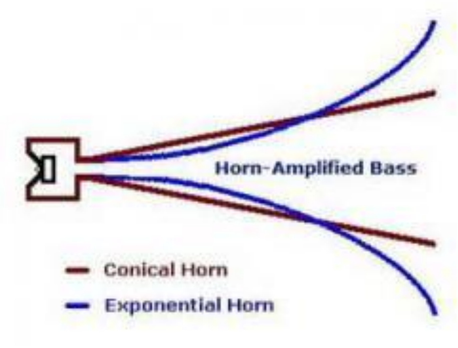
10. Appendix / CAD



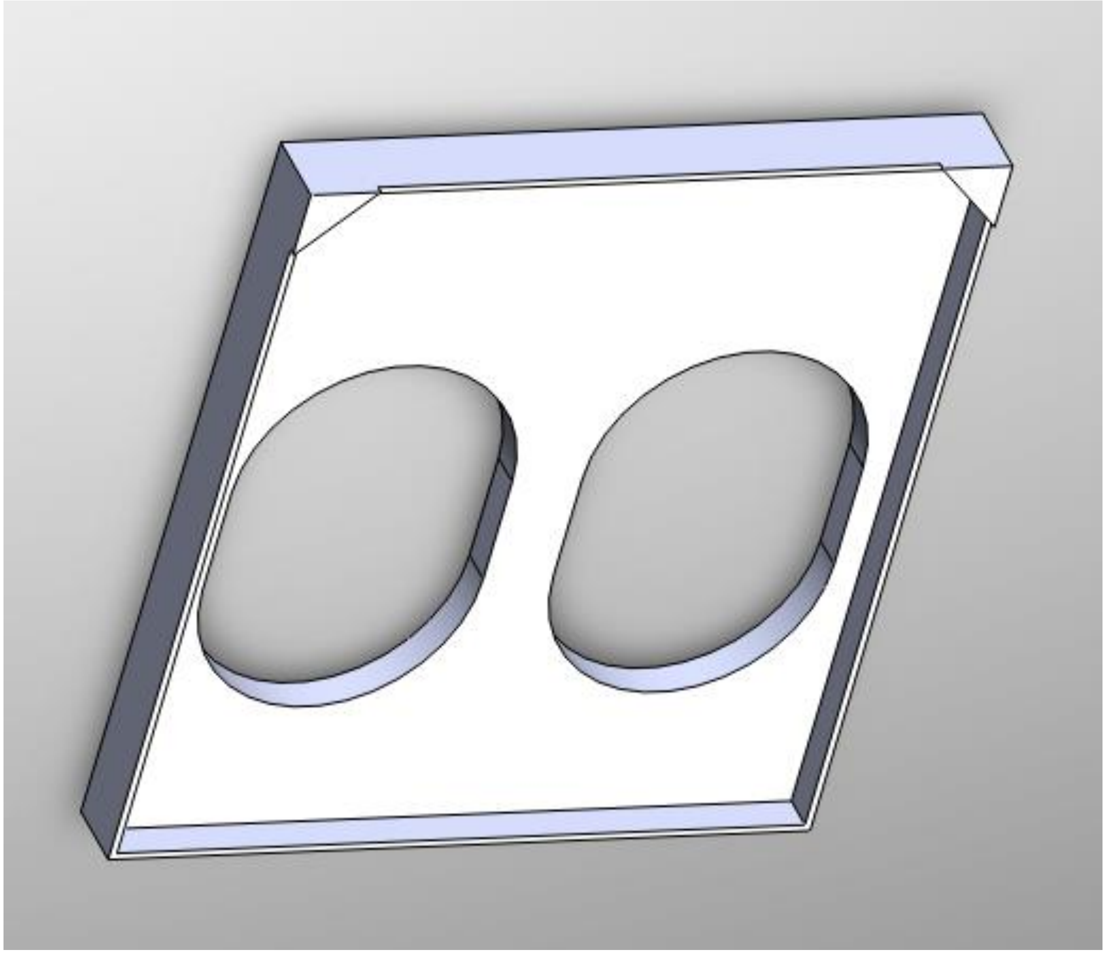
Sound Frequency Spectrum



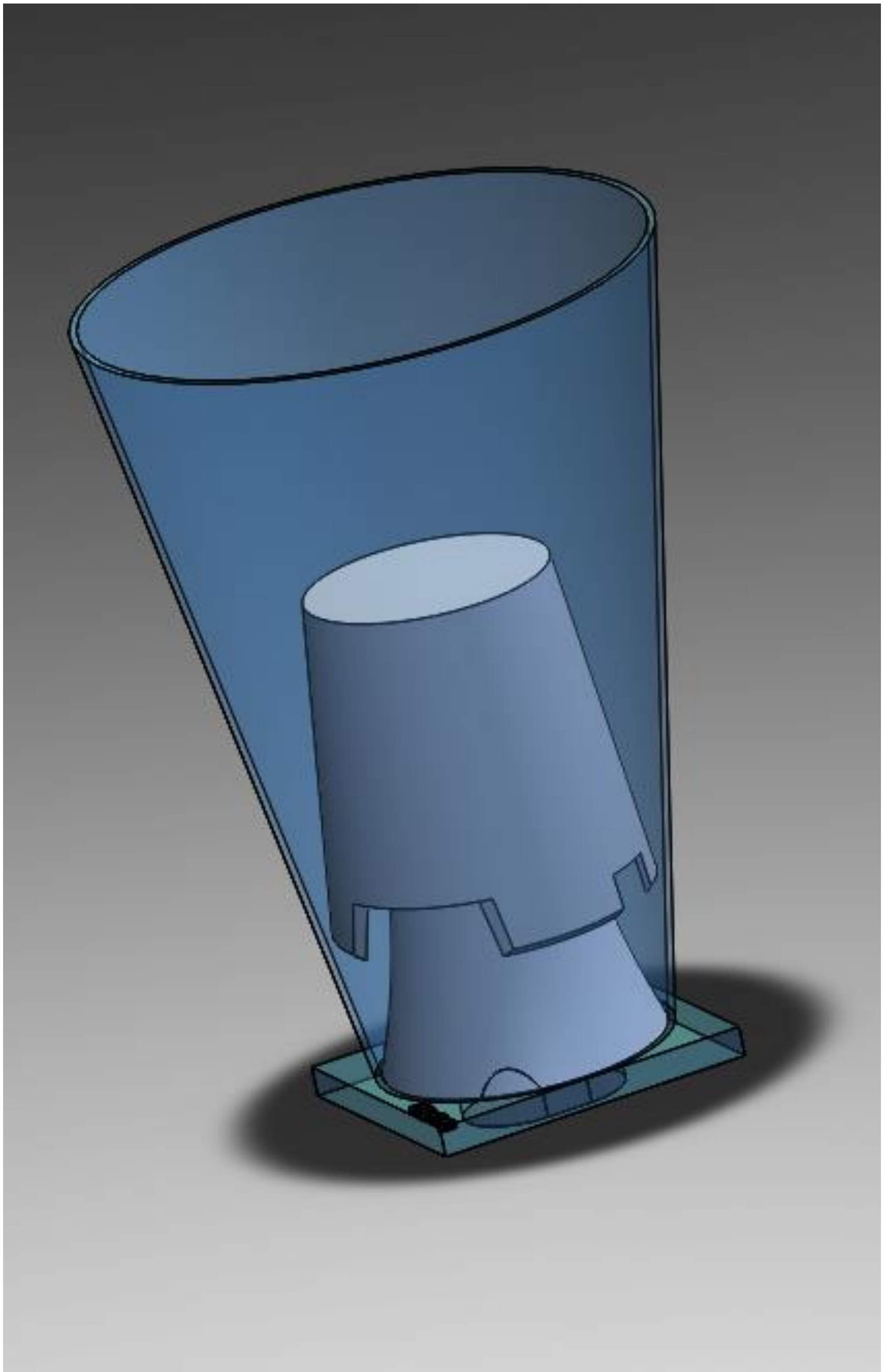
Visualization of Pressure Waves (Time vs. Pressure)



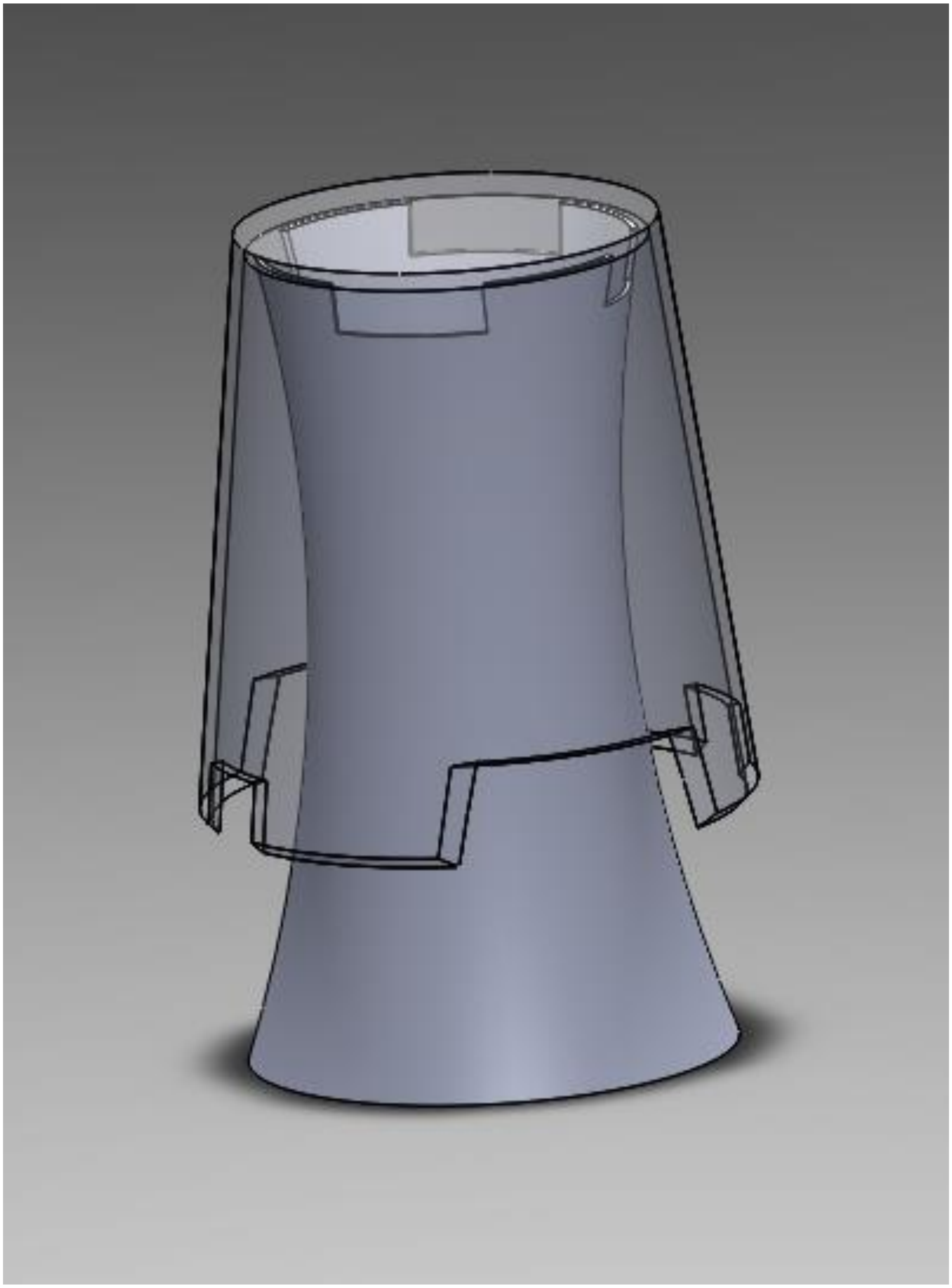
Conical vs. Exponential Horn



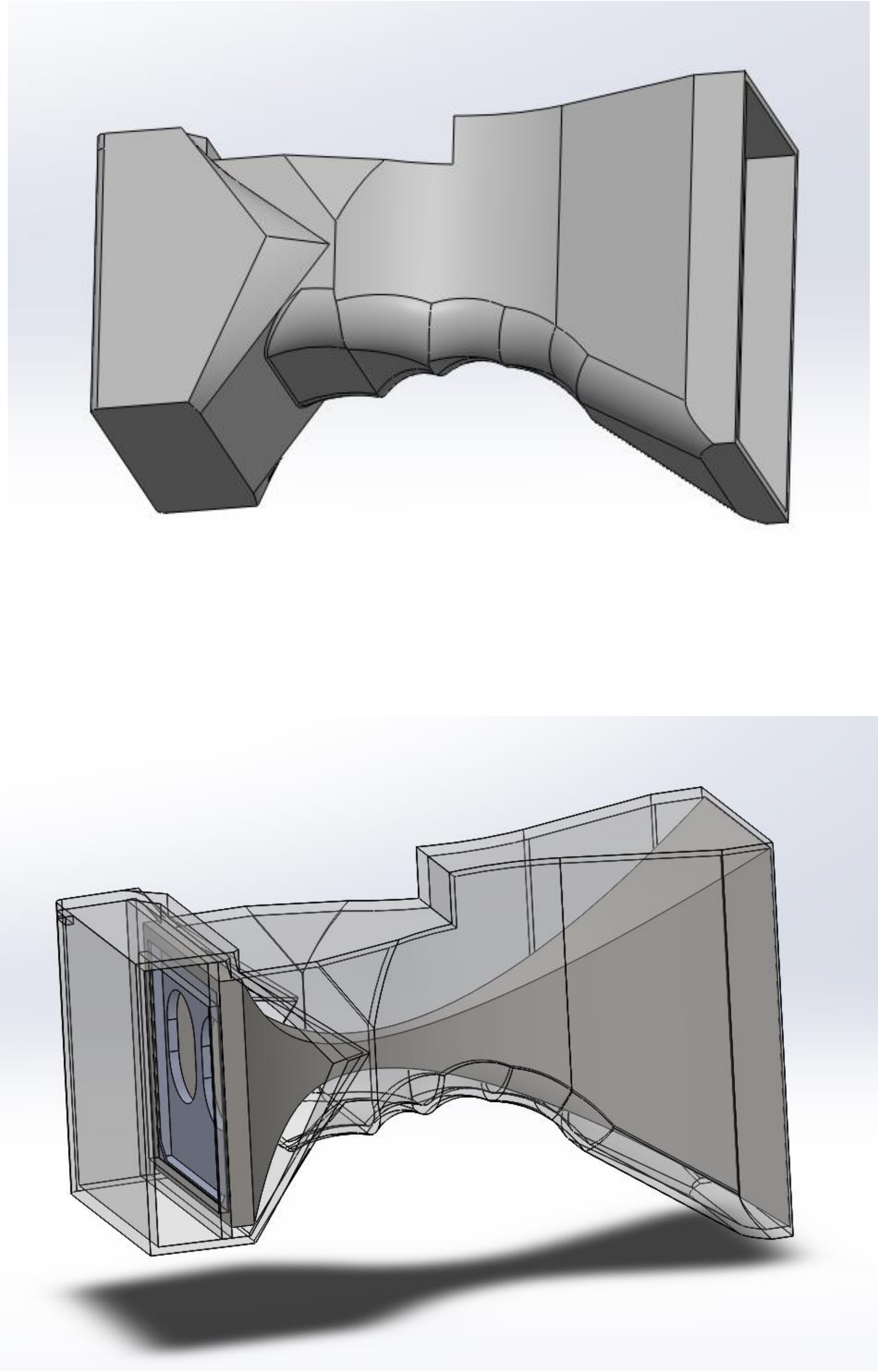
Speaker Housing



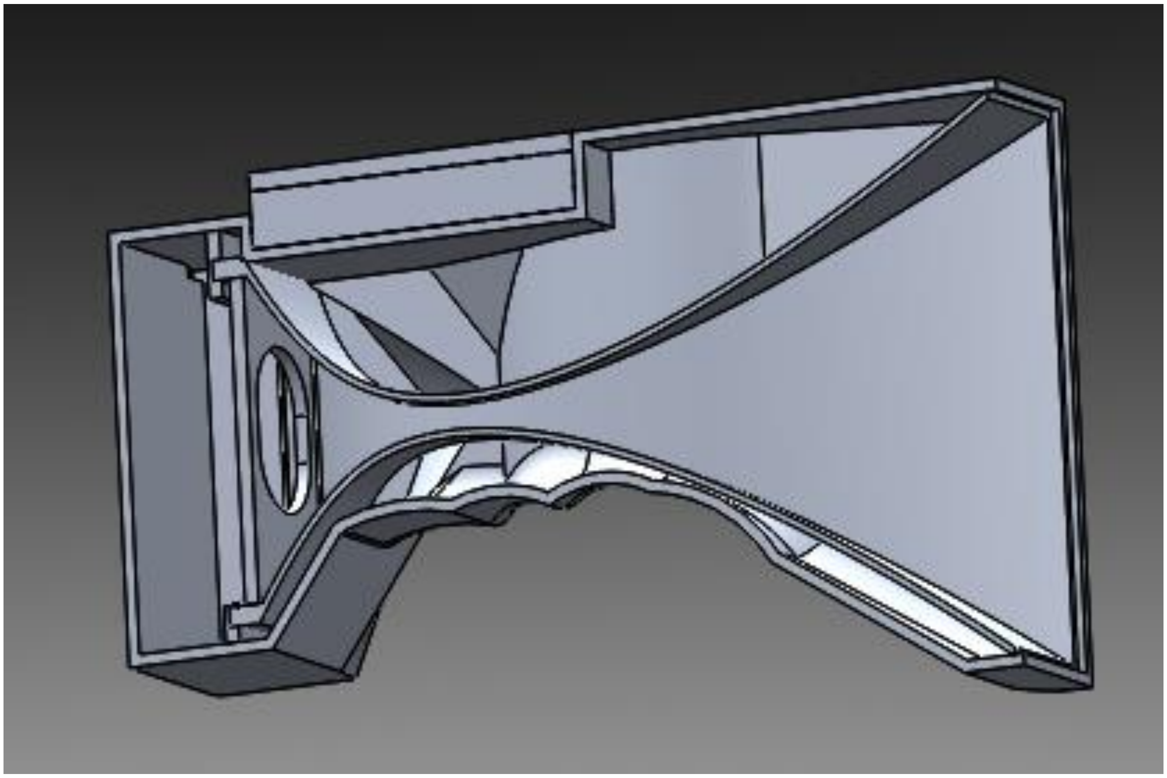
Conical Horn with Funnel



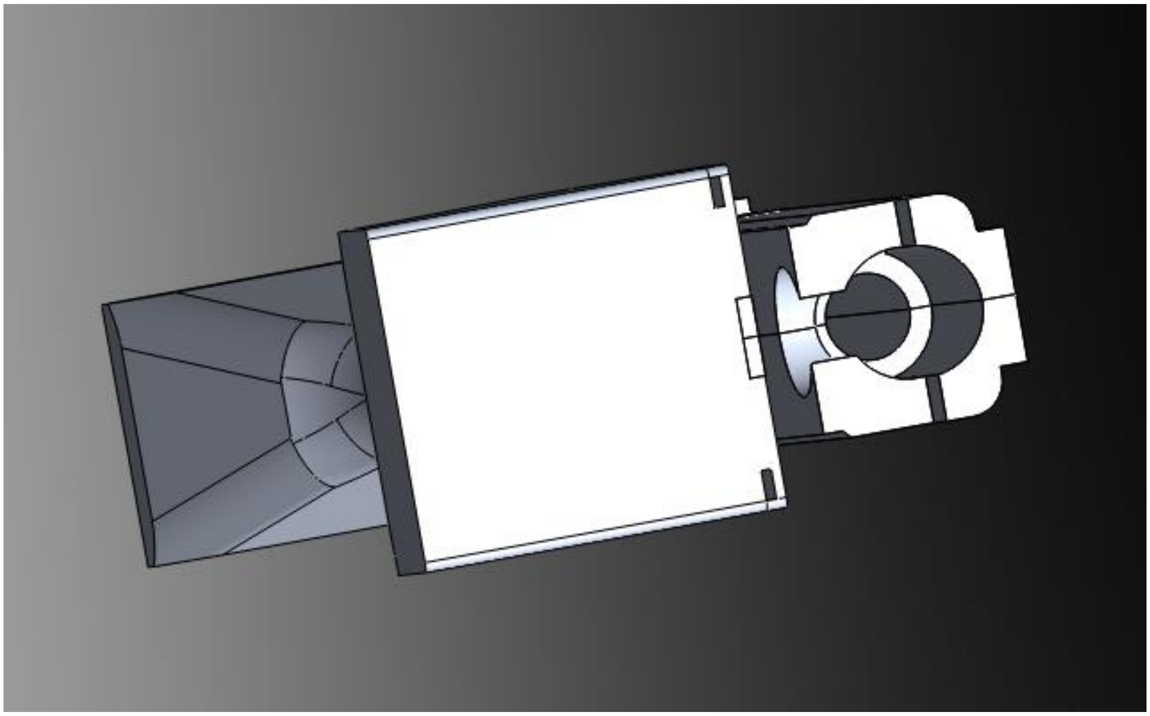
Funnel System



Exponential Horn Encasement



Horn Encasement Cross Section



Speaker Housing in Horn Encasement