# The Icon Horn Loudspeaker

by

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# Abstract

A horn loudspeaker in layperson terms is essentially taking a megaphone and integrating it into a standard speaker. Similar to a cheerleader yelling into a megaphone, the horn loudspeaker will amplify the sound from the speaker with no additional power needed. Using standard speaker horn theory, the geometry of the "megaphone" can be engineered to tune the acoustic performance tailored to loudness and/or specific acoustics frequencies. The horn contours are similar to traditional orchestra instruments such as the French horn, trumpet, and tuba. The iconic beauty of a horn married with the quantitative engineering theory creates an aesthetic yet functional design project. This project focuses on the Lumia Icon smartphone and creates a horn loudspeaker case accessory based on Tractix acoustic horn theory.

# Background

Figure 1. Party Trick: phone within a glass for loudness

Party trick:  The next time you find yourself in a group setting and want to use your phone to play aloud, place it into an empty glass so that the phone gets lodged against the glass side walls.  You may find that this crude yet simple adjustment will amplify the sound with no extra power needed.  Having taken Fundamental Acoustic Theory, I have a basic engineering understanding of how and why this would work, but practically, I would not carry a glass around in my pocket waiting for that perfect opportunity to dazzle and amplify.  (See Figure 1)

Generally, smartphone acoustics are not deciding factor when purchasing a phone.  Since the space requirement needed for the speaker components and adequate air volume directly compete with the product form and size, most smartphone acoustics are underperforming.  I saw an opportunity for an engineering solution!

Upon searching for horn-type smartphone accessories, I discovered that the majority of products on the market did not resemble the appropriate shape and geometry required for optimal performance.  These custom products would charge a premium for an accessory but deliver sub-optimal results.  Qualitatively observing the form and size of current smartphone horn accessories to that of proven concert speaker and musical instruments, one can see that the horn shape is not consistent.

Figure 2. Thomas Edison's Phonogram using a Flared Horn

The phonograph, invented in 1877 by Thomas Edison, used an iconic "flared" horn that we may recognize today (See Figure 2).  The phonograph was the very first mechanical recording device that would scribe the vibrations from incoming sound onto a rotating cylinder.  Upon playback, the device would trace the same grooves created and vibrate a

diaphragm to produce sound. The flared horn would amplify the sound from the diaphragm to an audible level through free space. Thomas Edison knew and utilized the fundamentals of acoustic theory and implemented them in his first phonograph. Even before the comings of Thomas Edison, European musicians and craftsmen were constructing horned instruments in the 1700s. Hammel of Dresden invented what we know today as the, “French Horn” (See Figure 3). The horn was actually invented in Germany but was made popular during the French King Louis the XI hunting trips where a horn was used to communicate and coordinate attacks. The horn needed to be human-powered but be loud enough to startle the prey into running. The French horn, like the phonogram, utilized the characteristic flared horn at the mouth with a narrow throat. The acoustic theory was understood even during pre-millennia times. If we fast forward to modern times, we can see this legacy of acoustic engineering in our everyday practical use.

Figure 3. French horn utilizing a flared contour

Figure 4. Altec Multi-cell Loudspeakers utilizing a flared contour

In many common concert venues or auditoriums, you may find horned loudspeakers used to accommodate large crowds and venues. I have seen these speakers many times throughout my youth, but never thought that they had a connection to Thomas Edison’s phonogram or the French Horn. But just like the French Horn, these modern day Altec Multicell Loudspeakers utilize a flared horn shape with a large mouth opening and a narrow throat (See Figure 4). Modern day technology using old proven acoustic theory.

Benchmarking current horned smartphone products, I found a myriad of shapes and sizes but very few products resembling a flared horn. Many products utilized a

simplified shape, presumably for ease of manufacturing and minimizing material costs, but not optimized for sound.  Other products have created larger horns which may have some aesthetic appeal, but again, these do not follow the acoustic mathematical theory that dictates the cross-sectional area of the horn contour.  Although these products may have functioned and appealed to the public, I qualitatively knew they were flawed.  After I surveyed the available products, it motivated me to analyze, design, manufacture, and test a product of my own making to see what I can come up with.  (See Figures 5)

Figure 5. Various Baseline Smartphone Horn Products

# Acoustic Fundamentals

Acoustic theory involves intensive mathematical models and algorithms that can lose meaning to the layperson fairly quickly. Instead, I will offer a practical guide to what a speaker actually is and how it works. Then I will explain the important components and tie in how the mathematical theories apply to the real physical world. The information provided below is to provide a base of information before entering into the detailed acoustic theory.

Horn Loudspeaker Components:

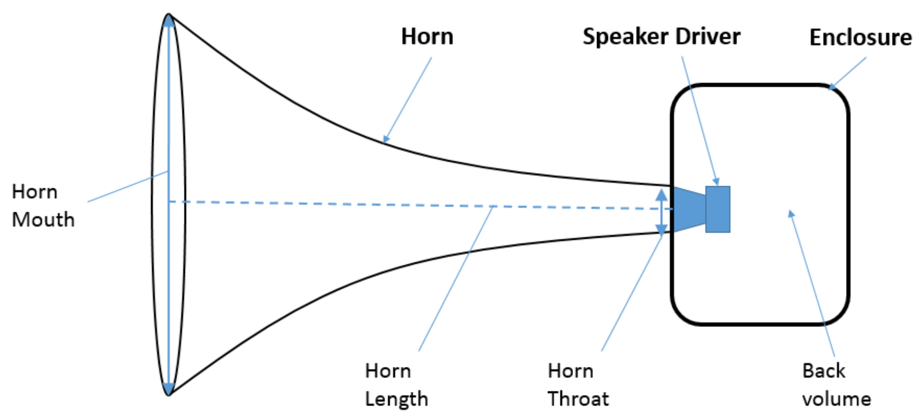



Figure 6. Typical Horn Speaker Components

The 3 main components of a basic horn speaker are: a horn, a speaker driver and a back volume / enclosure. (See Figure 6) All speakers utilize a back volume within some enclosure. The enclosure is what the user typically sees as the speakerbox and its main purpose is to prevent sound waves created from the driver from cancelling each other out. As the speaker driver moves, it creates a sound wave in front of the driver, but also in the back of the driver. Without the enclosure to act as a barrier, these sound waves would wrap around the driver and the peak of one wave could align to the trough of another wave and negate each other. If one were to expose a typical driver in free air without an enclosure, the lower frequencies would tend to cancel out first and the sound

would appear to lack bass or be too high pitched.  The enclosure also defines the quantity of the back volume of the speaker, or in other words, the air sealed inside the speakerbox.

The back volume quantity is critical to the speaker driver performance. Too small a back volume will cause a vacuum effect within the speakerbox and create mechanical losses within the driver in the form of air resistance and heat.  Imagine driving a simple handheld bicycle pump.  The driving handle of the pump is similar to the speaker driver where they both move air.  The chamber of the pump is similar to the back volume of a speaker that contain a volume of air.  If the bicycle pump is small, the user has to work hard to drive the handle and expend a lot of energy.  Since the volume of the pump is small, the air compresses quickly and builds up heat.  The same thing happens to a speaker with an undersized back volume, the driver has to work harder for the amount of stroke and heat builds up quickly.  The side effect would be damage to the speaker driver and/or sound distortion.  The lower sound frequency performance would suffer the most since at lower frequencies the sound waves are the longest and requires the most displacement of the driver.

Now, if the back volume were too large that is not ideal for the speaker performance either.  Having an oversized back volume does not create any mechanical issues to the driver, as it did with an undersized back volume.  An oversized back almost does the opposite, and the volume does not give adequate back pressure to the driver allowing it to move too freely.  At first, this may sound like an advantage, but without the proper back pressure on the driver, the drive can "over extend" during its travel and result in a louder output but with sound distortion.  As mentioned before, the back volume quantity is critical to the speaker driver performance and comes directly from the speaker driver parameters.

On the other end of the speaker lies the horn.  The horn is essentially a megaphone attached to the front or the back of the speaker driver and provides "free" sound amplification with minimal sound distortion. The horn mouth, horn throat, and overall horn length are critical features that are directly related to the parameters of the

speaker driver itself.  More details of the horn geometry will be explained later.  In between the horn and the enclosure lies the speaker driver.

Speaker Driver Components:

Below is a visual cross-section of a typical speaker driver.  The actual speaker used in the Icon smartphone had slight differences and will be explored in more detail during the Results and Analysis section.

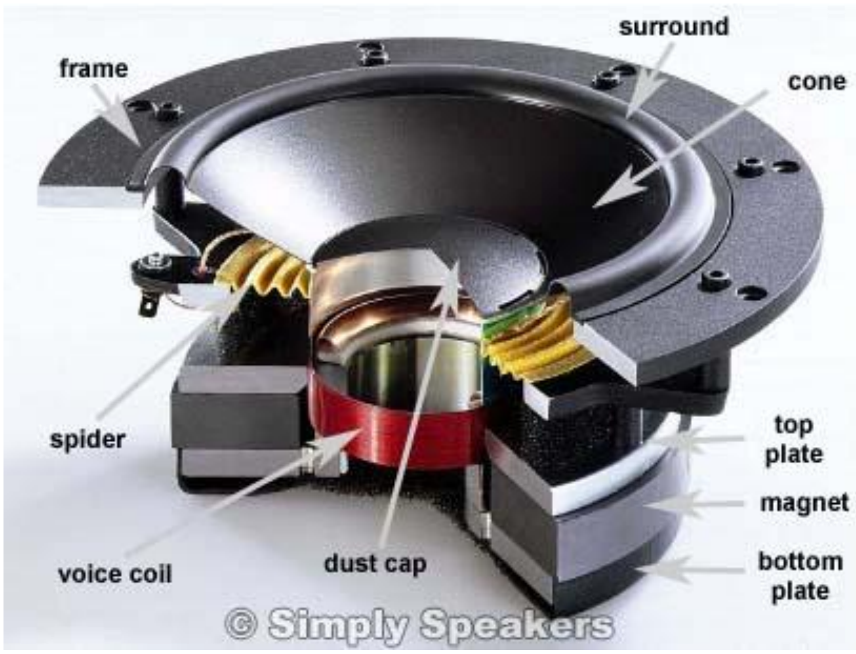



Figure 7. Speaker Driver Section View, Simply Speakers

Frame:  Provides the mounting structure of the speaker driver to the housing or speaker box.

Surround: Flexible relief portion of the speaker cone to allow for free movement of the cone while creating an air and dust seal between the environment and the inside of the driver.

Cone (diaphragm): portion of the speaker that oscillates and creates the sound waves in the air that are audible. Normally made of light weight material that is rigid and well damped to prevent any unwanted vibrations that lead to audio distortion.

Magnet: Standard magnet with North and South polarity. The magnet is used as a part of the driving force of the speaker, but will remain fixed and motionless.

Voice Coil: Made up of a wound coil of copper wire that lies near the stationary magnet. When current is applied to the copper coil, it creates a magnetic field that attracts or repels to the existing magnetic field in the speaker magnet. The jogging of the current change the magnetic field which moves the voice coil and the diaphragm. The voice coil is the driver force and the heart of a speaker driver.

Spider: The accordion shaped part of the speaker connects the voice coil to the diaphragm. The spider helps acts as a spring and centers the diaphragm so it is centered to the voice coil. The spider also helps return diaphragm to resting position after it has been oscillated by the voice coil.

Dust cap: Acts a sealing element for the cone. The shape of the cap can also impact the sound performance

Top/Bottom Plates: Non-magnetic structure pieces of the speaker driver used to sandwich the magnet and provide a track for the voice coil to move along.

Horn Theory:

The speaker driver oscillates a diaphragm to create sound pressure waves, which eventually vibrates our ear drums and is translated into the sound we hear. It is strange to think that a small diaphragm lodged away in a small smartphone can create such sounds. The truth is that is does produce sound, just not very efficient.

The small diaphragm has to move in small strokes and at high speed to create these sound pressure waves. As the diaphragm moves, it compresses the air just in front the diaphragm, which leads to higher local pressure. Based on Bernoulli's principle of a fluid dynamics, if there is an increase fluid pressure there is simultaneously a decrease in fluid velocity. The result is, the air just in front of the diaphragm has high pressure but low velocity. However, the air just beyond the diaphragm is still and at ambient pressure and can be considered to have relatively low pressure. These different pressures and speeds can be considered acoustic impedance; the disparity between the air pressure in front of the diaphragm and just beyond the diaphragm makes the speaker driver inefficient and acoustical energy is lost in the system.

The addition of a horn, however, will help couple the impedance of the air throughout the whole system making it more efficient. Many consider the horn feature as an "acoustic transformer" since its purpose is to change the high pressure, low velocity air at the horn throat to low pressure, high velocity at the horn mouth. The horn is able to achieve this by changing the cross-sectional area at different distances along the horn length. The horn begins with a narrow throat to constrict the amount of air subjected to the diaphragm and gradually opens to a flared mouth. The horn contour creates a transition where the air pressure, or load, on the driver can remain constant, therefore, maximizing the acoustic energy. By adding the horn, the majority of the energy from the speaker driver can be transferred into the air, which in turn creates more loudness.

To visually demonstrate this, imagine a large pit of balls that you are at the in the middle of. (See Figure 8A) The balls represent the air molecules. If you were to pump

your hand back and forth acting as the speaker diaphragm, you would move some of the balls, you would create a sound pressure wave.  As move your hand, you are creating local high pressure, and you will notice that only the balls locally near you will move (at position 1) while the balls farther away remain somewhat still (positions 2-5). This is the same occurrence with a speaker driver where the air pressure is different just in front of the diaphragm then the air pressure farther away.  Relatively little of the energy from your hand gets transferred into the majority of the balls.


Figure 8A. Speaker Diaphragm Analogy; Baseline

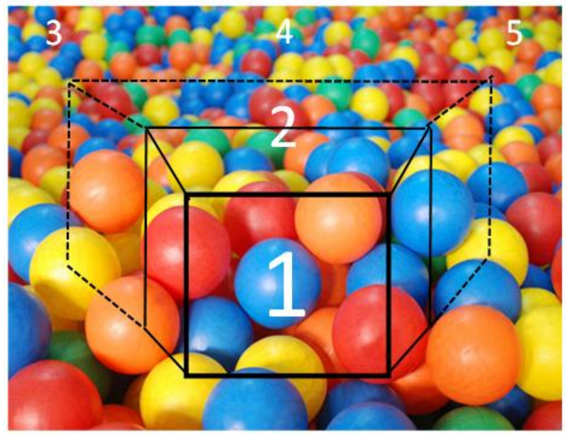



Figure 8B. Speaker Diaphragm Analogy; Horn

Now imagine, you have a flared air conditioning duct with you in the ball pit. (See Figure 8B)  As you move your hand through the duct at position 1, the flared duct helps channel the energy.  The increasing cross-section of the duct allows the energy to be transferred into more of the balls.  Instead of just moving a local group of balls near your hand, you are now moving a balanced group of balls through the duct.  The integration of a horn to a loudspeaker acts in same, where it transforms high pressure at the driver to low pressure at the mouth, and in-doing so allows more transfer of acoustic energy to the air.  The coupling of acoustic impedance, in this case air pressure, allows for a more efficient system and results in higher loudness.

The horn feature not only couples impedances, but also acts as a mean to focus and direct the sound waves for improved perceived loudness.  A typical sound wave in free space will move like a ripple in a pond and fan out 360' out from the source.  Since sound travels in three dimensions, the wave travels outward in a spherical manner

originating from the source. If you take that same source and place it on the floor, the spherical sound energy reflects off the floor and back into the air; this effect causes an increase in perceived loudness by two.  If you place the source on the floor against a wall, again, the waves are reflected again and the same sound energy travels within a quarter of a sphere, which leads to four times the perceived loudness.  Lastly, if you take the source and place it on the floor and in a corner that would result in one-eighth of a sphere, which would equal to eight times the loudness. (See Figure 9)

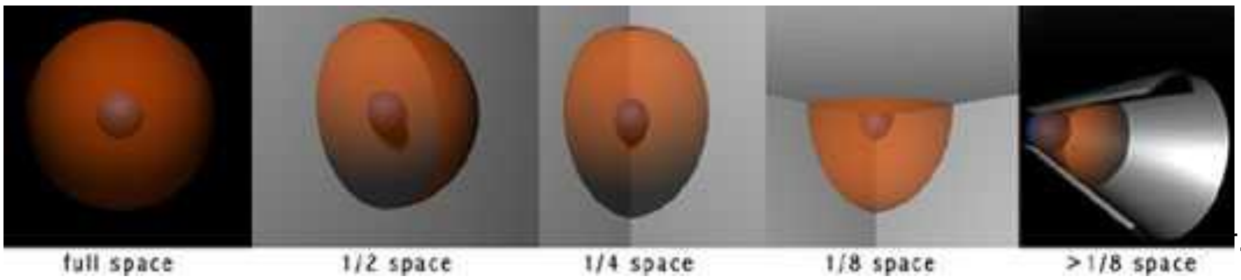



Figure 9: Sound Wave Propagation Diagram

Similar to the walls and floor, integrating a horn feature to a source will reflect and channel the sound waves and prevent them from scattering everywhere.  The horn creates a directional sound wave control that can increase perceived loudness by more than eight times!

Horn contours:

Adding a horn may in fact increase loudness, but adding a specific type of horn contour will depend much on the driver and the design.  Horn contours will differ by the cross-sectional area, rate of expansion, horn length, and most notably the cross-sectional area at the horn mouth.  Each type has its own trade-offs which will be explained below:

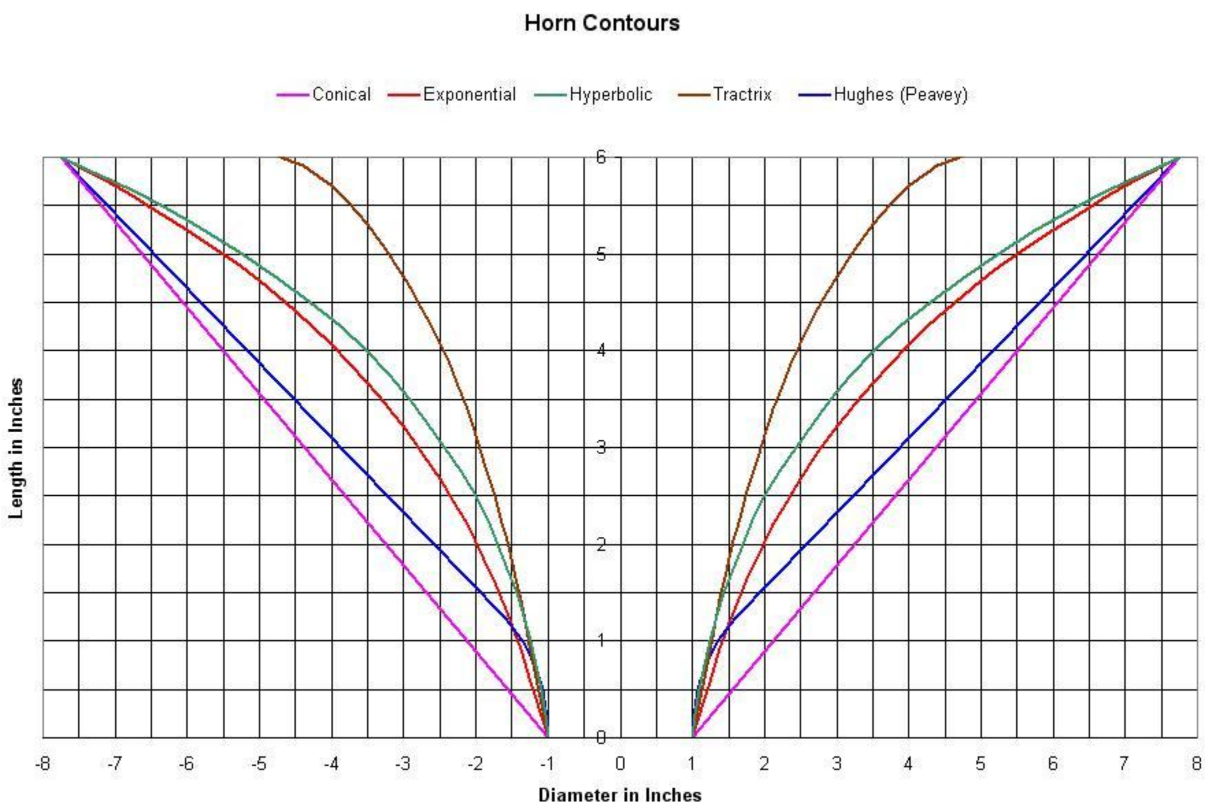



Figure 10: Different Horn Contour Shapes; Horn Length vs. Horn Diameter

Conical Contour:  As the name suggest, this contour is a simple cone that is truncated at the horn throat near the speaker driver.  This simplified design is easy to manufacture and calculate, but comes at the cost of efficiency and size.  If we recall the ball pit analogy, (See Figure 8) the addition of the horn helps match the acoustical impedance of moving air to still air from the horn throat to horn mouth regions.  Since the conical contour has a larger cross-sectional area at the throat region, too much air is

exposed to the speaker driver and acoustical energy is lost. Not only are conical horns too thick at the throat, they are generally longer in length to make up for the lower frequency distortion.

Exponential/Hyperbolic Contour: These are the most typical horn contours that are found in professional horn speakers. The cross-sectional area is determined by logarithmic functions that create a slow expanding contour at the horn throat and a flared opening at the horn mouth. These two profiles only differ slightly by the mathematical equations, but practically, the hyperbolic contour will tend to be slightly longer in horn length. These contours only main trade off is that there tends to be distortion in the lower bass frequencies. Similar to the conical contour, the exponential/hyperbolic contours expands just slightly too fast in the throat region, which subjects too much air to the speaker driver resulting in reduced performance.

Tractix Contour: The Tractix curve is commonly referred to as the most musical of all the contours since it creates the lowest distortion. Compared to all other contours the Tractix expands the slowest in the throat region and then expands the fastest in the mouth region. This unique contour allows the horn to meet the lower frequency performance and also have an overall shorter horn length. The trade-off of the Tractix is the complicated mathematics involved, and the manufacturing challenge of creating an aggressive flare accurately. The horn mouth diameter is typically the largest in a Tractix curve and directly impacts the operating frequency range.

# Design Process

The development of the Icon Horn Loudspeaker required several iterations due to unforeseen complications. Designing an accessory to integrate to an existing product requires that all the design compromises be made on my side, the accessory side. I intended to build a horn loudspeaker to accompany the Nokia Lumia Icon smartphone, therefore, no design changes can be made to the existing product. I will walk you through the design process starting with the initial concept through the final product.

Initial Concept:

After benchmarking the current iPhone horn products (See Figure 5) I knew I wanted to design an aggressive acoustical solution. I did not want to compromise the acoustical theory and engineering for ease of manufacturability and marketability. I wanted something simple yet effective and the aesthetics would be derived from the engineering.

My initial vision was to create a case that held the Lumia Icon in the landscape position with the volume keys pointed towards the ceiling. The horn mouth would sit on top of the keys with a pill shaped opening. The user would be able to access the keys freely due to the large opening of the horn mouth. I envisioned that the Horn Length could coil behind the case and be used to support the case + phone in position like a bicycle kickstand. The initial concept would be compact and minimalistic but completely functional. (See Figure 11)

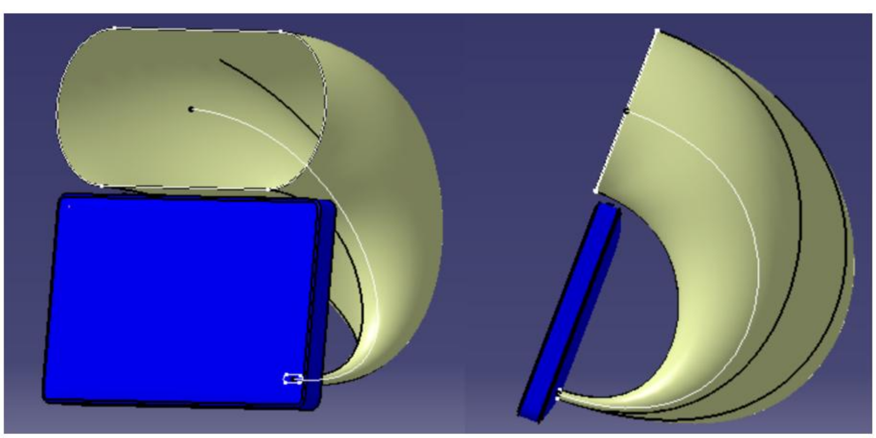




Figure 11. Initial 3D Concept for the Icon Horn Speaker

Design Requirements:

With my design vision retained, I set forth detailing a list of design requirements that I would not stray from unless I had just cause.

1) The final design should be designed to the Nokia Lumia Icon smartphone and use the internal embedded speaker driver within the device. The speaker driver dimensions, back volume, and speaker hole opening are fixed and cannot be changed. (See Figure 12 & 13)


Figure 12. Lumia Icon Internal Speaker Enclosure, Front / Back


Figure 13. Lumia Icon Speaker Port Dimensions (Back Cover)

2) The final design should utilize the Tractix horn contour for maximum loudness and musicality performance.

3) The final design shall be manufactured by rapid 3D prototyping using a Stereolithography machine (SLA) to achieve +/- 0.20mm accuracy

4) The final design shall be one part requiring no assembly. Once the phone has been placed inside the final design it should be self-standing.

5) The design shall have user access to the touch screen and the volume keys to allow for unimpeded user interface and volume control of the smartphone.

Development:

I had selected the Tractix horn contour base on its musical performance, and now I was governed to the Tractix mathematical equations to define the exact profile of the horn. The Tractix function calculates the cross-sectional area of the horn at some given distance from the horn throat; based on those data points a 3D contour can be constructed. Professor Ngozi Kamalu, had provided a Mathcad program that explicitly solved this function based on a handful of speaker driver parameter inputs (See Appendix A). These speaker driver inputs are referred to Thiele/Small parameters and are electromechanical parameters that are physically measured from a completed speaker driver. Typically, off-the-shelf speaker drivers will supply these Thiele/Small parameters for the consumer to integrate into their design. In my case, I was using a custom proprietary speaker driver within the Lumia Icon smartphone device and did not have the access to the complete manufacturer's specifications.

Lacking the critical speaker parameters, I had to adjust my design to utilize the limited inputs that I knew, but still gained maximum performance. I referred to Volvotreter's Round Horn Tractix Calculator that required me to supply two known inputs: the cutoff frequency and the horn throat radius. (See Appendix B)

Cutoff Frequency:

The cutoff frequency is the frequency at which the horn does not function below, therefore, does not add any value to the final sound output. Typically, the lower the cutoff frequency the larger the horn length and horn mouth required. Since low frequencies have longer wave lengths, longer horns are needed to provide the acoustic impedance matching described in Figure 8. Since the horn expands exponentially, a longer the horn will result in a larger horn mouth dimension. The cutoff frequency for my design is 850 Hz which means the horn will not amplify or impact any sound below that. Audile bass frequency ranges from 20 to 500 Hz typically, so my design compromised the lower bass regions, but retained the mid and high range for musical performance.

Horn Throat Radius:

The Horn Radius dimension is typically calculated using the Thiele/Small parameters. As mentioned before, I did not have access to these parameters, but I did have actual product dimensions to base my own horn throat dimension on. Since the Icon smartphone uses a 8.5mm x 1.75mm slot, the horn throat had to more than 8.5mm in diameter (4.25mm radius) to ensure the case did not cover up any of the audio channel. A throat radius of 5.05mm was selected. (See Figure 14)


Figure 14. Lumia Icon Speaker Opening to Horn Throat

Tractix Calculator Outputs:

With the two design inputs secured, I used the Tractix calculator to deliver three major outputs: Horn Mouth Radius, Horn Length, and Horn Radius at any position between the horn throat and horn mouth positions. (See Figure 15) Details of the calculations can be found in Appendix C.

| | | |
|---|---|---|
| $F_{cut\ off}$ (flare frequency) - free air | 850 | Hz |
| $R_T$ radius throat | 5.1 | mm |
| $R_M$ radius mouth | 63.66 | mm |
| Horn length | 141.9 | mm |

Figure 15. Calculated Critical Feature Results

The horn mouth was calculated based on the cutoff frequency input and as mentioned before, the lower the cutoff frequency the larger the horn mouth dimension. Since the horn mouth equation is exponential, small reductions in the cutoff frequencies resulted in large increases in the horn mouth dimension. As of result, the horn mouth radius was large enough to cover the mid-to-high frequency audio performance, but still small enough to still fit within the SLA machine manufacturing size limits. With the horn throat radius known and the horn mouth radius calculated, I implemented the Tractix formula and I was able to move onto to the next calculated output, the horn length.

Horn Bending and Cross-sectional Area Shape:

The Horn Length determined how much freedom I had to bend the horn profile to accommodate my design intent. The initial concept proposal had a pill-shaped cross-section, which mimicked the same speaker hole opening already present on the Lumia Icon smartphone (See Figure 13). The design was intended to hold the phone in the landscape position, where the horn would bend in a “U-turn” starting at the back of the phone and ending at the front. Additionally, the horn throat originated on one side of the phone and the horn mouth was to exit on the opposite side, where the keys are present. (See Figure 11) The horn length proved too short and the horn cross-sectional area too bulky to be able to bend the horn without having the 3D geometry kink and fold onto itself. I had to radically change the design intent to accommodate the Tractix calculated profile.

Since the horn length was relatively short, a characteristic of Tractix horns, I changed the design to move the horn mouth on the same long edge of the phone as the horn throat. As of result, the phone orientation could no longer be in the landscape position because the volume keys would lie facing into the ground and would no longer be user accessible. I changed the orientation to have the case hold the phone in the upright portrait position to still meet all design requirements. (See Figure 16)

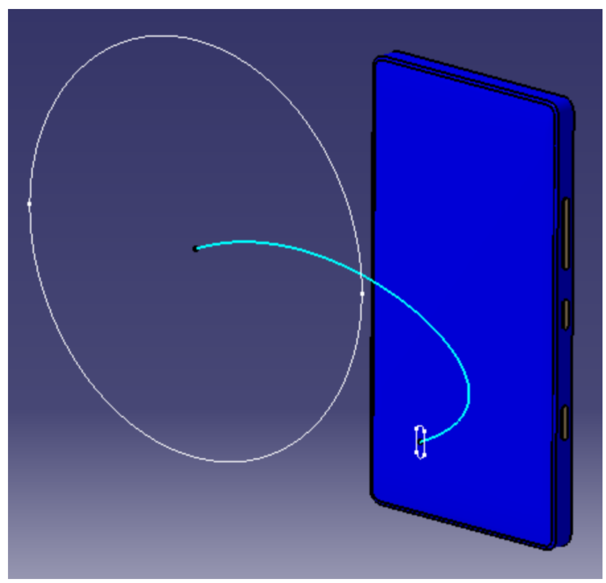


Figure 16. Horn Mouth Location and Horn Bend Path

Even with moving the horn mouth location, the horn bend was still too aggressive and created 3D cusps or kinks in the horn geometry. To solve this, I compromised the original pill-shaped cross-section to become a more stable circular cross-section and was able to balance the short horn length with the aggressive U-turn horn bend. Once the cross-section shape and horn bend were defined, I then turned to the Tractix calculator to fill different cross-sectional areas along different points of the horn profile.

As long as the cross-sectional area was correct at the exact distance away from the horn throat, bending of the horn would not negatively impact the sound performance. The result is a pure Tractix bounded 3D contour that has been bent in a U-turn to be integrated into my case. (See Figure 17)

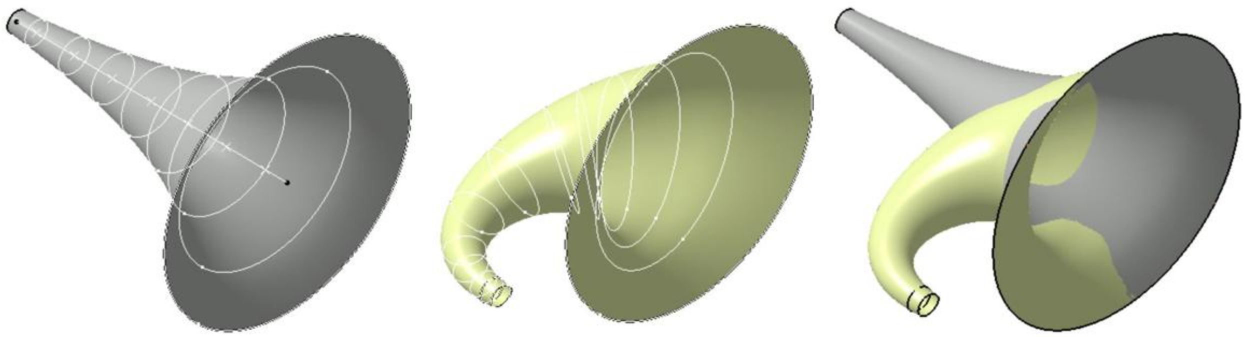


Figure 17. Tractix Horn Profile Bent in a U-Turn

I designed a simple case and support structure to compliment the bent horn structure and allowed full user-access to the volume keys and touch screen. The case utilized the horn mouth as a tangent anchor feature to the ground and ensured the unit would not tip over during full volume play. The final design was manufactured using a Stereolithography (SLA) rapid prototype machine. The SLA machine created 3D parts by adding material one thin cross-sectional layer at a time. This unique layer-by-layer construction method was critical in manufacturing the complex and hollow prototype, all while keeping an accuracy of +/- 0.20mm. The smooth and accurate finish was paramount to retaining acoustical integrity. (See Figure 18)

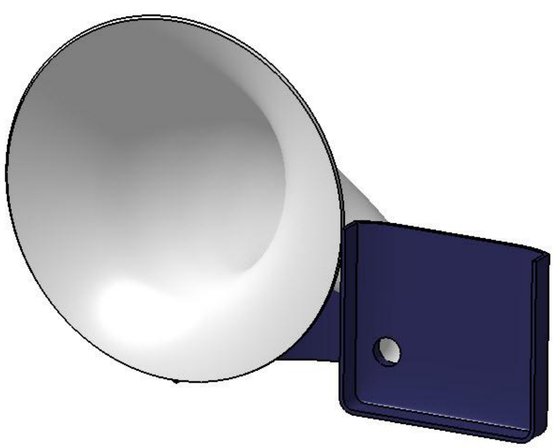


Figure 18. Final Icon Loudspeaker 3D Design

# Analysis & Results

Speaker performance can be quantitatively evaluated using a Sound Pressure Level (SPL) measured in decibels (dB) versus Frequency (Hz) plot. The plot basically shows the sound power level of a speaker across the entire human audible hearing range of ~20 to 20,000 Hz. An ideal frequency response plot will have a maximum flat region without any peaks or valleys, which would indicate sound distortion. (See Figure 19) The higher the value of SPL recorded, the higher the perceived sound loudness. Since the plot is on a logarithmic scale, an increase of 10 dB is equivalent to about twice the perceived loudness.

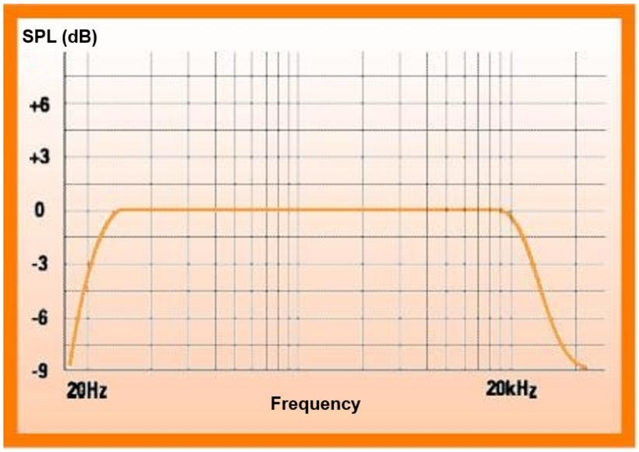



Figure 19. Ideal Sound Pressure Level Plot

My prototype was tested in an acoustic chamber that was lined with acoustic absorbing material. The chamber was designed to reduce if not completely remove any sound reflections and allow for high accuracy acoustic measurements. (See Figure 20) The Lumia Icon was staged directly in the center of the room with a microphone aligned and centered 250mm away from the speaker opening. Baseline measurements were taken on the Lumia Icon followed by Lumia Icon + Horn measurements. A six octave 100Hz to 20 KHz sound clip was played through both test scenarios and SPL plots were produced from the Audio Precision software to compare the data.

Figure 20. Typical Acoustic Testing

Baseline Lumia Icon SPL Performance:

The Baseline SPL plot showed a relatively flat frequency response holding at 20 dB from 1K to 7K Hz (Region B), which is typically the audible range for human speech. (See Figure 20) Being a smartphone, it makes sense that the audio performance be optimized for speech for hands-free use. However, the baseline plot lacked in the lower and higher frequencies, noted by the sloped output in Region A and C. As discussed earlier, a lack of back volume could result in poor performance in the lower bass region, but without the Thiele/Small parameters, I could not empirically confirm or deny this. The details of the internal audio back volume design were company confidential, therefore, the actual back volume was not reported.

The baseline plot also suffered in the high frequency range in Region C, which resulted in reduced high pitch performance in music. Since the slope drop-off in Region C was not as gradual as it was in Region A, it suggested that the performance loss was not as severe, therefore, harder to notice to the human ear. When I listened to music on the Lumia Icon, I clearly noticed the lack of bass, but the high tone performance was only noticeable when I compared the sound to a superior home audio sound system.

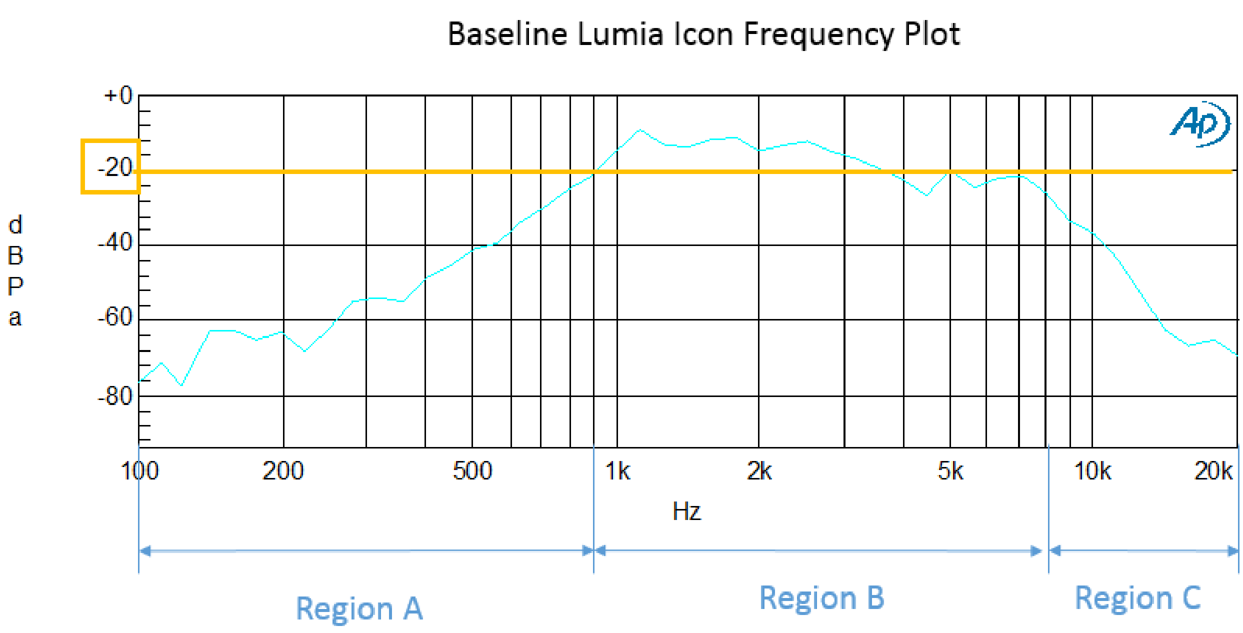



Figure 20. Baseline Lumia Icon Sound Pressure Level vs. Frequency Plot

Lumia Icon with Horn SPL Performance:

Using the same setup and testing parameters, a new SPL was produced with the addition of the horn. (See Figure 21) Clearly, the flat region of the plot lied around 40db starting from the Cutoff Frequency of 850 Hz to 10 KHz. The output showed a 20 dB gain in sound pressure level from the baseline, which is equivalent to roughly four times the perceived loudness! As expected, the plot also showed that the horn impacted only frequencies above the Cutoff Frequency of 850 Hz. The correlation between the acoustic theory and the actual test results suggested that the SLA manufacturing process was successful in creating a smooth and accurate prototype. Lastly, the plot showed improvement in the high frequency range performance and extended the flat region from 7 KHz in the baseline to 10 KHz. The high frequency improvement was a direct result to the Tractix contour and its characteristic performance in the mid-to-high frequency range. When the horn was tested it was obvious there was an increase in loudness, but simultaneously it also highlighted the poor bass performance. As seen in the plot, the gradual slope in the bass regions showed no change from the baseline, as expected.

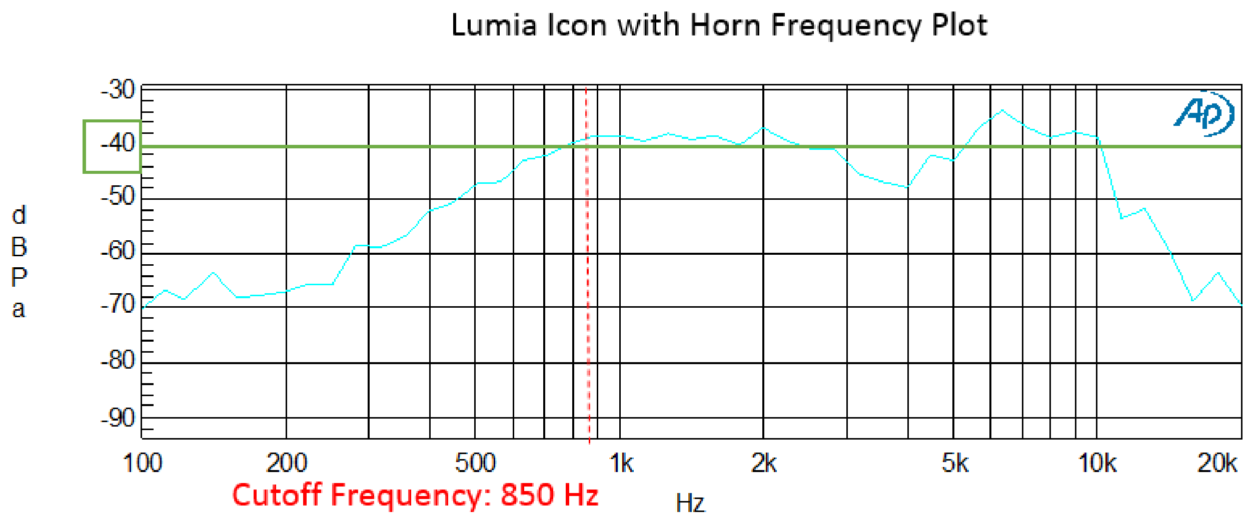



Figure 21. Lumia Icon with Horn Sound Pressure Level vs. Frequency Plot Speakers

# Recommendations

Although the Icon Horn Loudspeaker showed improvement over the baseline, there were glaring areas of improvement.  Below are recommendations:

1) Increase the back volume within the Lumia Icon phone itself to improve lower frequency response in the baseline performance.  Larger back volume comes at the cost the overall size and form of the phone.

2) Lower the cutoff frequency from 850 Hz to 100 Hz to allow the horn to improve the lower frequency region.  This change comes at a heavy trade-off as both the horn mouth and horn length become exponentially larger and SLA production may no longer be feasible.  Alternate manufacturing means will need to be explored.

3) Reduce the horn throat area to improve the acoustic impedance coupling, and in turn, increase lower frequency performance.  The throat area was circular, while the speaker hole itself was pill-shaped. The mismatch in shape made the junction inherently oversized, and exposed too much air to the speaker diaphragm, making it less efficient. The speaker opening shape on the Lumia Icon itself could be changed to circular to help reduce the horn throat area.

4) Empirically test the Lumia Icon speaker driver to obtain the Thiele/Small parameters. With the parameters, a more accurate back volume assessment can be made as well as more precise Tractix contour calculations. The overall impact could have a slight improvement over the entire speaker frequency range.

5) The air seal between the Icon Horn Case and the back cover of the Lumia Icon needs to be air tight to ensure none of the acoustic energy is blown outside the system. Improving the seal could improve the overall performance.

6) A total of 13 cross-sectional areas were used to construct the bent 3D Tractix contour.  The 3D CAD software interpolated the geometry between the data points. If the entire design spreadsheet of 400+ data points could be imported, the 3D contour could be more accurate and improve overall performance.

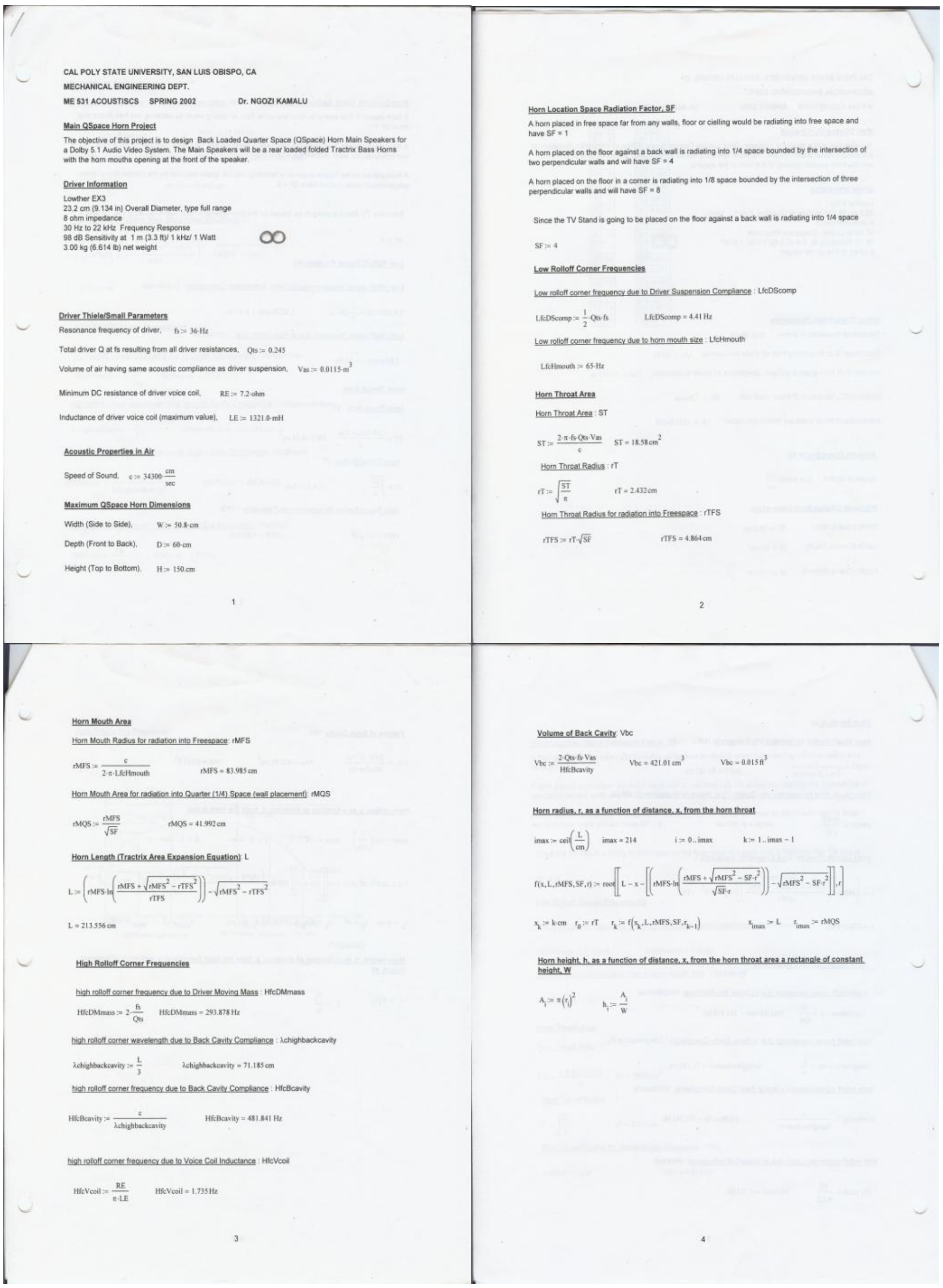
# Conclusion

The Icon Horn Loudspeaker was the first of its kind for the Lumia smartphone line. I adhered to the acoustical fundamentals, and created a true Tractix contoured horn that resulted in 20dB gains. The final design resulted in approximately four times increase of perceived loudness, while similar benchmarked products advertised only 13dB gains with 2.5 times increase loudness. The integration of the horn shows a dramatic difference in the frequency response within the mid-to-high frequency range. Unfortunately, the baseline frequency response of Lumia Icon (with no horn added) showed poor performance in the lower bass regions. As predicted, the addition of the horn did not improve this lower bass region, however, confidence was gained in accurately calculating the cutoff frequency when compared to the measured test results. In the end, given the design constrictions and limitations, the overall intent and requirements were achieved with the engineering correctly prioritized. (See Figure 22)


Figure 22. Final Icon Horn Loudspeaker Design

# Appendix A- Dr. Kamalu Calculator

Dr. Kamalu had provided a matlab based Tractix calculator during my ME 531 class. The program used Thiele/Small speaker driver parameters to calculate: Horn Mouth Area, Horn Length, Back Volume, Cutoff Frequency, and Horn Radius. The program is especially valuable since it breaks down the exponential Tractix formula to solve for the Horn Radius and at an exact and known distance from the Horn Throat. Knowing the Horn Radius at an exact distance from the Horn Throat helps with the 3D modeling and the manufacturing of the horn itself.



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ME 531 ACOUSTISCS SPRING 2002 Dr. NGOZI KAMALU

**Main QSpace Horn Project**

The objective of this project is to design Back Loaded Quarter Space (QSpace) Horn Main Speakers for a Dolby 5.1 Audio Video System. The Main Speakers will be a rear loaded folded Tractrix Bass Horns with the horn mouths opening at the front of the speaker.

**Driver Information**

Lowther EX3
23.2 cm (9.134 in) Overall Diameter, type full range
8 ohm impedance
30 Hz to 22 kHz Frequency Response
98 dB Sensitivity at 1 m (3.3 ft)/ 1 kHz/ 1 Watt
3.00 kg (6.614 lb) net weight

**Driver Thiele/Small Parameters**

Resonance frequency of driver, $fs := 36 \cdot Hz$

Total driver Q at fs resulting from all driver resistances, $Qts := 0.245$

Volume of air having same acoustic compliance as driver suspension, $Vas := 0.0115 \cdot m^3$

Minimum DC resistance of driver voice coil, $RE := 7.2 \cdot ohm$

Inductance of driver voice coil (maximum value), $LE := 1321.0 \cdot mH$

**Acoustic Properties in Air**

Speed of Sound, $c := 34300 \cdot \frac{cm}{sec}$

**Maximum QSpace Horn Dimensions**

Width (Side to Side), $W := 50.8 \cdot cm$

Depth (Front to Back), $D := 60 \cdot cm$

Height (Top to Bottom), $H := 150 \cdot cm$

1

**Horn Location Space Radiation Factor, SF**

A horn placed in free space far from any walls, floor or cielling would be radiating into free space and have SF = 1

A horn placed on the floor against a back wall is radiating into 1/4 space bounded by the intersection of two perpendicular walls and will have SF = 4

A horn placed on the floor in a corner is radiating into 1/8 space bounded by the intersection of three perpendicular walls and will have SF = 8

Since the TV Stand is going to be placed on the floor against a back wall is radiating into 1/4 space

$SF := 4$

**Low Rolloff Corner Frequencies**

Low rolloff corner frequency due to Driver Suspension Compliance : LfcDScomp

$LfcDScomp := \frac{1}{2} \cdot Qts \cdot fs$ $\quad LfcDScomp = 4.41\ Hz$

Low rolloff corner frequency due to horn mouth size : LfcHmouth

$LfcHmouth := 65 \cdot Hz$

**Horn Throat Area**

Horn Throat Area : ST

$ST := \frac{2 \cdot \pi \cdot fs \cdot Qts \cdot Vas}{c}$ $\quad ST = 18.58\ cm^2$

Horn Throat Radius : rT

$rT := \sqrt{\frac{ST}{\pi}}$ $\quad rT = 2.432\ cm$

Horn Throat Radius for radiation into Freespace : rTFS

$rTFS := rT \cdot \sqrt{SF}$ $\quad rTFS = 4.864\ cm$

2

**Horn Mouth Area**

Horn Mouth Radius for radiation into Freespace: rMFS

$rMFS := \frac{c}{2 \cdot \pi \cdot LfcHmouth}$ $\quad rMFS = 83.985\ cm$

Horn Mouth Area for radiation into Quarter (1/4) Space (wall placement): rMQS

$rMQS := \frac{rMFS}{\sqrt{SF}}$ $\quad rMQS = 41.992\ cm$

**Horn Length (Tractrix Area Expansion Equation): L**

$$L := \left( rMFS \cdot \ln\left( \frac{rMFS + \sqrt{rMFS^2 - rTFS^2}}{rTFS} \right) \right) - \sqrt{rMFS^2 - rTFS^2}$$

$L = 213.556\ cm$

**High Rolloff Corner Frequencies**

high rolloff corner frequency due to Driver Moving Mass : HfcDMmass

$HfcDMmass := 2 \cdot \frac{fs}{Qts}$ $\quad HfcDMmass = 293.878\ Hz$

high rolloff corner wavelength due to Back Cavity Compliance : λchighbackcavity

$\lambda chighbackcavity := \frac{L}{3}$ $\quad \lambda chighbackcavity = 71.185\ cm$

high rolloff corner frequency due to Back Cavity Compliance : HfcBcavity

$HfcBcavity := \frac{c}{\lambda chighbackcavity}$ $\quad HfcBcavity = 481.841\ Hz$

high rolloff corner frequency due to Voice Coil Inductance : HfcVcoil

$HfcVcoil := \frac{RE}{\pi \cdot LE}$ $\quad HfcVcoil = 1.735\ Hz$

3

**Volume of Back Cavity**: Vbc

$Vbc := \frac{2 \cdot Qts \cdot fs \cdot Vas}{HfcBcavity}$ $\quad Vbc = 421.01\ cm^3$ $\quad Vbc = 0.015\ ft^3$

**Horn radius, r, as a function of distance, x, from the horn throat**

$imax := ceil\left(\frac{L}{cm}\right)$ $\quad imax = 214$ $\quad i := 0..imax$ $\quad k := 1..imax - 1$

$$f(x, L, rMFS, SF, r) := root\left[ \left[ L - x - \left[ \left( rMFS \cdot \ln\left( \frac{rMFS + \sqrt{rMFS^2 - SF \cdot r^2}}{\sqrt{SF} \cdot r} \right) \right) - \sqrt{rMFS^2 - SF \cdot r^2} \right] \right], r \right]$$

$x_k := k \cdot cm$ $\quad r_0 := rT$ $\quad r_k := f(x_k, L, rMFS, SF, r_{k-1})$ $\quad x_{imax} := L$ $\quad r_{imax} := rMQS$

**Horn height, h, as a function of distance, x, from the horn throat area a rectangle of constant height, W**

$A_i := \pi (r_i)^2$ $\quad h_i := \frac{A_i}{W}$

4

# Appendix B- Tractix Calculator

This design spreadsheet by Volvotreter requires user inputs of Cutoff Frequency (Hz) and Horn Throat Radius (mm). Within the table, the Horn Mouth Radius (mm) and Horn Length (mm) are calculated. From those inputs, the remainder of the spreadsheet will calculate the radius horn at incremental distances from the horn throat. All data points marked in green where used to construct the 3D geometry. Detailed calculations can be found in Appendix C.

## Lumia Icon Tractix Round Horn

| | | |
|---|---|---|
| $F_{cut\ off}$ (flare frequency) - free air | **850** | Hz |
| $R_T$ radius throat | **5.1** | mm |
| $D_T$ diameter throat | **10.1** | mm |
| $R_M$ radius mouth | **63.66** | mm |
| $D_M$ diameter mouth | **127.32** | mm |
| $A_T$ throat area | **0.8** | cm² |
| $A_M$ mouth area | **127.3** | cm² |
| Horn length | **141.9** | mm |

**Note: Change red numbers only, others will be calculated!**

3D data pt.

| distance from mouth [mm] | distance from throat [mm] | radius [mm] | diameter [mm] | Area [cm²] |
|---|---|---|---|---|
| 141.9 | 0.00 | 5.05 | 10.10 | 0.80 |
| 138.3 | 3.58 | 5.34 | 10.69 | 0.90 |
| 136.6 | 5.30 | 5.49 | 10.98 | 0.95 |
| 134.9 | 6.97 | 5.64 | 11.27 | 1.00 |
| 133.3 | 8.59 | 5.78 | 11.57 | 1.05 |
| 131.7 | 10.18 | 5.93 | 11.86 | 1.10 |
| 130.2 | 11.73 | 6.08 | 12.15 | 1.16 |
| 128.7 | 13.24 | 6.22 | 12.44 | 1.22 |
| 127.2 | 14.71 | 6.37 | 12.74 | 1.27 |
| 125.7 | 16.15 | 6.52 | 13.03 | 1.33 |
| 124.3 | 17.56 | 6.66 | 13.32 | 1.39 |
| 123.0 | 18.94 | 6.81 | 13.62 | 1.46 |
| 121.6 | 20.29 | 6.95 | 13.91 | 1.52 |
| 120.3 | 21.60 | 7.10 | 14.20 | 1.58 |
| 119.0 | 22.90 | 7.25 | 14.50 | 1.65 |
| 117.7 | 24.16 | 7.39 | 14.79 | 1.72 |
| 116.5 | 25.40 | 7.54 | 15.08 | 1.79 |
| 115.3 | 26.62 | 7.69 | 15.38 | 1.86 |
| 114.1 | 27.81 | 7.83 | 15.67 | 1.93 |

| | | | | |
|---|---|---|---|---|
| 112.9 | 28.98 | 7.98 | 15.96 | 2.00 |
| 111.8 | 30.13 | 8.13 | 16.25 | 2.08 |
| 110.6 | 31.26 | 8.27 | 16.55 | 2.15 |
| 109.5 | 32.37 | 8.42 | 16.84 | 2.23 |
| 108.4 | 33.46 | 8.57 | 17.13 | 2.31 |
| 107.4 | 34.53 | 8.71 | 17.43 | 2.39 |
| 106.3 | 35.58 | 8.86 | 17.72 | 2.47 |
| 105.3 | 36.61 | 9.01 | 18.01 | 2.55 |
| 104.3 | 37.63 | 9.15 | 18.31 | 2.63 |
| 103.3 | 38.63 | 9.30 | 18.60 | 2.72 |
| 102.3 | 39.61 | 9.45 | 18.89 | 2.80 |
| 101.3 | 40.58 | 9.59 | 19.18 | 2.89 |
| 100.4 | 41.54 | 9.74 | 19.48 | 2.98 |
| 99.4 | 42.48 | 9.89 | 19.77 | 3.07 |
| 98.5 | 43.40 | 10.03 | 20.06 | 3.16 |
| 97.6 | 44.31 | 10.18 | 20.36 | 3.25 |
| 96.7 | 45.21 | 10.33 | 20.65 | 3.35 |
| 95.8 | 46.10 | 10.47 | 20.94 | 3.44 |
| 94.9 | 46.97 | 10.62 | 21.24 | 3.54 |
| 94.1 | 47.83 | 10.76 | 21.53 | 3.64 |
| 93.2 | 48.68 | 10.91 | 21.82 | 3.74 |
| 92.4 | 49.51 | 11.06 | 22.12 | 3.84 |
| 91.6 | 50.34 | 11.20 | 22.41 | 3.94 |
| 90.7 | 51.15 | 11.35 | 22.70 | 4.05 |
| 89.9 | 51.96 | 11.50 | 22.99 | 4.15 |
| 89.1 | 52.75 | 11.64 | 23.29 | 4.26 |
| 88.4 | 53.53 | 11.79 | 23.58 | 4.37 |
| 87.6 | 54.30 | 11.94 | 23.87 | 4.48 |
| 86.8 | 55.07 | 12.08 | 24.17 | 4.59 |
| 86.1 | 55.82 | 12.23 | 24.46 | 4.70 |
| 85.3 | 56.56 | 12.38 | 24.75 | 4.81 |
| 84.6 | 57.30 | 12.52 | 25.05 | 4.93 |
| 83.9 | 58.02 | 12.67 | 25.34 | 5.04 |
| 83.2 | 58.74 | 12.82 | 25.63 | 5.16 |
| 82.4 | 59.45 | 12.96 | 25.93 | 5.28 |
| 81.7 | 60.15 | 13.11 | 26.22 | 5.40 |
| 81.1 | 60.84 | 13.26 | 26.51 | 5.52 |
| 80.4 | 61.53 | 13.40 | 26.80 | 5.64 |
| 79.7 | 62.20 | 13.55 | 27.10 | 5.77 |
| 79.0 | 62.87 | 13.70 | 27.39 | 5.89 |
| 78.4 | 63.53 | 13.84 | 27.68 | 6.02 |
| 77.7 | 64.19 | 13.99 | 27.98 | 6.15 |
| 77.1 | 64.84 | 14.13 | 28.27 | 6.28 |
| 76.4 | 65.48 | 14.28 | 28.56 | 6.41 |
| 75.8 | 66.11 | 14.43 | 28.86 | 6.54 |
| 75.2 | 66.73 | 14.57 | 29.15 | 6.67 |
| 74.5 | 67.35 | 14.72 | 29.44 | 6.81 |
| 73.9 | 67.97 | 14.87 | 29.74 | 6.94 |

| | | | | |
|---|---|---|---|---|
| 73.3 | 68.57 | 15.01 | 30.03 | 7.08 |
| 72.7 | 69.18 | 15.16 | 30.32 | 7.22 |
| 72.1 | 69.77 | 15.31 | 30.61 | 7.36 |
| 71.5 | 70.36 | 15.45 | 30.91 | 7.50 |
| 71.0 | 70.94 | 15.60 | 31.20 | 7.65 |
| 70.4 | 71.52 | 15.75 | 31.49 | 7.79 |
| 69.8 | 72.09 | 15.89 | 31.79 | 7.94 |
| 69.2 | 72.65 | 16.04 | 32.08 | 8.08 |
| 68.7 | 73.21 | 16.19 | 32.37 | 8.23 |
| 68.1 | 73.77 | 16.33 | 32.67 | 8.38 |
| 67.6 | 74.32 | 16.48 | 32.96 | 8.53 |
| 67.0 | 74.86 | 16.63 | 33.25 | 8.68 |
| 66.5 | 75.40 | 16.77 | 33.54 | 8.84 |
| 66.0 | 75.94 | 16.92 | 33.84 | 8.99 |
| 65.4 | 76.47 | 17.07 | 34.13 | 9.15 |
| 64.9 | 76.99 | 17.21 | 34.42 | 9.31 |
| 64.4 | 77.51 | 17.36 | 34.72 | 9.47 |
| 63.9 | 78.02 | 17.51 | 35.01 | 9.63 |
| 63.4 | 78.53 | 17.65 | 35.30 | 9.79 |
| 62.9 | 79.04 | 17.80 | 35.60 | 9.95 |
| 62.4 | 79.54 | 17.94 | 35.89 | 10.12 |
| 61.9 | 80.04 | 18.09 | 36.18 | 10.28 |
| 61.4 | 80.53 | 18.24 | 36.48 | 10.45 |
| 60.9 | 81.02 | 18.38 | 36.77 | 10.62 |
| 60.4 | 81.50 | 18.53 | 37.06 | 10.79 |
| 59.9 | 81.98 | 18.68 | 37.35 | 10.96 |
| 59.4 | 82.46 | 18.82 | 37.65 | 11.13 |
| 59.0 | 82.93 | 18.97 | 37.94 | 11.31 |
| 58.5 | 83.39 | 19.12 | 38.23 | 11.48 |
| 58.0 | 83.86 | 19.26 | 38.53 | 11.66 |
| 57.6 | 84.32 | 19.41 | 38.82 | 11.84 |
| 57.1 | 84.77 | 19.56 | 39.11 | 12.02 |
| 56.7 | 85.23 | 19.70 | 39.41 | 12.20 |
| 56.2 | 85.67 | 19.85 | 39.70 | 12.38 |
| 55.8 | 86.12 | 20.00 | 39.99 | 12.56 |
| 55.3 | 86.56 | 20.14 | 40.29 | 12.75 |
| 54.9 | 87.00 | 20.29 | 40.58 | 12.93 |
| 54.5 | 87.43 | 20.44 | 40.87 | 13.12 |
| 54.0 | 87.86 | 20.58 | 41.16 | 13.31 |
| 53.6 | 88.29 | 20.73 | 41.46 | 13.50 |
| 53.2 | 88.71 | 20.88 | 41.75 | 13.69 |
| 52.8 | 89.13 | 21.02 | 42.04 | 13.88 |
| 52.3 | 89.55 | 21.17 | 42.34 | 14.08 |
| 51.9 | 89.96 | 21.31 | 42.63 | 14.27 |
| 51.5 | 90.38 | 21.46 | 42.92 | 14.47 |
| 51.1 | 90.78 | 21.61 | 43.22 | 14.67 |
| 50.7 | 91.19 | 21.75 | 43.51 | 14.87 |
| 50.3 | 91.59 | 21.90 | 43.80 | 15.07 |

| | | | | |
|---|---|---|---|---|
| 49.9 | 91.99 | 22.05 | 44.09 | 15.27 |
| 49.5 | 92.38 | 22.19 | 44.39 | 15.47 |
| 49.1 | 92.78 | 22.34 | 44.68 | 15.68 |
| 48.7 | 93.16 | 22.49 | 44.97 | 15.89 |
| 48.3 | 93.55 | 22.63 | 45.27 | 16.09 |
| 48.0 | 93.94 | 22.78 | 45.56 | 16.30 |
| 47.6 | 94.32 | 22.93 | 45.85 | 16.51 |
| 47.2 | 94.69 | 23.07 | 46.15 | 16.72 |
| 46.8 | 95.07 | 23.22 | 46.44 | 16.94 |
| 46.5 | 95.44 | 23.37 | 46.73 | 17.15 |
| 46.1 | 95.81 | 23.51 | 47.03 | 17.37 |
| 45.7 | 96.18 | 23.66 | 47.32 | 17.59 |
| 45.4 | 96.54 | 23.81 | 47.61 | 17.80 |
| 45.0 | 96.91 | 23.95 | 47.90 | 18.02 |
| 44.6 | 97.27 | 24.10 | 48.20 | 18.25 |
| 44.3 | 97.62 | 24.25 | 48.49 | 18.47 |
| 43.9 | 97.98 | 24.39 | 48.78 | 18.69 |
| 43.6 | 98.33 | 24.54 | 49.08 | 18.92 |
| 43.2 | 98.68 | 24.69 | 49.37 | 19.14 |
| 42.9 | 99.03 | 24.83 | 49.66 | 19.37 |
| 42.5 | 99.37 | 24.98 | 49.96 | 19.60 |
| 42.2 | 99.71 | 25.12 | 50.25 | 19.83 |
| 41.8 | 100.05 | 25.27 | 50.54 | 20.06 |
| 41.5 | 100.39 | 25.42 | 50.84 | 20.30 |
| 41.2 | 100.73 | 25.56 | 51.13 | 20.53 |
| 40.8 | 101.06 | 25.71 | 51.42 | 20.77 |
| 40.5 | 101.39 | 25.86 | 51.71 | 21.00 |
| 40.2 | 101.72 | 26.00 | 52.01 | 21.24 |
| 39.9 | 102.05 | 26.15 | 52.30 | 21.48 |
| 39.5 | 102.37 | 26.30 | 52.59 | 21.72 |
| 39.2 | 102.69 | 26.44 | 52.89 | 21.97 |
| 38.9 | 103.01 | 26.59 | 53.18 | 22.21 |
| 38.6 | 103.33 | 26.74 | 53.47 | 22.46 |
| 38.3 | 103.64 | 26.88 | 53.77 | 22.70 |
| 37.9 | 103.96 | 27.03 | 54.06 | 22.95 |
| 37.6 | 104.27 | 27.18 | 54.35 | 23.20 |
| 37.3 | 104.58 | 27.32 | 54.65 | 23.45 |
| 37.0 | 104.89 | 27.47 | 54.94 | 23.70 |
| 36.7 | 105.19 | 27.62 | 55.23 | 23.96 |
| 36.4 | 105.49 | 27.76 | 55.52 | 24.21 |
| 36.1 | 105.80 | 27.91 | 55.82 | 24.47 |
| 35.8 | 106.10 | 28.06 | 56.11 | 24.73 |
| 35.5 | 106.39 | 28.20 | 56.40 | 24.99 |
| 35.2 | 106.69 | 28.35 | 56.70 | 25.25 |
| 34.9 | 106.98 | 28.49 | 56.99 | 25.51 |
| 34.6 | 107.27 | 28.64 | 57.28 | 25.77 |
| 34.3 | 107.56 | 28.79 | 57.58 | 26.04 |
| 34.0 | 107.85 | 28.93 | 57.87 | 26.30 |

| | | | | |
|---|---|---|---|---|
| 33.8 | 108.14 | 29.08 | 58.16 | 26.57 |
| 33.5 | 108.42 | 29.23 | 58.45 | 26.84 |
| 33.2 | 108.71 | 29.37 | 58.75 | 27.11 |
| 32.9 | 108.99 | 29.52 | 59.04 | 27.38 |
| 32.6 | 109.27 | 29.67 | 59.33 | 27.65 |
| 32.4 | 109.54 | 29.81 | 59.63 | 27.92 |
| 32.1 | 109.82 | 29.96 | 59.92 | 28.20 |
| 31.8 | 110.09 | 30.11 | 60.21 | 28.48 |
| 31.5 | 110.36 | 30.25 | 60.51 | 28.75 |
| 31.3 | 110.63 | 30.40 | 60.80 | 29.03 |
| 31.0 | 110.90 | 30.55 | 61.09 | 29.31 |
| 30.7 | 111.17 | 30.69 | 61.39 | 29.60 |
| 30.5 | 111.44 | 30.84 | 61.68 | 29.88 |
| 30.2 | 111.70 | 30.99 | 61.97 | 30.16 |
| 29.9 | 111.96 | 31.13 | 62.26 | 30.45 |
| 29.7 | 112.22 | 31.28 | 62.56 | 30.74 |
| 29.4 | 112.48 | 31.43 | 62.85 | 31.02 |
| 29.2 | 112.74 | 31.57 | 63.14 | 31.31 |
| 28.9 | 112.99 | 31.72 | 63.44 | 31.61 |
| 28.6 | 113.25 | 31.86 | 63.73 | 31.90 |
| 28.4 | 113.50 | 32.01 | 64.02 | 32.19 |
| 28.1 | 113.75 | 32.16 | 64.32 | 32.49 |
| 27.9 | 114.00 | 32.30 | 64.61 | 32.79 |
| 27.6 | 114.25 | 32.45 | 64.90 | 33.08 |
| 27.4 | 114.50 | 32.60 | 65.20 | 33.38 |
| 27.2 | 114.74 | 32.74 | 65.49 | 33.68 |
| 26.9 | 114.99 | 32.89 | 65.78 | 33.99 |
| 26.7 | 115.23 | 33.04 | 66.07 | 34.29 |
| 26.4 | 115.47 | 33.18 | 66.37 | 34.59 |
| 26.2 | 115.71 | 33.33 | 66.66 | 34.90 |
| 26.0 | 115.95 | 33.48 | 66.95 | 35.21 |
| 25.7 | 116.18 | 33.62 | 67.25 | 35.52 |
| 25.5 | 116.42 | 33.77 | 67.54 | 35.83 |
| 25.2 | 116.65 | 33.92 | 67.83 | 36.14 |
| 25.0 | 116.88 | 34.06 | 68.13 | 36.45 |
| 24.8 | 117.11 | 34.21 | 68.42 | 36.77 |
| 24.6 | 117.34 | 34.36 | 68.71 | 37.08 |
| 24.3 | 117.57 | 34.50 | 69.01 | 37.40 |
| 24.1 | 117.80 | 34.65 | 69.30 | 37.72 |
| 23.9 | 118.02 | 34.80 | 69.59 | 38.04 |
| 23.7 | 118.25 | 34.94 | 69.88 | 38.36 |
| 23.4 | 118.47 | 35.09 | 70.18 | 38.68 |
| 23.2 | 118.69 | 35.24 | 70.47 | 39.00 |
| 23.0 | 118.91 | 35.38 | 70.76 | 39.33 |
| 22.8 | 119.13 | 35.53 | 71.06 | 39.65 |
| 22.6 | 119.34 | 35.67 | 71.35 | 39.98 |
| 22.3 | 119.56 | 35.82 | 71.64 | 40.31 |
| 22.1 | 119.78 | 35.97 | 71.94 | 40.64 |

| | | | | |
|---|---|---|---|---|
| 21.9 | 119.99 | 36.11 | 72.23 | 40.97 |
| 21.7 | 120.20 | 36.26 | 72.52 | 41.31 |
| 21.5 | 120.41 | 36.41 | 72.81 | 41.64 |
| 21.3 | 120.62 | 36.55 | 73.11 | 41.98 |
| 21.1 | 120.83 | 36.70 | 73.40 | 42.31 |
| 20.9 | 121.04 | 36.85 | 73.69 | 42.65 |
| 20.7 | 121.24 | 36.99 | 73.99 | 42.99 |
| 20.5 | 121.45 | 37.14 | 74.28 | 43.33 |
| 20.2 | 121.65 | 37.29 | 74.57 | 43.68 |
| 20.0 | 121.85 | 37.43 | 74.87 | 44.02 |
| 19.8 | 122.05 | 37.58 | 75.16 | 44.37 |
| 19.6 | 122.25 | 37.73 | 75.45 | 44.71 |
| 19.4 | 122.45 | 37.87 | 75.75 | 45.06 |
| 19.2 | 122.65 | 38.02 | 76.04 | 45.41 |
| 19.1 | 122.85 | 38.17 | 76.33 | 45.76 |
| 18.9 | 123.04 | 38.31 | 76.62 | 46.11 |
| 18.7 | 123.23 | 38.46 | 76.92 | 46.47 |
| 18.5 | 123.43 | 38.61 | 77.21 | 46.82 |
| 18.3 | 123.62 | 38.75 | 77.50 | 47.18 |
| 18.1 | 123.81 | 38.90 | 77.80 | 47.54 |
| 17.9 | 124.00 | 39.04 | 78.09 | 47.89 |
| 17.7 | 124.19 | 39.19 | 78.38 | 48.25 |
| 17.5 | 124.37 | 39.34 | 78.68 | 48.62 |
| 17.3 | 124.56 | 39.48 | 78.97 | 48.98 |
| 17.2 | 124.74 | 39.63 | 79.26 | 49.34 |
| 17.0 | 124.93 | 39.78 | 79.56 | 49.71 |
| 16.8 | 125.11 | 39.92 | 79.85 | 50.07 |
| 16.6 | 125.29 | 40.07 | 80.14 | 50.44 |
| 16.4 | 125.47 | 40.22 | 80.43 | 50.81 |
| 16.2 | 125.65 | 40.36 | 80.73 | 51.18 |
| 16.1 | 125.83 | 40.51 | 81.02 | 51.56 |
| 15.9 | 126.01 | 40.66 | 81.31 | 51.93 |
| 15.7 | 126.18 | 40.80 | 81.61 | 52.30 |
| 15.5 | 126.36 | 40.95 | 81.90 | 52.68 |
| 15.4 | 126.53 | 41.10 | 82.19 | 53.06 |
| 15.2 | 126.70 | 41.24 | 82.49 | 53.44 |
| 15.0 | 126.88 | 41.39 | 82.78 | 53.82 |
| 14.9 | 127.05 | 41.54 | 83.07 | 54.20 |
| 14.7 | 127.22 | 41.68 | 83.36 | 54.58 |
| 14.5 | 127.39 | 41.83 | 83.66 | 54.97 |
| 14.3 | 127.55 | 41.98 | 83.95 | 55.35 |
| 14.2 | 127.72 | 42.12 | 84.24 | 55.74 |
| 14.0 | 127.88 | 42.27 | 84.54 | 56.13 |
| 13.8 | 128.05 | 42.42 | 84.83 | 56.52 |
| 13.7 | 128.21 | 42.56 | 85.12 | 56.91 |
| 13.5 | 128.38 | 42.71 | 85.42 | 57.30 |
| 13.4 | 128.54 | 42.85 | 85.71 | 57.70 |
| 13.2 | 128.70 | 43.00 | 86.00 | 58.09 |

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|---|---|---|---|---|
| 13.0 | 128.86 | 43.15 | 86.30 | 58.49 |
| 12.9 | 129.02 | 43.29 | 86.59 | 58.89 |
| 12.7 | 129.17 | 43.44 | 86.88 | 59.29 |
| 12.6 | 129.33 | 43.59 | 87.17 | 59.69 |
| 12.4 | 129.48 | 43.73 | 87.47 | 60.09 |
| 12.3 | 129.64 | 43.88 | 87.76 | 60.49 |
| 12.1 | 129.79 | 44.03 | 88.05 | 60.90 |
| 12.0 | 129.95 | 44.17 | 88.35 | 61.30 |
| 11.8 | 130.10 | 44.32 | 88.64 | 61.71 |
| 11.7 | 130.25 | 44.47 | 88.93 | 62.12 |
| 11.5 | 130.40 | 44.61 | 89.23 | 62.53 |
| 11.4 | 130.55 | 44.76 | 89.52 | 62.94 |
| 11.2 | 130.69 | 44.91 | 89.81 | 63.35 |
| 11.1 | 130.84 | 45.05 | 90.11 | 63.77 |
| 10.9 | 130.99 | 45.20 | 90.40 | 64.18 |
| 10.8 | 131.13 | 45.35 | 90.69 | 64.60 |
| 10.6 | 131.27 | 45.49 | 90.98 | 65.02 |
| 10.5 | 131.42 | 45.64 | 91.28 | 65.44 |
| 10.3 | 131.56 | 45.79 | 91.57 | 65.86 |
| 10.2 | 131.70 | 45.93 | 91.86 | 66.28 |
| 10.1 | 131.84 | 46.08 | 92.16 | 66.70 |
| 9.9 | 131.98 | 46.22 | 92.45 | 67.13 |
| 9.8 | 132.12 | 46.37 | 92.74 | 67.55 |
| 9.6 | 132.26 | 46.52 | 93.04 | 67.98 |
| 9.5 | 132.39 | 46.66 | 93.33 | 68.41 |
| 9.4 | 132.53 | 46.81 | 93.62 | 68.84 |
| 9.2 | 132.66 | 46.96 | 93.92 | 69.27 |
| 9.1 | 132.80 | 47.10 | 94.21 | 69.71 |
| 9.0 | 132.93 | 47.25 | 94.50 | 70.14 |
| 8.8 | 133.06 | 47.40 | 94.79 | 70.58 |
| 8.7 | 133.19 | 47.54 | 95.09 | 71.01 |
| 8.6 | 133.32 | 47.69 | 95.38 | 71.45 |
| 8.4 | 133.45 | 47.84 | 95.67 | 71.89 |
| 8.3 | 133.58 | 47.98 | 95.97 | 72.33 |
| 8.2 | 133.71 | 48.13 | 96.26 | 72.77 |
| 8.1 | 133.83 | 48.28 | 96.55 | 73.22 |
| 7.9 | 133.96 | 48.42 | 96.85 | 73.66 |
| 7.8 | 134.08 | 48.57 | 97.14 | 74.11 |
| 7.7 | 134.21 | 48.72 | 97.43 | 74.56 |
| 7.6 | 134.33 | 48.86 | 97.72 | 75.01 |
| 7.4 | 134.45 | 49.01 | 98.02 | 75.46 |
| 7.3 | 134.57 | 49.16 | 98.31 | 75.91 |
| 7.2 | 134.69 | 49.30 | 98.60 | 76.36 |
| 7.1 | 134.81 | 49.45 | 98.90 | 76.82 |
| 7.0 | 134.93 | 49.60 | 99.19 | 77.27 |
| 6.8 | 135.05 | 49.74 | 99.48 | 77.73 |
| 6.7 | 135.16 | 49.89 | 99.78 | 78.19 |
| 6.6 | 135.28 | 50.03 | 100.07 | 78.65 |

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|---|---|---|---|---|
| 6.5 | 135.39 | 50.18 | 100.36 | 79.11 |
| 6.4 | 135.51 | 50.33 | 100.66 | 79.57 |
| 6.3 | 135.62 | 50.47 | 100.95 | 80.04 |
| 6.2 | 135.73 | 50.62 | 101.24 | 80.50 |
| 6.1 | 135.85 | 50.77 | 101.53 | 80.97 |
| 5.9 | 135.96 | 50.91 | 101.83 | 81.44 |
| 5.8 | 136.07 | 51.06 | 102.12 | 81.91 |
| 5.7 | 136.17 | 51.21 | 102.41 | 82.38 |
| 5.6 | 136.28 | 51.35 | 102.71 | 82.85 |
| 5.5 | 136.39 | 51.50 | 103.00 | 83.32 |
| 5.4 | 136.49 | 51.65 | 103.29 | 83.80 |
| 5.3 | 136.60 | 51.79 | 103.59 | 84.27 |
| 5.2 | 136.70 | 51.94 | 103.88 | 84.75 |
| 5.1 | 136.81 | 52.09 | 104.17 | 85.23 |
| 5.0 | 136.91 | 52.23 | 104.47 | 85.71 |
| 4.9 | 137.01 | 52.38 | 104.76 | 86.19 |
| 4.8 | 137.11 | 52.53 | 105.05 | 86.67 |
| 4.7 | 137.21 | 52.67 | 105.34 | 87.16 |
| 4.6 | 137.31 | 52.82 | 105.64 | 87.64 |
| 4.5 | 137.41 | 52.97 | 105.93 | 88.13 |
| 4.4 | 137.51 | 53.11 | 106.22 | 88.62 |
| 4.3 | 137.60 | 53.26 | 106.52 | 89.11 |
| 4.2 | 137.70 | 53.40 | 106.81 | 89.60 |
| 4.1 | 137.79 | 53.55 | 107.10 | 90.09 |
| 4.0 | 137.89 | 53.70 | 107.40 | 90.59 |
| 3.9 | 137.98 | 53.84 | 107.69 | 91.08 |
| 3.8 | 138.07 | 53.99 | 107.98 | 91.58 |
| 3.7 | 138.16 | 54.14 | 108.28 | 92.08 |
| 3.6 | 138.25 | 54.28 | 108.57 | 92.58 |
| 3.6 | 138.34 | 54.43 | 108.86 | 93.08 |
| 3.5 | 138.43 | 54.58 | 109.15 | 93.58 |
| 3.4 | 138.52 | 54.72 | 109.45 | 94.08 |
| 3.3 | 138.61 | 54.87 | 109.74 | 94.59 |
| 3.2 | 138.69 | 55.02 | 110.03 | 95.09 |
| 3.1 | 138.78 | 55.16 | 110.33 | 95.60 |
| 3.0 | 138.86 | 55.31 | 110.62 | 96.11 |
| 3.0 | 138.94 | 55.46 | 110.91 | 96.62 |
| 2.9 | 139.03 | 55.60 | 111.21 | 97.13 |
| 2.8 | 139.11 | 55.75 | 111.50 | 97.64 |
| 2.7 | 139.19 | 55.90 | 111.79 | 98.15 |
| 2.6 | 139.27 | 56.04 | 112.08 | 98.67 |
| 2.6 | 139.34 | 56.19 | 112.38 | 99.19 |
| 2.5 | 139.42 | 56.34 | 112.67 | 99.70 |
| 2.4 | 139.50 | 56.48 | 112.96 | 100.22 |
| 2.3 | 139.57 | 56.63 | 113.26 | 100.74 |
| 2.2 | 139.65 | 56.78 | 113.55 | 101.27 |
| 2.2 | 139.72 | 56.92 | 113.84 | 101.79 |
| 2.1 | 139.80 | 57.07 | 114.14 | 102.31 |

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|---|---|---|---|---|
| 2.0 | 139.87 | 57.21 | 114.43 | 102.84 |
| 2.0 | 139.94 | 57.36 | 114.72 | 103.37 |
| 1.9 | 140.01 | 57.51 | 115.02 | 103.90 |
| 1.8 | 140.08 | 57.65 | 115.31 | 104.43 |
| 1.8 | 140.15 | 57.80 | 115.60 | 104.96 |
| 1.7 | 140.21 | 57.95 | 115.89 | 105.49 |
| 1.6 | 140.28 | 58.09 | 116.19 | 106.03 |
| 1.6 | 140.35 | 58.24 | 116.48 | 106.56 |
| 1.5 | 140.41 | 58.39 | 116.77 | 107.10 |
| 1.4 | 140.47 | 58.53 | 117.07 | 107.64 |
| 1.4 | 140.53 | 58.68 | 117.36 | 108.18 |
| 1.3 | 140.60 | 58.83 | 117.65 | 108.72 |
| 1.2 | 140.66 | 58.97 | 117.95 | 109.26 |
| 1.2 | 140.71 | 59.12 | 118.24 | 109.80 |
| 1.1 | 140.77 | 59.27 | 118.53 | 110.35 |
| 1.1 | 140.83 | 59.41 | 118.83 | 110.89 |
| 1.0 | 140.89 | 59.56 | 119.12 | 111.44 |
| 1.0 | 140.94 | 59.71 | 119.41 | 111.99 |
| 0.9 | 140.99 | 59.85 | 119.70 | 112.54 |
| 0.9 | 141.05 | 60.00 | 120.00 | 113.09 |
| 0.8 | 141.10 | 60.15 | 120.29 | 113.65 |
| 0.7 | 141.15 | 60.29 | 120.58 | 114.20 |
| 0.7 | 141.20 | 60.44 | 120.88 | 114.76 |
| 0.7 | 141.25 | 60.58 | 121.17 | 115.31 |
| 0.6 | 141.29 | 60.73 | 121.46 | 115.87 |
| 0.6 | 141.34 | 60.88 | 121.76 | 116.43 |
| 0.5 | 141.38 | 61.02 | 122.05 | 116.99 |
| 0.5 | 141.42 | 61.17 | 122.34 | 117.55 |
| 0.4 | 141.47 | 61.32 | 122.63 | 118.12 |
| 0.4 | 141.51 | 61.46 | 122.93 | 118.68 |
| 0.4 | 141.55 | 61.61 | 123.22 | 119.25 |
| 0.3 | 141.58 | 61.76 | 123.51 | 119.82 |
| 0.3 | 141.62 | 61.90 | 123.81 | 120.39 |
| 0.2 | 141.65 | 62.05 | 124.10 | 120.96 |
| 0.2 | 141.69 | 62.20 | 124.39 | 121.53 |
| 0.2 | 141.72 | 62.34 | 124.69 | 122.10 |
| 0.2 | 141.75 | 62.49 | 124.98 | 122.68 |
| 0.1 | 141.77 | 62.64 | 125.27 | 123.25 |
| 0.1 | 141.80 | 62.78 | 125.57 | 123.83 |
| 0.1 | 141.82 | 62.93 | 125.86 | 124.41 |
| 0.1 | 141.84 | 63.08 | 126.15 | 124.99 |
| 0.0 | 141.86 | 63.22 | 126.44 | 125.57 |
| 0.0 | 141.88 | 63.37 | 126.74 | 126.15 |
| 0.0 | 141.89 | 63.52 | 127.03 | 126.74 |
| 0.0 | 141.90 | 63.66 | 127.32 | 127.32 |
| | | | | |

# Appendix C – Detailed Calculations

Equation 1: Solving for the Horn Mouth Radius, $R_m$

$$R_m = \frac{C}{2F_{co}}$$

$$C = Speed\ of\ Sound; 3400000\ mm/s$$

$$F_{CO} = Cutoff\ Frequency; 850\ Hz\ (user\ input)$$

$$\boldsymbol{R_m = 63.66\ mm}$$

Equation 2: Solving for the Horn Length, L

$$L = R_m \cdot \ln\left[\frac{\left(R_m + \sqrt{R_m{}^2 - R_x{}^2}\right)}{R_x}\right] - \sqrt{R_m{}^2 - R_x{}^2}$$

$$R_m = Horn\ Mouth\ Radius, 63.66\ mm\ from\ Equation\ 1$$

$$R_x = R_{t\,;}\ Horn\ Throat\ Radius, 5.05\ mm\ (user\ input)$$

$$\boldsymbol{L = 141.90\ mm}$$

Equation 3: Solving for position X distance from the Horn Throat with some incrimenal value of Horn Radius, Rx. Rx needs to be any value between Horn Throat (Rt)and Horn Mouth (Rm)

$$L - X = R_m \cdot \ln\left[\frac{\left(R_m + \sqrt{R_m{}^2 - R_x{}^2}\right)}{R_x}\right] - \sqrt{R_m{}^2 - R_x{}^2}$$

$$R_m = Horn\ Mouth\ Radius, 63.66\ mm\ from\ Equation\ 1$$

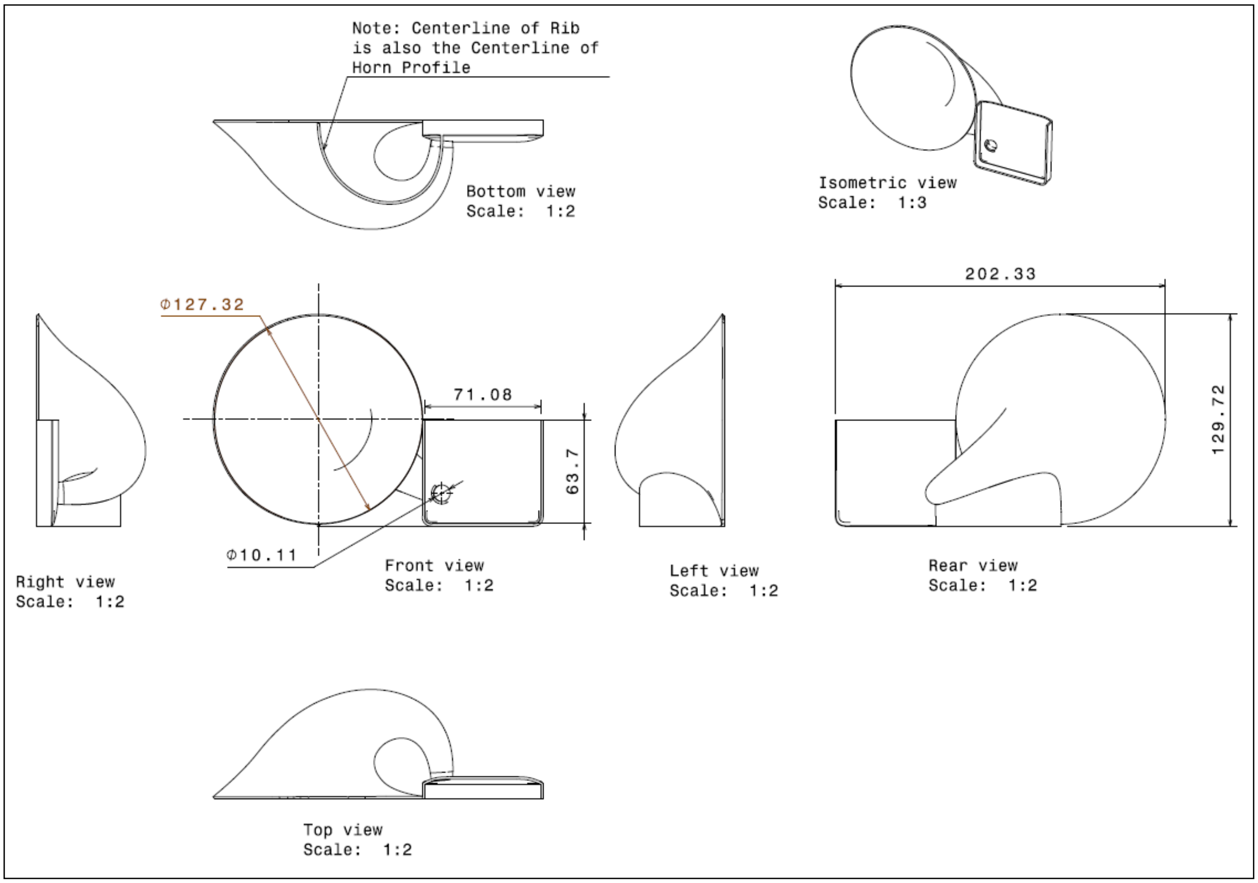
$$R_{t\,;}\ Horn\ Throat\ Radius, 5.05\ mm\ (user\ input)$$

$$R_x = Horn\ Radius, 5.49\ mm\ (R_t < R_x < R_m)$$

$$L = Horn\ Length, 141.90\ mm\ from\ Equation\ 2$$

$$\boldsymbol{X = 5.30\ mm; See\ Appendix\ B\ for\ all\ results}$$

# Appendix D: Mechanical 2D Drawing



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