**3D Printed Metamaterial Acoustics Lens**

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## Introduction

Acoustic lenses, which focus sound in much the same way that an optical lens focuses light, have been around for many years. They were first devised in 1949 by Bell Labs. Since then, numerous designs have been created, in all different shapes and sizes. They all focus on the same principles of bending sound towards a single point. However, many of these designs fail to take into account the phase differences between the different parts of the waves being focused. As a result of imperfect design, many of the designs focus sound in low efficiency. The design we focused on for our project, the metamaterial design, does take into account this phase difference. Our goal for this project was to design and 3D print a working and aesthetic metamaterial acoustic lens. We chose to 3D print it, rather than compose it out of some other material, due to the precision and solidity of the output, and for the fact that creating a working model gives anyone with a 3D printer access to the technology of acoustic lenses.

## Supports

The School of Art + Design provides an excellent work environment conducive to developing students' own creative direction. Students in other majors who are attending design classes are required to pay ninety five dollars for the facility fees. Since Guanya Niu was attending ARTS 444, we had access to extensive laboratory resources in art and design building. The equipment housed in digital labs provides students access to a wide range of hardware and technology, most importantly a number of 3D printers, including a dual extruder 3D printer.

## 3D Printing Technology

3D printing refers to the process of making a three-dimensional object from a digital file. A 3D printed object is created by adding successive layers of material under precise computer control to create an object. The object produced can be any shape and is produced from a 3D model of some sort. The manual modeling process of preparing geometric data for 3D computer graphics is similar to sculpting. In our case, we created our design using Autodesk Inventor for modeling. One of the major advantages of 3D printing is the reduction in errors, as the design can be corrected within the modeling software before printing.

The printer we used was a Stratasys Dimension Elite 3D printer, which features a dual extruder nozzle, allowing it to print the support structure required to print the lens's complex geometry. An average 3D printer could not feasibly print the lens, as to do so would require the printer to print free floating pieces, since it prints layer by layer. The support printed by the dual extruder printer can easily be dissolved in a liquid, leaving only the structure that we want.

## Science

Many acoustic lenses use strangely shaped designs to point the sound in particular directions. The metamaterial design, however, is able to focus sound by "confusing" it. Essentially, in the long wavelength regime (that is, if the wavelength is longer than the lattice constant, or the separation between the centers of the rings), the lens acts like a single material, yet, at the same time, the variations in the thickness of the toruses cause the sound to bend towards one point. This design is known as an acoustic gradient-index lens, as the index of refraction is gradually changed to direct the sound to one point.

The index of refraction varies through changing the filling fraction $f(r)$, defined as

$$f(r) = \pi R^2(r)/a^2$$

where $R$ is the minor radius of the toruses, $r$ is the distance from the center, and $a$ is the lattice constant. The filling fraction at the center of each ring where $r = na$ could be further simplified to

$$f(n) = \pi R^2(n)$$

where $n$ is the number of torus rings from the center (*i.e.*, the innermost torus would be $n = 1$).

The filling fraction is used to find the index of refraction, defined as

$$n(r) = \sqrt{1 + f(r)}$$

meaning that $n(0)$ (that is, the center), had an index of refraction of 1, while $n(7)$ in the original design, for example, had an index of refraction of 1.33, due to its minor radius of 0.5 cm. We were able to find the filling fractions and indexes of refraction for the rest of the rings in the original design after deducing that they had an exponential relationship.

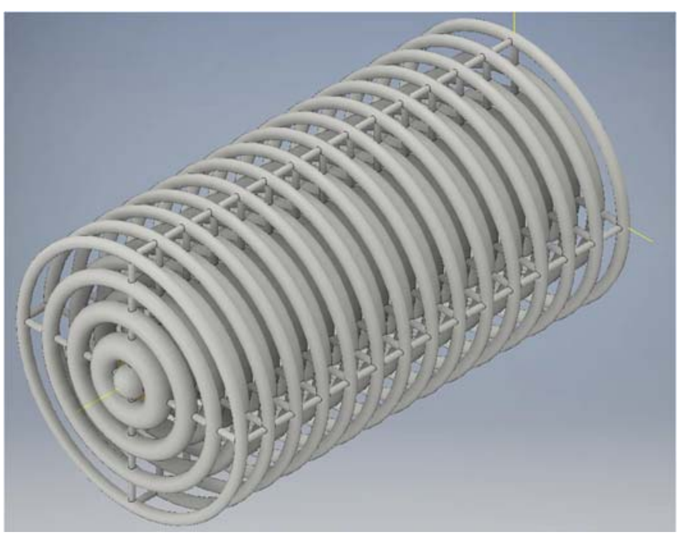
## Design

We based our design off of one created by V. Romero-Garcia, et al, in a paper titled "Wave focusing using symmetry matching in axisymmetric acoustic gradient index lenses". Their design consisted of seven sets of seven concentric toroids, whose centers were positioned 4 cm away from adjacent toroids, as well as seven spheres (one in the center of each set of toroids), each with a diameter of 4 cm. Their particular design had a focal length of 20 cm.

The challenges for our design were to recreate their design, as well as to make it small enough to 3D print efficiently, and to design it so that we could feasibly test it. We modeled their design in both Autodesk Inventor and COMSOL Multiphysics, the former for 3D printing purposes, and the latter to see if we could recreate their results, and then proceed to test our own version of their design. However, we were not able to get the proper setup to recreate their results, so we were forced to go into the 3D printing process without any theoretical data for our design.

We were not able to simply scale the lens down to a smaller size (from the 57 cm by 57 cm by 32 cm design created by Romero-Garcia et al to one that fit in the 30 cm by 30 cm by 30 cm printers available), as decreasing the radius of each of the toroids resulted in a decrease to the index of refraction for each one. This meant that any sound hitting the lens would focus at a point farther away, and the sound would not all be focused in the same place. Thus, our design was longer than the original, to compensate for the farther focusing. We also decreased the number of rings in each set of toroids to decrease the overall size of the lens, so that the lens fit within the parameters of the printers, and so that the lens was cost efficient.

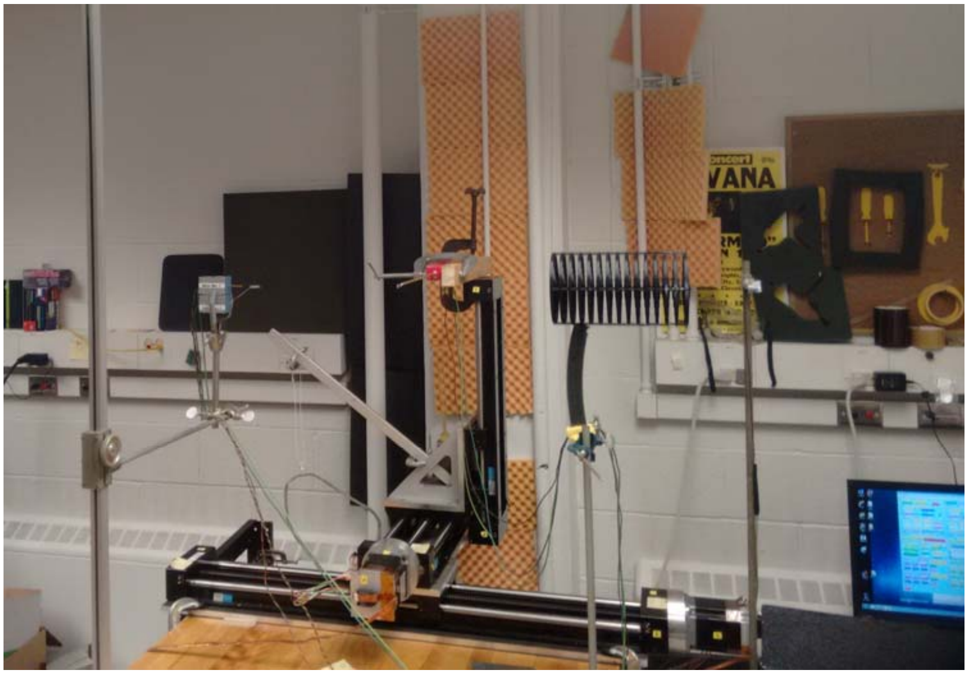
The last change we made from the theoretical design was to add a support structure. The design *was* supposed to be a series of free-floating (while remaining rigidly in place) rings, but considering that that is not something we could possibly test, we added supports in between the rings. These supports were 3 mm in diameter, the minimum thickness for some of the 3D printers that we planned to use.



*Final Design*

Experimental Setup

In order to test the ability of our lens to focus sound, we needed to place a sound source at one end of the lens, and scan the area around the other end of the lens with a microphone, in order to detect points where the amplitude of the sound peaks, and if that corresponds to the focal length of the lens. There are a number of issues in trying to set this up, however, namely that, in theory, there must not be anything around the lens, as that could disrupt the focusing process. Furthermore, the lens must be held steady so that the focus does not change over the course of the scanning process. Our final experiment setup is pictured below.



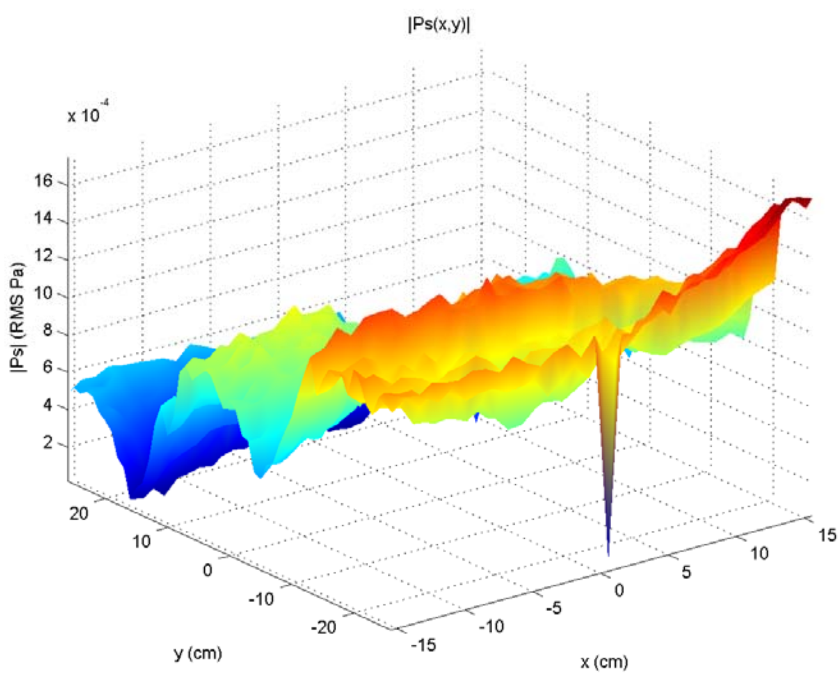
*Experimental Setup for our First Test*

The sound source for the first test, an earbud emitting a 1 kHz frequency, was positioned approximately 7.5 cm away from the end of the lens. This is where we believed the focal point to be. There is a mic sweeping a 52 cm long and 30 cm wide area directly in front of the other end of the lens, which gives us the data we need. There are also two control mics to measure the ambient sound in the area, so that we can factor out any noise not caused by the sound source.

For the second and third tests, the majority of the setup remained the same. However, the source was changed from a point source (the earbud) to plane waves (approximated by a speaker positioned around 6 feet from the lens), and for the third test, a 1 m2 piece of wood (baffle board) with a 15 cm diameter hole in it was placed just upstream of the lens to prevent the mic from picking up extraneous sounds.

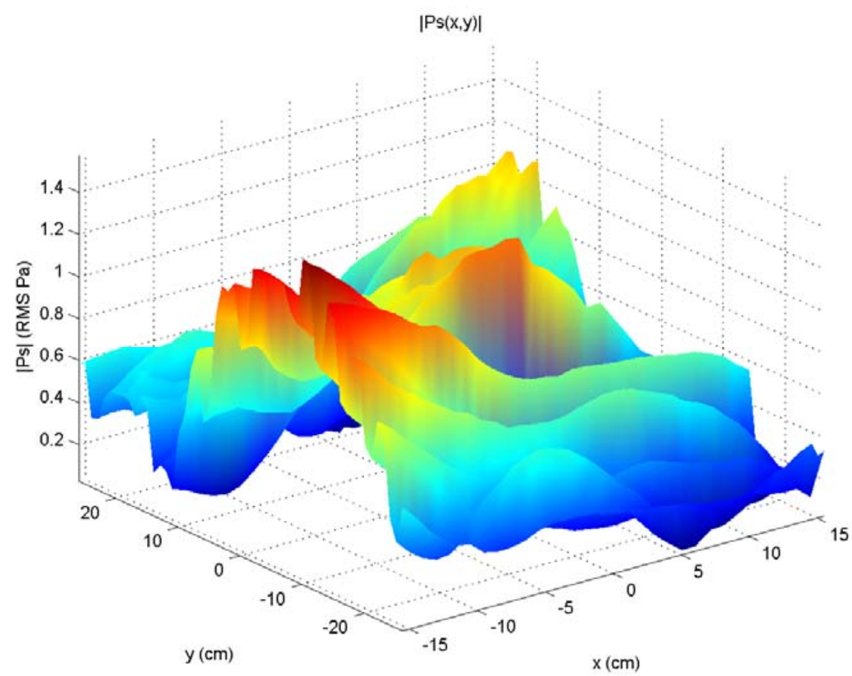
Results

The initial test had a point source placed at the point where we believed the focal point of the lens to be, 7.5 cm (five times the lattice constant of 1.5 cm). The results from this test were essentially plane waves throughout the area. It is clear from these results that the point source is not the proper way to test the lens, as no focusing occurred. Thus, for the second test, an approximation of plane waves was used.



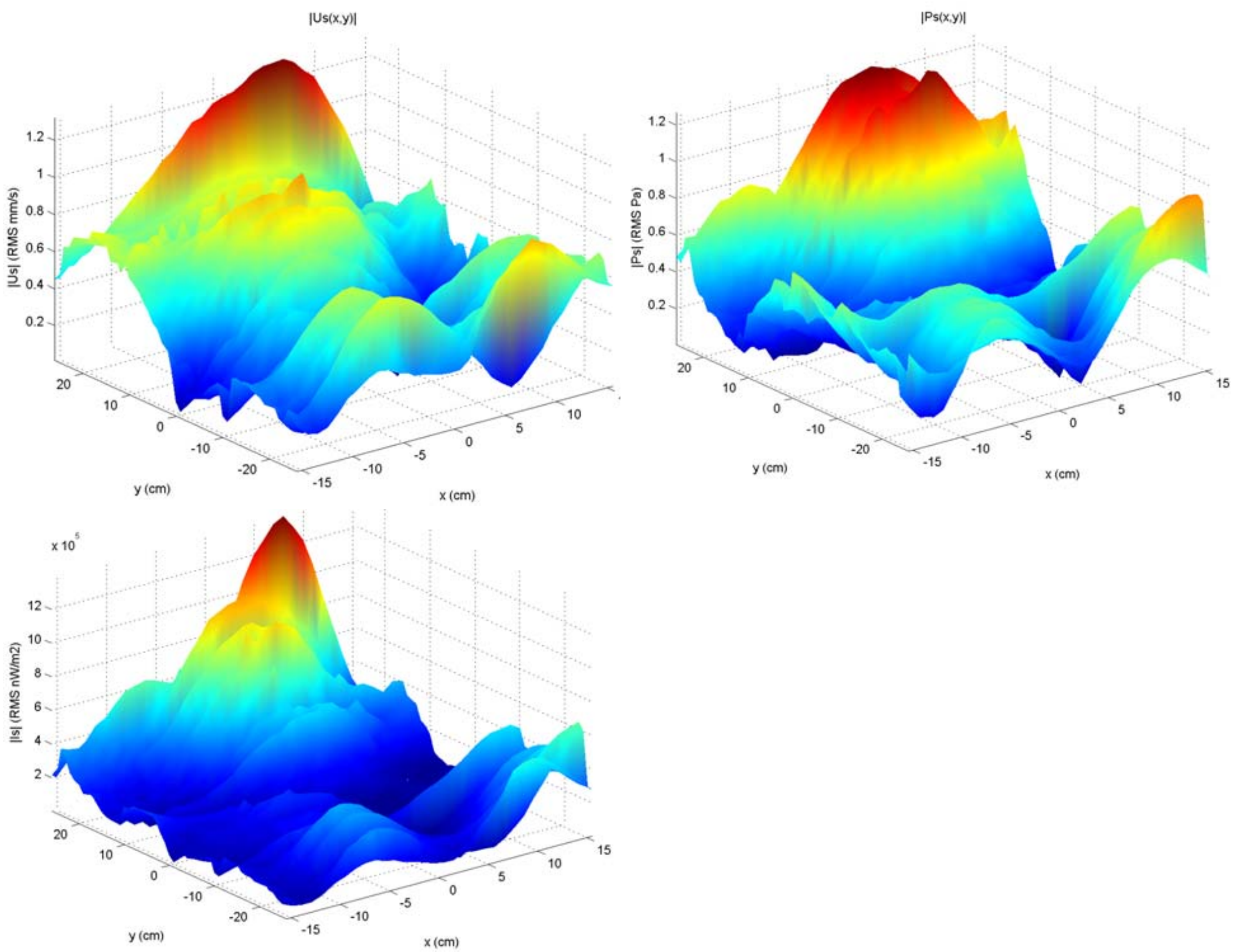

*Magnitude of the pressure throughout the area in the first test*

The second test showed much more evidence for the lens's ability to focus the sound. However, there appeared to be two focuses in the data, one at (-15,0) and one at (15,26), the former being the stronger of the two. It is possible that one of these "focuses" resulted from interactions between the sound emanating from the source and the environment. Namely, the waves could have been reflected off of various objects.




*Magnitude of the pressure throughout the area in the second test*

For the third test, we introduced a baffle just upstream of the lens to prevent extraneous sounds from affecting the results. The data gave a much clearer picture of a focus, at around (5,26), near where the weaker focus was in the second test. This result was not expected. We believed the focus to be ~7.5 cm from the lens, which would have resulted in a focus around (0, -20). Certainly we did not expect the sound to be focused anywhere but x=0, but the focus appeared to be slightly offset from the *y*-axis.




*Clockwise from top-left: Magnitude of Particle Velocity, Magnitude of Pressure, and Magnitude of Acoustic Intensity for the third test*

<u>Conclusion</u>

The final test seemed to show what we were hoping for: a focusing of sound at one point, as indicated by an increase in pressure, particle velocity and acoustic intensity at that point. However, it was not at the point that we expected it to be. In theory, it should have been somewhere on the y-axis, but instead it was slightly offset. Either the lens was not properly aligned (entirely possible, as the lens was damaged before testing), or that spike is not a result of the lens at all, and instead a result of reflections off of the surroundings. Either way, the results were not quite what we wanted (for one thing, the focus is too far off in the y-direction), which means we have to go back to the drawing board to find a lens that focuses where we want it to. In terms of the practicality of 3D printing a lens (perhaps in one's home, with a commercially available 3D printer), we must say that it was not very practical. Our rather small design took numerous hours, was rather costly, and required a dual-extruding 3D printing (not the sort of printer one would buy for home use, as it requires additional skills and equipment to use properly). These same restrictions prevented us from printing out and testing multiple acoustic lenses. That being said, given the opportunity, we would be interested in trying out more acoustic lens designs, perhaps refocusing the lens to the point we wanted it to be, perhaps testing out the effects of different numbers of rings, or perhaps testing the effects of the support material on quality of the lens.

References

Romero-Garcia, V., Cebrecos, A., Pico, R., Sanchez-Morcillo, V. J., Garcia-Raffi, L. M., & Sanchez-Perez, J. V. (2013, December 31). Wave focusing using symmetry matching in axisymmetric acoustic gradient index lenses. *APPLIED PHYSICS LETTERS*, *103*, 1-4.