Creating Personal Acoustic Spaces with Beamforming via Acoustic Metasurfaces

Opportunity Research Scholar: Rudra Goel

Mentor: Alan Liu

Faculty Advisor: Dr. Karthik Sundaresan

Mobile Advanced Research @ GaTech (MARGA) Lab

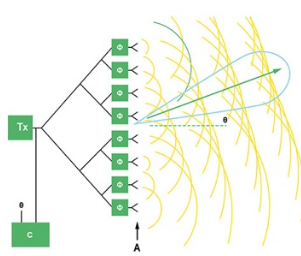
September 30th, 2024

Abstract

Linear beamforming for acoustic waves within the audible spectra is paramount in designing personal acoustic spaces, spatial zones wherein the edge is articulated by an acoustic wave as opposed to a physical barrier [7]. By channeling a signal towards a specific location solely through offsets in phase, acoustic energy can be more efficiently spent within the space and less noise is polluted into areas where sound is not needed. Doing so through metasurfaces is often desirable as it avoids costly speaker hardware arranged in a phased array [10]. This raises the question on whether metasurfaces can successfully manipulate the propagation of acoustic waves within the audible spectra to beamform and channel signal strength in a particular direction. In attempt to simplify the overall process, hobby microcontrollers, 1-3W speakers, microphones, audio amplifiers, and other peripheral components will be used to rig a testing apparatus. Furthermore, experiments with 3D printed metasurfaces affixed to the speakers will be conducted to measure the signal strength of the projected waves on the opposing side of the room. Successful implementation of an acoustic metasurface that can beamform will be reflected in data that illustrate a stronger signal towards one side of a microphone array within the audible frequency band.

Introduction and Motivation

The idea of channeling an acoustic source towards a desired location has gained traction in recent years. This concept though is quite novel; the technique used to focus transmitted signals to a specific location is known as beamforming [4] and it is used to improve the resolution of signals by amplifying the desired signal towards a receiver. This can be achieved in numerous ways, one of which is through a phased array of signal sources. This is a generally a set of acoustic or electromagnetic wave sources that each produce a signal with a different phase [2] where the resulting signals constructively interfere to produce the strongest signal in a desired direction. Figure 1 below taken from an article entitled “5G Beamforming: an engineer’s overview” illustrates how the major lobe encapsulates the strongest signal which is θ offset from the horizontal [3].



[3]

Figure 1. Resulting major lobe from a phased array of signal sources

Researchers at the Texas A&M University designed in *Development of an Economical 2-DOF Continuous-Scan Acoustic Beamforming Array* a linear phased acoustic array to achieve such beamforming. Although they were able to achieve source localization, they did so through a rotating array of sensors. This has the drawback that keeping the sensor array fixed to one direction inhibits the source localization resolution from increasing [1]. Alternatively, there has been substantial work done in utilizing metasurfaces to achieve beamforming. A metasurface is a thin, often subwavelength, material designed to offset the phase of an acoustic wave incident on it [5]. In *Phase-Optimized Multi-Step Phase Acoustic Metasurfaces for Arbitrary Multifocal Beamforming*, researchers designed a four-step phase metasurface to improve the transmission efficiency for ultrasonic waves [6]. Their experiments demonstrated accurate signal focusing on an arbitrary point; nevertheless, this paper focused on acoustic waves beyond range audible to the human ear. As such, there is yet to be substantial work in multi-focal acoustic beamforming for signals within the audible spectra.

Replace with Our Project

Our lab aims to manipulate the propagation of acoustic waves within the audible spectra towards a specific location with metasurfaces. In effect, by channeling a hearable acoustic source towards a specific location, a spatial zone wherein the edge is articulated by an acoustic wave as opposed to a physical barrier can be created, known as a personal acoustic space [7].

Research Question and Significance

In creating a personal acoustic zone, the area immediately succeeding the signal source, also known as the near field, of the acoustic wave needs to be manipulated in a way to direct most of its energy towards a specific direction, beamforming. The idea is to do so with inexpensive hardware and a fixed transceiver array. Metasurfaces offer a desirable route as they can deterministically offset the phase of an incident signal [5]. Doing so in an array of speakers begs the question, can we beamform with acoustic metasurfaces in the audible spectra to create personal acoustic spaces?

Existing studies have concluded that multifocal beamforming is possible with ultrasonic waves with applications in biomedical imaging and physical sensing [6] but is not conclusive of signals within the audible spectra for humans. Successful implementation of beamforming via acoustic metasurfaces allows for creating a spatial zone wherein most of the sound's energy is channeled; in effect, the sound will not be wasted on noise being polluted out into undesirable areas. This advantage could be extended to the fact that the signal source can then reduce its power if provided with a metasurface to channel the sound as compared to a source without a metasurface where more power is needed to project a stronger sound.

Methodology

With the goal of creating a personal acoustic space in mind, the research lies in designing a system to first project an audio signal from an array of speakers with a controlled amplitude. In doing so would require a microcontroller (MCU) to output a signal to a small speaker. Many microcontrollers currently available over the internet would suffice for this operation as we only intend to control minute properties of the outgoing sound wave, such as amplitude and/or phase. Examples of microcontrollers suitable include the Arduino, ESP32, Teensy4.1, etc. Additionally, a small, 8 Ohm 1 Watt speaker would function for experiments because it becomes rather easy to then attach prototypes of metasurfaces onto an array of speakers.

However, using an array of speakers connected to one hobby microcontroller would likely draw far too much current rated for the general-purpose input/output (GPIO) pins of the MCU. In addition to the two hardware mentioned previously, a LM386 Audio Amplifier is needed to properly supply the speaker array with power and keep the microcontroller functional since directly connecting multiple speakers to a single microcontroller would likely burnout the MCU [8]. Designing the metasurface will also be carried out by a CAD modeling software (Solidworks, Fusion360, GrabCAD, etc.) and prototyped using a 3D printer. Due to the sizing constraints and precision necessary to achieve the subwavelength nature of an acoustic metasurface, a resin printer will be advantageous as it can print materials with a <0.5mm layer height [9]. An array of microphones affixed to the opposite side of the speaker array is needed to measure the power, or gain, of the incoming signals. We expect to see a higher gain measured on microphones pointed to by the major lobe of the beamformed signal as compared to the rest of the microphones in the array.

In addition to a physical apparatus for experimenting, there must be significant work done prior in simulations. For this, MATLAB & Simulink will be used to perform beamforming simulations with a linear antenna array and specific weights at each point in the array to simulate a change in phase.

Rudra's role in this project will be to research, design, and carry out the manufacturing of proposed metasurfaces. Additionally, he will design and prototype the apparatus of the experiment by sourcing proper microcontrollers, speakers and other peripheral electronics.

Expected Outcomes

To properly demonstrate beamforming with acoustic metasurfaces, experiments should reflect a stronger signal in one side of the microphone array as compared to the opposite end. Data such as this would indicate how metasurfaces alone are properly able to manipulate the propagation of acoustic waves in the near field and direct them towards a specific location, known as beamforming. Consequently, these results can be extended to create personal acoustic spaces where people within the spatial zone are only able to hear most of the projected sound.

Expected Timetable

Date	Goal
October 1st, 2024	Perform simulations for linear beamforming • Create linear array with different weights in MATLAB/Simulink • Plot results onto a heatmap based on beamformed strength
October 8th, 2024	Replace elements in simulation with a metasurface • Design metasurface in CAD → use in simulations
October 22nd, 2024	Print metasurface on 3D printer • Preferably multiple prototypes across different types of 3D printers
October 29th, 2024	Sine wave test with metasurface • Integrate proposed hardware into apparatus and experiment
November 5th, 2024 – February 1st	Evaluate issues with previous experiments. Redesign metasurfaces, simulate and experiment • Assign different weights for different signals within the same set of speakers

	• Beamform for each signal such that the source only reaches a specific part of the room
March 8th, 2024	Design system applicable to wideband signals

References

[1] https://arc.aiaa.org/doi/10.2514/6.2023-3815

[2] https://en.wikipedia.org/wiki/Phased_array

[3] https://my.avnet.com/abacus/solutions/markets/communications/5g-solutions/5g-beamforming/

[4] https://www.mathworks.com/discovery/beamforming.html

[5] B. Assouar, B. Liang, Y. Wu, Y. Li, J. C. Cheng, Y. Jing "Acoustic metasurfaces" *Nature Reviews Materials* October 2018. Available: https://www.nature.com/articles/s41578-018-0061-4#Sec5

[6] https://www.mdpi.com/2072-666X/14/6/1176

[7] https://www.researchcatalogue.net/view/223095/223096

[8] https://docs.arduino.cc/tutorials/generic/simple-audio-player/

[9] https://formlabs.com/3d-printers/form-4/?&utm_source=google&utm_medium=paid-search&utm_campaign=NA.US.G.Hardware-SLAPrinters&utm_term=resin%20printer%203d&utm_content=Form_4&utm_device=c&_bt=705779801973&_bk=resin%20printer%203d&_bm=p&_bn=g&_bg=164797837877&gad_source=1&gclid=Cj0KCQjwxsm3BhDrARIsAMtVz6OagbvLnSc6dwlWCA_KERQ-NO_gFj9wewK1HunztsY5aIpEXtdQIaAaArbZEALw_wcB

[10] https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.4.024003#:~:text=Conventional%20phased%20arrays%20require%20a,forming%20a%20self%2Dbending%20beam.