Introduction

Acoustic metamaterials are artificially engineered structures, which are capable of manipulating acoustic waves in manners that are uncommon in conventional, naturally occurring materials. Owing to the novel characteristics they can be tailored to exhibit unique properties there has been an increased interest in this area in recent years , leading to significant advances in acoustic technologies and functional devices such as transformation acoustics, super-resolution imaging devices, acoustic sensing systems, acoustic cloaks, and acoustic filters.

The primary goal of this independent undergraduate research project is to develop an enhanced understanding of the acoustic meta surfaces and use it as a reflector for a single axis leviator to achieve acoustic levitation.

Preliminary Experiment

For the preliminary experiment, we conducted an experiment to achieve acoustic levitation by forming standing waves between the emitter(speaker) and reflector (meta surface).

Levitation is a process by which an object is suspended in a stable position against gravity, without physical contact. Levitation can be realized by various physical means, such as magnetic force, electrostatic force, aerodynamic force, acoustic radiation force and so on. In this experiment one dimensional levitation methods were used to suspend a particle between the reflector and emitter. An acoustic wave can exert a force on objects immersed in the wave field. These forces are normally weak, but they can become quite large when using high intensity waves due to the nonlinear characteristics. The forces can even be large enough to levitate substances against gravity force. This technique is called acoustic levitation.

A basic acoustic levitator has two main parts- a transducer producing sound waves and a reflector which in our case is the meta surface. The sound wave travels away from the transducer and bounces off the meta surface. These reflecting waves interact between its compressions and rarefactions causing interference. These interactions between two compressions amplifies one another and the interactions between compressions and rarefactions balances one another. Sometimes, this reflection and interference can combine to form a standing wave. Standing waves are a type of waves that oscillate in time but whose peak amplitude profile does not move in space. These standing waves have defined nodes (area of minimum pressure) and antinodes (area of maximum pressure).

Objects tend to move from areas of high pressure to low pressure, which means objects placed in the standing wave will move to the nearest node. Thus, the low pressure and low energy nodes are ideal places for objects in a standing wave to rest. The acoustic radiation pressure on the levitated objects sitting in the nodes are balanced by the pull of the earth thereby levitating the objects.

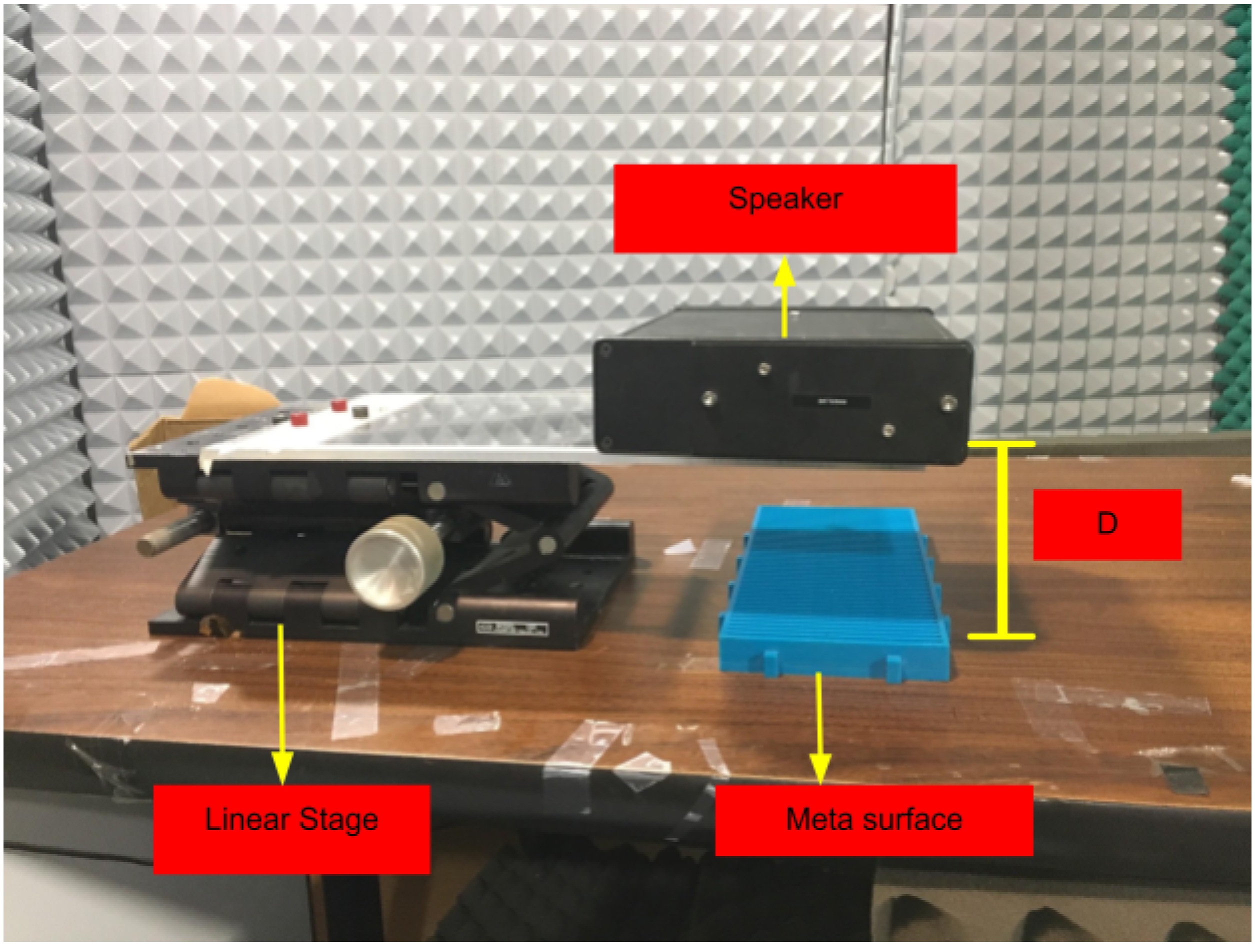

Fig 1: Experimental Setup

The set up shown above is used for testing to achieve acoustic levitation. The Peterson Speaker is used as the transducer to produce sound waves of various frequencies. The speaker is suspended from a vertical stage which can be used to change the height between the emitter and the reflector. The meta surface which acts a reflector is placed directly below the speaker to reflect the incoming waves. Sound waves with various wavelengths were used to levitate droplets of water and Styrofoam balls between the speaker and the meta surface.

The waves of different frequencies were used for testing. The table 1 consists of the frequencies and the corresponding wavelengths used for the experiment.

Wavelength for an acoustic sound waves is inversely proportional to its frequency and can be calculated from the following relation

$$\nu = \frac{c}{\lambda}$$

Where

$\nu =$ frequency of the acoustic sound wave

$c =$ speed of sound wave = 340 m/s

$\lambda =$ corresponding wavelength of the acoustic sound wave

D = distance between the transducer and the reflector(meta surface)

N	D (mm)	wavelength(mm^{-1})	frequency(Hz)
1	7.37	14.74	2327
2	7.37	7.37	4654
3	7.37	4.91	6981
4	7.37	3.68	9308
5	7.37	2.94	11635
6	7.37	2.45	13962
7	7.37	2.10	16289
8	7.37	1.84	18616
9	7.37	1.63	20943
10	7.37	1.47	23270
11	7.37	1.34	25597
12	7.37	1.22	27924
13	7.37	1.13	30251
14	7.37	1.05	32578
15	7.37	0.98	34905
16	7.37	0.92	37232
17	7.37	0.81	41886
18	7.37	0.77	44213

We operated the speaker at different nodes to produce standing waves between the speaker and the reflector(metasurface). Styrofoam balls were introduced in between the emitter and reflector to achieve acoustic levitation. But we were unsuccessful in achieving acoustic levitation. Hence we inferred that pressure field produced due to the standing waves was not strong enough to levitate the object.

Experiment 2

For second experiment we decided to calculate the magnitude of pressure fields for three different models of electromagnetic speakers. This experiment was done in order to choose a speaker that can produce the strongest pressure field for achieving acoustic levitation.

The three different speakers used are shown below

Fig 2: Speaker A, B and C respectively

The pressure fields for the standing waves produced by these speakers can be approximated by using the sensitivity of each speaker.

We know

$$Pressure = \frac{Output\ Voltage}{Sensitivity}$$

Thus pressure for each speaker can be calculated by dividing output voltage measured by the microphone by the sensitivity of each of the speaker. We used a B&K microphone to record the voltage output from each of the three speakers operating at various frequencies. The voltage measured by the microphone was plotted versus different operating frequencies for each of the speakers. This output voltage was then divided by the sensitivity of each speaker to obtain the pressure fields for each speaker as a function of frequency.

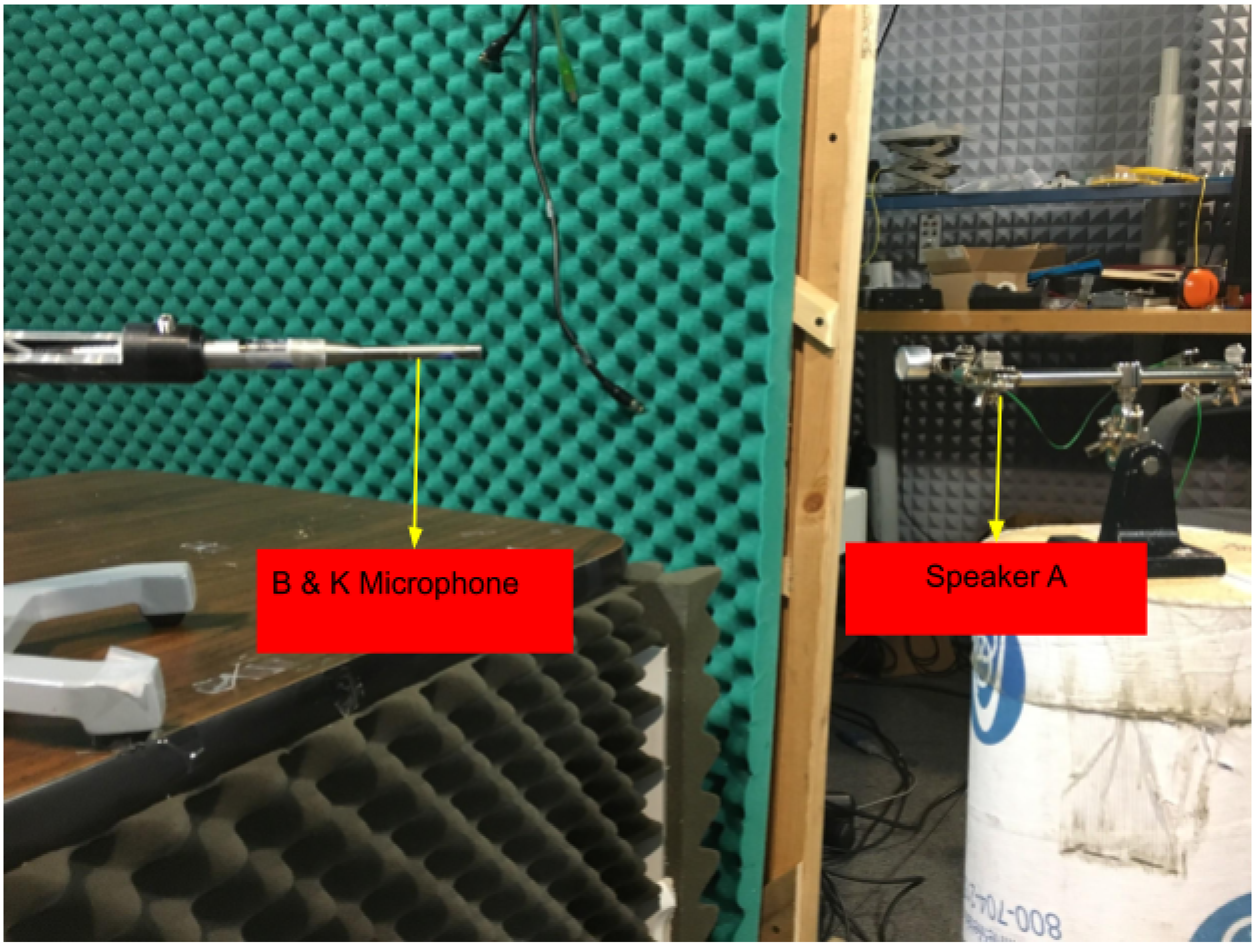

Fig 3

Fig 4

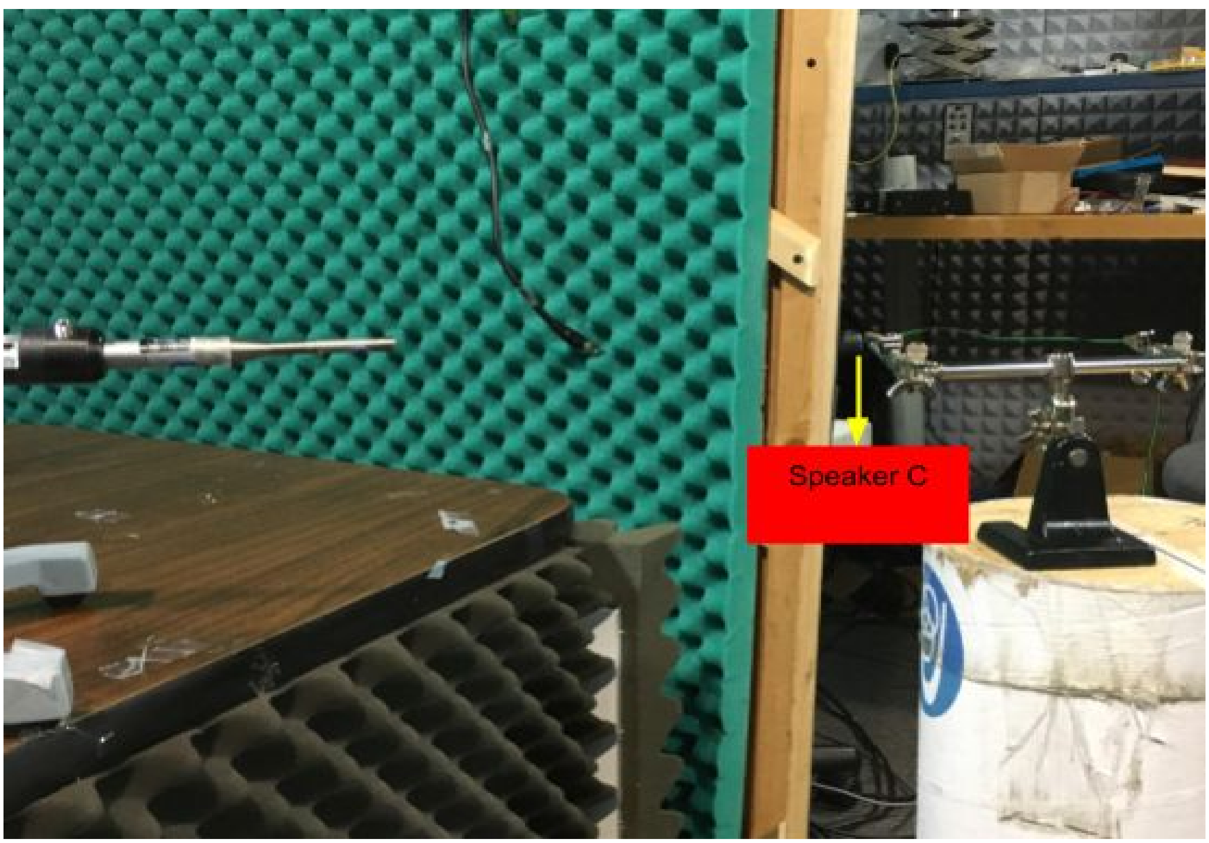

Fig 5

When operating the the speakers for various frequencies of sound waves, Speaker A had the highest pressure field for a range of frequencies as compared to Speakers B and C. Thus we decided to create an array of Speaker A to produce a field of standing waves to achieve acoustic levitation.

Experiment 3

For our third experiment we decided to use a phased array of speakers to transmit sound waves with specific phases and time delays. These arrays are mostly used in radar, sonar and ultrasonic imaging since they can dynamically steer and shape the beam. But recently these ultrasound array have been used to produce a field of standing waves to levitate small objects in their pressure fields. Therefore, in order to achieve our goal of acoustic levitation we decided to built a flat plate array consisting of two rows and six columns holding together a total of twelve speakers.
In order to design our flat plate array we used SolidWorks and the part was then 3d printed.
This 3d printed array was then mounted on top of a vertical stage controlled manually to alter the distance between the array of speakers(emitter) and the meta surface (receiver).

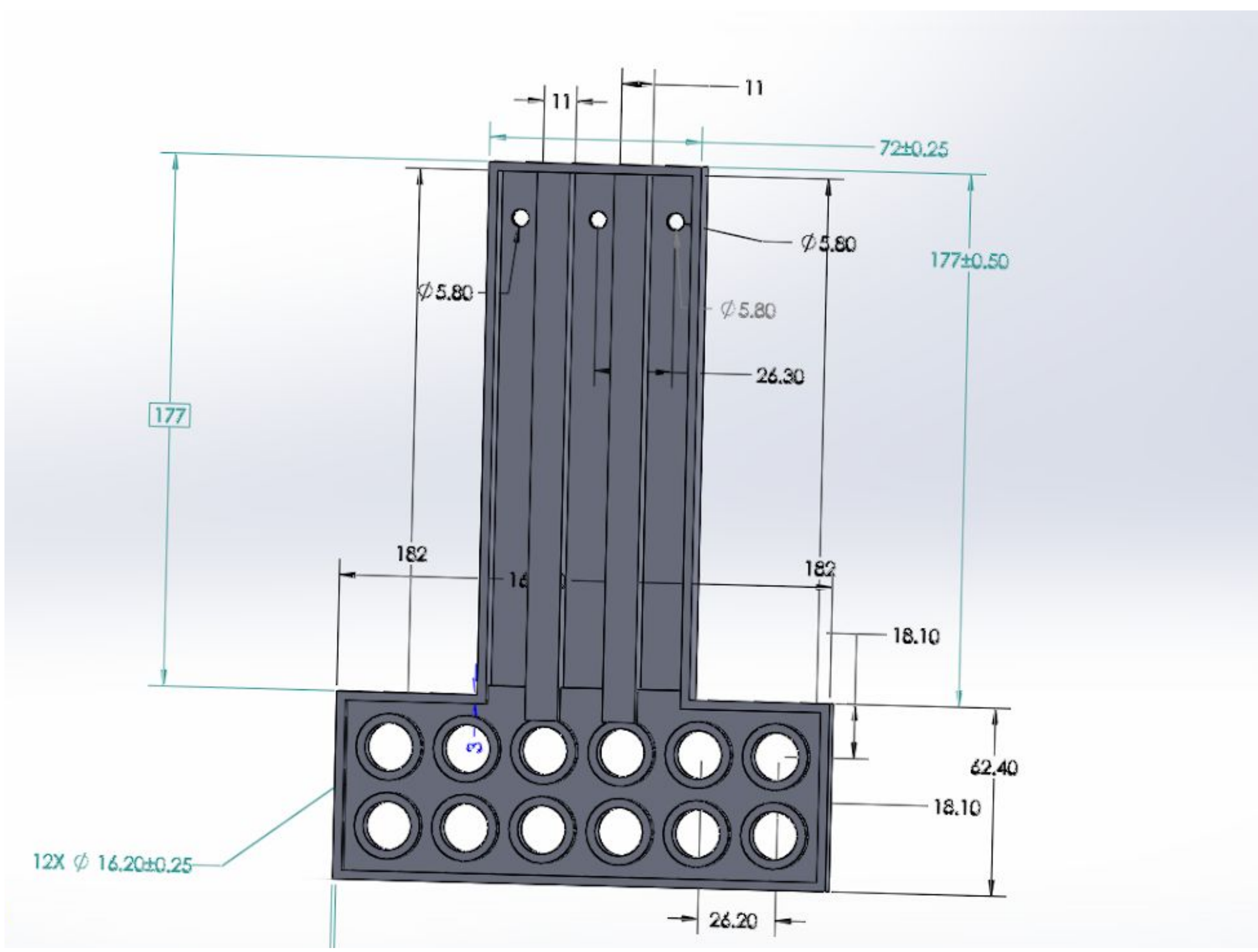

Fig 6: CAD model for Flat plate array

Our next step was to arrange the speakers in the array and the speaker when being powered should produce in phase sound waves to produce a field of standing waves. In order to arrange the speakers in phase we marked their polarities. The transducers have a polarity and it is important to glue them in the base oriented with the same polarity. The easiest way to mark the polarity of a transducer is by connecting it to an oscilloscope and poke the inside with a thin wire.

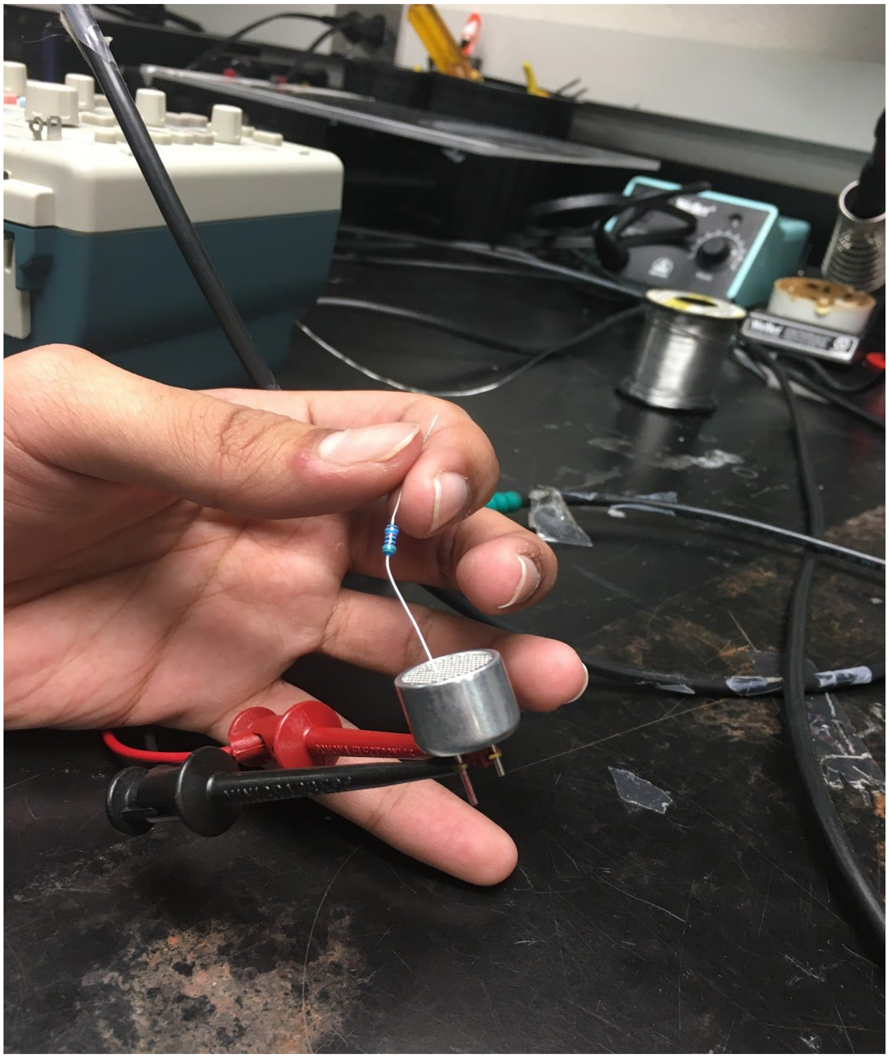

Fig 7: Poking of speaker with a thin wire

On poking if the spike goes up, mark the leg connected to the positive part of the probe. If the spike goes down, mark the leg connected to the ground. This was repeated for all the twelve speakers.

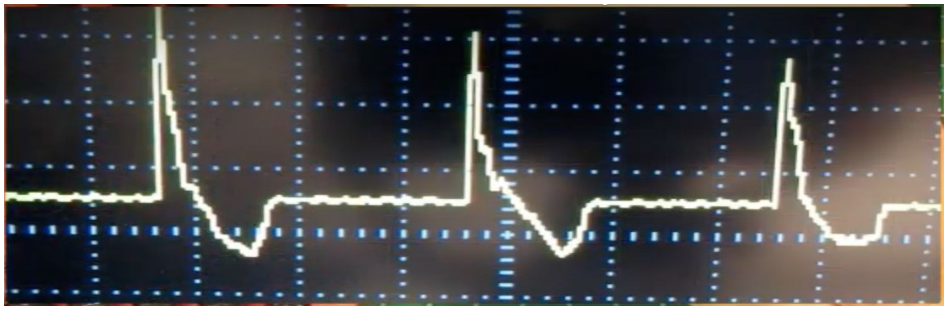

Fig 8: The spike goes up

The spike on the oscilloscope goes up indicating the positive polarity of the speaker. Similarly the spike goes down in the figure below, indicating the negative polarity of ground of the speaker.

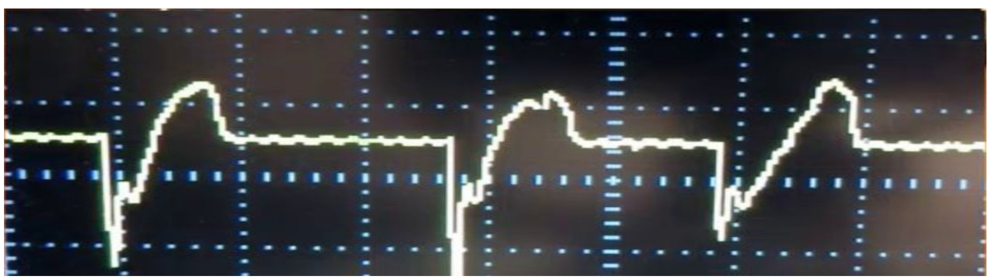

Fig 9: The spike goes down

Experimental Setup

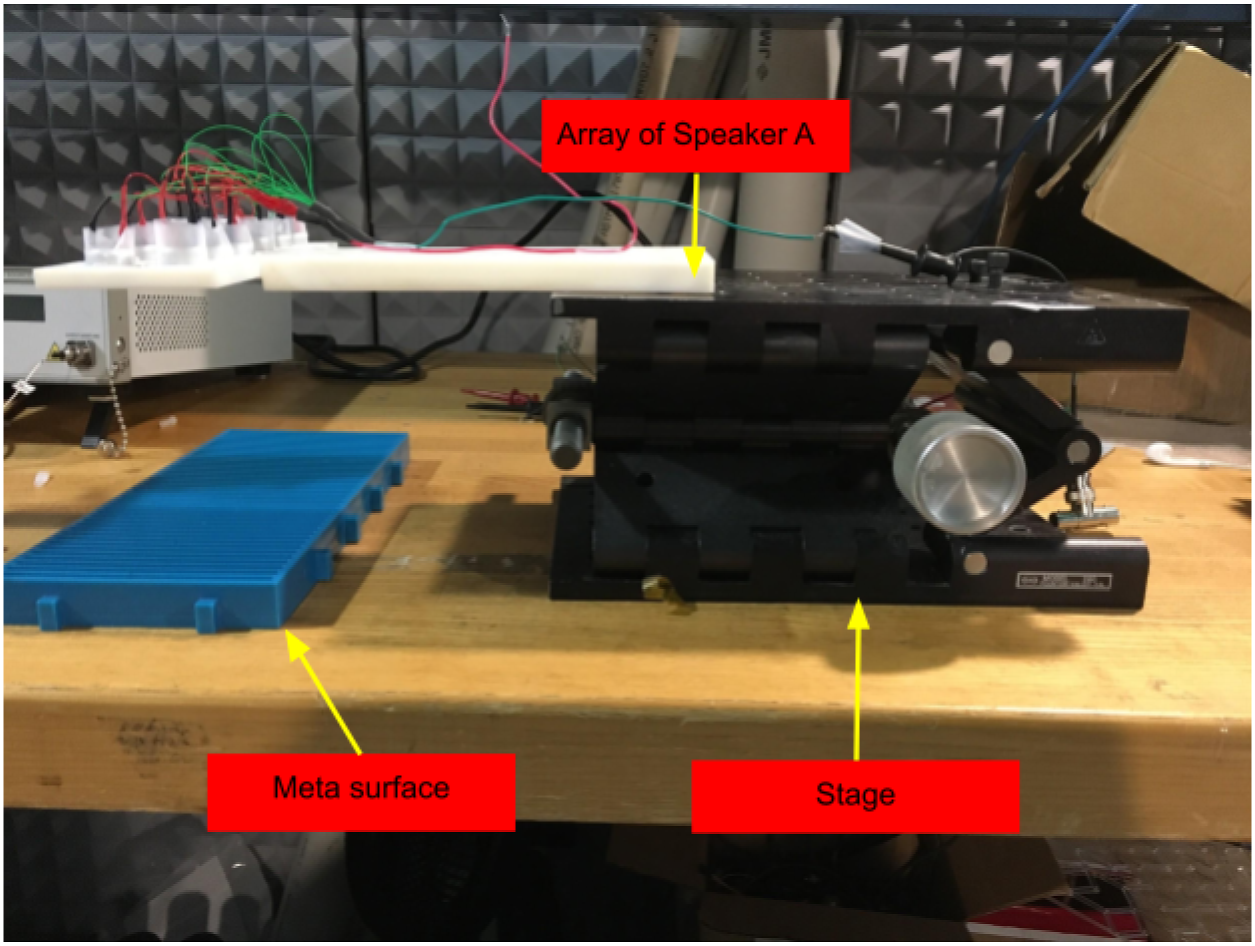

Fig 10: Array of speakers

The setup above shows an array of twelve speakers all connected to a common positive terminal and a ground. The flat array is mounted on top of a linear stage whose height can be altered to change the separation distance between the speakers and the metasurface. The metasurface sits right below the array of speakers and reflects the incoming sound waves thereby producing standing waves.

The waves of different frequencies were used for testing. The table 2 consists of the frequencies and the corresponding wavelengths used for the experiment.

wavelength(mm^{-1})	frequency(Hz)
14.74	2327
7.37	4654
4.91	6981

3.68	9308
2.94	11635
2.45	13962
2.10	16289
1.84	18616
1.63	20943
1.47	23270
1.34	25597
1.22	27924
1.13	30251
1.05	32578
0.98	34905
0.92	37232
0.81	41886
0.77	44213

Again we operated the array of speakers at different nodes to produce standing waves between the speakers and the reflector(metasurface). Styrofoam balls were introduced in between the emitter and reflector to achieve acoustic levitation. But we were unsuccessful in achieving acoustic levitation. Hence we inferred that pressure field produced by the array of speakers were still not strong enough to levitate the object.

Experiment 4

For our fourth experiment we decided to built a single axis levitator to suspend particles in the standing waves produced by the single axis levitator. To achieve our goal we used two in phase speakers of Type A and clamped them to a holder while facing each other.

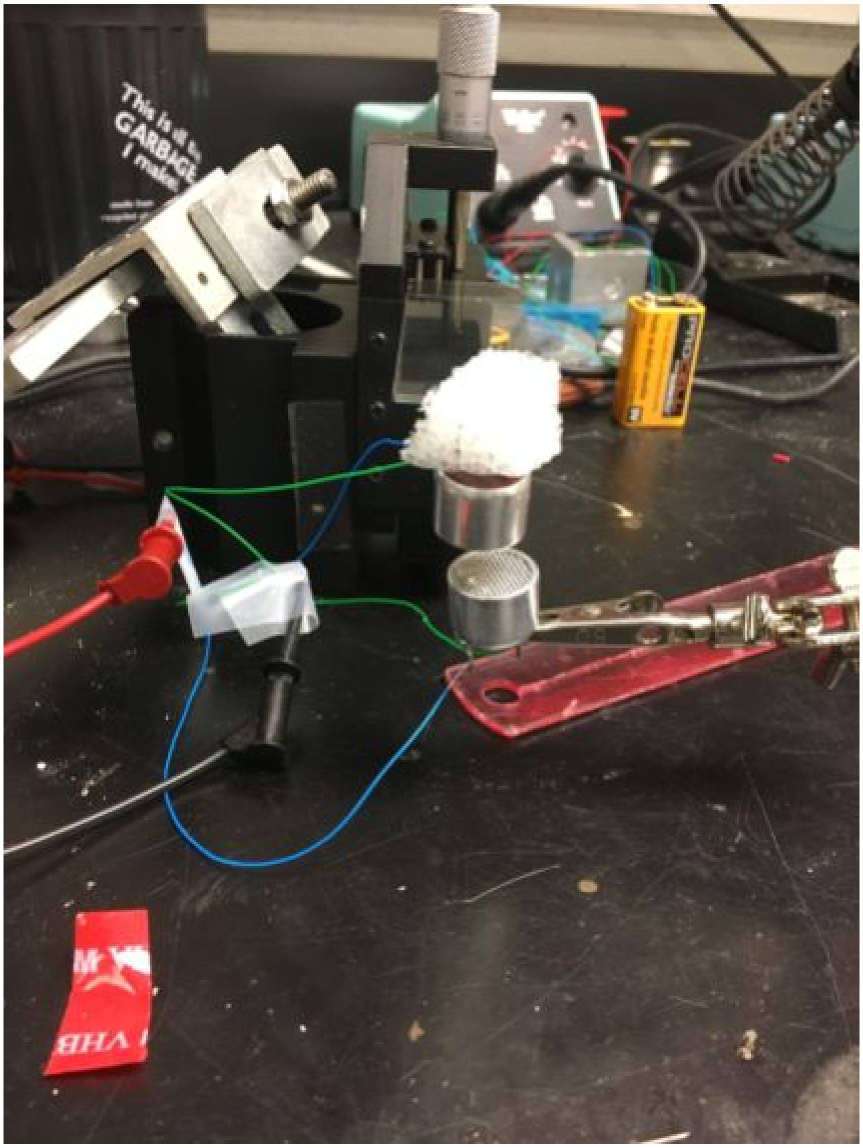

Fig 11 : Single axis levitator

The two speaker were connected to the amplifier and were operated at various frequencies. But again the standing waves produced were unsuccessful in holding the object in its pressure field.

Summary of the independent study

Acoustic metasurfaces are capable of sustaining and propagating acoustic waves with high wave vectors have been studied in this independent research work. These metasurfaces possess unique characteristics which are as a direct consequence to their fundamental construction. The goal of this research work is to achieve acoustic levitation with high-k metasurfaces and use this understanding to develop novel devices with enhancement performance and capabilities. We performed four different experiments to achieve acoustic levitation using the metasurface as a reflector. But we were unsuccessful in levitating objects. Hence it was inferred that the pressure fields created by the speakers were not strong enough to levitate an object.

References

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