Experimentally Studying the Effectiveness of Acoustics in Controlled Propulsion using Sonic Transducers

Sam Sanders[1]
Mississippi State University, Mississippi State, MS 39762

In this experiment, the effectiveness of acoustic transducers in propelling a small boat through water is studied. A circuit is developed which uses a 12 V battery and an Arduino Nano to power and provide a 40 kHz signal to an array of acoustic transducers, which are mounted to a small container used as a boat. Two different arrays are used, both a 10-transducer array and a 5-transducer array. The motion of the boat through water is recorded to create a position-time plot, and a trendline is applied to this plot to represent the position equation. This position equation is used to find the acceleration equation of the boat and thus the net force acting on the boat for each of the transducer arrays. Assuming that the net force on the boat is the sum of the propulsion force and the water drag force, a set of equations is formed to solve for both the propulsion force of each transducer as well as the drag force acting on the boat in both setups. It's calculated that the propulsion force provided by each transducer is around 6 micropounds, while the average drag force for each setup is on the order of 25-30 micropounds. As well as providing quantitative data focusing on produced acoustic propulsion, this experiment also demonstrates the importance of acoustics as a means of propulsion and the future implications of this topic.

Nomenclature

a = acceleration of the boat
C = constant associated with the drag equation
C_D = drag coefficient
D = drag force acting the boat
F = net force acting on the boat
m = mass of the boat and circuit setup
P = propulsion force of a single transducer
P_{total} = propulsion force of an entire array of transducers
R^2 = coefficient of determination
ρ = density
S = reference area
s = position of the boat
V = velocity of the boat
V_{avg} = average velocity of the boat

I. Introduction

IN today's world, there are many reasons to have a controlled source of propulsion. Whether it be fighter jet, submarine, or even fishing boat, propulsion is one of the key factors. However, in modern times, there is also often the need for undetectable propulsion. There are many examples of vehicles that undetectable propulsion would benefit, mainly all military. For example, even if a fighter jet has a miniscule radar cross-section, infrared (IR) sensors can still detect the heat emitting from the powerplant. Moreover, even if the aircraft cannot be detected by thermal or radar devices, the engine can often still be heard from a large distance away. Therefore, it's easy to see that the use of undetectable propulsion is the next step in advancing military technology.

On the other side of the spectrum, there is an increasingly evident need for technological improvement in the field of microscale and nanoscale submerged propulsion. Particularly, this need relates to the medical and biological

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[1] Undergraduate Student, Aerospace Engineering Department, AIAA Student Member.

industry. For example, microscale drug delivery robots have become a popular topic in the medical world. Modern propeller technology commonly used for submerged vehicles fail in many ways when it comes to microscale propulsion. For one, the miniaturization of the common propulsion system is extremely difficult, and physical scaling laws (friction, heat generation, etc.) often make this task impossible [1].

For many years, the force produced by concentrated acoustic waves has been studied for various research topics. However, the use of this acoustic force as a propulsion force has rarely been considered until recent studies. There are many reasons why the force produced by acoustic waves would be beneficial in the field of propulsion. First, acoustic propulsion is most often achieved using very high frequency waves outside the human hearing range. Many acoustic force-producing devices are in the MHz range, while the human hearing range only extends to around 20 kHz. Therefore, acoustic propulsion is essentially “silent” to humans, and this frequency is outside the range of most modern acoustic probes. Second, because the attenuation of sound is what produces the force in these devices, the sound has vanished by the time it has traveled a few feet from the device. Therefore, even if the sound could be detected, the acoustic sensor would need to be extremely close to the source of the acoustic waves. Third, because of the nature of these acoustic devices, they do not generate very strong magnetic fields. This means that along with being acoustically silent, these acoustic devices are also electromagnetically silent. Lastly, because these acoustic devices contain no moving parts, they could likely be easily miniaturized to be used with microscale and nanoscale submerged vessels [2].

In this report, the effectiveness of acoustic propulsion is examined by creating two acoustic transducer arrays controlled by an Arduino board. These transducer arrays are attached to a small boat, and the movement of the boat as well as the force acting on the boat are studied. Knowing both the net force on the boat and the different individual forces acting, the force of each acoustic transducer is found as well as the drag force on the boat. Finally, the results of the experiment are summarized and further implications of the findings are discussed.

II. Experiment Setup

The first step of setting up the experiment was to ensure that the transducer arrays were working effectively. This required a circuit setup that consisted of an Arduino Nano (used to send the correct frequency to the transducers), a 12 V battery (used to power both the Arduino board and the transducers), a driver board (used to deliver the power and signal to the transducer arrays), and two ultrasonic transducer arrays. By two ultrasonic transducer arrays, it is meant that one set-up has one row of transducers powered while the second set-up has both rows of transducers powered. A rudimentary picture of this setup can be seen below in Fig. 1. In the picture, you can see the transducer array to the bottom left. Directly above it is the Arduino nano board. In the center right is the driver board, while the component in the center is a switch which allows for the power to be turned on and off. The 12 V battery is shown in the top right.

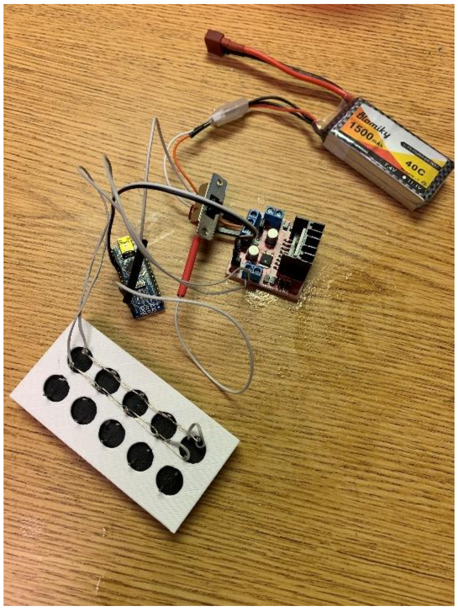

Fig. 1 Picture of Transducer Circuit Setup.

After the circuit was completed, the search for an appropriate water vessel began. First, a piece of foam shaped like a standard boat seemed like the best option. However, due to the weight of the circuit setup compared to the weighth of the foam, achieving a weight balance was nearly impossible. Therefore, after attempting this design multiple times, the decision was made to try another design. The next design was a pontoon-shaped foam configuration. It was thought that this design, while not as creative or aesthetically appealing, would offer easier floatation and a simpler weight balance. However, this design experienced the same problems. The weight balance problem is amplified by the fact that while it's better for all components to sit beneat the waterline, the transducers have to be sitting outside of the water. Therefore, there is no good solution that accomplishes both of these tasks simultaneously.

Another configuration that was tested was the pontoon that had only the transducers attached with long wires. The rest of the circuit setup sat away from the water, connected to the float only by the long wires. However, when this design was attempted, the long wires were too heavy, and the movement of the boat could not be accurately observed. The tautness of the wires could not be overcome by the acoustic propulsion force. After much trial and error, the setup transitioned to one where the entire circuit sits in the bottom of a small plastic container. While this is not the most aesthetically pleasing or sleek design, acoustic propulsion and the correlating movement had already been observed when using a small plastic container. While the design of the floatation device is an important aspect of the experiment, it is not the main focus of the experiment, which is to observe the effectiveness of acoustic propulsion regardless of what type of boat is being propelled.

The acoustic transducers are placed on the back of the boat, pointing parallel to the water. The boat is placed in a small tub, approximately 3 feet long and 2 feet wide, filled with about four inches of water. After being placed in the water and letting the water return to static conditions, the circuit is powered on, and the position of the boat is recorded in one second intervals. As mentioned previously, the two transducer arrays refer to the same transducer array using either one row or both rows of transducers. Therefore, one setup has 5 transducers propelling the boat, while the other setup has 10 transducers propelling the boat. Both setups were recorded ten different times, so there were a total of twenty tests conducted. A picture of the boat configuration can be seen in Fig. 2, while a picture of the testing setup is shown in Fig. 3.

Fig. 2 Picture of Boat Configuration with One Row of Transducers Being Used (Bottom Row)

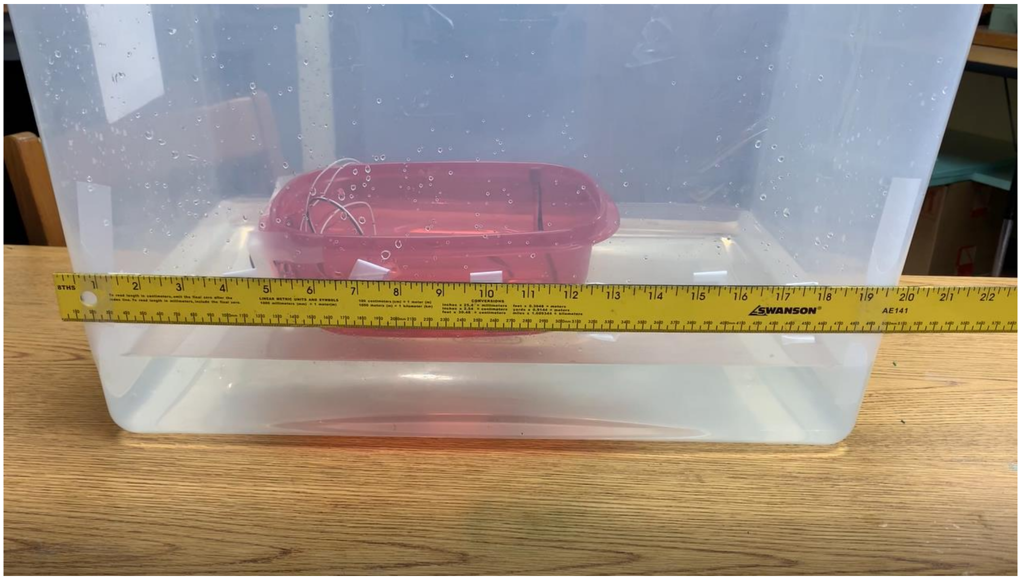

Fig. 3 Picture of Testing Setup

III. Data Acquisition

As mentioned in the experiment setup section, the Arduino board provides the signal function to the acoustic transducers. The signal that is output from the transducers is a 40 kHz acoustic signal. While frequency is usually on the order of MHz for acoustic propulsion experiments, this experiment seeks to observe the effects of a lower frequency signal on the effectiveness of the propulsion. The pressure of the 40 kHz acoustic waves produced by the transducers produces a force on the water or any other surface that it hits. Following Newton's 3rd Law, this produces an equal and opposite force on the transducer and thus the boat. Therefore, the acoustic waves produced by the transducers produce a propulsion force on the boat. This is the basis for the data collected from the experiment.

By recording the linear motion of the boat across the water with respect to time, a graph is formed which shows the linear position of the boat at any given time. There were ten trials conducted for both setups. The position-time graph for the 5 transducer setup is shown in Fig. 4, while the graph for the 10 transducer setup is shown in Fig. 5.

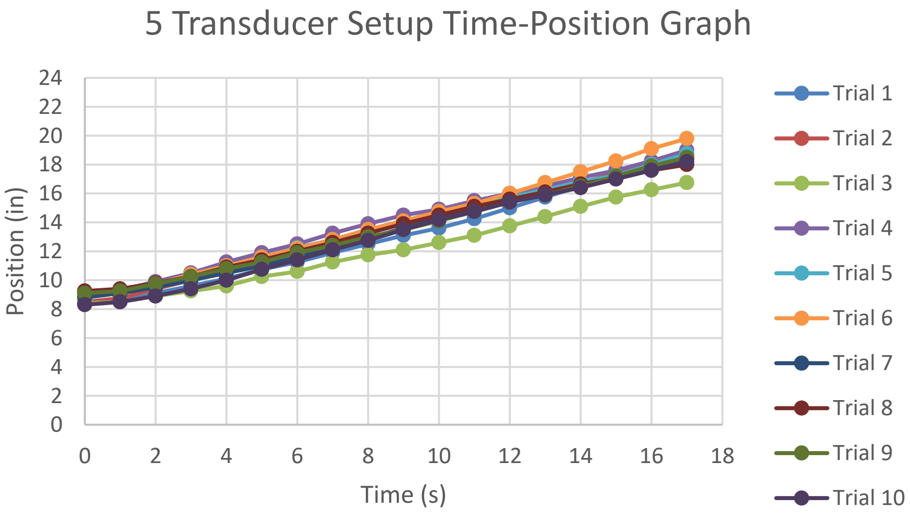

Fig. 4 Time-Position Graph for 5 Transducer Setup

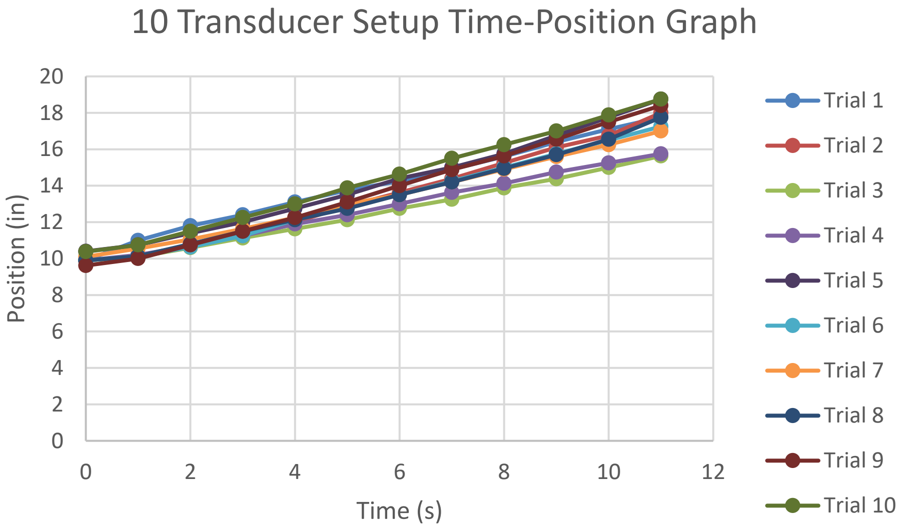

Fig. 5 Time-Position Graph for 10 Transducer Setup

After this, an average curve for both setups was formed. The average for the 5 transducer setup is shown in Fig. 6, and the average for the 10 transducer setup is shown in Fig. 7.

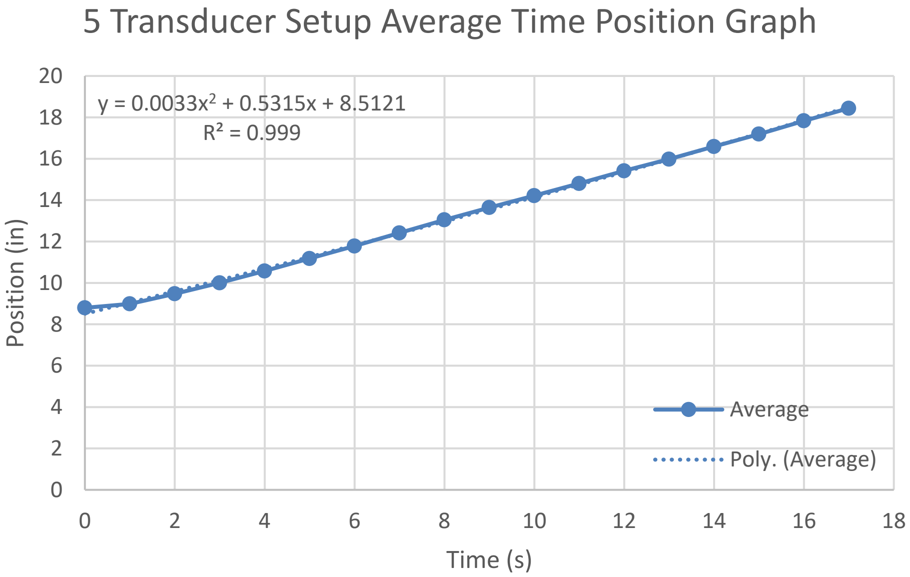

Fig. 6 Average Curve for 5 Transducer Setup

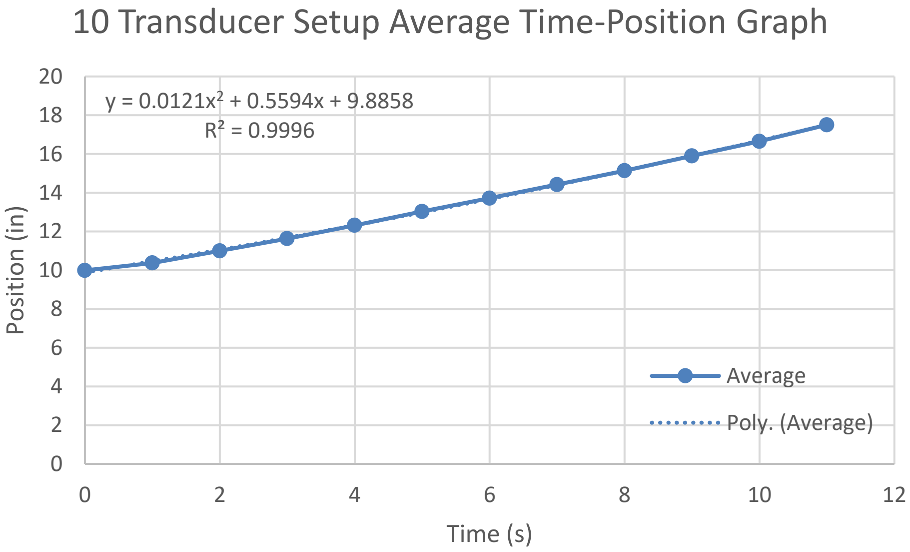

Fig. 7 Average Curve for 10 Transducer Setup

It should be noted here that both curves have a trendline being applied, with the equation and coefficient of determination shown in the top left. Both curves appear to be mostly linear, but a 2nd-order polynomial trendline is being used instead of a linear trendline. This will be discussed later.

Now that the position equation for both setups has been found, the method for solving for the forces will be discussed. It's assumed that the only two forces acting on the boat are the propulsion force and the drag force of the water. While there is not an equation for the propulsion force, there is one for the drag force, as shown in Eq. (1).

$$D = \frac{1}{2}\rho V^2 S C_D \tag{1}$$

While it is not simple to find values for density, reference area, and especially drag coefficient, these can be treated as constants between both setups. This is because, as mentioned previously, the two transducer arrays are actually just one array with either one or both rows of transducers turned on. In this way, the density, reference area, and drag coefficient, as well as the mass of the setup, can be kept constant. From now on, this constant in the drag equation will referred to as C. The only variable between the setups is the velocity. The force summation for both setups can be described as follows in Eq. (2) and Eq. (3).

$$F_5 = 5P - {V_5}^2 C \tag{2}$$
$$F_{10} = 10P - {V_{10}}^2 C \tag{3}$$

Here, P is the acoustic force produced by each transducer. Using the position equations found earlier, the overall force, F, can be found for both setups. Also using the position equations, the velocities, V, for both setups can be found. Therefore, this set of two equations has two unknowns and is easily solvable. However, if the net force on the boats is equal to zero, this set of equations cannot be solved. A linear position equation would indicated a zero acceleration and thus a zero net force. This is why the trendline used for both curves is 2nd-order polynomial instead of linear. While it is true that at some point in the boat's motion the drag will equal the propulsion force and the net force will equal zero, it is assumed for this experiment that neither of the setups reached maximum drag during the recorded trials.

Therefore, the two additional calculations needed to solve for these two equations are the net force and the velocity of each setup. For the net force, the second derivative of the position equation is taken to get the acceleration. This acceleration is multiplied by the mass (constant for both setups) to get the total force. This is done for the 5 transducer setup in Eq. (4-6) and for the 10 transducer setup in Eq. (7-9).

$$a_5 = \frac{d^2 s_5}{dt^2} = 0.0066\ \frac{in}{s^2} = 0.00055\ \frac{ft}{s^2} \tag{4}$$
$$m_5 = m_{10} = 222\ g = 0.01521\ slug \tag{5}$$
$$\boldsymbol{F_5 = m_5 a_5 = 8.3665\ micropounds} \tag{6}$$

$$a_{10} = \frac{d^2 s_{10}}{dt^2} = 0.0242\ \frac{in}{s^2} = 0.00202\ \frac{ft}{s^2} \tag{7}$$
$$m_{10} = m_5 = 222\ g = 0.01521\ slug \tag{8}$$
$$\boldsymbol{F_{10} = m_{10} a_{10} = 30.7278\ micropounds} \tag{9}$$

Next, the average velocities of both setups will be found. This is done by first finding the 1st-order velocity equations and then finding the average value of both functions. This is shown in Eq. (10-11) and Eq. (12-13).

$$V_5 = \frac{ds_5}{dt} = (0.0066t + 0.5315)\ \frac{in}{s} \tag{10}$$
$$\boldsymbol{V_{avg,5} = \frac{1}{18-0}\int_0^{18} (0.0066t + 0.5315)\, dt = 0.5909\ \frac{in}{s} = 0.04924\ \frac{ft}{s}} \tag{11}$$

$$V_{10} = \frac{ds_{10}}{dt} = (0.0242t + 0.5594)\ \frac{in}{s} \tag{12}$$
$$\boldsymbol{V_{avg,10} = \frac{1}{11-0}\int_0^{11} (0.0242t + 0.5594)\, dt = 0.6925\ \frac{in}{s} = 0.05771\ \frac{ft}{s}} \tag{13}$$

Now, the system of equations developed earlier can be solved for both P, the propulsion force of each transducer, and C, the constant related to the drag equation. This is shown in Eq. (14-15) and Eq. (16-17).

$$8.3665\ x\ 10^{-6} = 5P - 0.04924^2 C \tag{14}$$
$$30.7278\ x\ 10^{-6} = 10P - 0.05771^2 C \tag{15}$$

$$\boldsymbol{P = 6.1543\ micropounds} \tag{16}$$
$$\boldsymbol{C = 0.00926\ \frac{slug}{ft}} \tag{17}$$

Therefore, it’s calculated that each acoustic transducer is producing just over 6 micropounds of propulsion force. Finally, the drag force and propulsion force of each setup can be calculated as seen in Eq. (18-19) and Eq. (20-21).

$$\boldsymbol{D_5 = 0.04924^2 C = 22.4516\ micropounds} \tag{18}$$
$$\boldsymbol{D_{10} = 0.05771^2 C = 30.8399\ micropounds} \tag{19}$$

$$\boldsymbol{P_{total,5} = 5P = 30.7715\ micropounds} \tag{20}$$
$$\boldsymbol{P_{total,10} = 10P = 61.5430\ micropounds} \tag{21}$$

After conducting the experiment, an acoustic scanning setup was used to visualize the acoustic wavefield being produced by both the 5 transducer setup and the 10 transducer setup. An acoustic microphone attached to a CNC machine was used to acoustically scan the transducer array, which was powered by a function generator. These scans can be see in Fig. 8 and Fig. 9

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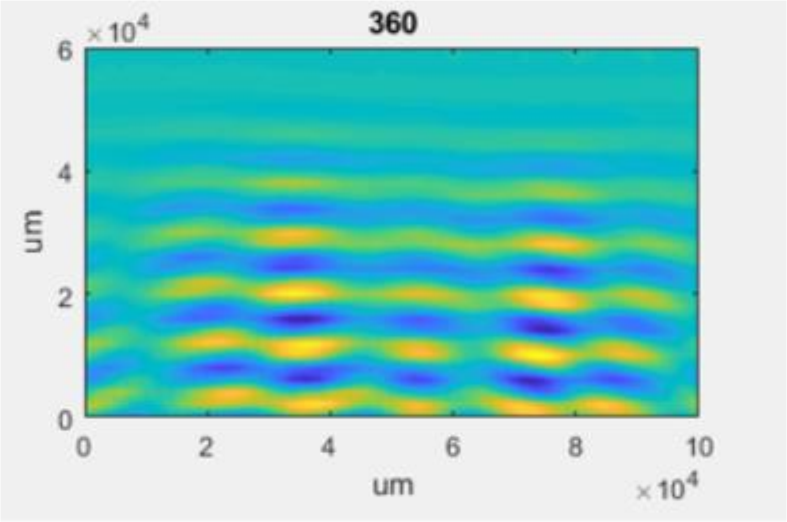

Fig. 8 Acoustic Scan of the 5 Transducer Setup

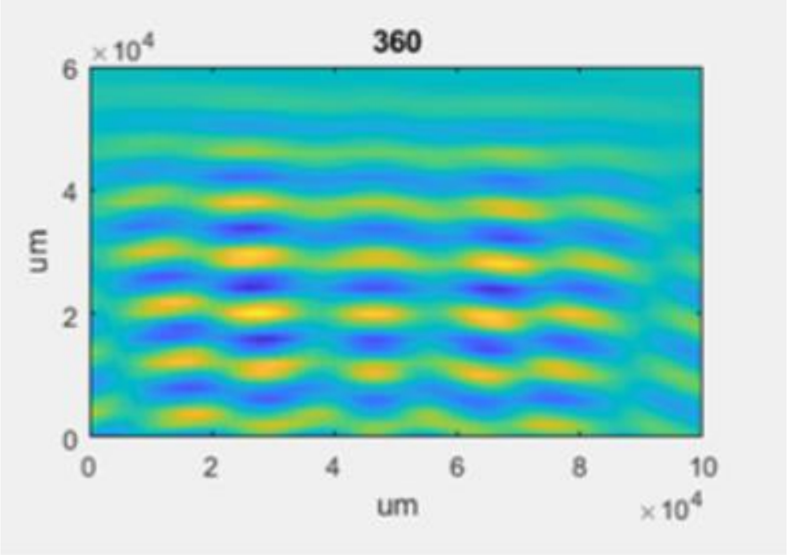

Fig. 9 Acoustic Scan of the 10 Transducer Setup

This scan is done from a top-down view of the arrays. The bounds of these scans encompass about 3 in x 3 in, so it is a relatively small area being scanned. It can be seen that at the bottom of the scans, the acoustic waves are the strongest. This would be the area closest to the transducers. As expected, the acoustic waves attenuate as the distance from the source increases. Also, it appears that the 10 transducer setup is producing a stronger signal that takes a longer distance to attenuate. No major differences can be seen mainly because the second row of transducers is lined up directly beneath the first row of transducers.

IV. Conclusion

In this experiment, it was demonstrated that a small boat can be effectively propelled through water using only acoustic means of propulsion. Although the force produced on the boat is relatively small, around 6 micropounds produced for each transducer, the implications for this type of propulsion are infinite. As mentioned in the introduction, this type of propulsion is acoustically silent, undetectable outside of a few feet from the source, electromagnetically silent, and easily miniaturizable due to the fact that it contains no moving parts.

Although this experiment provided very interesting information about acoustic propulsion and its effectiveness, there are still areas of research that are open to more exploration. First, the idea of an actual boat could be expanded upon. For this experiment, as shown previously, a fairly rudimentary design was used for the boat being propelled. However, future experiments could involve a more streamlined boat that experiences less drag on the water. This would make for even more efficient propulsion. Second, while this experiment only utilized transducers that are used outside of water, there are also transducers that are made to be used in water. This could prove to be useful for submersible water vehicles. Third, more research could go into examining the actual propulsion force being created. While this experiment sought to study the effects of the propulsion, there could be research done on the actual phenomena that are creating the forces as well as how to most effectively create these forces. Finally, it is possible that multiple arrays of transducers could be powered at different times to effectively steer the boat. Therefore, tests could be done to not only propel the boat, but also to steer it on different paths. Expanding upon this idea, Bluetooth could allow for wireless control of these propulsion devices. These are just a few areas that could be explored, but there are nearly endless ways to continue learning in this field.

Acknowledgments

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