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Harvesting Electricity from Sound Waves: An Application of Faraday's Law

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Harvesting Electricity from Sound Waves: An Application of Faraday's Law

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Abstract

A sound is a fascinating tool in human life. We encounter sound pollution every day from hearing, talking, transportation, and much more. This is one source of energy that is often overlooked as a frontier to use to our advantage. An abundance of sound pollution is constantly being wasted as it dissipates back into the environment. This study introduces the concept of converting the energy stored in sound waves into electricity through the application of Faraday's Law. This is accomplished using a diaphragm, magnetic field, and wiring. The diaphragm of the device captures the kinetic energy of the sound and transfers it to the wiring, causing a minor movement of the wire within the magnetic field. This movement leads to variable magnetic flux. When the magnetic flux through a conductor changes, an electromotive force is produced. With electrons now engaged, a current is therefore induced, and in turn, an electrical charge. We successfully produced voltage from soundwaves of varying frequencies using this device. This shows that accessing sound energy with this device is not only possible but with a loud enough source and an optimized design, it can produce usable quantities of electricity. The energy produced in this application can be used in education, and even in the industry if scaled up. The voltage was measured in the presence of 3 different frequencies and 3 trials were performed for each of those frequencies. The ANOVA test conducted in this paper shows that the data is statistically significant. The most important result of the experiments is that a statistically significant AC signal, produced only when exposed to sound, thereby proves that sound is causing the electrical signal. It is extremely likely that, when scaled up and in the right conditions, our device could supply usable electricity by recovering energy from the sound.

Introduction

This paper investigate a small-scale project that illustrates the potential of using sound energy as a means of creating electrical energy to be stored and reused. The objective of this project was to create a a prototype device that could convert sound and vibrational energy to a voltage that could be captured on a small scale. Although the main goal of the device was to provide a proof of concept, the ideas outlined in this paper are intended to be applied on a much larger scale.

From the perspective of Sarah Jansen *et al*, (2011), there is potential in the idea of capturing energy from sound, but researchers have not yet made it feasible to do so in a way that is efficient enough for real-world implementation. Alternatively, Sarah Jansen *et al* is prioritizing harvesting energy from the sun when considering energy conservation options since Sun is the free abundant energy source to the earth. According to Bhatnagar et al (2012), by viewing sound as a mechanical form of energy in the form of a wave, it becomes easier to imagine how sound can become electricity. - The oscillation of the sound waves creates pressure, which then allows the sound to be converted to an alternative form of energy. While piezo materials and transducer were discussed as methods of converting this energy in Bhatnagar *et al* (2012), we decided to create a design that does not rely on these more expensive materials and take advantage of Faraday's Law instead. Romer *et al* (1982) discusses how whenever the magnetic flux through a conductor changes, an electromotive force, or voltage, is produced. This electromotive force then spurs the movement of electrons, thereby inducing a current. - The device reported in this paper creates this magnetic flux by orienting permanent magnets such that their axes of magnetization are normal to the face of a diaphragm at rest. The magnetic flux is then able to change because of the normal vectors to the points on the diaphragm change direction due to the oscillation of the diaphragm. It is also possible to calculate magnetic field intensity from permanent magnets in 3D space as reported by Camacho *et al*. (2013), which is also beneficial in the optimization of this device. -

This physics of this design is fundamentally similar to that within a microphone as reported by Wente *et al*. (1931). The sound waves carried by vibrations in the air enter the microphone and move the diaphragm back and forth. The coil attached to the diaphragm moves as well. The magnets then produce a magnetic field cutting through the area created by the coil. As this area changes, an electrical current is produced which is then used to amplify the sound from the microphone. - We applied the efficient mechanics of a microphone to our device but instead of amplifying this energy, we collected it in the form of stored voltage through a custom circuit design.

The purpose of this project was to determine whether this concept of transforming sound energy into electrical energy could be realized through a simple and cost-effective design. This design could then be scaled to capture more significant voltages as a novel form of renewable energy. It is hypothesized that this design will be effective because it works in a similar way to a microphone and researchers have addressed this idea, but it has never been actualized in the form of a project.

Methods and Approach

After extensive research on work surrounding the conversion of sound waves as well as Faraday's Law, the group began to brainstorm possible designs to successfully accomplish this conversion. It was essential that our design was practical, inexpensive, as well as simplistic. Following these major constraints, we were able to guide our design steps surrounding this study. We had access to laser cutting, 3D printing, and several sources to acquire materials. We believed that 3D printing would allow us the most freedom in terms of creating the design, while also staying in the realms of practically, affordability, as well as simplicity.

We had to consider what the most important things to our project were, and which we had to put less priority on. Functionality was our biggest priority, as we needed to make a working product above all else. Our next priority was cost, since we had a low budget, and an expensive prototype would hurt its feasibility. Our next biggest priority was how sturdy the prototype is. In real applications, it can be subject to large forces, so it needs to be able to withstand that, as well as hold powerful magnets close together without breaking. Ease of use was our next biggest priority, since it was not essential, but an easy to use prototype is better than a complicated one. Our next worry was the size, since we did not want to make the device huge, but also wanted to make it an appropriate size for our purpose and applications (a speaker or air horn). Finally, our last priority was aesthetics. We wanted our project to be aesthetically pleasing but were unwilling to sacrifice any other priority for it.

Our initial design had a diaphragm that was coated in a copper foil and sat directly in between two magnets (Figures 1 and 2). We believed that this would be a simple way to have movement in between two magnets, and thus, produce a charge. This entire apparatus would be placed in a cylindrical housing, where we would have open slots to allow the sound waves to go through. This design however was not developed, yet rather provided us a good basis to design off. We found that the copper foil would not stretch easily under these situations, which would prevent movement in between the magnets and thus an inability to acquire charge.

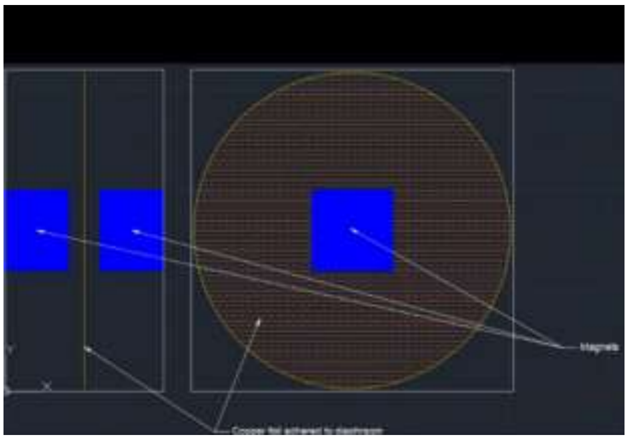

Fig 1: *Initial 2D Design*

Fig 2: *Initial 3D Design*

Instead, we decided to use a coil of wire attached to a diaphragm at a right angle, with the coil in between the magnets. We believed this would be easier to create motion in-between to magnets, as well as allow us to have a higher gain if we wished to increase the number of loops. With this, we transitioned to having a paper diaphragm being placed right at the front of the device. The two magnets were placed in holders on either side of the coil. We created this design to be manufactural with the 3D printers available to us (Figs 3 and 4).

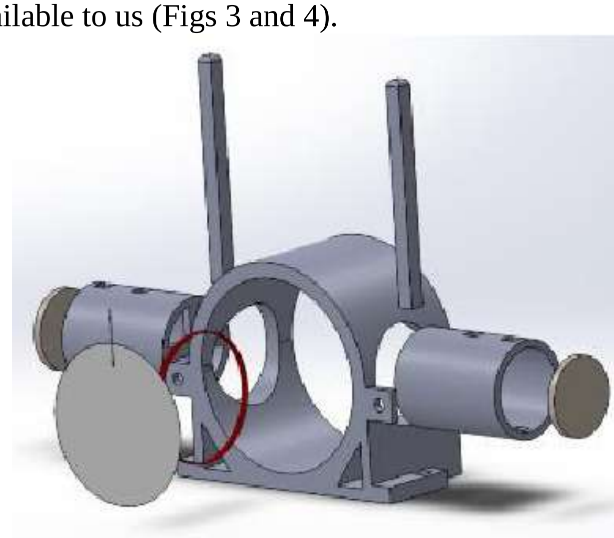

Fig 3: *Final Design*

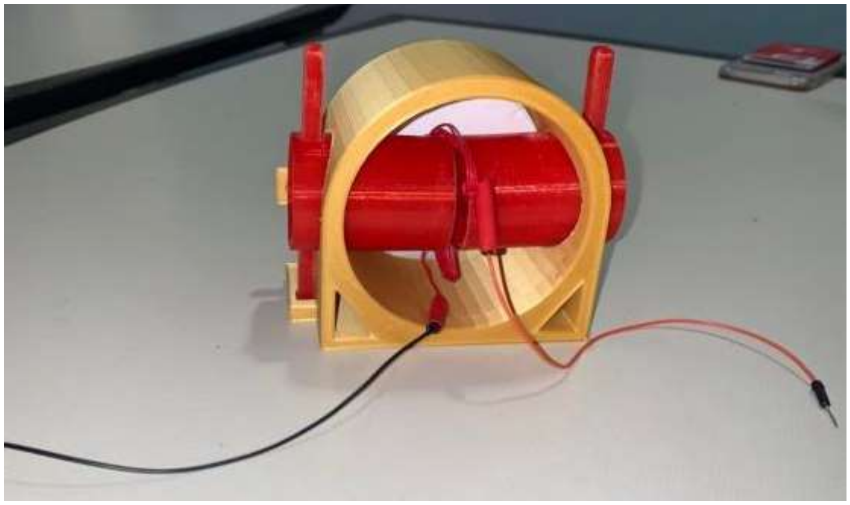

Fig 4: *Assembled Design*

This design largely placed us on the right path, yet we found that our diaphragm was still too tightly enclosed. Instead of fastening it with another piece, we decided to loosely connect it to a string. This fastened the diaphragm while also allowing it to move with ease. With our apparatus created, we needed to hook it up in order to collect data. We soldered wires to the ends of the coil and connected it to our Sparkfun Redboard. We originally had the intention of having an LCD screen display the voltage, but we decided that directly having the data appear on our computer.

Design Details

The basis of the design is applying Faraday's Law of Induction to generate electricity from changing flux. There are several methods to accomplish this including rotating a coil within a magnetic field or forcing a magnet through a coil. However, these methods are not tailored to the type and magnitude of motion caused by sound. Sound causes matter to oscillate slightly rather than rotate or move linearly. Therefore, instead of forcing a more massive magnet (with respect to mass not volume) through a coil, the device forces a relatively less massive coil through a magnetic field. As it oscillates, field lines enter and exit at different rates thereby creating a change in the overall flux through the coil. The magnitude of the electromotive force (ε) induced within the coil is described by Faraday's Law as shown in the equation below,

$$\mathscr{E} = -N\,(d\phi/dt)$$

where N is the number of turns of the coil and ϕ is the magnetic flux through the coil.

The interface that best allows sound to oscillate the coil in a linear motion is a diaphragm made of a light, flexible material. Paper satisfies those criteria and is quite inexpensive, so it is the material chosen for this model. The diaphragm vibrates due to the slight variation in air pressure created by sound. The vibration of the diaphragm is transferred to the coil through direct contact. The diaphragm is a critical part of the device because, without it, the coil would not oscillate.

Therefore, deciding how to properly secure it to the rest of the device was crucial in the design process. If the diaphragm were secured too rigidly, the amplitude of the vibrations would decrease. On the other hand, if the diaphragm were insufficiently secured, it stands the risk of becoming detached from the device thereby eliminating its effectiveness. To allow for the optimal combination of freedom of motion and stability, string was chosen to suspend the diaphragm in place.

The coil used was comprised of 15 turns of 26-gauge copper-tin wire with a rather thick insulation. Although this is what we were able to obtain for our project, ideally the insulation would be much thinner so that the coil could have many more turns with the same amount of mass and size.

The magnetic field is produced by two 35 neodymium disk magnets. The magnets used in the model are less than optimal in field strength; stronger magnets should be used in any applications of this technology. The magnets are held in place by 3D-printed components which fit into the larger 3D-printed enclosure of the device and can be adjusted in spacing using pegs and slots (Figure 5). The enclosure with two open ends would ensure that a column of air is created between the diaphragm and the opening. However, plastic is not very strong and does not conduct magnetic flux very well. For these reasons, metal would the ideal material instead of plastic for the magnet enclosures.

The voltage produced will be fed to the analog input of the Sparkfun Redboard where it will be converted to a digital signal that can be displayed on the serial plotter as a function of time.

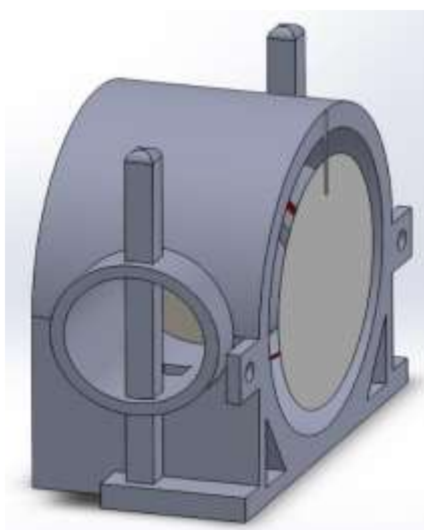

Fig 5: *3D Render of Final Design*

Data Collection

To collect data, the voltage induced in the coil was fed into a non-inverting operational amplifier circuit which amplified the signal and fed it into the analog input of the Sparkfun Redboard. The voltage was then saved in a table and graphed using Arduino Code software and in Microsoft Excel. The data in these forms was easy to save, display, and use for analysis. The data shown in Figures 6a, 6b and 6c represent the voltage produced by the device and was measured at various frequencies (69Hz, 70Hz, and 74Hz).

The voltage produced by the model is very slight due to its small scale and the fact that the sound used to test does not contain very much energy. Therefore, the OpAmp circuit was necessary to measure it with the Redboard. The operational amplifier used is the MCP6002. This circuit was tested using voltage dividers to create various test voltages. The input voltages, and the output voltages are shown in Fig 7. The output voltages were read using an analog input on the Redboard and displayed to the serial monitor. Based on this data it is clear that the OpAmp circuit does not behave ideally and that the total resistance in the voltage divider is likely not the exact values expected due to resistance in the steel wires and the tolerances of the resistors. This would explain why the data points do not fit a linear regression perfectly and why the intercept of the trendline is not zero (as shown in Fig 7). However, the trendline is sufficient to allow us to calculate approximately how much voltage is produced from our device. The R^2 value of the trendline is 0.9932 which means that the trendline matches the data closely. The slope of the trendline is approximately 180 so that is what was used as the gain in calculations.

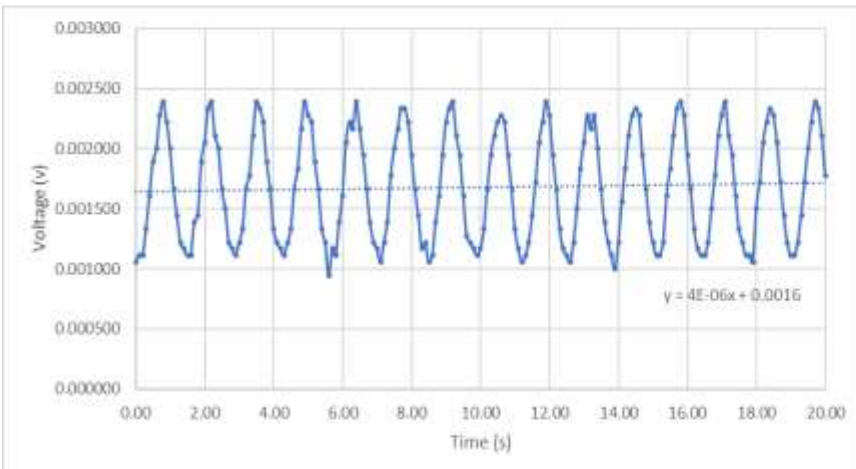

Fig 6a: *Voltage measured at 69 Hz.*

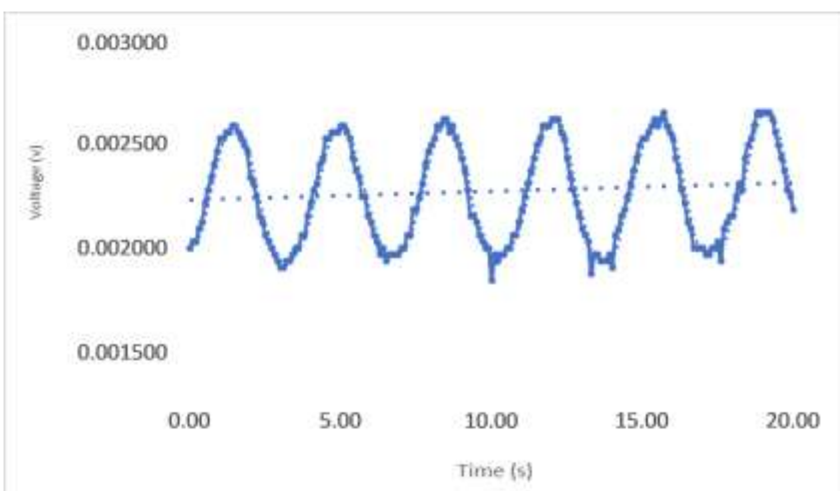

Fig 6b: *Voltage measured at 70 Hz.*

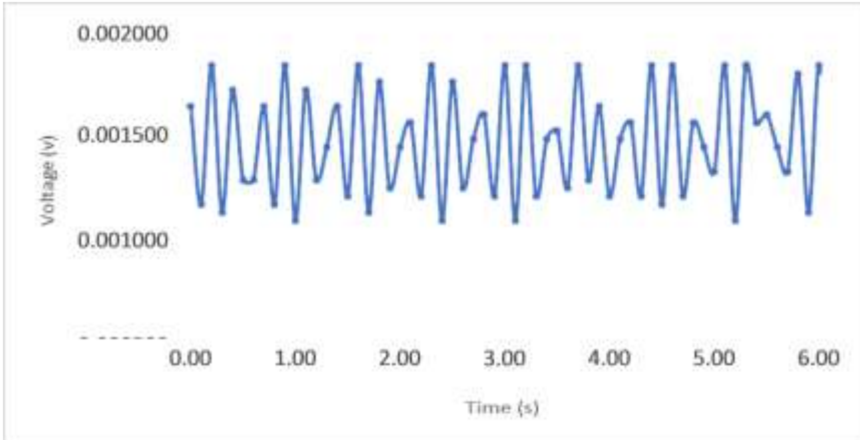

Fig 6c: *Voltage measured at 74 Hz.*

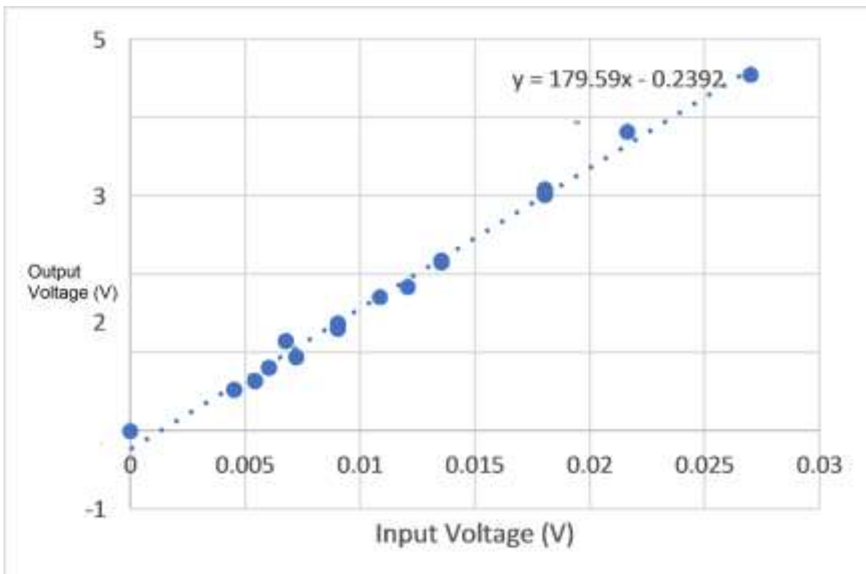

Fig 7: *OpAmp Test Raw Data. Relationship between output versus input voltages of Sparkfun Voltmeter with OpAmp.*

Results and Discussion

Based on the Op Amp Test shown in Fig. 7, the gain for the circuit is approximately 180. That value for the gain was used in calculating the true potential difference created by the device by dividing it from the measured voltage. Based on the how the 9 trials performed there is a clear signal produced when the device is exposed to sound that is distinct from noise. This can be concluded by comparing the data to the control in which there was minimal sound impinging the diaphragm. In the control the voltage remained almost perfectly constant at 0.31V at the output of the OpAmp (0.0017V at the output of the device). However, the voltages measured when sound was played into the device varied significantly from the control.

The data was compared to the control using an Analysis of Variance (ANOVA) test, which compares two groups of data. The null hypothesis is that there is no difference between the voltage produced without moving the diaphragm and the voltage produced when the diaphragm is moved.

The alternative hypothesis states the opposite; there is a statistically significant difference between the two groups. The average p-value for every frequency and each trial was 0.02, thereby proving the significance of the data and disproving the null hypothesis. Table 1 confirms that there is a statistically significant difference between the voltage produced without moving the diaphragm and the voltage produced when the diaphragm is moved due to sound.

	Trial 1	Trial 2	Trial 3
69 Hz	1.91E-05	6.69E-05	8.07E-66
70 Hz	5.85E-32	1.69E-45	2.02E-38
74 Hz	1.44E-59	3.21E-28	2.62E-68
Ave	0.02		

Table 1: *ANOVA Values for Each Trial Including Average ANOVA for All Trials*

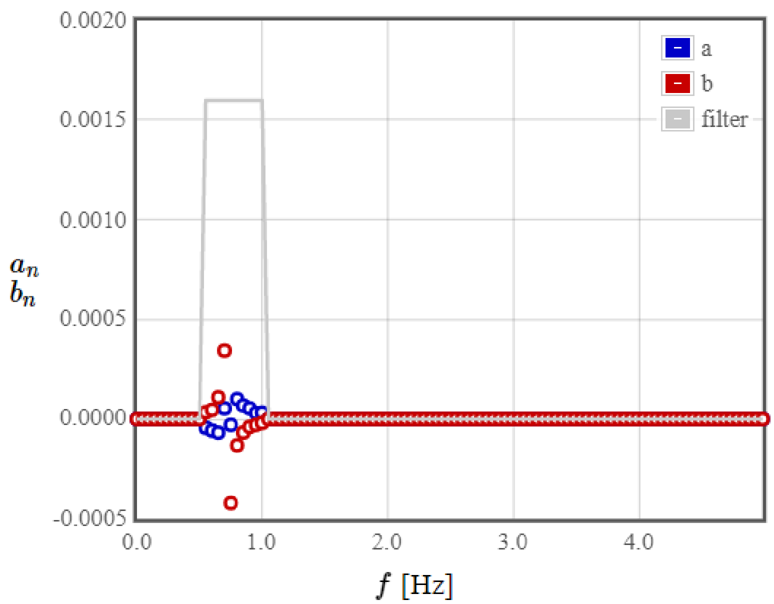

Fig 8a: *Bandpass Filter applied to data from trial 1 of 70 Hz.*

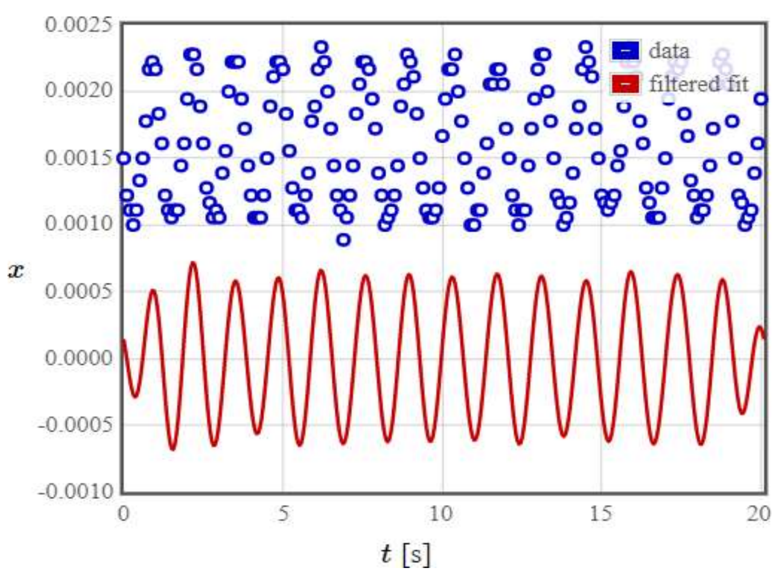

Fig 8b: *Filter results compared to data from trial 1 of 70 Hz.*

The reason the voltage in the control test was not zero is due to charge build-up on the ground of the Redboard. This charge resulted in a DC offset on the AC signal measured in the experiment. This offset could be prevented by incorporating capacitors into the circuit or by discharging the circuit every time charge starts to accumulate. This was discovered after the data was collected so the data still includes the offset, but future data could be taken without it. The offset suddenly changed about 7 seconds into Trial 3 of 69 Hz resulting in a drop in the values. However, the offset then increased and returned to its original amount. A Fourier analysis of the data from Trial 1 of 70 Hz was performed using an online application [6] Using this website, the data was able to be filtered to remove the offset so that the waveform would be centered at 0 as shown in Figure 8. The voltage graphs appear sinusoidal because the voltages were produced from the oscillation of a coil due to sound waves. However, the frequencies of the measured signals were very low compared to the frequencies of the sound. This is likely because only 10 samples were taken per second making the sampling rate 10 Hz and the Nyquist frequency 5 Hz whereas the frequencies of the sounds were 68, 69, and 70 Hz. Therefore, there was likely significant aliasing in constructing a waveform from the data. A sampling rate of at least 140 Hz was unattainable due to the fact that each loop of the code used took on average 12 milliseconds meaning it was impossible to sample frequently enough to produce the correct waveform.

As the results show, sound that often goes to waste can be converted to electricity. With optimization and development for a larger scale, such as a louder environment, this design can be utilized for energy harvesting.

In terms of cost, our model is relatively inexpensive due to the availability of free 3D printing. Due to the very low power output it would take a significant amount of time to pay for itself, however it would eventually. Therefore, it represents a low risk, low reward investment that will pay off.

Conclusion

Our tests show that our model and design work. The device can produce a voltage in a circuit from sound energy in its environment. The prototype picked up energy, which is usually just wasted and dissipated, so any energy converted is an improvement. However, our prototype can be further developed, and improvements can be made. The size of the actual device can be optimized based on the specific application and where the device is being used. Also finding a wire that fits more to our needs in the project would give us better results. This would give us a better coil, which would greatly improve the results. These changes may not make our device capable of solving the energy crisis the world is experiencing, but it could make the device much more cost-effective and allow the device to become widely used. This project also helped to develop our skills. We had to learn how to solve problems that came up in the project, as well as better our skills in design and programming software to be able to use them for the project. We all gained invaluable experience by going through this project and learned what it is like to work with an engineering group to create something. With a little bit of improvement and optimization for specific conditions, our prototype could be used to efficiently convert sound energy to electrical energy in real-world settings.

Due to decibels being placed on a logarithmic scale, just moving the product to a location of 10 decibels higher would be in an environment ten times as loud, scaling up the energy to a higher magnitude. Our speaker was able to only produce about 90 decibels, but a landing strip at an airport or on an aircraft carrier can read up to 140 decibels. A real application of our device would have an input of about 100,000 times as loud of an input, so theoretically the output would be that much as well.

Our test was able to conclude the feasibility of a new source of clean energy: sound. The product was not made with optimized materials nor design, yet still functioned. At its current stage, it can be purposed for education, providing students a visual on how energy is conserved and can be converted. Yet through further optimization such as sturdier materials and stronger magnets, as well as placing it in a loud environment that the product was intended for, the product could be brought to a point of commercial functionality. We theorized that with these improvements, we could create a product that builds upon the success of our project and can be implanted in an industrial setting.

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