OSCILLUS: Harnessing Wave Energy

Samuel Hibbard
College of Engineering
Northeastern University
Boston, USA
hibbard.s@husky.neu.edu

Cory Lafleur
College of Engineering
Northeastern University
Boston, USA
lafleur.c@husky.neu.edu

Jordan Leong
College of Engineering
Northeastern University
Boston, USA
leong.j@husky.neu.edu

Jakob Ringberg
College of Engineering
Northeastern University
Boston, USA
ringberg.j@husky.neu.edu

Damon Artis
College of Engineering
Northeastern University
Boston, USA
artis.d@husky.neu.edu

Bala Maheswaran
College of Engineering
Northeastern University
Boston, USA
mahes@coe.neu.edu

Abstract— **The global temperature is rising due to the unnatural production of energy by humans. Today, energy production systems for electricity and heat account for 31% of global greenhouse gas emissions. With this in mind, our team set out to find a clean and sustainable way to produce electrical energy. We are aware that there have been several attempts at harnessing wave energy before, but all of them have been commercially unsuccessful. This is why we are trying to approach this from another angle. We wanted to make our energy source readily available to individuals, rather than requiring the massive capital of a large power plant or energy farm. We settled on a wave power generator named Oscillis that can source energy from the endless oscillation of large bodies of water. Water ecosystems are oftentimes seen as fragile, that are not to be disturbed which was an important aspect of our design. The design of this device allows it to be attached to land and none of its parts are physically touching the water except the floating body at the end of a rack and pinion. Another key component of the design allows for both the upward and downward motion of waves to be captured to generate energy. Although our prototype is smaller than the actual product would be, it is able to capture wave energy and shows promise for the future of this product.**

I. INTRODUCTION

The flow of water has been used to create energy for almost two millennia. However, capturing energy from the oscillation of waves is a new area of research dating back to less than twenty years. The fundamental idea in wave energy converters is to use the linear motion of the oscillation of waves and use it to create electrical energy. A previous attempt of a wave energy converter was Wave Star: a series of floats attached to long arms that oscillated and pushed fluid through hydraulic pumps to eventually turn a turbine. Problems with this design were a limited efficiency and a large cost to maintain the complicated system causing the project to eventually be scrapped. Our design does not focus on hydraulics which are costly to maintain but instead on a simple rack and pinion system.

An object, such as a buoy, rises and falls with the waves due to their buoyant force. This buoyant force is created because the pressure on the top of an object is less than the pressure on the bottom of the object as pressure increases with depth. This causes an upward force on the bottom of the object, known as the buoyant force. In order for the object to float, the density of the object must be less than the density of water. For our design, the mass of the buoy plus the mass of the rack and pinion divided by the volume of the water displaced by the buoy must be less than the density of water.

There was research done on buoy geometries for wave energy converters that stated the optimal shape for the buoy is a sphere. This finding was based on the surface area to volume ratio and how the shape responded to pressure. The fundamental technology behind most energy creation from a spinning axle is the electric generator. As magnets move inside a thick coil of wire, it creates an electromotive force, emf, and induces a current in the wire through what is known as Faraday's Law. This electrical energy can then be used to power machines and households or charge batteries. The rotating output shaft, when connected to a motor, can produce electrical energy.

II. DESIGN APPROACH AND METHODS

At the onset of our design trials, we created a small prototype of the gear train in which we utilized LEGO® gears to create a rack and pinion attached to a two-to-one directional rotation converter. The rack and pinion converts the linear motion of the waves into rotational motion. The bi-directional motion converter operates using a differential gear and two ratchets. If the input is clockwise, the ratchet holds the differential housing in place, while the internal gears rotate, and spin the output counterclockwise. If the input is rotated counterclockwise, the differential gear housing is allowed to rotate, and a second ratchet causes the output shaft to rotate with it, creating a constant counterclockwise output (see Fig. 1).

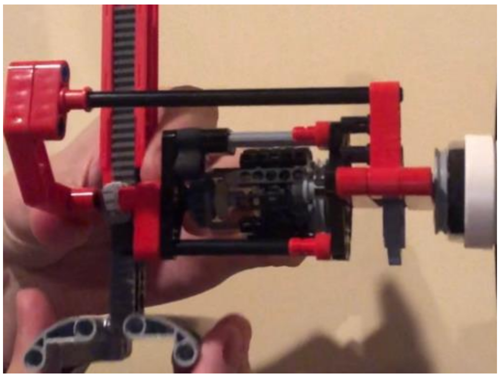

Fig. 1. Prototype of the gear train.

This prototype worked well and became the basis of our design. Potential areas of improvement centered around the rack and rack slider as well as the ratchet. We decided that the LEGO® gears were the most reliable and well-built option based on our budget to use as gears. The alternative gear options all had more issues compared to the LEGO® gears. 3D printed gears proved to have decreased precision and increased cost while laser-cut gears were brittle and unreliable. Finding gears elsewhere proved to be pointless as they would give us similar results to the LEGO® gears at an additional cost.

We decided to purchase a linear rail and slide to reduce the friction of the motion. The rack was attached to the slide, which was in turn attached to the linear rail so the rack and slide moved up and down with minimal friction. The rack was designed and laser cut out of acrylic and made three sheets of acrylic thick for strength. A new rack allowed for many advantages such as allowing the length to be increased, better meshing with the pinion gear, and increase the area to attach to the buoy. The rack was attached to the linear slide by inserting small rectangles that were laser cut on the back of the middle piece of the rack into holes on the linear slide. The rectangles were made so the rack was held to the linear slide with only friction.

Also, we decided to redesign the ratchet from the prototype to reduce the friction. A lighter rubber band was used in order to decrease the force required to overcome the ratchet. A CAD model of the redesigned gear train is shown in Figure 2.

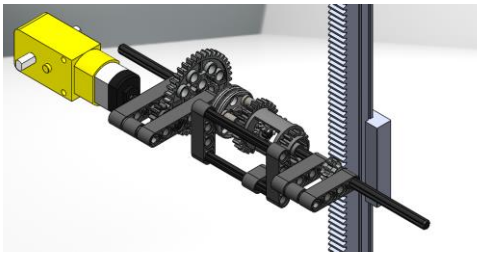

Fig. 2. CAD of the gear train with a new rack, ratchet and a motor.

A motor had to be attached to the output axle, where the white piece is in Fig. 1, to be back driven and generate electrical energy. We decided to use a 4.5V Sparkfun motor as our generator due to its availability and low cost. Along this path, we refined the gear ratios of our gear train to better suit our motor. The motor was the most cost-efficient choice but not the most energy-efficient.

In order to house our gears and motor, as well as to have a place to mount the rack and pinion, we decided to laser-cut a box out of acrylic. This allowed us to securely enclose the gears and motor within separate compartments and easily attach the rack the correct distance from the pinion gear. Also, this increased our design’s water-resistance as the gear train is in close proximity to water. Designing this custom box allowed us to customize attachment points and was simple to integrate with the LEGO® gears. The LEGO® gears connect at defined distances so the box only needed holes at set distances for them to properly align with the box as show in Figure 3.

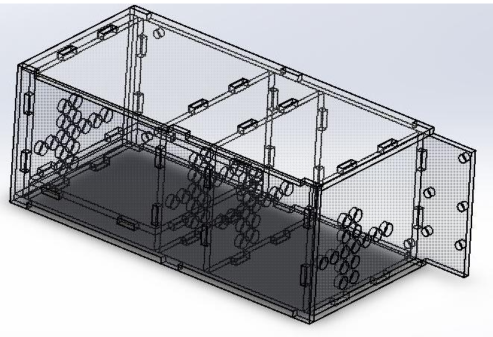

Fig. 3. Gearbox CAD model.

The flotation device used was a Styrofoam hemisphere. We choose to use Styrofoam for the prototype due to its low cost, manipulability, and water resistance. For a final design, we would use more expensive materials for long term exposure to water, as well as have a complete sphere. A half sphere was used in the prototype due to the size limits of our testing box. A photograph of our wave energy converter is shown in Figure 4.

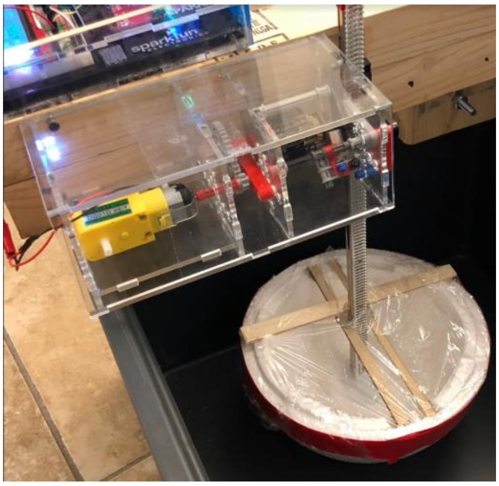

Fig. 4. Photograph of the wave energy converter.

In order to test our design, we needed a wave generation device and container for water. After extensive research, we purchased a long plastic tub meant for holding files. The thickness and reinforcements of this bin was able to hold the volume and pressure of the water we required, and the height of the box was sufficient for creating waves of the size we needed without losing water. In terms of creating the waves, a piece of acrylic attached by a hinge was the most straightforward approach to moving the water in a wave-like manner. Having this piece of acrylic be oscillated by people allowed the waves to be either irregular or standing to better replicate ocean waves.

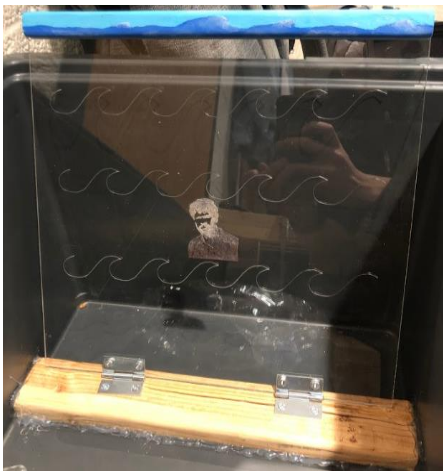

Fig. 5. Photograph of wave creator.

In the field, the wave energy converter could be attached at the end of docks or under bridges, but for our prototype we needed to mount the wave energy converter to the testing bin. In our design, it is attached to the inside of the plastic tube which we purchased. The mount was made out of one horizontal piece of wood which was then accompanied by two vertical pieces of wood that fit snugly against the short side of the tub. This mount gives the gearbox a secure mounting point and it positions the buoy in a good position a short distance away from the wall [Figure 6].

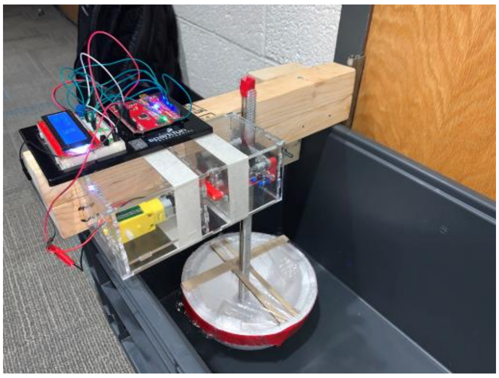

Fig. 6. Wave energy converter mounted to box.

Our final assembly is shown in Figures 7 and 8.

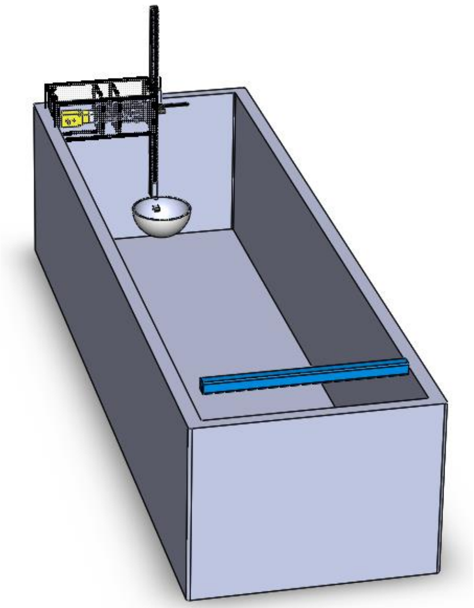

Fig. 7. CAD model of final assembly..

Fig. 8. Photograph of final assembly.

III. RESULTS

We tested our design using an Arduino board to record the voltage of the generator over a period of time. The board was wired to the computer which recorded a value proportional to the voltage on the analog input. This was necessary in order to obtain useful data about the voltage and power being created by our design. The program was tested by hand spinning the motor to prove a voltage value was obtained. Once we knew that the code gave an accurate value of the voltage created by back driving the motor, we mounted the Arduino board to our gearbox and connected the motor.

Once the buoy had been connected to the rack and linear slide, we found the necessary buoyant force for the buoy to oscillate with the waves. The buoyant force must be equal to the weight of the rack and pinion and buoy added to the frictional force in the gear train. We used a scale to measure the mass of the rack and pinion and buoy, finding the mass of the system to be 190 g. Multiplied by gravity, the weight of the rack and pinion and buoy was calculated to be 1.86 N. To determine the force of friction in the gear train, we placed the gear train so the rack was parallel with the floor, so gravity was no longer a factor. The force required by the scale to move the rack up and down along the linear slide, the frictional force, was 1.765 N. By adding the weight along with the force of friction, the required buoyant force was found to be 3.62 N. Using the formula that the volume of water displaced is equal to the buoyant force divided by the density of water multiplied by gravity, the volume of buoy displaced was calculated to be 3.73×10^{-4} m^3. The total volume of the buoy was calculated using the formula for the volume of a sphere. Our buoy had a radius of 3.75 in or 0.09525 m. The total volume of our buoy was calculated to be 3.62×10^{-3} m^3. As the volume displaced by the buoy was less than the total volume of the buoy, it floated. The percent of the buoy that would be underwater was calculated as the ratio of the volume of water displaced over the total volume. This was calculated to be 10.22%. This reveals that a higher gear ratio could have been used with a buoy this size. Around 50% of the buoy should be submerged to maximize the energy output per square meter our device takes up.

To understand how much energy could be produced by our system, we filled a water tub with water to a height of 4.5 inches, attached our Arduino to the motor, and began making waves using our acrylic sheet and hinge set-up. Once the waves began moving in a consistent rhythm under the buoy and it began to constantly oscillate, we recorded the voltage output by the motor [Figure 9].

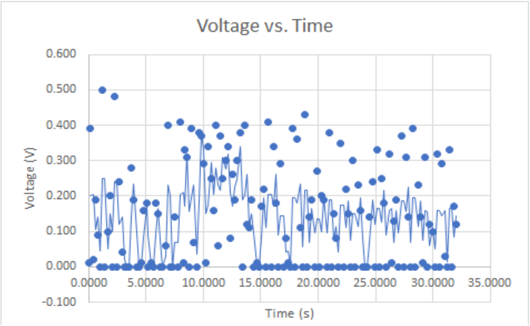

Fig. 9. Graph of voltage as a function of time.

The data values were compiled in Excel using the PLX-DAQ macro for Excel. A moving average trendline was added. The trendline follows a roughly sinusoidal curve. The values showed that over each wave, we were able to produce a maximum of 0.3 V on both the upwards and downwards motion of the buoy. To make this data easily accessible to bystanders, we chose to include a small LCD screen that displays the real-time voltage output of the generator as well as the maximum generator output obtained.

The theoretical power output of our system is based on the change in the potential energy of our buoy and rack and pinion. The power output is given by the formula:

$$P = \frac{mgh}{\frac{1}{2}T}$$

where m is the mass in kilograms, g is gravity, h is the height between two extrema of the wave, and T as the period of the wave. Our first test was done with our buoy's average net change in height between two extrema in the wave as 0.036m with half the period of a wave equal to 0.43s. Plugging into the equation yielded:

$$P = \frac{0.190 * 9.81 * 0.036}{0.43} = 0.156\,W$$

This theoretical power output of our system could be compared to the measured power output to determine the efficiency of our system.

The power of our system was measured by finding the average voltage of an open circuit for a long series of waves. The average voltage was determined to be 0.145V. The internal resistance of the generator was measured to be 5.0 **Ω**. Figure 10 shows the power output of our system over time. The experimental power output was computed by the formula $P = V^2/R$.

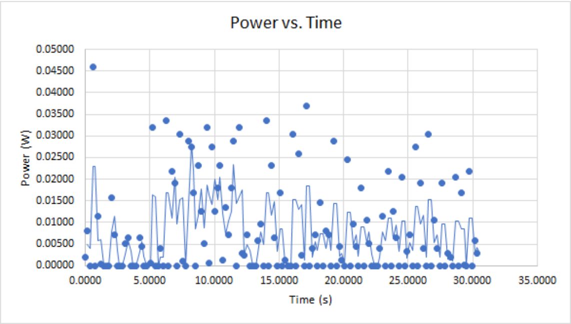

Fig. 10. Graph of power output from the generator as a function of time.

From the graph, the average power output of our system was 8.3 mW. The efficiency of our linear to rotational energy converter was computed as:

Efficiency = $(P_{out} / P_{in})\times100$

= (0.0083W/0.156W)×100 = 5.32%

We then repeated the experiment with a different height and period to confirm our experimentally determined efficiency. For the second trial, the average height between adjacent extrema was determined to be 0.04m with the time between those two heights as 0.51s. This made our theoretical power output as 0.146W. Data was collected in the same manner as the first trial and plots of the voltage as a function of time [Figure 11] and the power as a function of time [Figure 12] were created.

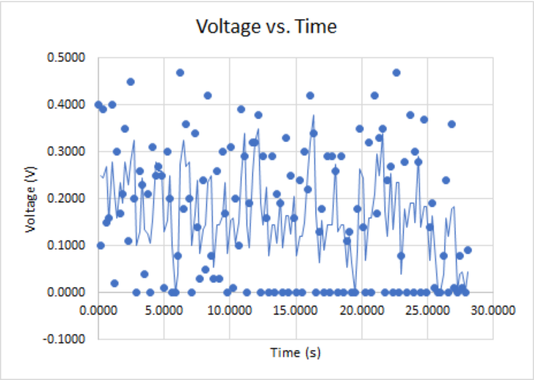

Fig. 11. Graph of voltage as a function of time.

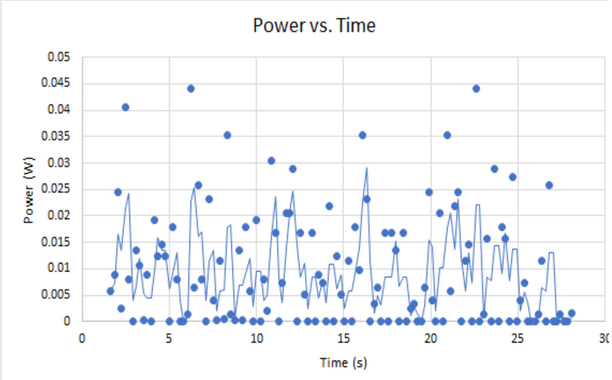

Fig. 12. Graph of power as a function of time.

The average voltage was determined to be 0.167 V. With an internal resistance of 5 **Ω**, the average power was determined to be 9.49 mW. The efficiency was determined as (0.0095 W/0.146W)×100 = 6.50%.

A comparison of the two trials shows that as expected, the amount of energy produced is directly related to the amplitude and period of the waves. These should track roughly linear but more experimentation would be needed to confirm the relationship. The efficiency from both trials were roughly similar with an average of an efficiency of 5.9%. The data may suggest that the larger wave amplitude causes our system to be more efficient. In trial two, the amplitude was larger even though the period was also larger and the efficiency increased. More experimentation would need to be done to fully examine the relationship between the wave height and the efficiency of our system.

The difference in the change in height of the wave verse the change in height of the buoy was nearly identical. However, energy was lost in converting the motion of the buoy into electrical energy. There are many possibilities for this low efficiency. Primarily, the motor used was a Sparkfun motor which has relatively low efficiency. This means that electrical energy exiting the motor was far less than the rotational kinetic energy entering the motor. A simple way to improve the efficiency of our system would be to use a more efficient motor. Another source of error is in the gear train itself. Friction between the rack and pinion and the gears themselves are sources where energy was lost. A way to reduce this loss would be to use more efficient gears than Lego® gears. While this would add to the cost of the mechanism, it would improve efficiency.

IV. DISSCUSSION

While energy production is typically a controversial topic because of the many resources required and the disturbance it has on its surrounding environment, wave energy is renewable, sustainable and produces virtually no pollution. The few common controversies around wave energy include concerns the devices might be harmful to the ocean floor and ecosystems that live there, could impact life in the oceans that use sound to communicate, and can be navigational hazards in the middle of the ocean and coastal erosion because of altered waves and tides. In addition, the ocean is commonly a place where many recreational activities take place and nearshore wave systems could affect the safety and the visual views of the shoreline. We believe that our product addresses these issues, and has a very low impact on the environment, and therefore is very attractive to customers. Our design is most commonly designed to be attached to the end of docks and undersides of bridges. The whole system is also designed to be small and will blend in with the other poles that hold the dock or bridge in place. The buoy in the prototype was made out of a Styrofoam plastic blend. While the buoy in the prototype was made from a Styrofoam and plastic blend, Styrofoam is not the best buoy material for use in the ocean as it has the potential to break down and further pollute the water. In a real model, the buoy would be made out of synthetic rubber or plastic which will still be buoyant, but will be more beneficial for the environment.

V. CONCLUSION

Wavestar was one of the most competitive contenders in the wave-energy field and they spent around 50 million US dollars to create their wave-energy converter. To make our concept, we spent 120 US dollars. More research would have to be done into our systems durability and scaling up our system but preliminary data suggest that a full scale model of our prototype would be far cheaper and more appealing to customers than Wavestar.

We expect the cost of a full scale Oscillis to range from $500 to $900. This involves scaling it up so that buoy has a radius of 0.5 m. As only 10% of our initial buoy's volume was displaced, this would involve scaling up the buoyant force by a factor of 500. Also, the waves our prototype was tested with were roughly 7.5 times smaller than waves found in open water for the full size model which are conservatively estimated at an average of one foot. If we improve the efficiency with industrial parts and a more efficient motor, we expect that our efficiency could easily reach 10% or higher. Using these assumptions to scale up our prototype, we expect the power output to increase from 0.0094 W to 71 W or 51 kWh/unit in a month. For reference, the average household uses 900 kWh/month. This would mean that with 18 Oscilli, only 18 square meters of space, an entire home could be powered. In comparison, it takes 48 square meters of solar panels to produce the same energy output.

Previous designs of wave energy converters faced a major challenge in storms and maintenance. Rough seas could damage the device so they had to be lifted out of the water during storms. Also, long maintenance periods prevented their usage. Our design is far simpler than previous attempts and would have relatively low and easy maintenance. Also, our design is intended to be far closer to shore so there is a smaller likelihood that the waves would become too powerful that they could damage it which would reduce time out of the water.

Our product is aimed more towards single households. Individuals may purchase one or multiple Oscilli, as people currently do with solar panels but they would be limited by the cost and the availability of room off a dock. Rather than a complete replacement for other sources of clean energy, it can be used in tandem with them.

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