11-15-2018

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Recommended Citation  
Campbell, Angusina; Lee, Aaron; Bentz, Amy; Lau, Darren; and Wong, Travis (2018) "Developing an Ocean Wave Buoy to Generate Renewable Energy," Mānoa Horizons: Vol. 3 : Iss. 1 , Article 5.
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Developing an Ocean Wave Buoy to Generate Renewable Energy

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Humans pollute the earth with fossil fuel emissions. The pollution leads to increased ocean acidification and smog. One solution to lessen this damage is to utilize renewable energy. Ocean wave power is a renewable energy harvested by Wave Energy Converter (WEC) buoys. WECs generate energy by oscillating in the waves. The most efficient power generation by buoys happens when their natural oscillating matches the wave period (the rate at which each wave contacts the buoy); this phenomenon is known as resonance. The buoy that captures wave energy most effectively is the Oscillating Water Column (OWC) because of its ability to capture waves from any position. The Wave Energy Team designed, fabricated and tested an OWC with the main objective of generating renewable power. For the potential power, O‘ahu’s east side was chosen as the test site. The aim of this project was to deploy the buoy in an intermediate wave zone, the area between surf and deep water. In this work, wave data were collected through a simulation and scaled for practical application. A small wave buoy resonant was then developed for a two-second wave period. Finally, the results were applied to a large-scale buoy. The feasibility of creating a resonant OWC was demonstrated in the assigned zone. Resonance was achieved for the smaller buoy hull in the controlled testing site. The larger buoy, when deployed in the ocean, produced about 0.3 milliwatts when pushed up and down with artificial oscillation.

Angusina Campbell
I am a mechanical engineering graduate of the University of Hawai‘i at Mānoa. This article was my senior design group project. I chose this subject because I grew up around the ocean and believe that it is an excellent source of renewable energy. Being project manager was incredibly challenging, and through it, I learned determination.

Amy Bentz
I am currently an undergraduate Mechanical Engineering student at the University of Hawai‘i at Mānoa. I had the opportunity to research, design, test, and fabricate a Oscillating Wave Column Spar buoy that converts the waves’ mechanical energy into usable electrical energy. For this project, I was the budget coordinator and also the mooring subsystem team lead.

Darren Lau
I am a mechanical engineering graduate of the University of Hawai‘i at Mānoa. I was responsible for collecting research and deciding upon a material for the system and its parts. I also researched and assisted in designing the turbine, generator, storage device and power distribution throughout the system.
1. Introduction (Background and Context)

Fossil fuels and other forms of nonrenewable energy damage the environment. In recent years this damage has been so extensive that moving to alternate sources of fuel is almost inevitable. Ocean wave power is one available source of energy. This renewable energy can be harvested by buoys called Wave Energy Converters (WEC), when oscillating in waves.

One of the most efficient WEC devices is an Oscillating Water Column (OWC). The OWC can capture wave energy in any orientation, while having a simple, low-maintenance design with few moving parts (Falcão and Henriques 2015). More specifically, the OWC consists of two parts: a hull and a power takeoff system. The hull comprises a flotation portion, a long hollow cylinder, and a ballast. The power takeoff system consists of a turbine located inside the cylinder and a generator attached to the turbine. Specific OWC styles include “backward dent duct” styles, “U-shaped” styles and “spar” styles (Falcão and Henriques 2015). For this project, a “spar” shape was selected due to its ease of manufacturing, deployment, and maintenance (“Near Shore Floating Oscillating Wave Column: Prototype Development and Evaluation”). Figure 1 shows a diagram of a spar-style OWC.

After designing the OWC, the buoy's power output needed to be maximized. To achieve this goal, it was necessary to match the natural bobbing of the buoy with the rate at which the waves contact the buoy, known as the wave period (Aoun, Harajli, and Queffeulou 2013). This synchronization is called resonance. Therefore, to generate the most power possible, the buoy needed to bob naturally with ocean waves at a given location.

The target area for the OWC was the intermediate wave zone. This zone is defined as the region between deep-water waves and behind where the waves start to break (Antonini et al 2013). This location was chosen so that the buoy could be deployed by a single person.

To select the deployment site, wave conditions in O'ahu were researched using available deep-water buoy data collected by NOAA over a nine-year period. Based on this research, a site on the east side of the island, shown in Figure 2, was selected. The east side is an ideal location to deploy the spar WEC buoy because it interacts with the constant trade winds from the northeast and the stronger winter swells from the northwest (Cheung 2014). The other sides of the island are partially blocked from these conditions due to O'ahu’s orientation, as shown in Figure 3 (Chamberlain and Moberly 1964, Fletcher and Vitousek 2008).

Due to the smaller scale of this project, the purpose of the spar buoy was modified to powering data-gathering sen-
The buoy needed to be scaled to fit the wave flume. A 1:6 scale was selected for increased convenience in building a larger model. After the right scale was chosen, an operational range had to be determined. A buoy design was chosen that functioned for 80 percent of average intermediate wave zone conditions to ensure that it would be operational for most of the year.

2. Methods and Materials

2.1 Hydrodynamics of a Buoy Hull

The goal of wave flume testing was to observe the way the buoy hull responds to the waves, modifying its design to achieve resonance. To simplify OWC response, the team chose to analyze the hull as a common mathematical model, a mass-spring-damper (Figure 4).

In a buoy-ocean system, the ballast of the OWC acts like the mass. OWC buoyancy, or flotation, acts like the spring, and drag force acts like the damper. Each component helps the buoy achieve resonance. Initially, the mass affects the natural oscillation period of the buoy. The more mass attached to the buoy, the longer its period of bobbing up and down will be. This effect is useful when a longer period of the buoy is desired to match the period of incoming waves. Then, the buoyancy helps the OWC “spring” back to a floating position. This action ends the oscillation of the buoy for a single wave and prepares it for the next wave cycle. Without this motion, the buoy could not generate power. Finally, drag force causes the buoy to slowly return to the rest position. It was necessary to minimize the drag for the OWC so that it could oscillate more efficiently. These three factors affect pressurization in the OWC’s inner chamber.

The OWC buoy hull has an inner cylinder-shaped chamber that is open at the bottom. When a wave contacts the buoy, the water level within this chamber rises and creates a burst of increased pressure. This pressure gradient makes the turbine spin, and consequently power the generator and sensors. With the right combination of mass, buoyancy, and drag, the greatest pressure change within the column will be produced, resulting in the maximum possible power output of the buoy.

In summary, design changes alter the natural period of the buoy and its potential power output. They can be modified to help the buoy achieve resonance and obtain maximum power.

2.2 Power Takeoff

2.2.1 Turbine

This subsection will discuss the aerodynamic influences on a turbine. Many turbine designs exist for OWC devices, but the most commonly used and cost-effective model is the Wells turbine, shown in Figure 5.

With a performance that excels in small airflows, the
Wells turbine is suitable for the spar buoy design. Whereas a traditional windmill-style turbine would only work when the buoy rose or fell, a Wells turbine is bidirectional and would turn in both circumstances. While these turbines have lower efficiency compared to traditional turbines, their bidirectionality was more valuable for this project (Lakzian, Nazeryan, and Soltanmohamadi 2015).

The design of the buoy is affected by its ability to produce lift with minimum drag. Lift can be affected by density, compressibility, viscosity, velocity of air, surface area, the air travels, and the shape and body of the blade as the airflow contacts it. Lift can be summarized in Equation 2, where $C_L$ is the coefficient of lift; $\rho$ is the density of air; $V$ is the air velocity, and $A$ is the swept surface area.

$$L = \frac{1}{2} C_L \rho A V^2$$

Drag force can be represented the same way as lift. In Equation 2, the drag coefficient $C_D$ comprises skin friction and form drag of an airfoil. Drag is related to the flow speed, its direction, Reynolds number of the flow (a value that denotes a smooth or turbulent flow), and other factors that involve airfoil design (turbine blade). Induced drag may also occur due to the lift because of the distribution of the lift across a wing. High pressure on the bottom of the wing mixes with low pressure on the top of the wing, distributing a swirling flow near the tip of the blades. This causes the effective angle of attack (the angle between the airflow and the centerline of the blade) to change and induce a drag along the wing (NASA 2015).

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

Many factors influence a turbine’s design, particularly its size, the blade shape, and the aerodynamic efficiency. With a higher lift to drag ratio, the blade will begin to be more aerodynamically efficient. However, with a higher angle of attack, the turbine will stall. The design implemented in the spar buoy system involves two guide vanes, shown in Figure 6, that adjust the angle of attack on the surface of the blades. The purpose of the guide vanes is to act as an airflow interrupter to allow the turbine blades to receive the most efficient airflow.

During oscillation, a flow of air is created by the rising motion of the spar buoy. When the buoy falls, an airflow with a different velocity is created. Because of this variation, the airflow may become turbulent before it reaches the turbine. When the turbulent airflow hits a surface such as a turbine blade, it creates drag. As a result, turbulent airflow generates less energy as compared to a case of laminar airflow.

### 2.2.2 Generator

A DC micro motor wind turbine generator was chosen for the small-scale model, shown in Figure 7. It was selected for its high capacity, small size, and low cost.

### 3. Wave Data and Testing

#### 3.1 Wave parameter calculations

The coordinates of the nearshore location chosen were latitude 21.61°N and longitude 120.11°E. This location was inputted into SWAN, and the sampling rate was taken daily over a nine-year period. Data output by the numerical modeling system can be seen in Figures 8 and 9.

![Figure 6](image1.png) **Figure 6** SolidWorks model of guide vanes (left) and 3D-printed model (right).

![Figure 7](image2.png) **Figure 7** Micro generator for power takeoff system.

![Figure 8](image3.png) **Figure 8** Estimated nearshore wave period data outputted by SWAN from 2011 to 2018.
This data was used to find operational ranges that could be scaled and tested in the wave flume. SWAN gathered 2,504 data points over nine years. After percentages were found, the data points were counted, starting at the column with the highest number of occurrences. Various operational ranges and scales of the wave heights and periods were calculated and are listed in Table 1.

### Table 1  Operational ranges of wave periods and their heights

<table>
<thead>
<tr>
<th></th>
<th>MIN, MAX, AVERAGE</th>
<th>1:6 SCALE</th>
<th>1:8 SCALE</th>
<th>1:10 SCALE</th>
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<tr>
<td>WAVE PERIOD RANGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>83%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Min (s)</td>
<td>4.23</td>
<td>1.73</td>
<td>1.5</td>
<td>1.34</td>
</tr>
<tr>
<td>Max (s)</td>
<td>8.63</td>
<td>3.52</td>
<td>3.05</td>
<td>2.73</td>
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<tr>
<td>48%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min (s)</td>
<td>5.11</td>
<td>2.1</td>
<td>1.81</td>
<td>1.62</td>
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<tr>
<td>Average (s)</td>
<td>6.21</td>
<td>2.45</td>
<td>2.12</td>
<td>1.9</td>
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<tr>
<td>Max (s)</td>
<td>6.87</td>
<td>2.81</td>
<td>2.43</td>
<td>2.17</td>
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<td>27%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Min (s)</td>
<td>5.55</td>
<td>2.27</td>
<td>1.96</td>
<td>1.76</td>
</tr>
<tr>
<td>Average (s)</td>
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<td>2.45</td>
<td>2.12</td>
<td>1.89</td>
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<td>2.63</td>
<td>2.27</td>
<td>2.03</td>
</tr>
<tr>
<td>All Scaled Data</td>
<td>Average</td>
<td>6.36</td>
<td>2.6</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.713</td>
<td>0.291</td>
<td>0.252</td>
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<tr>
<td></td>
<td>Max</td>
<td>17.1</td>
<td>6.96</td>
<td>6.03</td>
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<tr>
<td>WAVE HEIGHT RANGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>82.10%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Min (m)</td>
<td>0.6</td>
<td>0.1</td>
<td>0.075</td>
<td>0.06</td>
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<tr>
<td>Max (m)</td>
<td>2.1</td>
<td>0.35</td>
<td>0.263</td>
<td>0.21</td>
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<td>54.50%</td>
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<td>Min (m)</td>
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<td>0.15</td>
<td>0.113</td>
<td>0.09</td>
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<td>Average (m)</td>
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<td>0.213</td>
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<td>Max (m)</td>
<td>1.65</td>
<td>0.275</td>
<td>0.206</td>
<td>0.165</td>
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<tr>
<td>25%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Min (m)</td>
<td>1.2</td>
<td>0.2</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Average (m)</td>
<td>1.35</td>
<td>0.225</td>
<td>0.168</td>
<td>0.135</td>
</tr>
<tr>
<td>Max (m)</td>
<td>1.5</td>
<td>0.25</td>
<td>0.1875</td>
<td>0.15</td>
</tr>
<tr>
<td>All Scaled Data</td>
<td>Min (m)</td>
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<td>0.226</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Average (m)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Max (m)</td>
<td>4.47</td>
<td>0.74</td>
<td>0.559</td>
</tr>
</tbody>
</table>

It was determined that the smallest possible scale simulated in the wave flume and affordably scaled to a larger model was the 1:8 scale, tested at half the average wave parameters. However, upon further testing, the original 1:6 scale was too large for the flume to safely reproduce. Therefore, the scaling was reduced to 1:8. Calculations that corroborate this testing were performed and are listed in Table 1. After testing the 1:8 scale, it was unable to reproduce the desired 80 percent wave range. This problem was due to the wave flume capacity. The flume was too small and narrow for certain wave heights and periods. Consequently, when the waves in the actuator chamber (Figure 10) splashed against the back of the flume and the paddle, damages to the electric equipment near the flume were probable. The testing range was reduced two more times but these issues still persisted. The team finally decided to match the buoy oscillation period to the period of an average wave. The conditions that could be accurately simulated in the wave flume were a 0.06 m wave height and a 1.07 second wave period.

### 3.2 Testing Iterations

Due to the small size of the wave flume (Figure 10), it was impossible to test the buoy as a complete unit. The smallest practical diameter of the turbine was determined to be three inches, double the size of the inner diameter of the 1:8 buoy model. It was impractical for the turbine to be 3D-printed any smaller. It was then decided to test the hull alone and extrapolate data for the buoy’s functionality as a whole. Therefore, it was important to first determine the effects of mass and buoyancy prior to model construction.

The first iteration was made from foam, 1.5-inch polyvinyl chloride (PVC) pipe, a PWC adapter, and a steel flange. Steel washers were added for additional ballast. This prototype was nicknamed “Bob 1” and can be seen in Figure 11.

Testing showed that Bob 1 could not produce enough...
Such buoyancy, the buoy’s natural period could then be adjusted simply by the addition of mass. In this prototype, the team replaced the steel pipe ballast with flattened, contoured lead sinkers. This substitution increased the oscillation period by approximately 26 percent.

To determine the buoy’s natural period, the buoy was deployed in the wave flume and subjected to a vertical disturbance, monitoring the response back to equilibrium with the use of an accelerometer. No waves were created during this period, as they would interfere with the experiment. Figure 15 is a depiction of the oscillation of the buoy.

Ideally, a buoy should be able to oscillate freely at resonant conditions without any interference at the seafloor. More mass can only be added as long as the buoy drafts a distance that does not contact the bottom surface. Therefore, mass was added to the buoy at half-pound intervals to determine the effect of added mass on both period and draft. Figure 16 demonstrates this interaction.

It was determined that due to limited water depth, the buoy’s natural period could not match resonant conditions power to activate a turbine. To mitigate this issue, the team reduced the buoyancy to increase buoy pressure for each oscillation, creating more lift for the turbine. The team also decided to add a graduated capture column, increasing the bottom of the PVC pipe and flange to a two-inch diameter. These modifications resulted in “Bob 2,” shown in Figure 12.

After testing, it was found that the buoyancy was too small. The pressure change improved, but the buoy sank too low in the water, and damaged a sensor. In addition, the steel flange increased drag on the buoy. The team then decided to make another prototype, shown in Figure 13.

For Bob 3, the team experimented with two floats of equal volume but different buoyancy distributions. The team also removed the steel flange and substituted a steel pipe. This created ballast and reduced the drag on the buoy. Bob 3a had better column pressure, but Bob 3b had more stability. These discoveries led to the fourth iteration, “Lead Bob” (see Figure 14).

For the buoy’s fourth iteration, a single floater style was selected. It featured a slimmer cross-section area to promote a heaving response during the motion of the waves. By fixing such buoyancy, the buoy’s natural period could then be adjusted simply by the addition of mass. In this prototype, the team replaced the steel pipe ballast with flattened, contoured lead sinkers. This substitution increased the oscillation period by approximately 26 percent.

To determine the buoy’s natural period, the buoy was deployed in the wave flume and subjected to a vertical disturbance, monitoring the response back to equilibrium with the use of an accelerometer. No waves were created during this period, as they would interfere with the experiment. Figure 15 is a depiction of the oscillation of the buoy.

Ideally, a buoy should be able to oscillate freely at resonant conditions without any interference at the seafloor. More mass can only be added as long as the buoy drafts a distance that does not contact the bottom surface. Therefore, mass was added to the buoy at half-pound intervals to determine the effect of added mass on both period and draft. Figure 16 demonstrates this interaction.

It was determined that due to limited water depth, the buoy’s natural period could not match resonant conditions.
(two-second wave period) because of the amount of mass needed to achieve such a period. Consequently, it was decided that the target period of the buoy should occur at half the desired wave period, resulting in a one-second wave period. It was then hypothesized that the buoy would work at a harmonic of the resonant condition. This harmonic meant that the buoy would bob up and down twice at a one-second wave period, which would be equivalent to bobbing once during a two-second wave period.

4. Results

The period matching at 1:1 ratio could not be achieved. Therefore, an oscillating buoy at the 2:1 ratio was examined to see if some performance characteristics at resonant conditions could be maintained. At resonant conditions, the distance between the buoy at its highest point and its lowest point during oscillation is the greatest. This displacement results in the greatest potential for power. To perform these tests, the hydraulic performance of the buoy was observed with an ultrasonic sensor aimed downward and perpendicular to the OWC surface, monitoring water column displacement. The team then tested the buoy at various wave heights and wave periods to see if its performance would decrease at dissonant (out-of-sync intervals) conditions and begin to restore at harmonic intervals. It was observed that some desired results could be achieved through the use of harmonics; however, compared to that of resonance, much smaller displacements were produced. Eventually, resonance was achieved at the desired harmonic, two oscillations for a one-second period.

A half-scale model was made (Figure 17) based on the same principles as the small prototypes. The ballast was constructed from plywood and had indentations for lead weights. The bottom of the buoy was contoured to allow for improved water intake. A half-scale turbine was 3D-printed, and a generator was salvaged from a desk fan.

The half-scale model was tested at China Walls, located on O‘ahu’s south side. Because the buoy’s operating range was so small, it could not achieve resonance in those particular wave conditions. Therefore, the OWC was pushed up and down to mimic contact from the waves. With this artificial oscillation, the buoy produced 0.3 milliwatts of power.

5. Conclusions

To lessen the impact of fossil fuels on the environment, it is necessary to find sources of renewable energy. One source is ocean wave power, which can be harnessed through WEC buoys that use wave motion to generate energy. A spar-style OWC buoy is one of the most useful WEC devices due to its ability to produce power regardless of orientation in the waves. It generates power most efficiently when the natural bobbing of the buoy is in resonance with the period of the waves in which it is deployed. It was decided, therefore, to create a resonant buoy to convert wave energy to electrical power. This device was developed according to the principles of buoyancy and the OWC modeled as a mass-spring-damper system. Resonance of a spar-style OWC buoy through added mass and harmonics was successfully achieved. Possibilities for future research include increasing the buoy’s operational range so that it is resonant over more wave conditions, creating a greater potential for power output. Another possible research option would be to test different styles of buoys in the intermediate wave zone. Overall, ocean energy harvested by OWCs is a viable replacement for fossil fuel.
Acknowledgements

The team would like to thank the Department of Mechanical Engineering at UH Mānoa as well as Boeing for their generous financial contributions to this project. The team would also like to thank Kamanu Composites for the use of their computer numerical control machine and UH Mānoa alumnus Gavin Nall for assistance in buoy float fabrication. Graduate students Nicholas Ulm and Jean-Louis Genest provided assistance on this project. Civil and Environmental Engineering Department Technician Mitch Pinkerton and Assistant Technician John Imai provided access to the wave flume. The team would also like to thank Dr. Bardia Konh for advising this project as well as Dr. A Zac Trimble and Dr. Trevor Sorensen for their assistance. Mechanical Engineering Technician Lewis Moore provided shop and safety training and guidance. Hawai‘i Space Flight Lab Researcher Yosef Ben Gershom and graduate student Saeed Karimi generously donated their time to help the team edit and improve this project. UH Mānoa alumnus Blake Tolentino, former renewable energy senior design project manager, provided the original impetus for this project. Dr. Reza Ghorbani also provided initial assistance. Oregon State University graduate student Aisha McKee gave the team recommendations regarding equipment. UH Mānoa student Jason Borgida assisted the team with testing. The team project manager would also like to thank UH Mānoa graduate students Richie Chio, Alex Dvornikov, Kevin Keefe, Andy Meyer, and Jack Runburg for the use of their office when writing and editing this article.

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