IN-OCEAN EXPERIMENTS OF A WAVE ENERGY CONVERSION DEVICE WHEN MOORED TO AN ANCHOR AND TO A DROGUE

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ABSTRACT

We present the results of in-ocean testing of a heaving point source wave energy converter (WEC) off the coast of Honolulu, Hawai'i. The principle of operation of the WEC device is to convert vertical heave displacement into a rotational action, which generates electrical power. The heave displacement is created by the WEC system riding incoming waves relative to an anchoring system. Two deployment cases of a single WEC device were ocean tested with the goal of collecting power data based on the type of the anchoring method. The anchoring methods are referred to as the single-body case (moored system) and double-body case (drogue anchored system). The single-body case consists of the WEC system being held in place via a taut mooring line connected to an anchor. The double-body case consists of the WEC system being held by a sea anchor or drogue. This allows the system to partially float free and drift, but still have adequate vertical resistance to extract power as waves pass. The experiments were carried out on the south shore of Oahu during the summer of 2012. The WEC system was equipped with sensors to measure and record the heave displacements, the generated power output, and the surface elevation. To accurately measure the WEC system's heave displacement, a rotary sensor was used to measure angular displacement the WEC system's spool rotated for each wave. An Aquadopp measured the total pressure from the sea floor up-wave from the WEC system. A voltage logger was used to measure the voltage across a resistive load to calculate the power the WEC system generated. The realtime experimental data were collected and analyzed to determine the power generation profile, the WEC system's heave displacements, surface elevation, and heave response amplitude operator (RAO) for both cases.

KEY WORDS

Wave energy conversion device; Drogue; Power take-off device; In-ocean experiments; Buoy; Motions; Irregular waves

INTRODUCTION

Over the years, many systems have been developed to extract power from ocean waves, tides, and currents. Wave energy has become a main focus due to higher energy densities and predictability [McCormick, 1981]. Wave energy is the transport of energy by ocean surface waves and the capture of that energy for the use of electricity generation. A device that is able to convert wave energy is typically called a wave energy converter (WEC). Modern scientific pursuit of wave energy was pioneered by Yoshio Masuda's experiments in the 1940s. Masuda tested multiple wave energy devices at sea, with several hundred units used to power navigation lights [Washio, 1998]. One of the more famous WEC devices was Stephen Salter's 1974 invention of the Salter Duck. In small scale lab tests, the Duck's curved cam-like body absorbed 90% of wave energy and converted it to electricity with 81% efficiency [Salter, 1978]. In recent years, multiple studies have been carried out on heaving point source energy converters and their potential power production [Foster, 2011; Kim and Oh, 2008; Roesler, 2011].

Government organizations in the United States, such as the National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and the United States Navy, use buoys throughout the world to monitor environmental conditions and disaster events. The launching of a global array of 1,250 drifting buoys was completed in September 2005 and some 300 new drifters are deployed annually [NASA, n.d.]. Modern Surface Velocity Program (SVP) drifters include a holey-sock drogue centred at 15 m depth and surface float with a 30 cm to 40 cm diameter. It could contain batteries in four to five packs, each with seven to nine alkaline D-cells, a transmitter, a thermistor to measure sea surface temperature, and possibly other instruments measuring barometric pressure, wind speed and direction, salinity, and ocean colour. Once deployed, a modern SVP drifter lives an average of 400 days before ceasing transmission [NOAA, 2012]. Acoustic sensors can draw up to 100 to 200 W of continuous power during operation, thus limiting the battery life in most cases to 12 to 24 hours on one battery charge [Davis et al., 2009]. The operating lifetime of freely floating buoys are limited by onboard battery power. Recharging is so impractical and costly that many buoys are designed to sink to the bottom after a period of operation. The cost and environmental impact of sending batteries and electrical equipment to the bottom of the ocean is a strong motivation for developing a free floating wave energy conversion buoy that would trickle charge the batteries. A monitoring station with a WEC device could sustain a longer design life, save on the maintenance costs, and have decreased environmental impact.

A freely floating WEC buoy would use a drogue's drag properties to provide a stable anchor point relative to the wave motion. Research on different types of buoy and drogue combinations was done to determine the forces of the submerged body subjected to the forces of surface shear, wave, swell, and current between the buoy and drogue [Vachon, 1977]. Lab experiments were done to determine the hydrodynamic drag coefficients of drogues used for drift control on free floating buoys [Holler, 1985].

Starting in 2008, a wave energy converter prototype capable of capturing and converting energy from wave induced heaving motion in shallow water environments was developed [Davis et al., 2009]. Phase 1 of the project concluded in 2009 with a WEC that successfully produced 23-53 W of peak power during sea trials performed at the Kilo Nalu Near Shore Observatory on Oahu, Hawai'i [Symonds et al., 2010]. Phase 2 of this project began in August 2009. Phase 2 was to improve on the Phase 1 prototype and produce between 100-200 W of power [Symonds et al., 2010]. More recent experiments were completed in June 2012 with the production of 100-200 W of power from the WEC device. Different anchoring methods, referred to as the single-body case and double-body case, were tested during the ocean trials to compare the results. Both methods had the same WEC setup, referred to in this paper as the WEC system. The WEC system consisted of a buoy rigidly attached to the WEC frame which supported water-tight housings, ballast, and measuring equipment. The single-body case consisted of the WEC system held in place via a taut mooring line attached to an anchor and extracting energy as a wave passed. The double-body case consisted of the WEC system held by a sea anchor or drogue that allowed the system to freely float and still have adequate vertical resistance necessary to extract energy as a wave passed.

The WEC system's power take-off is nonlinear and only extracts power when the WEC system motion is positive. This WEC system has several unique features including a magnetic coupling across an interface window, which allows torque to be transmitted from the wet portion of the device to a completely sealed dry portion containing the generator and associated electronics. The WEC system is axisymmetric and insensitive to wave direction. The design does not rely on heave resonance (the heave resonance period is 1.1 s), and therefore is not overly dependent on particular wave frequencies.

EXPERIMENTS

In the single-body case, the WEC system was moored to an anchor on the sea floor. In the double-body case, the WEC system was moored to a conical drogue or sea anchor. Both cases are shown in Figure 1. The drawings are not to scale.

The WEC system used during the June 2012 ocean trials is shown in Figure 2. The WEC system consists of a Polyform A5 buoy (with a diameter of 68.6 cm and height of 91.4 cm), PVC mount, WEC frame, ballast, and WEC device that are all rigidly connected together to form one body.

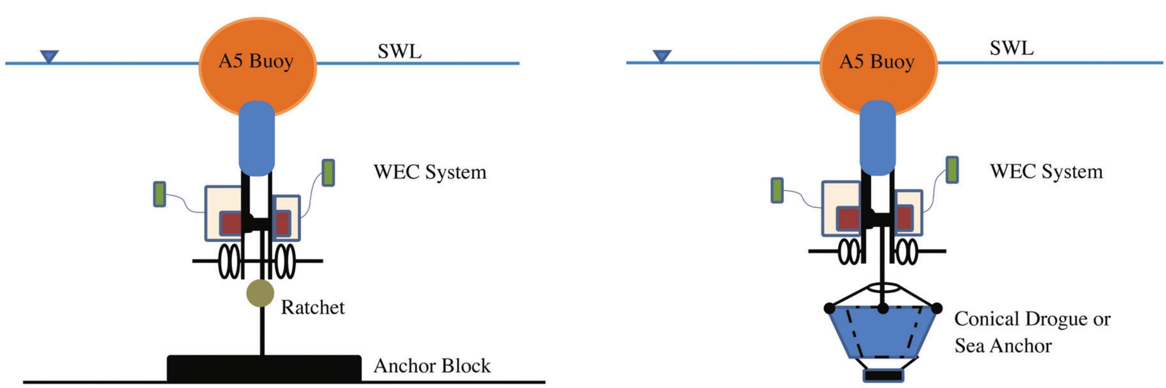

Figure 1: Model of single-body case (right) and double-body case (left).

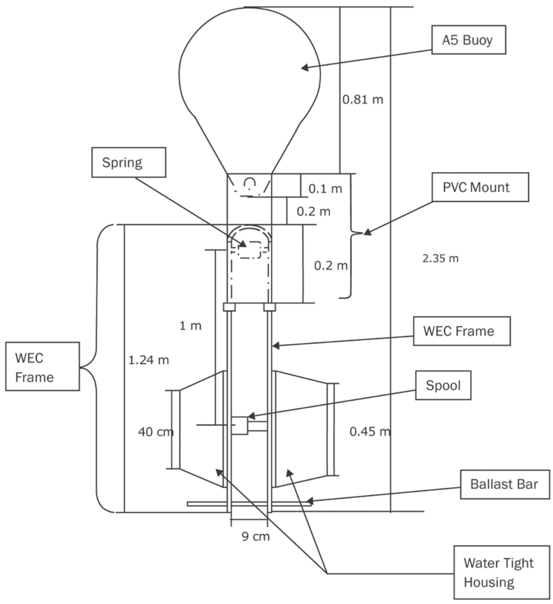

Figure 2: The wave energy converter system.

PREPARATION

Wave Energy Converter System and Drogue

The WEC frame was redesigned from previous experiments to improve the range of the WEC system motion, which affects the functionality of the WEC system. The WEC's motion was limited by two things: spring retract force and allowable travel, or fetch. Spring retract force is the amount of force that the WEC system's spring retracts the mooring line. The WEC system's spring line and mooring line wrap around two different diameters on the spool. Since the spool is the connection point between the spring and mooring lines, this produces an effective gearing ratio on the spring retract force. The spool allowed the WEC system to move up and down the mooring line as the waves actuated the machine. The spring retract force had to overcome the resistance in the gears and magnets to allow the WEC system to fully reset as each wave passed. The fetch, the distance the spring can extend, is the distance from the spring to the spool; this limits the amount the WEC generator could rotate. The fetch was extended by increasing the total length of the WEC frame. The WEC frame, spring, and spool are shown in Figure 3. The spring is at the top of the frame and the spool is between the two water-tight casings.

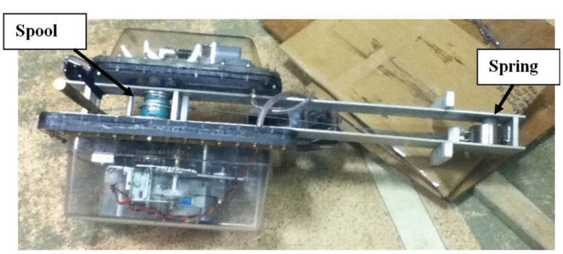

Figure 3: Wave energy converter frame.

There was a need to balance the fetch and spring retract force: too much fetch and the spring would not be able to retract; too little fetch and the spring would slam into the spool, limit the power generation, and potentially damage the WEC system. To balance the retract force with the fetch, a spool ratio of 2.5/3 was chosen. This allowed the WEC spring a retract force of 88 Newton (N), and a max extension length of 1 m; therefore, the WEC system could handle approximately 1.2 m wave height in this configuration. The WEC system would not travel the full wave height because of losses in buoy motion and a delayed heave reaction.

A resistor was used as a load for the WEC system during the ocean trials. The resistor was chosen based on the estimated velocity the WEC system would ride the wave (that corresponds to the generator RPM) and maximum torque the magnetic couple could take without slip. The power generated at other resistance values were found from laboratory test results for the generator shown in Figure 4 [Engelmann, 2012].

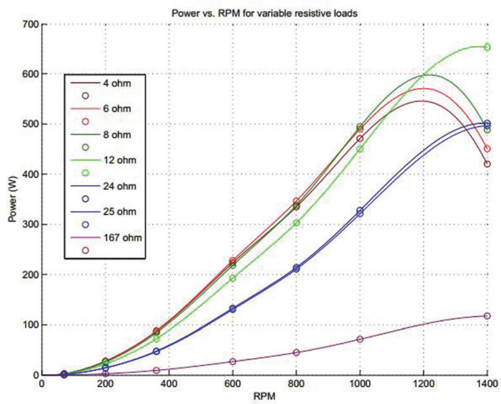

Figure 4: Generated power for a given generator and load.

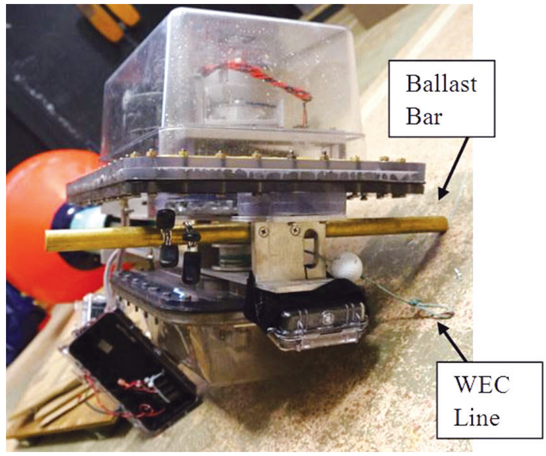

Figure 5: Base of the wave energy converter system.

The buoyancy of the WEC system was calculated to determine the proper ballasting needed for the WEC system to rest vertically (without trim). The bottom of the WEC system needed to be negatively buoyant and hang under the A5 buoy. The net buoyancy of the WEC system was found to be 113 N, with one side being 22 N more buoyant than the other because of different sizes in the water-tight containers. 178 N of standard barbell weight (wet weight of 141 N) was used to ballast the WEC system. The ballast weights were mounted on a bar that was perpendicular to the machine and bolted down to a plate in the WEC frame as seen in Figure 5. Ballast weights were arranged to ensure level trim, which allowed the WEC system to achieve maximum spring extension and power output.

The drogue was ballasted to hang vertically under the WEC system and to return to an intended depth if pulled up by the WEC system. It was ballasted by a 27 N rebar top ring, 13 N weight, and chain (weight in air). The drogue had enough negative buoyancy to sink, but was not so great to cause the flexible body of the drogue to collapse and lose its frustum form.

To ensure the bodies would be stable during testing, the centre of gravity and centre of buoyancy positions were calculated for each body. The WEC system was approximated with a circular cylindrical shape, and the drogue was approximated by a hollow frustum. For both bodies, the centre of gravity was below the centre of buoyancy on the same vertical line.

Assembly

The A5 buoy was rigidly attached to the WEC frame with a PVC pipe via a turnbuckle. Two water-tight housings were attached to the WEC frame for the power take-off device and the rotary sensor. The WEC system in Figure 6

Figure 6: Wave energy converter system assembled.

	Height (m)	Top radius (m)	Bottom radius (m)
Drogue	1.515	0.455	0.063

Table 1: Drogue dimensions.

was 2.4 m long and weighed 441 N without ballast. Pelican boxes were attached to both water-tight housings for the voltage data loggers.

A ratchet was attached to the line coming from the WEC system. The ratchet held 4.57 m of line that would connect the WEC line at the surface to a loop made in the single-body case mooring line. The ratchet was used to attach the WEC system to the mooring line, as well as add tension to the mooring line.

The drogue shape was chosen based on the experiments of Vachon [1973]. He observed that the conical drogue moved very little in response to heave, as the connecting lines absorbed much of the heave motion.

The drogue was assembled to a circular rebar frame, which prevented the top ring of the frustum from collapsing and served as ballast weight. The drogue's top straps were tied to a carabiner for connection to the double-body mooring line that attached to the WEC system. A ballast weight of 13.3 N (in air) was attached to the bottom to keep the drogue at its full vertical extension. The fully assembled drogue is shown in Figure 7. The drogue dimensions are listed in Table 1.

Mooring lines for the single-body and double-body cases were Amsteel Blue 7/64 line. The line is low-stretch so as not to decrease the efficiency of wave energy capture. This rope

Figure 7: Assembled drogue.

exhibits high strength-to-weight ratio, is stronger than a wire rope, and is neutrally buoyant. On the single-body case mooring line, a large carabiner was tied to the end to clip into an eye bolt on the 1.21 x 1.21 x 1 m concrete anchor block. A loop was tied at 16.8 m from the mooring side of the rope for the ratchet's carabiner. The double-body case mooring line was tied to the carabiner that attached to the top of the drogue.

Measuring Equipment

The WEC system was prepared for experimentation and data recording by the equipment listed in Table 2. The rotary sensor directly measured the heave displacement experienced by the WEC system. The rotary sensor outputs to a voltage data logger. The Aquadopp measured the total pressure. Linear wave theory was used to obtain the surface elevation of the incoming waves from the Aquadopp data. The Aquadopp was mounted to a frame that rested on the sea floor 1 m up-wave in the predominant wave direction

Sensor Equipment	Bits	Accuracy	Rate (Hz)	Measured
Nortek Aquadopp [Nortek AS, n.d.]	16	0.5%	1	Pressure
Eagletree power logger [Eagletree Systems, n.d.]	12	0.5%	10	mV
Madgetech VOLT101A [Madgetech, n.d.]	12	0.05%	4	mV
Celesco RT8510 rotary sensor [Celesco, n.d.]	16	0.04%	4	mV/Degree

Table 2: Measuring equipment.

from the WEC system. Another voltage logger was connected to the generator and resistive load to measure the voltage over the resistor. For this experiment, the load resistor used was 50 ohms.

The rotary sensor and data logger were bench tested separately and together. The rotary sensor came calibrated from the manufacturer. A multimeter and DC voltage generator were used to test the rotary sensor. The DC generator provided power to the rotary sensor and the output voltage was read by the multimeter. The voltage was converted by the factory conversion ratio of volt per degree. The range of motion and sensitivity of the rotary sensor needed to be verified, so the rotary sensor was spun in multiple increments over the full range, and the distances confirmed.

The voltage data logger was calibrated from the manufacturer and had a program interface to read the recorded data, set sample interval, set the clock, and set start and stop times. The logger was connected to the DC power source and the voltage held for 15 seconds then moved to another voltage setting. The logger was confirmed by looking at the recorded data on the computer and compared to the known voltage settings.

For the final bench tests, the rotary sensor and voltage data logger were setup to replicate their arrangement during the ocean trials. The rotary sensor was powered by a constructed 27 V battery pack and connected to the voltage data logger inputs. The rotary sensor was rotated a precise distance and the accuracy was checked by looking at recorded change angular position. The Aquadopp, rotary sensor, and data logger were time synced according to National Institute of Standards and Technology time. A separate voltage data logger was set to begin recording when input voltage across the resistor was received. The logger's data were used to find the power produced by the WEC system's generator. The rotary sensor's data logger was manually started before the ocean experiments and the rotary sensor continuously output voltage once powered. After testing, all sensors were checked for drift over time.

OCEAN TRIALS

The wave climate at the site was checked to ensure the wave heights would be sufficient to actuate the WEC system during trials. From the recorded data, the site was found to have 1.05 m significant wave height, whereas the web site Surfline.com [2012] forecast 1-1.52 m significant wave height. We used the University of Hawai'i's 7.62 m boat *Kilo Kai* to conduct the experiments. GPS points were taken of the anchor block for the single-body case and the start as well as the end location of the double-

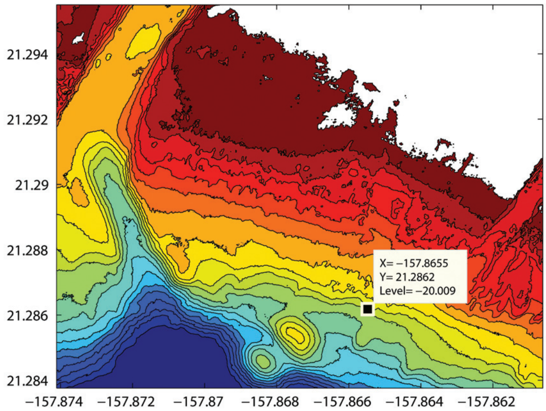

Figure 8: Site bathymetry and anchor location.

body case. The site bathometry and anchor location are shown in Figure 8 [Pawlak, 2012].

Single-Body Case

A tag line was attached to the WEC system, and the ratchet was clipped onto the WEC line. The WEC system was lowered into the water, where divers took the extended portion of the ratchet and clipped the carabiner to the loop on the mooring line. The divers ratcheted up the excess line to create a taut mooring, but care was taken not to cause any extension in the WEC system's spring. This allowed the WEC system to be held securely in place and to achieve full range of extension. The WEC system during the trials is shown in Figure 9.

During the single-body case, wave conditions were about 0.5 m swell height with periods of 15-16 s; however, shorter wind waves and boat wakes sometimes provided larger waves at random times. The WEC system was allowed to run undisturbed for two hours in about 20 m of water.

Double-Body Case

The WEC system was pulled to the side of boat and the double-body case mooring line clipped onto the WEC line. The single-body

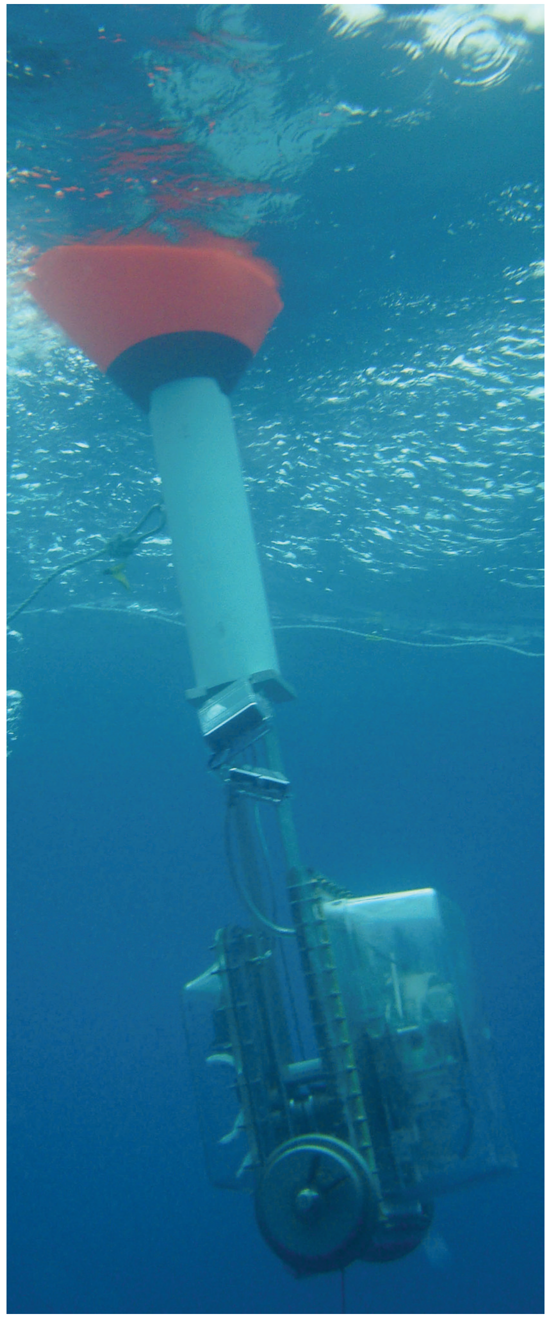

Figure 9: Wave energy converter system during moored trial.

case mooring line and ratchet were unclipped and the drogue tossed overboard and allowed to sink naturally. It was checked to ensure the drogue was extended and was directly below the WEC system. A tag line was left on the freely floating WEC system for control in case it drifted into boat traffic or too close to shore. The WEC system floated in 16-19 m of water. The double-body was similar to the single-body case except there was no ratchet and the mooring line connected directly to the WEC system.

RESULTS AND DISCUSSION

From the experimental data, the WEC system's heave displacement, drift, and generator's RPM were determined from the rotary sensor data. The calculated WEC system's heave displacement spectrum was compared against the wave spectrum to obtain the heave RAO and damping ratio of the WEC system.

Raw Data

Single-Body Case

Figure 10 shows the surface elevation and the WEC system's heave displacement. Both are measured relative to the sea floor. The red line is the tidal change over time during the trial [NOAA, 2012].

Surface elevation follows a positive upward slope because the distance between the sea floor and the still water level increased with the tide. This is also true for the surface elevation in the double-body case; therefore, the tidal components of both experiments were removed from the surface elevation data sets. The main effect the tide could cause is slamming in the WEC system if the mean water level increased by 60 cm, but because the test was for a short duration, the change in tide level was not a main concern.

When the change in water elevation due to tidal effects is removed from the WEC system's heave displacement, as in Figure 10, it is noticeable that the drift acting on the WEC

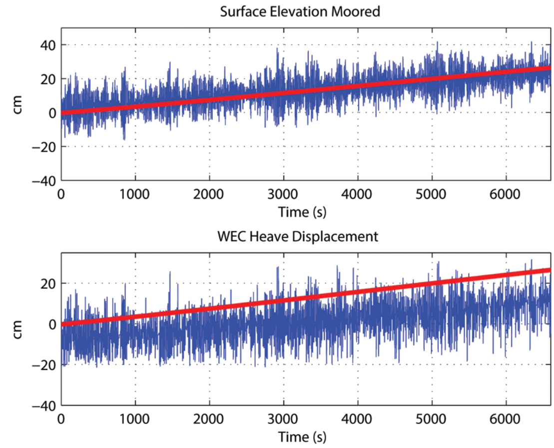

Figure 10: Surface elevation and wave energy converter heave displacement with tide lines.

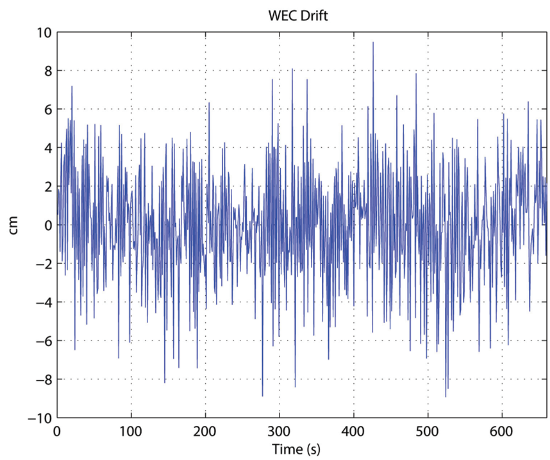

Figure 11: Wave energy converter vertical contribution of horizontal drift.

system causes it to not exactly follow the tide line.

The vertical contribution of the horizontal drift is caused by the waves pushing the WEC system with each passing. The vertical component of horizontal drift in Figure 11 was found by Equation 1. The drift was found for every 100 data points of the WEC heave displacement and tide.

Drift = mean(WEC Displacement - Tide);
Detrended Displacement = (RAW WEC Displacement - Tide - Drift) (1)

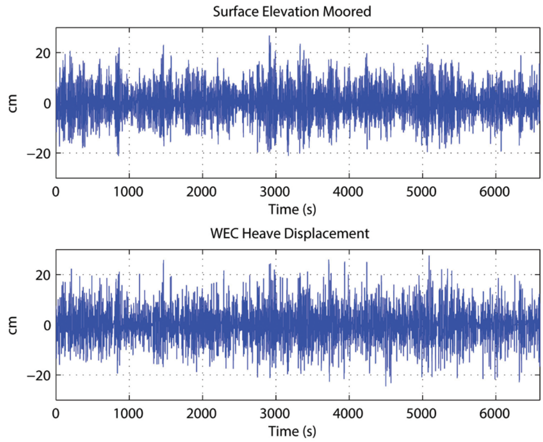

Figure 12: Detrended surface elevation and wave energy converter heave displacement.

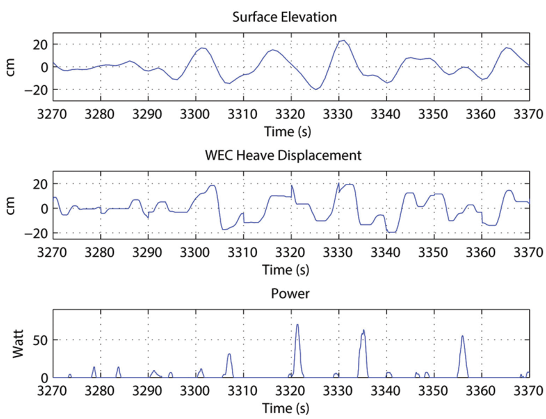

Figure 13: Surface elevation, wave energy converter heave displacement, and power section.

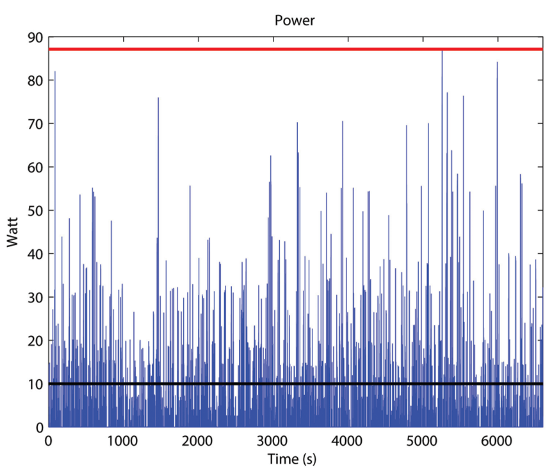

Figure 14: Power output.

The detrended surface elevation and WEC system's heave displacement can be seen in Figure 12.

In Figure 13, corresponding peaks in the surface elevation, WEC system heave displacement, and power output can be seen in this section of data. The power reaches a peak on the positive slope of the WEC system's heave displacement because power was only generated when the WEC had a positive velocity. In other words, the WEC system only converted energy when heaving upward along the wave crest.

The maximum power output was 87 W and the average output over the experiment was 10 W, as shown by the red and black lines, respectively, in Figure 14.

The mean revolutions per minute (RPM) values were calculated to predict the power output for the WEC system connected to different electrical loads. The generator's average RPM was calculated from the rotary sensor's angular displacements by Equation 2:

$$\text{Rev} = \left(\frac{\text{Degrees Measured by Rotary Sensor}}{360}\right)$$
$$\text{IRPM} = \left(\frac{\text{Rev}}{\text{dt}}\right) * 60$$
$$\text{RPM} = (\text{Gearing Ratio}) * \text{IRPM} = \left(\frac{13}{1}\right) * \text{IRPM} \tag{2}$$

where Rev is revolutions per time step, IRPM is the instantaneous RPM, and the gearing ratio is the ratio of the angular velocity of the input gear to the angular velocity of the output gear. The RPM at the generator was 830 RPM. At 830 RPM, with a 24 ohm load, the generator would have produced just over 200 W. With a load of 4 ohms, slightly higher resistance than most 12 V Gel lead acid batteries, the WEC system's generator would produce about 350 W which would be able to recharge the battery.

Double-Body Case

Figure 15 shows the surface elevation with the tidal component removed, WEC system's heave displacement, and power output. The spikes in the WEC system's heave displacement and power output do not match large surface elevation events shown.

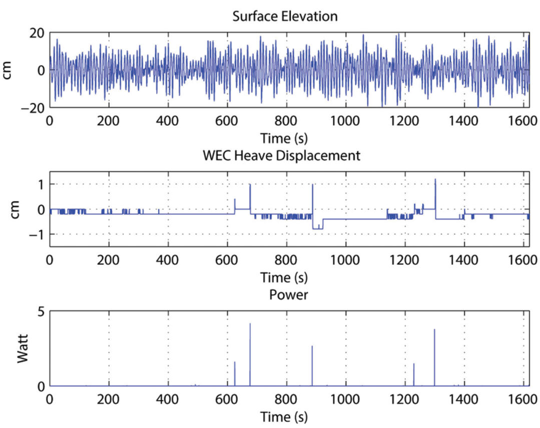

Figure 15: Surface elevation, wave energy converter heave displacement, and power.

The surface elevation in both cases had similar significant wave height and peak period values. However, only a slight WEC system displacement, less than 2 cm, was measured. This indicated that the drogue could not create enough anchoring resistance to enable the WEC system to capture wave energy.

The generator spun with an average of 16.4 RPM and a maximum of 232 RPM. At 232 RPM, a 24 ohm load, the generator would produce about 20 W. A load of 4 ohms would produce about 50 W.

Filtered Data

Because of the results observed in the double-body case, only the single-body case will be discussed further. Figure 16 shows a section of Figure 12. It can be seen that the WEC system's heave displacement shows plateaus, or clipping, in the signal. This is caused by a slight delay in the spring retracting, which caused the device to delay for a few seconds. This clipping was smoothed with digital filtering.

The raw spectra of the surface elevation and WEC system's heave displacement are shown in Figure 17. The WEC system's heave displacement spectrum is larger than the surface elevation spectrum at T > 20s and T < 10s, where T is the period (s).

This would mean the WEC system was excited by something other than waves or the WEC system covered the Aquadopp sensor and caused false data. It was not possible for the WEC to be excited by anything other than waves and the sensor was placed up-wave in the predominant wave direction to avoid the WEC system drifting over the sensor. Therefore, the WEC system's heave displacement data had high and low frequency noise. A 4th-order digital Butterworth filter (0.14 Hz and 0.048 Hz) was used to create a band-pass filter to filter the high and low frequency noise from the signal. In Figure 18, the original WEC system's heave displacement is overlaid with filtered heave displacement. The band-pass filter smoothed the clipped sections data and retained much of the signal.

Spectrum and RAO

Single-Body Case

Figure 19 shows the spectra of the filtered WEC system's heave displacement and surface elevation. The surface elevation's peak at 15 s

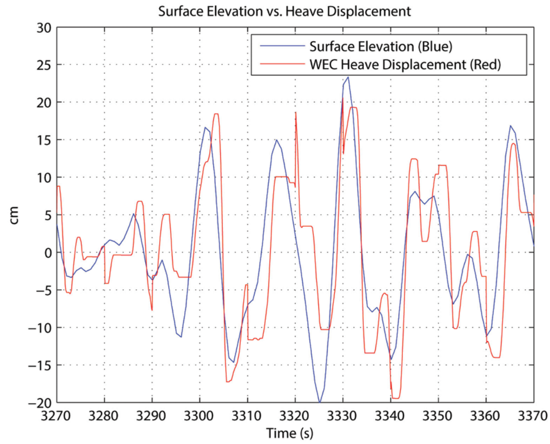

Figure 16: Detrended surface elevation and wave energy converter heave displacement section.

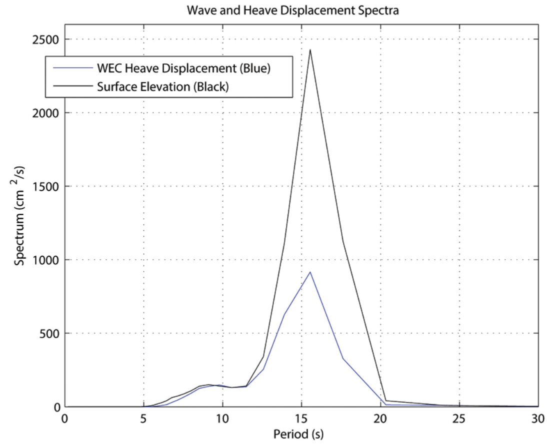

Figure 19: Wave and heave displacement spectra.

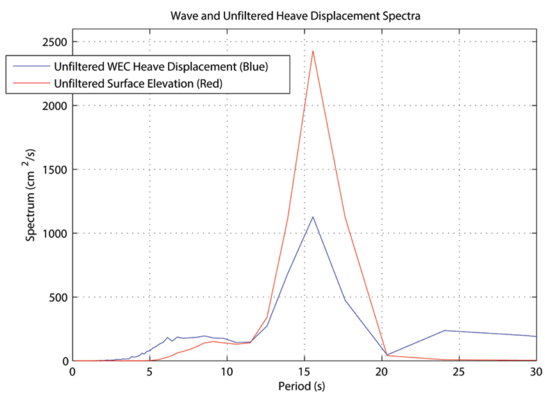

Figure 17: Unfiltered surface elevation and wave energy converter heave displacement spectra.

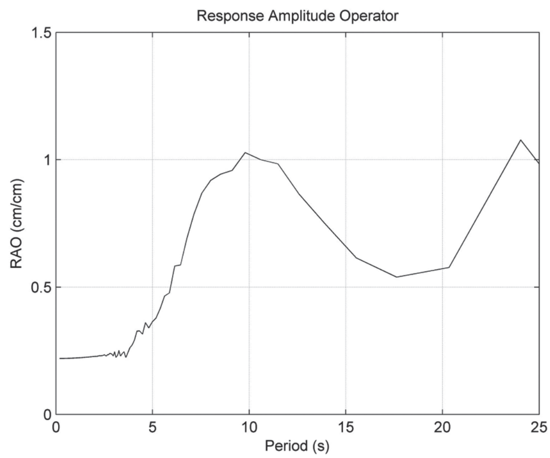

Figure 20: Heave response amplitude operator.

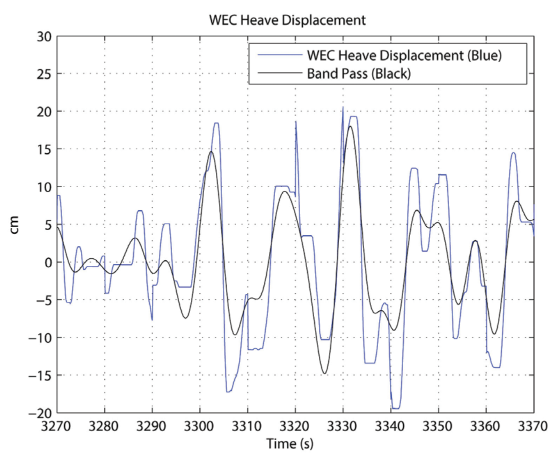

Figure 18: Different filters of wave energy converters heave displacement section.

corresponds to the wave swell on the day of testing. A similar peak is seen in the spectrum of the WEC system's heave displacement. This is caused by the WEC system riding the waves and being excited by a majority of the 15 s period waves. The differences in the amplitudes of the two spectra are caused by wave damping and the power take-off damping. The ratio between the two peaks, $S_{WEC}(T)/S_{se}(T)$, is the damping ratio, where $S_{WEC}(T)$ is the spectrum of the heave displacement and $S_{se}(T)$ is the spectrum of the surface elevation.

The heave response amplitude operator (RAO) in Figure 20 is determined from Equation 3:

$$RAO = \sqrt{\frac{S_{WEC}(T)}{S_{se}(T)}} \tag{3}$$

The RAO (heave motion amplitude/wave amplitude) shows little response at low periods and a unit response around 10 s and 25 s. Between 15 s and 20 s, a dip occurs, which corresponds to the damping ratio found in Figure 19. When the WEC system converts wave energy, there the RAO is less than 1.0; on the other hand, when the system was not excited enough to convert energy, it has a unit response to the incoming waves.

CONCLUSIONS

The WEC system provided a maximum power output of 87 W for a 50 ohm load from one power take-off device when moored in 0.3 m to 0.6 m seas. In a production model, the WEC system would have two power take-off devices, which could result in a maximum power output of 174 W when moored in 0.3 m to 0.6 m seas. A smaller resistive load in the WEC system will produce even greater power. A typical Gel lead acid battery has a resistive load of 2.4 ohms or smaller. The WEC system would be able to trickle charge the batteries of a buoy, which would increase the design life and save on the maintenance costs.

A free floating WEC system anchored to a drogue would produce less power than a moored WEC. However, with proper drogue depth and sizing, the authors' conjecture is that the free floating WEC system could have power output similar to a moored WEC system and be able to trickle charge batteries.

A band-pass filter smoothes the clipped sections of the WEC system's heave displacement. The filtered data creates a less noisy spectrum and a smooth RAO. The WEC system would have an RAO of 1.0 (similar to a circular cylinder) for periods greater than 10 if not for the power take-off device. The power take-off device created a damped spectrum and dip in the RAO by taking energy from the wave and converting it into electrical energy.

In future works, the double-body case will be tested in deeper water, which will ensure that the drogue is placed at a depth of 50% or more of the average wavelength, and therefore not affected by the presence of waves. The next testing phase would extend the experiments for a longer period of time and possibly incorporate a battery and a small resistive load. Also, both cases would be tested in multiple sea states. Multiple drogue shapes would be tested to determine which drogue will provide the best anchor point.

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