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Modeling of a Wave Energy Oscillating Water Column as a Point Absorber Using WEC-Sim

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***Abstract*—This study evaluates the accuracy of using the open-source wave energy converter modeling WEC-Sim code to model an oscillating water column (OWC) as a virtual point absorber. WEC-Sim is a free, open-source hydrodynamic modeling extension of MATLAB/Simulink, and is designed primarily for ease of use and the modeling of oscillating body wave energy converters (e.g., point absorbers). Oscillating Water Columns are a different class of wave energy converter and can be difficult to model. If OWCs can be accurately modeled as oscillating bodies, it may more easily enable the use of well-established hydrodynamic theory and control theory that exists for oscillating bodies for better simulated estimation of performance. Comparison of simulation and experiment were conducted on OWCs in the OH Hinsdale Wave Research Lab at Oregon State University. Results show good agreement between the experimental OWCs and the simulated virtual point absorber over most ranges of operation, with the exception of near-resonant frequencies, in which case the virtual point absorber over-predicts performance. For regular waves, the accuracy of modeling an OWC as a point absorber was generally within 5%, except near the device resonant period, in which case the heave amplitude modeling error was 11.4% and the power modeling error was 25.0%. For an irregular sea state of dominant period 2.6 s, the modeling error in power was 2.0%.**

***Index Terms*—Wave energy, experiment, modeling, simulation**

I. Introduction

This paper investigates if an Oscillating Water Column (OWC) wave energy converter can be modeled as a point absorber using the open-source WEC-Sim (Wave Energy Converter-SIMulator) code. WEC-Sim is implemented using MATLAB/Simulink and was developed by a collaboration between Oregon State University (OSU), the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL). WEC-Sim has been verified through code-to-code comparison, and has undergone preliminary validation through comparison to experimental data [1]–[5]. Additionally, validation of the WEC-Sim code with scaled device tank testing was performed at Oregon State University (OSU) in the summer of 2016. WEC-Sim was chosen because it is a free, open-source, and integrated with MATLAB/Simulink, which is a familiar analysis platform for many engineers. (Besides WEC-Sim, commercial software such as WaveDyn [6] and ProteusDS [7] – which have undergone validation against experiment – are also suited for this study.) OWCs are wave energy converters in which the wave energy is converted to high-speed airflow [8]–[13]. They are well-suited to both floating and on-shore deployments, and have many attractive construction and robustness considerations. A detailed description of their operation is given in Section II.

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However, modeling OWCs requires a complex consideration of coupled pneumatics, air turbine behavior, and hydrodynamics [14]–[18]. This motivates a simplistic OWC modeling approach that better allows leveraging of well-known simple floating body hydrodynamics and control theory, in both the frequency and time domain. Some theoretical work has been published in this area [19], but this paper extends to experimental validation. If this research discovers that WEC OWCs are well modeled by virtual point absorbers, it will allow control designers to more rapidly develop and deploy controller and estimator designs, which can decrease the cost of energy of the final design and allow WEC developers to explore more options early in the design, and downselect to promising designs more quickly. This paper presents a comparison of experimental performance of an OWC and simulated expected results of a virtual point absorber, to investigate the accuracy and limitations of this virtual modeling approach.

Some of the specific questions to be addressed are: 1) how well can an OWC turbine be modeled as a linear damper? 2) how well does the virtual point absorber model match the experimental results, especially for motion and power? 3) is the model accurate over all conditions? 4) can the experimental data inform the numerical model to improve its accuracy near resonance?

II. Oscillating Water Column Description

There are many ways to classify ocean wave energy converters. In this work, we use three main categories:

- Oscillating Water Column (OWC)
- Oscillating Body
- Overtopping

Oscillating Water Columns are devices in which a enclosed chamber has an underwater opening such that waves cause the water floor of the chamber to rise and fall, thus pressurizing the air in the chamber. A narrow aperture in the chamber wall or ceiling provides a pathway for high-speed bi-directional airflow due to the oscillating pressure. An air turbine is placed at the aperture to capture the energy. Typically a unidirectionally rotating turbine, such as a Wells Turbine, is used [20].

Oscillating Body is a broad category that includes devices in which a solid body, either submerged or floating, is pushed in a cyclical fashion by the oscillating pressure of the incoming ocean wave. Often there are two or more bodies in the system,

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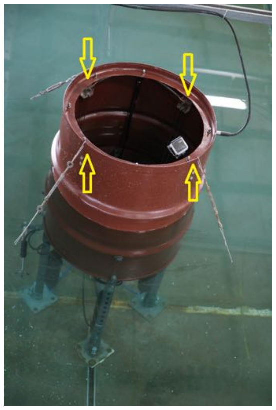

Fig. 1. The prototype of an oscillating water column device when the air chamber is open. As waves approach, the water inside the chamber rises. As waves retreat, the water inside the chamber drops. The arrows show the location of the four wave gauges used for recording the water surface elevation inside the chamber.

Fig. 2. The prototype of the oscillating water column device when the upper funnel, which includes the aperture to the air outtake/intake stack, is attached to the top of the chamber. The butterfly valve that emulates an air turbine is located 1/3 of the way up the stack, and an orifice plate and pressure gauges for measuring flow is located 2/3 of the way up the stack.

and a mechanical conversion mechanism, such as a hydraulic piston or linear generator, is placed between the bodies to convert energy during the relative motion of the bodies [21]–[24].

OWCs require a very different modeling process than oscillating bodies. Oscillating bodies can be modeled with basic Newtonian mechanics, in which hydrodynamic forces can be expressed in simplified forms as a function of the body motion and the incoming water surface elevation. This simple approach works reasonably well for small motions and non-breaking waves, and is the cornerstone approach for modeling for control.

On the other hand, modeling OWCs requires treatment of the flow of compressible fluid (i.e., air) through various segments of the converter which vary in length, width, and shape, in addition to the hydrodynamics [25], [26]. This modeling is generally more complex.

Therefore, there is potentially a great benefit for being able to model OWCs as a virtual oscillating body. It allows the usage of well described linear hydrodynamic and control theory on the OWC modeling and control problem.

The Oscillating Water Column experimental set up used in this work is shown in Fig. 1 and Fig. 2, and the schematic and dimensions shown in Fig. 3. A butterfly valve is located approximately 1/3 of the way up the outtake/intake stack. The valve approximates an air turbine, and the valve position (i.e., how open or closed) can be utilized to control the effective damping provided by the turbine, as described in Section V. Air flow is measured by an orifice plate 2/3 of the way up the stack; air pressure is measured on both sides of plate. These measurements, combined with knowledge of the exact orifice dimension, allow for an accurate estimate of air flow.

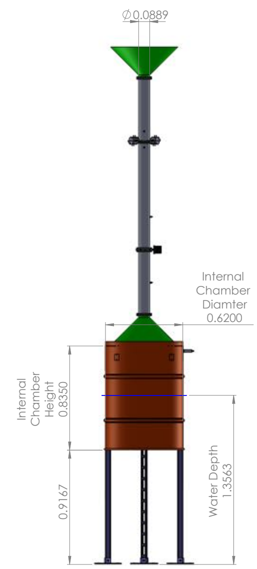

Fig. 3. Experimental OWC dimensions. The bottom of the barrel is open to the water. A butterfly valve, to emulate a air turbine Power Take Off, is located approximately 1/3 of the way up the stack. An orifice plate for measuring air flow is located 2/3 of way up the stack.

III. Modeling an OWC as a Point Absorber

The cylinder of water trapped in the barrel is treated as a solid body with the same density of water. The forces on this virtual body are then the wave excitation force (diffraction and Froude-Krylov forces), the radiation force, hydrostatic stiffness (bouyancy), and the power take off (PTO) force. The frequency dependent excitation and radiation forces for the virtual body can be determined with Boundary Element Method tools such as WAMIT or AQWA. The PTO force is the pressure of the air in the enclosed chamber above times the water cross sectional area. The damping of the virtual PTO is then the OWC water surface pressure times area divided by the water surface upward speed (which is the upward speed of the virtual body), and is therefore a function of the stack valve position.

The process is as follows

1) With experimental setup, measure OWC chamber water surface motion, pressure, and airflow for different sea states and different valve opening positions.
2) From the experimental data, determine effective PTO

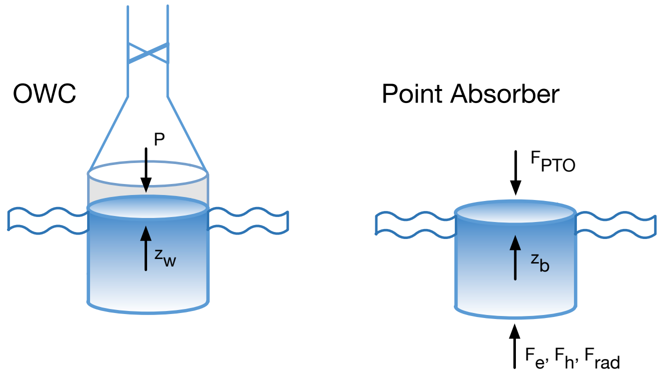

Fig. 4. Modeling of an OWC as a virtual point absorber. The water contained within the OWC chamber is modeled as a solid body of the same density of water. Boundary Element Method tools, such as WAMIT or AQWA, can be utilized to determine the excitation (F_e), radiation (F_{rad}), and hydrostatic stiffness (F_h) forces on the virtual body. The PTO force is the OWC chamber pressure times the chamber cross sectional area.

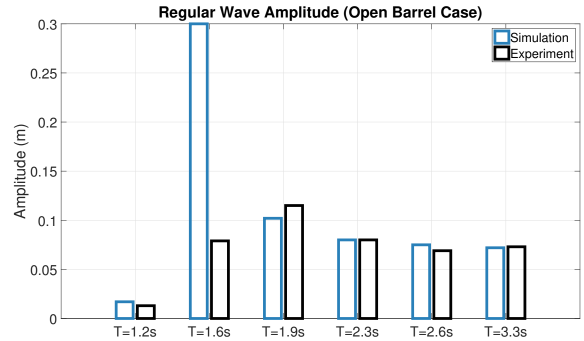

Fig. 5. Comparison of the open barrel experimental water elevation and the simulated virtual point absorber vertical heave position. There is in general very good agreement except for the 1.6 second period, which is near the virtual point absorber resonant frequency. This suggests that simulated results at or near resonance may be overstated with respect to the experimental results.

damping by measuring OWC chamber water surface speed vs. the force on the OWC water surface (pressure times area).

3) Create point absorber model with a single body the same size, dimension and density of OWC chamber water. Use a Boundary Element Method tool to determine frequency dependent excitation force, radiation force, and hydrostatic stiffness.
4) Input frequency dependent parameters and body properties to WEC-Sim.
5) Simulate the virtual point absorber in WEC-Sim using the same PTO damping as corresponds to valve setting, determined in Step 2.
6) Compare experimental OWC water surface motion and power (i.e., chamber pressure times stack flow) to simulated virtual point absorber body motion and power.

The key assumptions and limitations in the modeling are as follows:

1) The simulation model does not include any air compressibility effects (although they could be added, and this would be a good topic for future research).
2) The hydrodynamics are assumed to be linear, based on potential flow theory.
3) The turbine is modeled in the hardware as a controllable butterfly valve, therefore no stalling behavior is present [27].
4) The flow impedance of the orifice plate is not considered separately from the airflow impedance of the butterfly valve.

IV. Open Barrel

As an initial comparison, the barrel is left open and the experimental OWC water surface elevation for regular waves is compared with the predicted motion of the virtual body in WEC-Sim. The results are shown in Fig. 5. The results show that the simulation of the virtual point absorber motion match the actual measured water surface elevation well, with error between simulation and experiment around 10% or less except for waves at a 1.6 second period. Here a resonance is predicted for the virtual point absorber, but this is not seen in the OWC experiment, causing an error of 27% at a period of 1.2 s and 274% at a period of 1.6 s. This result is actually fairly typical when comparing linear hydrodynamic theory to experiment: actual damping effects tend to be more significant and have a larger impact on reducing device motion than is predicted by the linear theory, which can typically predict very low intrinsic mechanical impedances at or around the resonant frequency Therefore, care must be taken in all comparisons near this frequency.

V. PTO Modeling and Determination of Effective Damping

In an Oscillating Water Column, an air turbine would be placed at the chamber aperture to capture the energy in the air as it rushes in and out of the chamber. In the Oscillating Water Column prototypes used in this research, an automotive butterfly valve located in the stack is used to emulate the turbine. The valve angle is controlled via stepper motor, with an angle of 0 degrees representing a closed valve, and an angle of 90 degrees representing a fully open valve. When the valve is open, there is very little impedance to air flow in and out through the stack, and the air pressure above the water in the chamber is approximately atmospheric pressure.

When the valve is nearly closed, the airflow impedance is high. When the water in the chamber rises with an incoming wave, the air above the chamber will exit through the stack, but only slowly due to the high impedance. Thus the air above the water will be pressurized above atmospheric pressure, and will exert a force downward on the water equal to the pressure times the chamber area. When the wave is retreating, the water in the chamber will fall, which will cause the air pressure in the chamber to decrease below atmospheric, which will cause a relative upward force on the water.

Therefore, when we consider the water in the chamber to be solid, as in the case of modeling the OWC as a virtual point absorber, the valve position is analogous to PTO damping: force on the virtual body proportional to body velocity.

This relationship is quantified by a series of experimental hardware tests in which the chamber pressure and water surface velocity are plotted against value position and regular wave period, shown in Fig. 6. The slope of the chamber pressure vs water surface velocity is the equivalent PTO damping for the virtual point absorber, and is shown as the value B in each plot.

In the plots we see the expected major relationship that decreasing the valve angle increases the air flow impedance and thus increases the effective damping. However, there are some higher-order effects present. In some of the plots, particularly in the middle-left, a noticeable hysteresis is visible. This is due to compressibility of the air. If the working fluid (i.e., air, in this case), were not compressible, there would be a one-one relationship between the water surface speed and the speed of the fluid. However, in the case of the air, there is now a phase delay between the water surface position, and the build-up of pressure that creates the flow through the stack. Therefore, on a phase plot, like pressure vs. velocity such as is plotted, we expect an open shape. If the system were linear and the excitation perfectly sinusoidal, the shape on the phase plot would be a perfect ellipse.

We see an additional non-linearity in that the linear damping approximation tends to over-predict the damping at low speeds and under-predict the damping at high speeds. In other words, the damping shape is that of something like a quadratic instead of perfectly linear. This is due to the fact that pressure across a pipe or aperture is related to the square of the flow.

Therefore, the expected presence of compressibility *and* non-linear pressure-flow relationships are directly visible in the results.

The question then follows, is a linear damping approximation, which ignores compressibility and a non-linear pressure-flow relationship, adequate? That question is addressed in the experimental comparisons of the next section.

VI. Regular Waves: Modeling and Experimental Comparison

Regular wave comparisons of displacement (i.e., position) and power are shown in Fig. 7 and Fig. 8, respectively. The significant wave height is 0.136 m and the period is varied between 1.2 sec and 3.3 sec. The valve angle (and hence effective PTO damping) is varied between 0 deg (fully closed) and 80 deg open. For wave periods of 1.9 sec and greater, there is a generally good agreement between experiment and simulation. However, as predicted in Section IV, there is a deviation in performance most pronounced around the resonant frequency of the simulated virtual point absorber, where the simulated virtual point absorber is predicted to have large motions and produce more power than was observed in the OWC.

The modeling accuracy, as shown in Fig. 7 and Fig. 8, expressed as Mean Absolute Error using a base of 0.08 m for amplitude and a base of 8 W for power, is given in Table I.

The results confirm that near the resonant periods the modeled results deviate in heave motion amplitude by 11.4%, and 25% in power, with the simulated results generally over-predicted. Generally however, outside of the resonant periods, the modeling is fairly accurate with mean absolute errors generally 5% or less.

Period	Amplitude MAE	Power MAE
1.2 s	4.2%	2.5%
1.6 s	11.4%	25.0%
1.9 s	3.0%	11.9%
2.3 s	1.7%	4.5%
2.6 s	2.5%	1.9%
3.3 s	3.5%	4.9%

TABLE I
Accuracy of Modeling in Regular Seas

VII. Irregular Waves: Modeling and Experimental Comparison

For irregular sea conditions, 10 different trials were run in which valve angle (PTO damping for simulation) was varied for a single sea state of peak period 2.6 s and significant wave height of 0.136 m. The results are shown in Fig. 9. The results show very good matching, with the simulated results having a very slight over-prediction of power for moderate valve angles. The Mean Absolute Error (MAE, using a base power of 3 W), over all valve angles is 2.0%.

This is further illustrated in the probability distribution shown in Fig. 10. The probability distributions are formed from the analysis of the experimental OWC and simulated virtual point absorber power timeseries. The probability mass functions provide more detail, and show that for high damping values (i.e., low valve angles), the simulation under-predicts the power, where at larger valve angles, the simulation over-predicts higher power events and under-predicts low power events.

VIII. Conclusion

This work sets out to evaluate the effectiveness of modeling an Oscillating Water Column (OWC) as a point absorber. The reasons for this approach include the ability to leverage the considerable foundational modeling and control knowledge of point absorbers and floating bodies to the relatively less studied wave and fluid flow dynamics of the OWC.

The results show that the virtual point absorber approach does in fact demonstrate fairly strong accuracy to modeling the OWC within certain limitations. First, a good model of the virtual point absorber PTO damping as how it relates to the OWC air flow impedance is necessary. It has been demonstrated that a straightforward set of empirical tests can determine this model. Second, it must be understood that frequencies near the resonant frequency of the virtual point absorber will yield simulated estimates of power and motion larger than will be observed in the actual OWC. This is a caveat that actually applies to many wave modeling problems in which linearity is assumed: performance at resonance will typically be over-predicted. Third, the compressive effects of the chamber air tend to create a hysteresis in the observed PTO damping.

For regular waves, the accuracy of modeling an OWC as a point absorber was generally within 5%, except near the device resonant period, in which case the heave amplitude modeling

Fig. 6. PTO damping approximation. Each subplot is chamber pressure (i.e., PTO force) vs. chamber water surface vertical speed. The slope of the best fit line then represents the effective damping for that valve setting. The rows of the subplots are for different periods of regular waves, and the columns are OWC valve positions.

error was 11.4% and the power modeling error was 25.0%. For an irregular sea state of dominant period 2.6 s, the modeling accuracy in power was 2.0%.

In conclusion it is demonstrated that the presented modeling technique is a reasonable first order approximation for modeling and control development, provided the limitations near the resonant period are taken into account. However, in a real seas environment, only a portion of the energy and interactions are happening at or near resonance. The irregular seas results show that when the total energy conversion across all frequencies is accounted for, it does not add significant error to the total performance. Indeed, for irregular sea conditions, the modeling shown in this paper was found to only have a few percent error compared against the experimental results, thus making the demonstrated method a strong tool for predicting performance and helping to expedite the OWC design process.

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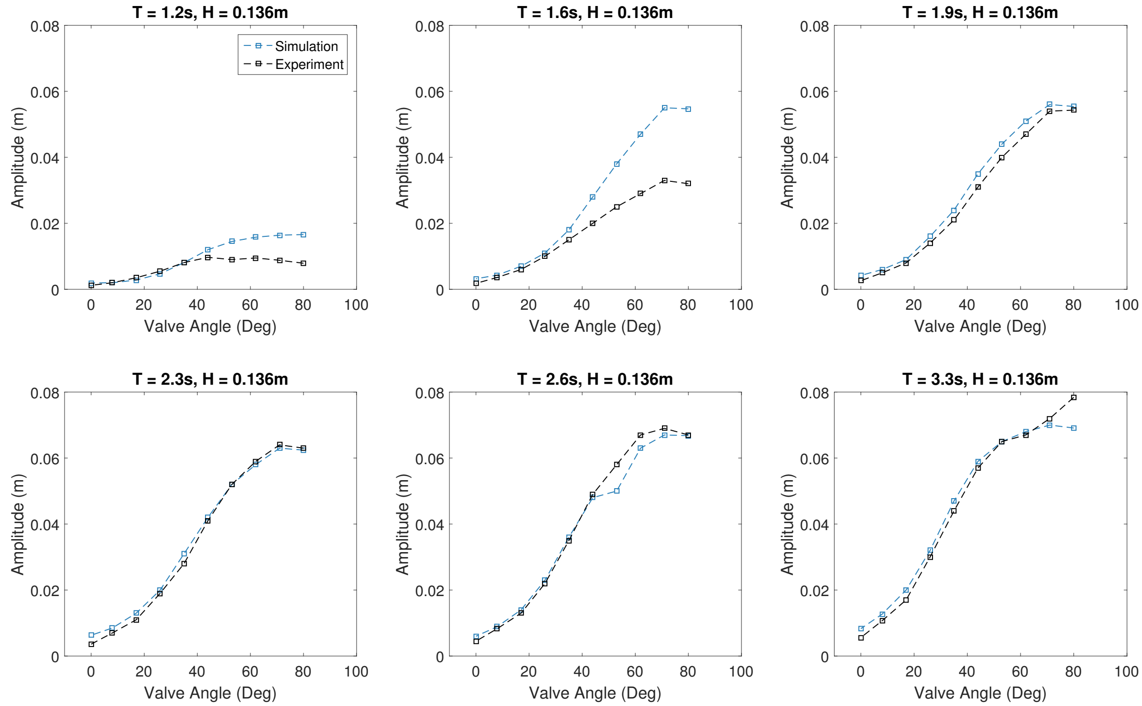

Fig. 7. Comparison of experimental OWC chamber water elevation and virtual point absorber body elevation for varying regular sea periods. The results show a relatively good match except for regular wave frequencies near the virtual point absorber resonant frequency.

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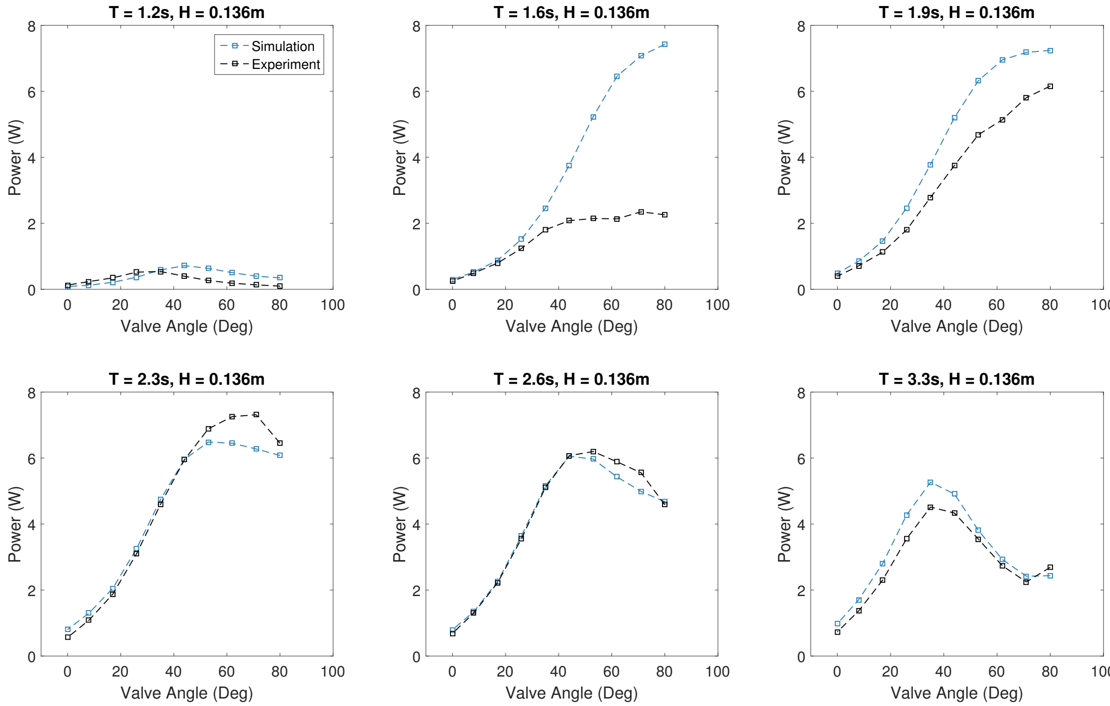

Fig. 8. Comparison of experimental OWC PTO power and virtual point absorber PTO power for varying regular sea periods. As with the motion plot above, the results show a relatively good match except for regular wave frequencies near the virtual point absorber resonant frequency, but near the resonant frequency, the simulated results over-predict the experimental.

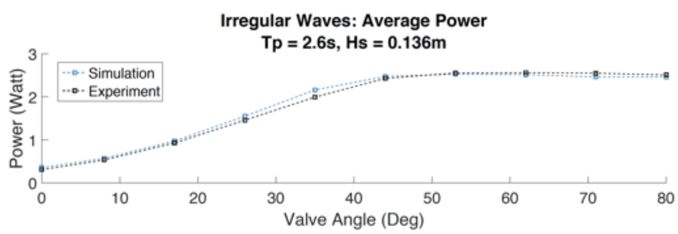

Fig. 9. Power in irregular waves. The mean absolute error between simualtion and experiment (using a base power of 3 W) is 2.0%

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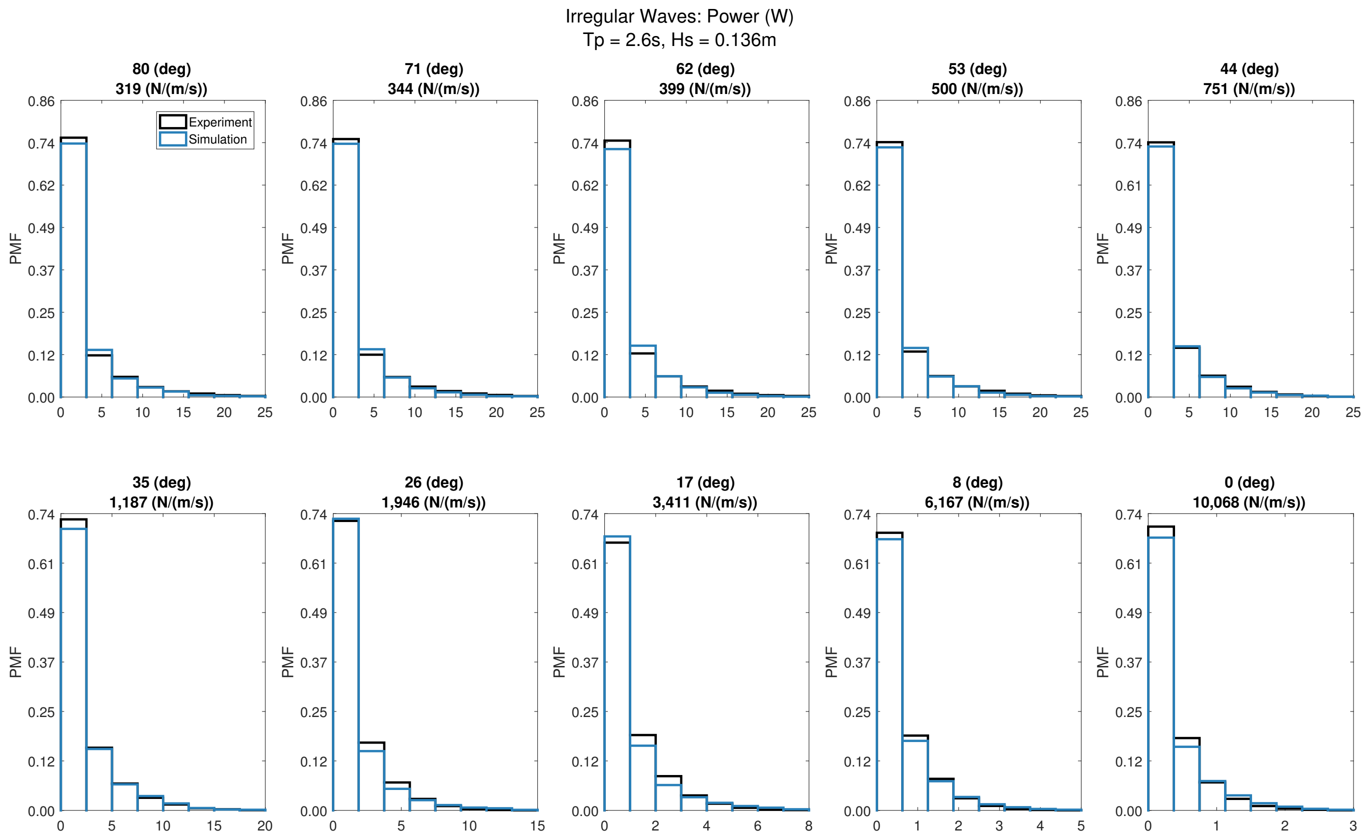

Fig. 10. PMFs for irregular waves.

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