WEC-SIM MODEL VALIDATION OF THE AZURA PROTOTYPE DEVICE

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ABSTRACT

A wave to wire time domain numerical model of the Azura prototype wave energy converter (WEC) was developed using WEC-Sim. A detailed model of the hydraulic power takeoff (PTO) system was included. Two versions of the model were developed, the first using a fully linear hydrodynamics model and the second using nonlinear hydrostatic and Froude-Krylov forces. The device was simulated using both models in a variety of irregular wave conditions. Simulation results were compared to experimental results from an ongoing ocean test of the Azura prototype that is taking place in Hawai'i. The WEC-Sim results generally show good agreement with observed mean power, estimated annual energy production, and response amplitude operator results. The nonlinear model results match experimental data more closely than the linear model.

INTRODUCTION

The Azura is a prototype wave energy converter (WEC) that is owned by Northwest Energy Innovations (NWEI) and is currently undergoing ocean testing at the grid connected 30 meter berth of the US Navy's Hawai'i Wave Energy Test Site (WETS). The deployment, which began in June 2015, is scheduled to last one year. The goals of this test include proving ocean viability and collecting performance data to aid in commercialization of the technology.

The Azura is a two-body point absorber device. It consists of a large reactive hull and an active float that can rotate 360°. The relative rotation of the active float and reactive hull drives a hydraulic power takeoff to harness energy. The configuration of the active float allows energy to be harvested from both the heave and surge motions of the device. A photo of the Azura device at WETS is shown in Figure 1.

The focus of this extended abstract is on validation of NWEI's performance model of the Azura device. Many of the numerical methods used to model WEC performance have been adapted from techniques used to model

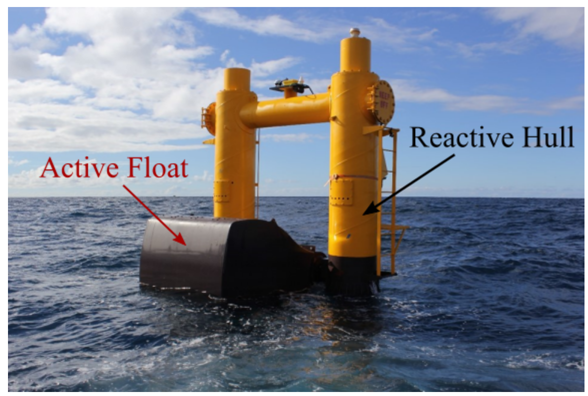

Figure 1: The Azura prototype device deployed in Hawai'i.

large ships and floating platforms. One potential problem with this approach is WECs are designed to operate differently than large ships. Instead of minimizing motions, WECs are often designed to operate near resonance. While a growing amount of data is being made available from small scale wave tank tests, performance data from large scale WEC deployments is still extremely limited. Due to this fact, there is still some uncertainty in how well different modeling approaches will predict energy capture of WECs in the open ocean.

In this extended abstract we present validation results of a performance model developed using WEC-Sim [1]. The model is a wave to wire time domain model that includes a detailed PTO model, hydrodynamic forces, viscous losses, and a simplified mooring model. Simulation results are compared to experimental data from the Azura prototype Hawai'i deployment. Since the primary goal of a performance model is estimating annual energy production (AEP), results are compared for irregular wave runs in various bins of the device power matrix. Including a detailed PTO model allows for more accurate estimates of AEP that account for system losses, but also introduces additional model complexity and uncertainty into the WEC-Sim Model.

The accuracy of two different model configurations are compared, one using a linear hydrodynamic model and the second using a weakly nonlinear hydrodynamic model. Numerical results presented here are either normalized or shown as percent differences relative to experimental data in order to protect NWEI proprietary information.

METHODOLOGY

Performance modeling of the Azura used the open-source WEC-Sim code, developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories [2]. WEC-Sim solves the time-domain equations of motion for a WEC in Matlab-Simulink. See Figure 2 for the Simulink diagram of the Azura WEC-Sim Model.

WEC-Sim requires some external information to model a WEC. One necessary piece of information is boundary element method results containing the linear radiation, diffraction, and Froude-Krylov force coefficients. All boundary element results for this work were generated using NEMOH, an open source code developed at Ecole Centrale de Nantes [3]. Salome-Meca software was used to generate input meshes for NEMOH [4]. Estimation of viscous drag coefficients is also required by WEC-Sim, as viscous losses can have a significant impact on the amount of power produced by a WEC [5]. For this modeling work drag coefficients were tuned until simulation results closely matched recorded data. Moments of inertia, also required to run WEC-Sim, were obtained directly from CAD models.

In addition to applying linear wave theory to calculate excitation and buoyancy forces, WEC-Sim has the option to calculate the buoyancy and Froude-Krylov force using a weakly nonlinear approach [1]. This weakly nonlinear approach calculates the Froude-Krylov and hydrostatic forces based on the instantaneous water surface elevation and body positions. A discretized representation of the body is used to perform the calculation. This approach has the potential to improve the modeling of accuracy of bodies that have a wetted cross sectional area that changes radically near the mean free surface. In this work we compare results using the linear and nonlinear method for the active float. Linear theory is used for the hull in both cases.

A dynamic model of the PTO is required to use WEC-Sim. A detailed dynamic model of the Azura hydraulic PTO was developed in Matlab-Simulink and coupled to the WEC-Sim model. The PTO model accuracy was validated independently from the hydrodynamics for a variety of sea states. Experimental float angle data was used as an input to the hydraulic model. Simulated PTO torque and output power were compared to experimental data. These checks showed that the Simulink model accurately predicted output power within 10% over a wide range of operating conditions. The detailed configuration of the hydraulic PTO is not presented here to protect NWEI proprietary information.

A simple mooring model is also included in the WEC-Sim model. The Azura uses a 3 point, taut mooring designed to minimize the forces on the Hull in the heave direction. WEC-Sim allows for inclusion of a mooring stiffness matrix in the form

$$F_m = K_m x, \tag{1}$$

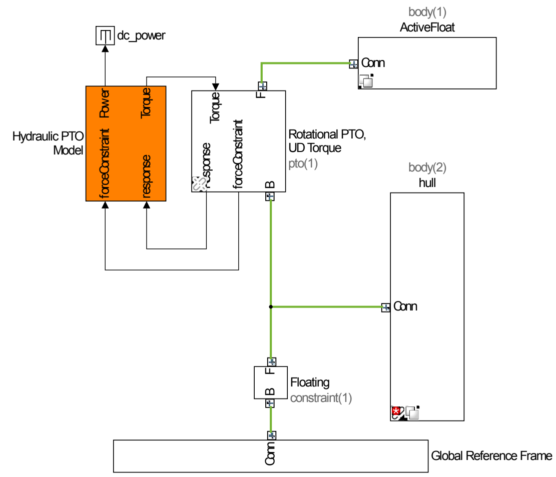

Figure 2: WEC-Sim Simulink diagram of the Azura prototype device.

where x is the position vector of the hull, and K_m is the mooring stiffness matrix. To determine the mooring stiffness matrix, a quasi-static model of the mooring system was developed. This quasi-static model was then used to estimate the effective mooring stiffness K_m.

EXPERIMENTAL DATA

The Azura device is heavily instrumented to measure motion, crucial PTO parameters, and power output during ocean testing. Two independent data acquisition systems (DAS) are installed on board the Azura prototype to record the operational data that was used to validate numerical model results. An NWEI DAS records output power and PTO data such as hydraulic pressure and flow, electrical currents and voltages, and float angle. A DAS installed by NREL records device heave, pitch, and roll motion, mooring loads, compass heading, and device GPS location. The two DAS collect data at 10 Hz and 20 Hz sampling rates respectively. Directional wave spectral data is recorded by a Datawell DL Waverider® buoy that has been deployed by the University of Hawai'i near the device.

For comparison to model results, experimental data from July through October of 2015 was binned according to the IEC Technical Specification 62600-100 regarding power performance assessment of wave energy converters [6]. The normalized power matrix binned by significant wave height and energy period as well as annual energy production estimated from this data is used for comparison with model results.

WEC-Sim requires a wave spectrum input for each sea state simulated. A representative spectrum for each significant wave height and energy period bin was determined by averaging each measured wave spectrum recorded by the Waverider® buoy in each bin. This process developed an average wave spectrum for each bin in the sea state occurrence matrix.

SIMULATION RESULTS

The WEC-Sim model's accuracy was checked against experimental data in various ways, three of which are presented here. First shown is a comparison of simulated and experimental output power for high occurrence bins of the power matrix. Second, AEP estimations at WETS calculated from both simulated and experimental data are compared. Finally, response amplitude operators generated from simulated and experimental data for hull heave and float angle are compared.

Power Matrix Comparison

WEC-Sim models were run for a selection of bins in the power matrix. Due to the high computation cost of running the hydraulic PTO model and a weakly nonlinear WEC-Sim model, not all bins were simulated. All bins with an occurrence greater than 5% at the test site were run, along with some additional strategic bins. The most frequently occurring conditions at WETS are wave heights between 1 to 2 meters, and energy periods between 6 and 9 seconds.

For each simulated bin, both the linear and weakly nonlinear WEC-Sim model was run. The percent difference between the simulation results and experimental data for each power matrix bin is shown in Figure 3. Each simulation was run for 1000 seconds, with a step size of 0.0002 seconds. Fast dynamics in the PTO model necessitated the small simulation step size. The radiation forces were calculated using the state space model approximation. For the nonlinear hydrodynamic simulations, the nonlinear force terms were calculated at a reduced step size of 0.01 seconds to reduce runtime.

The linear model's percent error in power prediction ranges from -10% to 38%, with the accuracy in the most frequent bins falling between 5% to 25%. The nonlinear model's percent errors ranged from -13% to 35%, with accuracy in the most frequent bins falling between -5% and 21%.

The nonlinear model provides more accurate power capture predictions than the linear model for significant wave heights greater than 1 meter and energy periods less than 10 seconds. This indicates that the drastically changing cross sectional area of the active float has a significant effect on the response of the float. Not accounting for this nonlinear effect increases estimated power capture in many power matrix bins.

Both models significantly overestimate power capture for significant wave heights less than 1 meter. This error is likely caused by errors in the hydraulic PTO model, which is more difficult to model in low energy sea states. Since these bins in the power matrix do not contribute significantly to AEP due to the low incident wave energy, less emphasis was placed on improving the PTO model in this operating regime.

AEP Results

AEP at the WETS test site was calculated using the WEC-Sim power matrix results described in the preceding section. To estimate power produced in the bins without results or data, a 2D-plane was fit to the available data using a least-squares approach. This plane was used to estimate power values only in empty bins. The percent error of the AEP estimates calculated from WEC-Sim results are compared to experimental data in Tab. 1. This approach to estimating power produced in bins may introduce additional error to the AEP calculation method. These additional errors are minimized by only using the best fit plane to estimate power output in infrequently occurring power matrix bins. A more rigorous approach to estimating power output in bins without simulation results is a potential area of future work.

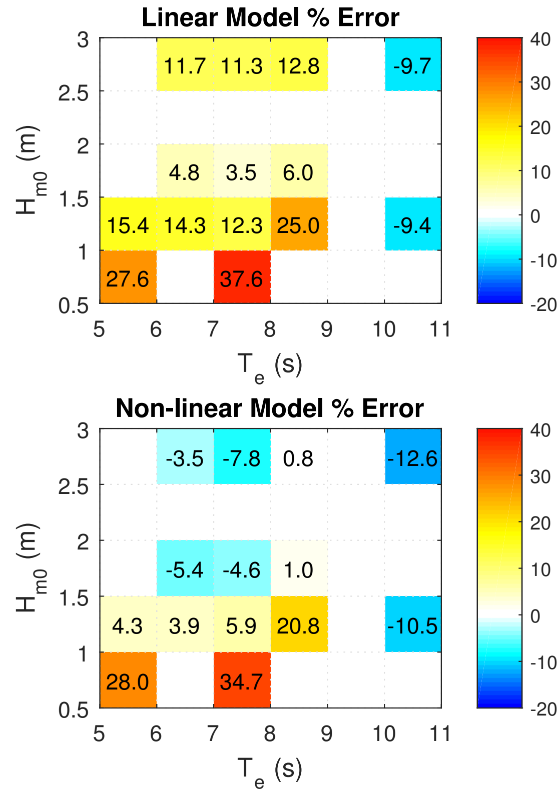

Figure 3: Power matrix showing percent difference between WEC-Sim electrical power capture and mean experimental power capture. A positive value indicates the WEC-Sim model over-predicted power produced.

Table 1: Percent error in AEP estimates for both WEC-Sim models relative to WETS experimental data.

Model	Pct. AEP Error
Linear	9.8%
Nonlinear	1.0%

The AEP estimated using the nonlinear WEC-Sim model matches the AEP estimated using experimental data very closely. The linear WEC-Sim model slightly overestimates AEP, which is consistent with the power matrix results. When nonlinear hydrodynamic effects are not modeled, AEP is overestimated.

Response Amplitude Operator Results

A response amplitude operator (RAO) analysis was also performed to ensure that WEC-Sim accurately models the motions of the Azura device. Since it is a complex vector, it contains both magnitude and phase shift information. If the water surface elevation spectrum is known at the device location, a complex RAO can be calculated using Eqn. 2, where S_{xx} is the wave spectrum, and S_{xy} is the cross spectrum between response and waves.

$$H(\omega) = \frac{S_{xy}(\omega)}{S_{xx}(\omega)} \tag{2}$$

Otherwise, if water surface elevation measurements made close to but not at the device are used, the RAO magnitude with no phase information can be calculated using Eqn. 3, where S_{yy} is the response spectrum.

$$|H(\omega)|^2 = \frac{|S_{yy}(\omega)|}{|S_{xx}(\omega)|} \tag{3}$$

For the WEC-Sim model results water surface elevation at the device is known, so Eqn. 2 was used. RAOs were calculated from experimental data using two methods. The first method used wave spectra data recorded by the Waverider® buoy located near the device to calculate RAO magnitude using Eqn. 3. The second method used data from a water pressure sensor located on the Azura's hull below the water surface to reconstruct the water surface elevation time series data at the device using linear wave theory. Complex RAOs were than calculated using this data. While the magnitude of wave spectra calculated using pressure sensor data is likely less accurate than wave spectra data from the Waverider®, the water pressure data analysis allowed complex RAOs to be calculated from experimental data that include valuable RAO phase information.

The RAO analysis was performed for two key modes of motion, the heave of the hull and the relative angle between the float and hull (float angle). RAOs were calculated from the irregular wave WEC-Sim model results for bins with significant wave heights between 1-3 meters, and energy periods between 5-9 seconds. The complex RAO from each of these cases was then averaged. RAOs from the experimental data were calculated using both methods from 5 different 30 minute data sets covering a range of sea states. The experimental RAOs were then averaged for smoothing.

Plots comparing the WEC-Sim and experimental float angle and hull heave RAO results are shown in Figures 4 and 5 respectively. The y-labels on the RAO magnitude plots were removed to protect NWEI proprietary information. There is not a significant difference between the RAO results for the linear and nonlinear WEC-Sim results. The linear WEC-Sim float angle magnitude is slightly reduced from the nonlinear model results, but all other RAO values match very closely.

The WEC-Sim RAOs closely match the experimental RAOs between wave periods of 4 to 9 seconds. There is some difference between the modeled and experimental RAO magnitudes at periods less than 3 seconds and greater than 10 seconds. This discrepancy is thought to be caused by a combination of numerical errors and sensor inaccuracies at higher and lower frequencies.

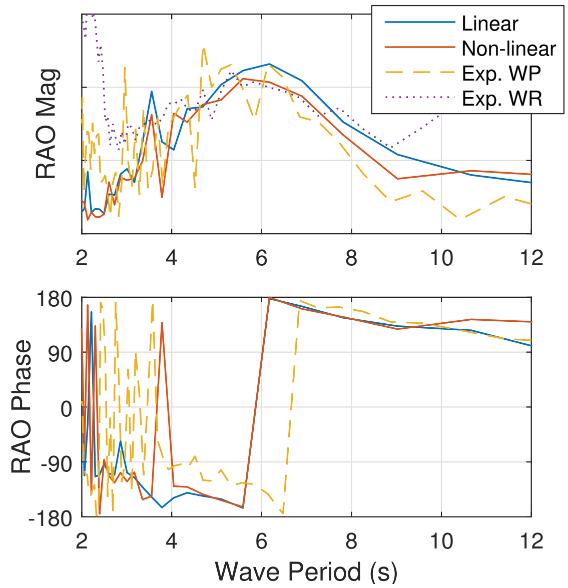

Figure 4: Float angle RAO magnitude and phase. Exp. WP indicates RAO data calculated from water pressure sensor, Exp. WR indicates results calculated using Waverider® data.

DISCUSSION

A wave to wire WEC-Sim model of the Azura device was developed, that included a detailed model of the hydraulic PTO. Model results from irregular wave simulations in a variety of representative wave spectra at the deployment location were compared to experimental data. Comparisons of model accuracy were made for individual power matrix bins as well as overall AEP predictions.

Two WEC-Sim configurations were tested, one using linear hydrodynamic forces, and the other using a weakly nonlinear model that calculates the hydrostatic and Froude-Krylov force based on the instantaneous water surface elevation and body position of the active float. While both WEC-Sim models did a reasonable job predicting power capture, the nonlinear model was more accurate in a wider range of sea states. There is also close agreement between simulation and experimental results for hull heave and float angle RAOs. No significant difference was seen between RAO results from the linear and nonlinear WEC-Sim models. Other errors in the modeling that were identified include inaccuracies in the viscous drag model, the linearized mooring model, inaccuracies in the PTO model at long wave periods, and sensor measurement errors.

The results show nonlinear hydrodynamic effects have a significant effect on power capture predictions for the Azura prototype. This is not necessarily true for all WEC designs, but should be considered for geometries where the cross sectional area changes significantly near the mean water line.

1. ACKNOWLEDGEMENTS

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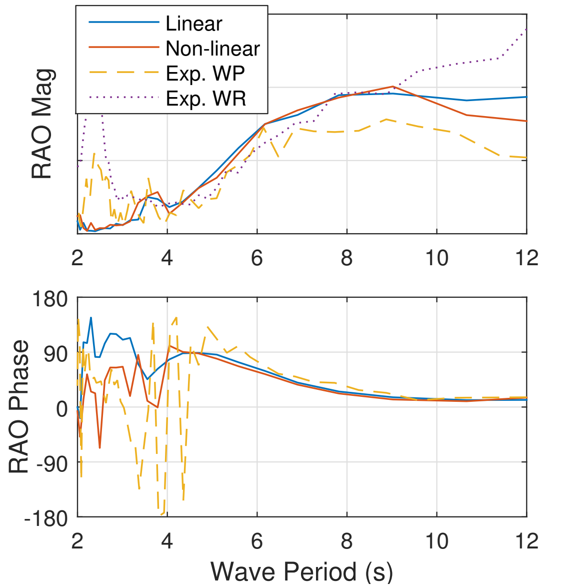

Figure 5: Hull heave RAO magnitude and phase. Exp. WP indicates RAO data calculated from water pressure sensor, Exp. WR indicates results calculated using Waverider® data.

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