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NUMERICAL and EXPERIMENTAL ANALYSIS of a NOVEL WAVE ENERGY CONVERTER

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ABSTRACT

A novel point absorber wave energy converter (WEC) is being developed by Columbia Power Technologies, LLC (CPT). Numerical and physical experiments have been performed by Columbia Power, Garrad Hassan and Partners (GH) and Oregon State University (OSU). Three hydrodynamic modeling tools including WAMIT, GH WaveFarmer, and OrcaFlex are used to evaluate the performance of the WEC. GH WaveFarmer is a specialized numerical code being developed specifically for the wave energy industry. Performance and mooring estimates at full scale were initially evaluated and optimized, which were then followed by the development of a 1/33rd scale physical model to obtain comparable datasets, aiming to validate the predictions and reduce the uncertainty associated with other numerical model results. The tests of the 1/33rd scale model of the CPT WEC were recently carried out at the multi-directional wave basin of the O.H. Hinsdale Wave Research Laboratory (HWRL), in conjunction with the Northwest National Marine Renewable Energy Center (NNMREC) at OSU.

This paper presents details of the modeling program and progress to date. Emphasis is given to the coupling of WAMIT with GH WaveFarmer for performance estimates and the coupling of WAMIT with the OrcaFlex model for mooring load estimates. An overview of the novel 3-body WEC, including operation and mooring system, is also presented. The 1/33rd scale model functionality is described including an overview of the experimental setup at the basin. Comparisons between the numerical and experimental results are shown for both regular and irregular waves and for several wave

headings and dominant directions using a number of spreading functions. The paper concludes with an overview of the next steps for the modeling program and future experimental test plans.

1.0 INTRODUCTION

Ocean wave energy has great potential to be a significant contributor of renewable power for many regions in the world. The development of a WEC is an undertaking which involves multiple tasks which in turn require diverse expertise. Maximizing energy extraction under normal operating conditions and mooring a wave energy device to ensure survivability in extreme conditions requires much research and development. Furthermore, the development program requires careful planning and sufficient steps of increasing complexity to optimize the design, reduce the uncertainty associated with performance, ensure appropriate mooring and survivability to mitigate the risks and reduce costs.

When developing a new WEC the ability to evaluate the impact of significant design changes in the performance of the machine relatively quickly and at a low cost is of pivotal importance. The development of a numerical simulation which is able to address these issues is the typical answer to such a problem. Although there are some similarities with the offshore oil & gas industry in terms of the numerical tools that can be applied, the specific nature of wave energy conversion often requires that custom-made numerical approaches are developed. CPT has been working with GH, which is currently developing a numerical package that loads the hydrodynamic properties from an external solver (WAMIT in this instance)

for all the bodies that constitute the WEC, locks the relevant degrees-of-freedom and iterates on the control strategy and other external forces. The use of such tool allowed the design assessment of more than 6,000 configurations from a total of five initial concepts, converging into the design presented in Section 2.

To increase confidence in the numerical predictions, allowing its extension to develop complex models, an experimental modeling program at various scales has been devised (also with the assistance of GH). The complexity and size of the experimental models is also staged, to allow a detailed assessment of particular phenomena related to either moderate (performance) or extreme (survivability) sea states. Such experimental program capitalized on the proximity and familiarity of the CPT engineering team with the experimental facilities at OSU, namely the Tsunami Wave Basin (TWB). In the present paper the validation of the performance predictions estimated via GH WaveFarmer with the experimental results from a 1/33rd scale model tested in the TWB are presented.

2.0 SYSTEM DESCRIPTION

The CPT WEC (Manta) is designed to absorb wave energy in both heave and surge motions that produce relative pitch between the floats and spar; the relative surge and heave motions are depicted in Fig. 1. The system converts the heave and surge motion into high torque rotary motion, using direct drive rotary (DDR) generators to provide simple and reliable energy conversion [1].

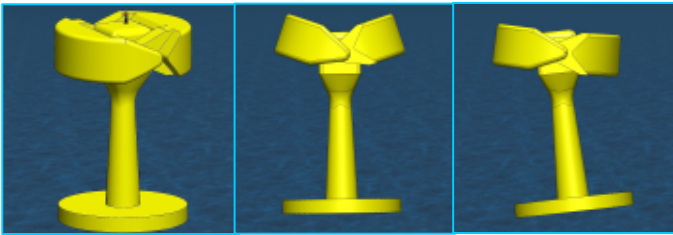


Fig. 1. CPT Manta.

The buoy is comprised of three moving bodies; fore float, aft float and spar. The spar is designed to stay relatively stationary in heave by using a large damper at its base. Each float is connected to the top of the spar through a drive shaft. The forward float is connected to the starboard DDR generator and the aft float is connected to the port drive shaft and generator. Normally oriented with the fore float heading into the wave, the incoming heave and surge forces of the waves force the fore float and aft float to rotate about the spar and drive the generator. Approximate full scale diameter is 18m and draft from surface to the lowest point on the buoy is 25m.

3.0 NUMERICAL MODELING OVERVIEW

Models have been developed for performance and mooring evaluation. GH Wave Farmer is coupled with WAMIT, power takeoff (PTO) loads, WEC mass matrices, inertial matrices,

and mooring loads to evaluate energy capture performance of the WEC and to optimize its shape.

OrcaFlex was chosen under this project as the main hydrodynamic modeling tool for mooring analysis. OrcaFlex is a time domain tool which gives it the capability to model nonlinear mooring arrangements where frequency domain modeling cannot. The model added mass and damping terms are imported from the WAMIT frequency-domain modeling.

3.1 GH WAVEFARMER MODEL

The GH WaveFarmer software package consists of an equation of motion solver for each specific module: frequency and time domain, respectively. The hydrodynamic properties, i.e., the solution of the radiation problem (added-mass and radiation damping coefficients) and of the diffracting problem (exciting force), are loaded from WAMIT, for all the bodies that constitute the WEC (three in the case of the CPT WEC). As these are dependent on geometry alone, iteration on the wetted profile requires a new WAMIT model. The GH WaveFarmer kernel then queries the user with regard to which modes of motion are physically locked to which (e.g., if all bodies move coherently in surge, there is only one surge in the equation of motion and not N , with N being the number of bodies), which results in the reduction of the computational burden and a better link between the numerical model and the physical reality (less subject to numerical inaccuracies if, e.g., large external stiffness matrices are used to artificially lock degrees-of-freedom).

The mass matrix of the assembly is also loaded as an input to the simulation, as are the control parameters of the external forces; these include both the PTO and the mooring force. For the former, and for validation with the 1/33rd scale design, linear damping characteristics were modeled. A final input to both modules is the sea state, which can be defined via regular or irregular waves. For the latter, real (measured) or modulated spectra (Pierson-Moskowitz, Bretschneider or JONSWAP) can be used as input. Currently GH WaveFarmer is being extended to model the performance of multiple WECs in a wave farm.

The frequency domain module of GH WaveFarmer allows the calculation, along with the response amplitude operator (RAO) and the relative capture width (RCW), of response surfaces which give the average absorbed power as a function of the sea state, the PTO damping coefficients and the control strategy. The results can then be taken into account when doing more detailed assessments in the time domain module of GH WaveFarmer, which allows nonlinear external (mechanical) forces to be modeled (unlike its frequency domain counterpart). The most critical variables that can be assessed in the time domain include the PTO force / moment, the motion and velocity in all relevant degrees-of-freedom and the instantaneously absorbed power. A representative example of RCW performance is shown in Fig. 2. The actual damping

coefficients, wave period, and RCW values are omitted due to their proprietary nature. Plots of this type provide for informed decisions regarding device optimization. Of particular note is the ability to model the control of device performance using different values of damping (B) and to extend the frequency response to a wide range of wave periods.

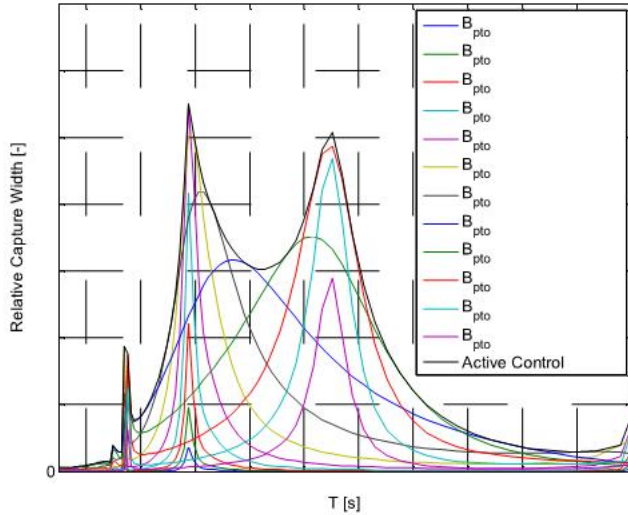


Fig. 2. RCW vs. Period (T) and damping (B).

The core objective of the validation effort was to evaluate and optimize the WEC hydrodynamic performance. The exploration of non-linear PTO forces is of long term interest and will be evaluated during later stages of optimization. The ongoing modeling effort will take into account non-linear PTO forces to develop the most cost-effective WEC design. Time domain models have been used to perform an initial investigation on the capability of the model. Fig. 3 shows time domain predictions of instantaneous (red) and average (blue) power delivered from the WEC.

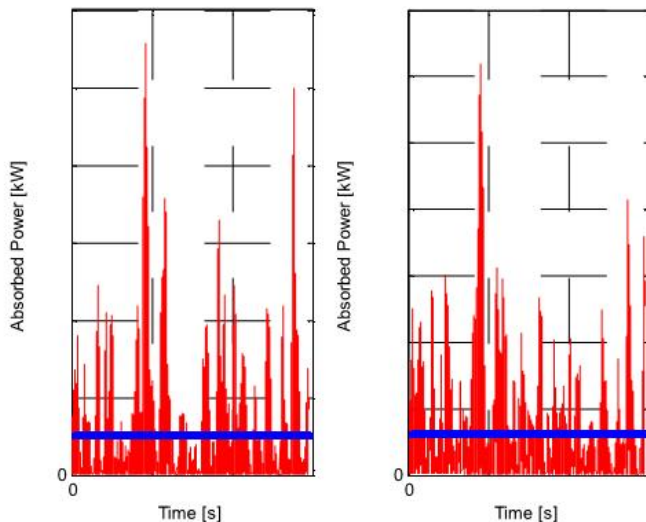


Fig. 3. Fore (left) and Aft (right) time domain power prediction.

3.2 ORCAFLEX MODEL

OrcaFlex is a time-domain numeric solver that gives an accurate numerical solution of the WEC response to external forcing functions and provides for graphical representation of these results to aid in the interpretation of how the numerical model correlates to the real world. Bodies modeled in OrcaFlex include buoy and vessel planar simulations in 3 degrees of freedom, and 3D simulations with 6 degrees of freedom.

OrcaFlex provides several basic connection types for modeling a variety of different mooring systems. These connections include springs, dampers, tethers, and lines. With these tools one can quickly define a variety of connection systems, such as multiple body interactions, multiple sea floor connections, linear or rotary linkages, and many other types of configurations. For example, a bearing can be modeled by adding two very stiff springs aligned perpendicular to the intended axis of rotation and to each other, thus as with a bearing, the object does not move in the plane normal to the axis of rotation and it is free to rotate about the defined axis. The line types can be customized to include structural damping, mechanical stress, frictional coefficients, stiffness parameters, spring rates, un-stretched lengths, and so forth in the analysis.

OrcaFlex contains a classification of bodies known as 6D Buoy which was initially chosen to model the Manta Buoy. 6D Buoys are used to model any style of surface piercing body that requires all six degrees of freedom in the numerical analysis. They also allow for the discrete characterization of hydrodynamic properties including volume, water plane stiffness, center of buoyancy, center of gravity, mass, and rotational inertia. The dynamic properties include the six dimensional terms of damping, drag, and fluid inertia. The physical properties from the tank test article are used to define the numerical 6D buoy.

Links were chosen for the connection components to model the real world system. Four spring links were used to model the floats' rotary bearings mounted to the spar, four additional damping Links were used to model the electrical generator damping, and 3 Links were used to model the Manta's mooring system. Fig. 4 shows the final OrcaFlex model, consisting of three 6D Buoys and eleven Links.

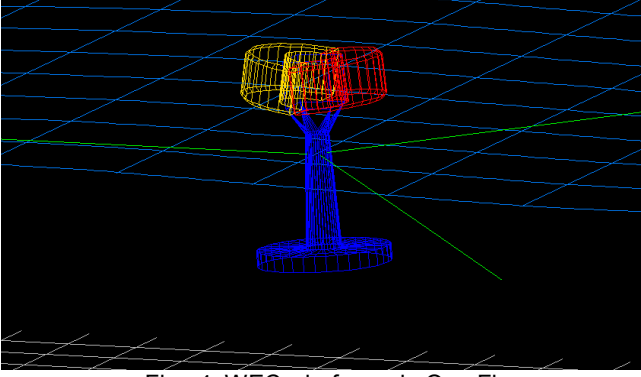


Fig. 4. WEC wireframe in OrcaFlex.

Unfortunately the spring and damper elements are limited to linear motion. Therefore in order to model rotary damping, i.e., the rotary electric generator, a novel arrangement of linear components is used. Ideally for the rotary generator damping the use of a simple velocity proportional damping coefficient would be used, given in (1) as:

$$T_{GEN} = B\omega \quad (1)$$

where T_{GEN} is the generator torque, B is the rotary damping coefficient in $[kNms]$, and ω is the rotational speed. Converting this to a generator force at a distance as in (2) allows for the implementation of a linear damper to closely approximate angular damping of the system.

$$T_{GEN} = F_{GEN} * r = c * \omega * r^2 \quad (2)$$

where r is the leverage arm and c is a linear damping coefficient $[kNs/m]$. However this only works for a damping force tangent to the rotating arm. With one end of a linear damper fixed at $x = \infty$ to Body 1 and the other end to Body 2 as depicted in Fig. 5, the angle between the moment arm and the damper tracks a sinusoid governed by (3).

$$T_{GEN} = c * \omega * r^2 * \cos^2 \theta \quad (3)$$

Conveniently, the trigonometric identity in (4) can be used to define two dampers 90° apart in order to model a constant rotational damping. This relationship allows for modeling of generator torque that is proportional to speed and independent of position as in (5).

$$\cos^2 \theta + \sin^2 \theta = 1 \quad (4)$$

$$T_{GEN} = c * \omega * r^2 * (\cos^2 \theta + \sin^2 \theta) \quad (5)$$

Fig. 5 shows a graphical representation of this novel linear to rotary damping arrangement that creates a perfect velocity

proportional torque.

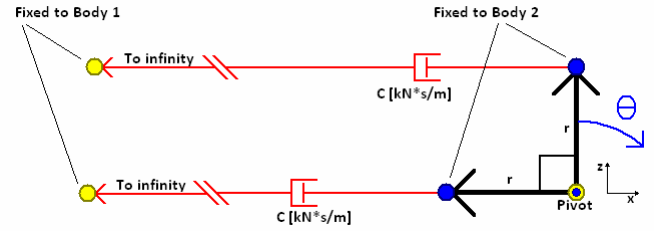


Fig. 5. Diagram of linear to rotary damper arrangement.

For obvious reasons the dampers are fixed to Body 1 at a significantly large value rather than at $x = \infty$. Also by choosing $r = l$ the damping equation simplifies to (6).

$$T_{GEN} = c * \omega * (\cos^2 \theta + \sin^2 \theta) \quad (6)$$

4.0 WAVE BASIN EXPERIMENTAL TESTING

Experimental testing of the 1/33rd scale WEC was performed at OSU's O.H. Hinsdale Wave Research Laboratory (HWRL) in a three-dimensional wave basin with a large-stroke multi-directional wavemaker, shown in Fig. 6. Three separate data acquisition systems were used to gather WEC hydrodynamic and performance data; the HWRL data acquisition system, the dSPACE WEC data acquisition system, and a PhaseSpace optical motion tracking system. Three data acquisition systems collected more than 80 unique parameters during wave basin experimental testing. An array of nine resistive wave gauges and one acoustic doppler velocimeter (ADV) captured wave profile data that is used as input data to the numerical modeling. Calibration of these wave gauges was verified every morning prior to testing using a 10 point waterline check and a monochromatic wave test to check linearity.



Fig. 6. Directional wave basin at Oregon State University.

The process of tank testing of the WEC was performed by three researchers and a lead test coordinator. An organized and synchronized method was used for each specific tank test. A PhaseSpace calibration and alignment check was performed each morning in the tank along with the WEC and mooring

calibration and set-up.

Each of the systems' data sets recorded filename and trial duration for each specific trial, then processed at a sample frequency of 50Hz and aligned with a trigger signal. Scaled monochromatic waves of discrete frequency and amplitude provided RAO information using the PhaseSpace optical motion tracking system. The PhaseSpace system recorded motion with six degrees of freedom for each of the three WEC rigid bodies. The system provided sub-millimeter resolution at an initial sample rate of 480Hz. LED markers were mounted on rigid carbon-fiber rods, shown in Fig. 7, redundant LEDs ensured motion tracking of the bodies even if a portion of the LEDs were submerged. Each of the impulse LED markers has a unique frequency, allowing the PhaseSpace system to triangulate their coordinates in virtual space. Three associated markers can create a rigid body in PhaseSpace. On the WEC rigid bodies, six markers, three per pole, were used for higher redundancy and accuracy.

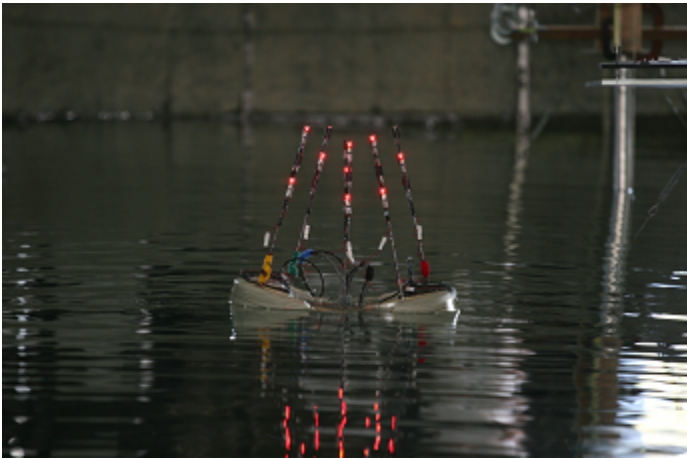


Fig. 7. PhaseSpace LED marker poles for WEC rigid body tracking in the wave basin.

A custom designed embedded controller (EC) was located in the nacelle of the WEC. A six-degrees-of-freedom inertial sensor, integrated into the EC, was used to monitor the linear acceleration and angular velocity of the spar in 3-axes of motion. The EC also monitored two high-resolution encoders, one attached to each of the rotary DC motor-generator dampers. The 4-quadrature output of each encoder is processed by the EC to accurately determine the angular position and velocities of the generator shafts relative to the WEC spar. In addition, the EC measures the torque at each generator shaft via two torque transducers integrated into the WEC. The data monitored by the EC was reported every 2ms to an onshore PC. The WEC motion data system was validated by the calibrated PhaseSpace optical motion tracking system and provided additional redundancy in the data collection.

Onshore computers, located approximately 20m from the

WEC test location, were used to capture the data reported by the PhaseSpace motion capture system and the WEC EC. A single board rapid prototyping system designed by dSPACE Inc. (DS1103) allowed PTO control optimization through an embedded proprietary control algorithm and allowed the data from the EC to be captured and recorded. The dSPACE data collection system captured parameters including the PTO speed and position (relative motion between float and spar), PTO torque, six axes of acceleration of the spar, an array of onboard temperatures, generator voltages and currents, mooring loads as well as the wave maker trigger signal used for data synchronization.

A custom designed software “control panel” was written for the DS1103, shown in Fig.8 that allowed an operator to view the current testing parameters in real time as the various tests were being performed.

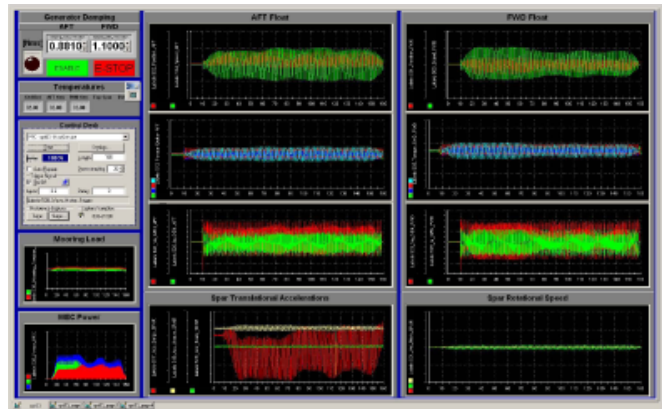


Fig. 8. Screen shot of dSPACE GUI during testing.

4.1 PERFORMANCE TEST RESULTS

PTO speed and torque are ultimately the most relevant parameters for performance analysis. It is also useful to recognize the magnitude and phase of the bodies' motions in order to develop a better understanding of how power is being absorbed.

Plotting PTO torque vs. speed was valuable in comprehending how well the PTO hardware and control system did to track the commanded torque. Verifying the linearity of this graph in Fig. 9 also allowed for diagnosing the PTO performance in real time.

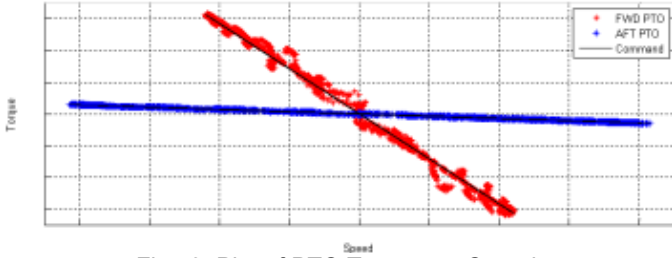


Fig. 9. Plot of PTO Torque vs. Speed.

Ultimately the control system maintains the PTO torque at the commanded set point as it shifts in real time. Fig. 10 shows how well the PTO controls worked in a realistic wave climate. Notice some small violations due to static friction in the model PTO about the zero crossing. For a 1/33rd scale test article operating in the region of Watts and milli- Watts, the precision with which its mechanical components, controls, and instrumentation performed is of particular note.

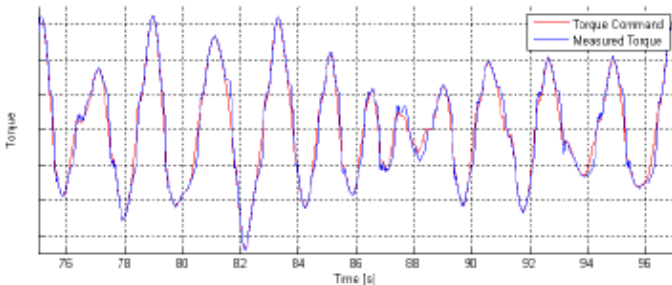


Fig. 10. Plot of Commanded Torque and Measured Torque.

4.2 MOORING TEST RESULTS

Testing revealed that mooring, in addition to holding a WEC on station in all wave climates may also have the ability to significantly affect performance. Experimental evaluation of differing mooring positions on performance allowed for identification of a preferred connection point.

The scaled wave basin experimental testing used a mooring approach that was based on a concept mooring design developed for full scale deployment. Unlike the rest of the scaled experimental WEC, exactly scaled mooring components do not accurately create the same effective mooring behavior due to the nonlinear viscous effects on relatively small lines. Rather than developing mooring components that would attempt to recreate the same behavior, a simplified single horizontal spring mooring line was used to achieve the target mooring spring rate. Mooring spring rate is a term used to describe the often nonlinear load vs. deflection characteristics of the mooring system. The lengths of the mooring lines were chosen to provide the same amount of yaw restraint as the full scale mooring. The pretension on the experimental mooring was also set based on Froude scaled forces from the full scale design.

The important experimental testing parameters that affected the mooring behavior were the WEC's X position (surge

direction), the spar pitch, and the mooring load on the mooring lines. Fig. 11 shows how the mooring loads climbed from static pretension as the waves began to impact the WEC at the beginning of each trial. The port and starboard mooring loads track well as the WEC is forced by the periodic wave.

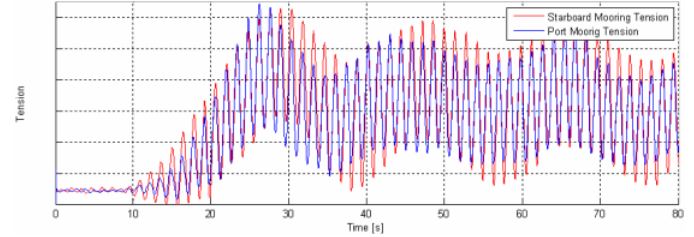


Fig. 11. Time series of mooring line loads.

A mooring spring rate consistent with the full scale design was used first, and then another mooring stiffness was explored. The WEC was subjected to waves from 22.5° , 45° , and 90° to observe how yaw heading was affected. This testing was highly informative regarding WEC performance and yaw control and provided additional insights regarding mooring spring rate and pretension.

5.0 NUMERICAL & EXPERIMENTAL COMPARISONS

Concluding the numerical model development and experimental testing, the GH Wave Farmer (performance model) and Orca Flex (mooring model) are compared with the 1/33rd scale tank test data. To perform these comparisons, the 1/33rd scale test results were scaled up to full scale to allow for comparison against the numerical models.

5.1 PERFORMANCE COMPARISONS

Power and RCW for the experimental device was measured for each wave period tested and a plot of RCW vs. period is shown as circles in Fig. 12, while the continuous line shows the numerically predicted RCW in GH WaveFarmer. In this test, damping was fixed, thus producing a torque command that is proportional to speed. As indicated in Fig. 2, a fixed damping value does not provide for optimal damping over the entire spectrum, however, it provides for quantitative comparison between numerical and experimental results (the purpose of this testing).

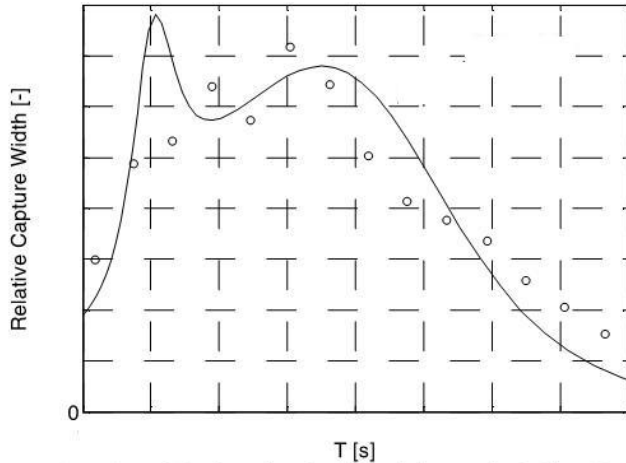


Fig. 12. Numerical (-) vs. experimental (o) RCW.

As seen, the numerically predicted and experimental RCW show good correlation. Although the actual magnitude of RCW is omitted, for proprietary reasons, the results show that both trend and magnitude are a close match.

Comparisons of RAO's were performed for all tests in the frequency scan. Fig. 13 represents fore and aft float relative pitch with respect to the spar. This RAO is of particular interest as it corresponds to relative motion, speed and output power level. Note the excellent correlation with aft float RAO and reasonably good correlation with the fore float.

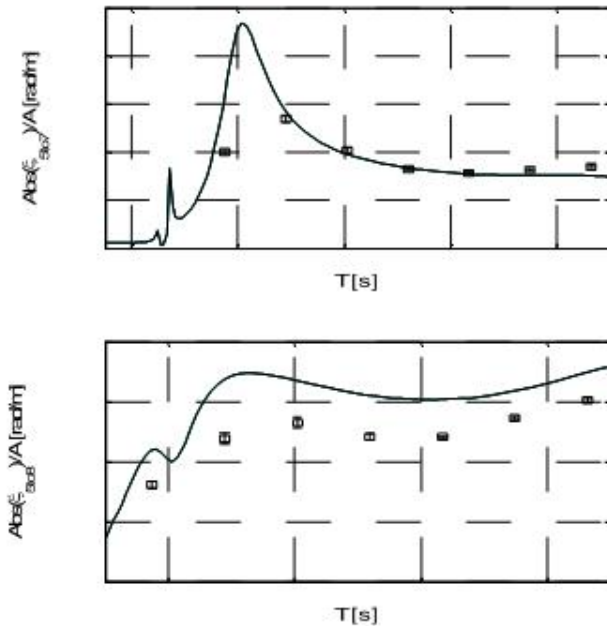


Fig. 13. Relative Pitch RAO comparison.
Numerical (-) vs. Experimental (\square).
Aft float top, Forward float bottom.

5.2 MOORING COMPARISONS

Mooring comparisons rely on having a complete set of body motion and mooring tension results from experimental testing and a reliable numerical model. The mooring experimental and numerical results are compared for a variety of wave conditions including various wave amplitudes, frequencies, and real seas. The goal of the validation process is to ensure any and all characteristics of the experimental testing are captured in the numerical modeling and any discrepancies can be accounted for. One such discrepancy resulted from the PTO cabling.

The mooring hardware for the experimental testing was well characterized but also quite soft. This softness presented a unique situation resulting in the PTO cable having a significant influence on the WEC position and orientation. The PTO cable extended from the bottom of the WEC to the seafloor and inadvertently acted as an additional mooring force. To compensate for this in the OrcaFlex models a somewhat higher mooring spring rate was required to recreate the same mooring effect that the PTO cables had on the WEC.

In an effort to create a numerical model that mimics the characteristics of the mooring system used during experimental testing, an OrcaFlex model was needed. The original plan to build an accurate model involved importing the full hydrodynamic parameters including added mass, damping and diffraction wave loading from the WAMIT modeling effort into OrcaFlex as vessels. Each of these parameters was represented in 6 degrees of freedom, for each of the three bodies, and for each wave frequency investigated with WAMIT. Importing these parameters into OrcaFlex is made simple with a convenient import function in OrcaFlex.

WAMIT modeling provided a single frequency dependent 18×18 matrix that captured the parameters of all three bodies as well as the coupling between these bodies. OrcaFlex can only accept a single frequency dependent 6×6 matrix for each body which presents a challenge. To overcome this difference a Matlab script was written that parsed out three separate 6×6 matrices from the original 18×18 matrix representing the three bodies. The data that described the coupling between the bodies was unavoidably neglected. With these new 6×6 matrices imported into OrcaFlex vessels, the mooring results were evaluated.

Regrettably the three vessel model of the WEC exhibited uncharacteristic behavior involving unstable oscillations which lead to the simulation halting. Once more when the added mass and damping matrices were set as constant values rather than frequency dependent terms, the simulation remained unstable. This consistency points to an error in the load RAO's. Two theories exist which may explain this error. The first is a possible format discrepancy in the load RAO phase angle. If the phase angle ever exceeds ± 180 degrees WAMIT wraps the data to remain within ± 180 degrees. It's

possible that OrcaFlex is not able to recognize this change and interprets the phase to be 180 degrees off, a likely source of instability, currently under investigation. The second possibility points to the coupling data being removed from the WAMIT output. This removed data represents 2/3rds of the information from the coupled model. Although it was assumed that this information was of a higher order than the individual body data, it is unknown how much of an effect the absence of this data can cause.

As another verification of the modeling process, a new model made of OrcaFlex 6D buoys was used to create a coupled WEC model. Constant added mass and damping values were extracted from the WAMIT data for the frequencies of interest. This model proved stable under all wave frequencies however displayed some inconsistencies when compared to the experimental testing results. Fig. 14 shows comparison between experimental surge and OrcaFlex predictions. While this particular test frequency shows reasonable correlation, other frequencies did not and additional work on this mooring model is required.

A final approach under development should correct the present shortcomings and provide a reliable model for mooring design. The model will be more streamlined and focus on the mooring alone. For this model a WAMIT simulation will be run on the whole WEC system as a single body. The resulting frequency dependent 6x6 hydrodynamic matrix can be used on a single OrcaFlex vessel. This single vessel method removes any doubt about the missing coupling data. The model is intended for mooring characterization and will not allow for performance characterization, nor will it allow for predicting forces due to float motions relative to the spar. This work is still in progress and future results will be available in the subsequent journal paper.

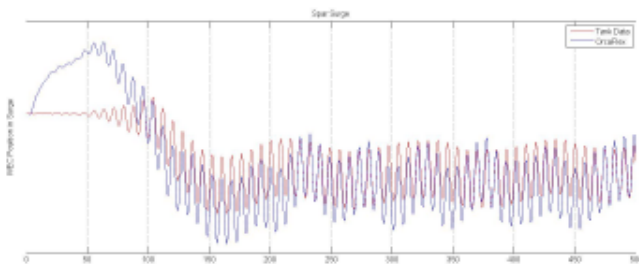


Fig. 14. Model vs. Experimental surge displacement.

6.0 CONCLUSIONS

A wave energy converter design has been numerically modeled and optimized to increase energy capture using linear wave theory in the frequency domain. Energy performance in regular and real seas was numerically predicted and verified using 1/33rd scale tank test results.

A novel approach for implementing rotational damping

through linked linear dampers was presented and examined. Attempts at using this linked 3-body model proved to be limited when evaluating mooring loads at all frequencies. Future work will evaluate a single body approach for mooring design analysis.

A highly accurate suite of experimental tools and test regime were deployed and presented for the purpose of confirming numerical performance and mooring predictions. The results of the testing and validation of the numerical simulation allow for staged development of the WEC concept with increased confidence.

7.0 ACKNOWLEDGEMENTS

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8.0 REFERENCES

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