WEC-Sim Array Development and Experimental Comparison Study

Preprint

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WEC-Sim array development and experimental comparison study

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Abstract—**Wave energy is still considered to be an emerging industry, and one significant contribution that researchers are making is to find solutions that reduce costs. The National Renewable Energy Laboratory and Sandia National Laboratories have contributed to this by creating WEC-Sim, an opensource modeling toolbox, to assist with early design decisions related to the design of wave energy converters (WECs). Previously, studies involving WEC-Sim have focused on single WEC modeling. In this paper, we will conduct a validation study to investigate the accuracy and ability of WEC-Sim to model arrays of WECs. The results from the WEC-Sim array simulations are compared to those from an existing experimental study. In addition, the array model is used to investigate the interaction between the WECs in the array and the influence of array spacing on the WECs' hydrodynamic performance.**

Keywords— **model validation, wave energy converter arrays, WEC-Sim**

I. INTRODUCTION

Wave energy is still considered to be in the early development phase. The high costs of prototyping and deploying devices have led researchers and developers to look for early design options that cut down on costs. To assist with the design process and bring down early phase costs, numerically modeling the devices is often an early step. The boundary element method (BEM) [1,2,3] has been widely used to determine the hydrodynamic coefficients and excitation forces to model wave energy converter (WEC) arrays [4-9]. There is a wide range of literature investigating and modeling the behavior of single-device hydrodynamic interactions, while there is still room for further investigation into WEC arrays. It is also well understood that to increase the power of WECs, the devices will likely be deployed in arrays. Many studies have focused on optimal array layout and separation distance. These studies are beneficial to investigating how devices act in arrays, but do not provide a modelling framework that could work for a wide variety of devices. By creating a baseline for simulating WEC arrays, a toolset could be used for any type of WEC design to better understand the overall interactions of the devices.

The National Renewable Laboratory (NREL) and Sandia National Laboratories (Sandia) have jointly developed the modelling tool WEC-Sim to assist with early design decisions for WECs [10]. One aspect that has not been thoroughly investigated in WEC-Sim is the capability of modeling multiple WECs in an array or a farm. This paper presents the first steps toward code development and validation efforts for research on power management and control for WEC arrays, which aims to reduce the power fluctuation and the integration impacts of WEC plants in both distribution and transmission grids and in isolated power systems. Previously, NREL investigated methods to reduce the overall power fluctuations for a single WEC. In which, a hydraulic power-take-off (PTO) model was developed and coupled with WEC-Sim to conduct an assessment of power smoothing methods [14]. The conclusions from the study showed a variety of methods for smoothing out different sized fluctuations in the data and ways of implementing the methods into the PTO of a WEC. Once a foundation for using arrays in WEC-Sim is established, this research could also expand to include power smoothing techniques for larger WEC networks.

In a previous study by NREL, Sandia, and Aalborg University (AU), a validation on a single Wavestar WEC was conducted to validate the WEC-Sim model for the WEC [15, 16]. The validation was used in the WEC Control Competition (WECCCOMP), which is a two-part competition that first models optimal PTO for a WEC in WEC-Sim, then tests the control in a series of tank tests. The validation consisted of two comparisons: force motion without wave excitation and linear resistive control with wave excitation. Using a coefficient of determination as the evaluation requirement, the highest error found in the WEC-Sim model of the WEC was 7% [15]. In this paper, the second validation study is an expansion on the study by increasing the number of WECs.

This paper investigates the implication of using arrays in WEC-Sim. This includes three different comparisons.

For the first comparison conducted in this study, we analyzed the validity of OpenWARP—a NEMOH-inspired boundary element method (BEM) code [2] that parallelizes the hydrodynamic computations [17]. The second comparison investigates the accuracy of the array model in MATLAB by comparing the outputs from an experimental study conducted by SNL and AU. The third comparison explores the body-to-body interaction simulated in WEC-Sim as the rows in the array are moved closer together.

II. Methodology

A. Numerical Model

This study focuses on increasing the capabilities of WEC-Sim to incorporate more complex systems into the modeling toolbox. WEC-Sim, a MATLAB/SIMULINK tool is being developed by Sandia and NREL with funding from the U.S. Department of Energy's (DOE's) Water Power Technologies Office [13]. The toolbox is an open source simulator that inputs BEM code results and models an inputted WEC design, which can be comprised of rigid bodies, PTO systems, as well as mooring systems.

To use WEC-Sim there are three main inputs—the model geometry, the BEM outputs, and the WEC-Sim input file. Additional features include the mooring capabilities and PTO parameters. For the purposes of this study, the default values for the mooring and PTO functions were used. The default values for both functions are zero in WEC-Sim and were defined this way to simplify the model for the validation studies.

There are a number of BEM codes currently used in the wave energy industry. Of the codes used in the marine energy industry, frequency domain models are more common. Commercial codes include WAMIT, AQWA, Aquaplus, and WADAM [15]. Another code is NEMOH, an open source BEM code that was developed in 2014 by Ecole Centrale de Nantes [2]. The primary advantages of BEM codes over methods like CFD modeling are low computational cost and high-resolution results.

WEC-Sim is compatible with three BEM codes—WAMIT, AQWA, and NEMOH. Fig. 1. displays the basic structure of WEC-Sim. As mentioned before, this study explores the use of OpenWARP in WEC-Sim. OpenWARP is a BEM code developed through a coding competition in 2014 [14]. The output from this competition was a parallelized version of NEMOH with improvements on computational efficiency.

To test the validity of OpenWARP, the output was compared to WAMIT. The three outputs of interest in this comparison were the normalized added mass, normalized damping coefficient, and the excitation force. The normalized added mass can be written as:

$$\bar{A}_{i,j}(\omega) = \frac{A_{i,j}(\omega)}{\rho} \quad (1)$$

where $A_{i,j}$ is the added mass coefficient outputted from the BEM code, ω is the frequency, and ρ is the density. The normalized damping coefficient can be written as:

$$\bar{B}_{i,j}(\omega) = \frac{B_{i,j}(\omega)}{\rho\omega} \quad (2)$$

where $B_{i,j}(\omega)$ is the damping coefficient. The normalized excitation force can be written as:

$$\bar{X}_{i}(\omega,\beta) = \frac{X_{i}(\omega,\beta)}{\rho g} \quad (3)$$

where X_i is the excitation force coefficient and g is the gravitational force.

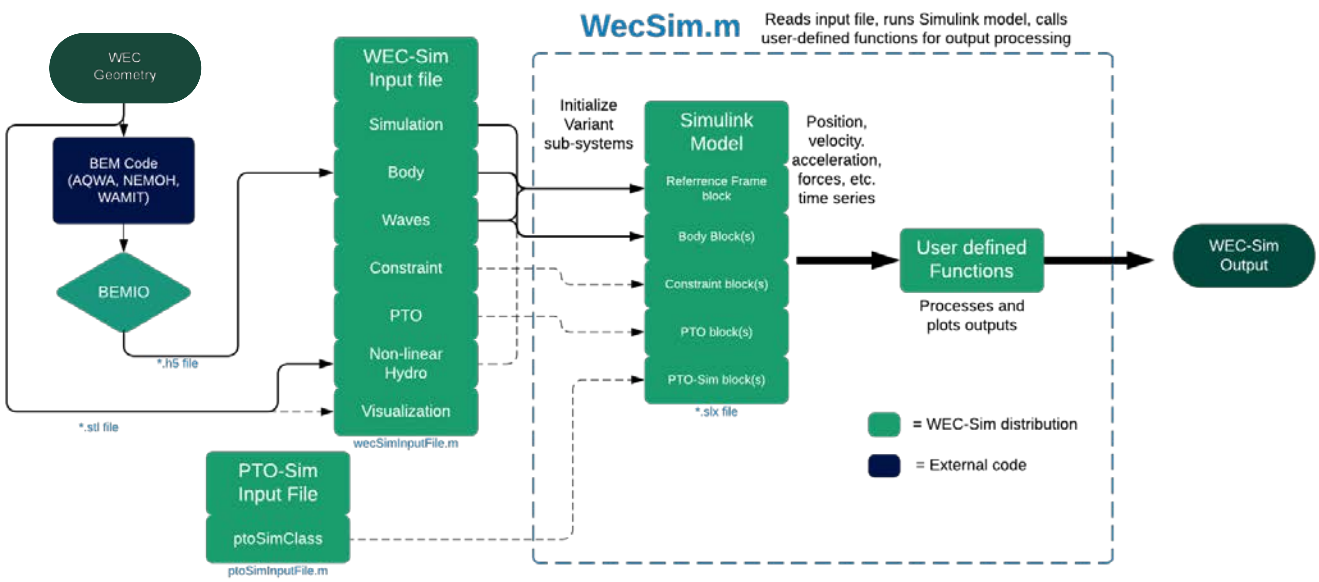

Fig. 1. WEC-Sim workflow diagram (from WEC-Sim website).

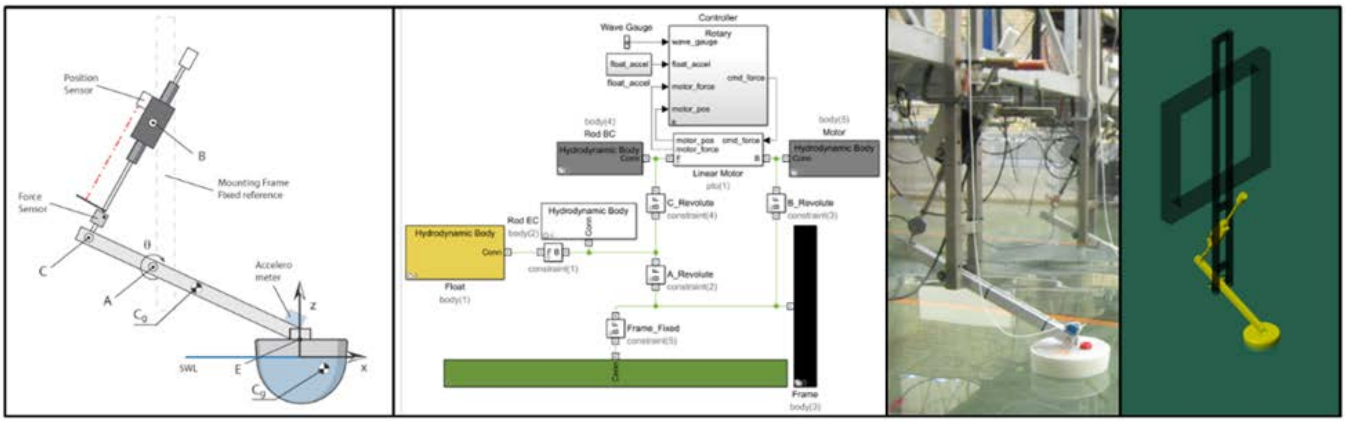

Fig. 2. (a) Diagram of Wavestar device experimental setup. (b) WEC-Sim model of the device. (c) Experimental setup of the WEC. (d) WEC-Sim simulated device [16].

These three outputs were used to assess the validity of OpenWARP because the results from these equations would be the first indication of whether the BEM outputs were correct. When comparing two different BEM codes, there should be consistent water displacement and excitation force magnitude because the float geometry is constant in both methods. The OpenWARP BEM run was replicated to match the inputs from the WAMIT run provided on the WECCOMP repository. The test included 420 frequencies with a range of 0.2 to 84.0 rad/s to match the data collected from the WECCCOMP verification [12].

B. *Model setup*

1) *WEC device*

The Wavestar WEC is being developed by Wavestar Energies and was originally patented in 2003 [13]. A 1/20-scaled Wavestar WEC is being used for the WEC controls competition hosted by Sandia and NREL as well as the experimental tests conducted by Sandia and AU [13,16]. The WEC draws energy by the up and down movement of the float connected to a fixed point with an arm (Fig. 2). For the purposes of this study, the same scaled device from the WECCOMP competition is used. The dimensions of a single device can be found in Table I. For a single Wavestar device, five bodies representing each component of the WEC were simulated in WEC-Sim. Fig. 2d shows the simulated WEC with all five of the simulated bodies.

TABLE I
SCALED WAVESTAR DIMENSIONS

Parameter	Value [unit]
Float Mass	3.075 [kg]
Float Cg (x, z)	(0.051, 0.053) [m]
Float MoI (at Cg)	0.001450 [$kg \cdot m^2$]
Float Draft	0.11 [m]
Float Diameter	0.256 [m]
Arm Mass	1.157 [m]
Arm Cg (x, z)	(-0.330, 0.255) [m]
Arm MoI (at Cg)	0.0606 [$kg \cdot m^2$]
Hinge A (x, z)	(-0.438, 0.203) [m]
Hinge B (x, z)	(-0.438, 0.714) [m]
Hinge C (x, z)	(-0.621, 0.382) [m]

TABLE II
WAVESTAR FLOAT LOCATION

Float #	X [m]	Y [m]
1	0.0	- 0.35
2	0.0	0.35
3	1.6	0.75
4	1.6	0.0
5	1.6	- 0.75

2) *Array implementation*

The array setup replicates the unpublished experimental tests completed by Sandia and AU. Fig. 3 displays the array layout of five devices used while Table II describes the location of each WEC. In the experimental tests, the array went through a series of regular and irregular long-crested waves. For this study, three regular sea states were chosen from the eleven tested at AU.

The three regular wave states compared in this study only vary in the wave period. To fully investigate the modeling capabilities of WEC-Sim, the wave states were chosen to give a range for the size of WEC being modeled. They were also chosen based on how clean their data was from the experimental tests.

TABLE III
REGULAR WAVE STATES

	R1	R2	R3
H [m]	0.06	0.06	0.06
T [s]	0.776	1.00	1.49

These wave states are further described in Table III. The experimental tests for the regular waves varied due to the repetition of the wave state generated for each tank test. Time intervals of 5 seconds were therefore used to compare the results to the simulated WEC responses. In choosing the time intervals, data from the experimental tests were selected when there was no PTO being enforced on the array.

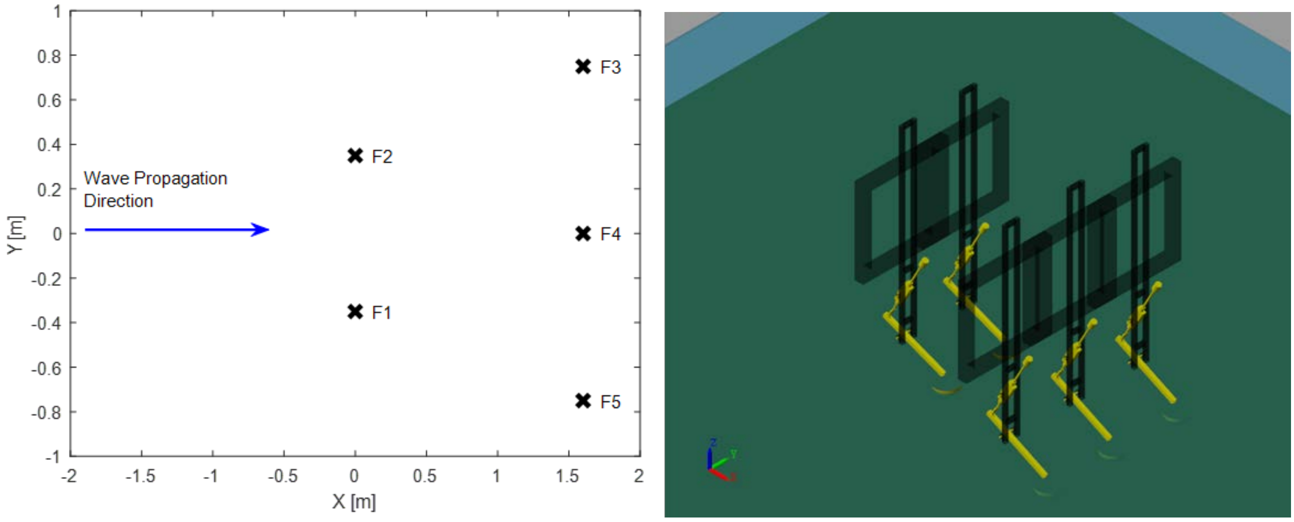

Fig. 3. (a) WEC location for the five Wavestar devices. (b) The isometric view of the simulated WEC-Sim array.

TABLE IV
ARRAY SEPARATION CASES

Case #	Row two x-axis location [m]
1	0.4
2	1.00
3 (control)	1.6

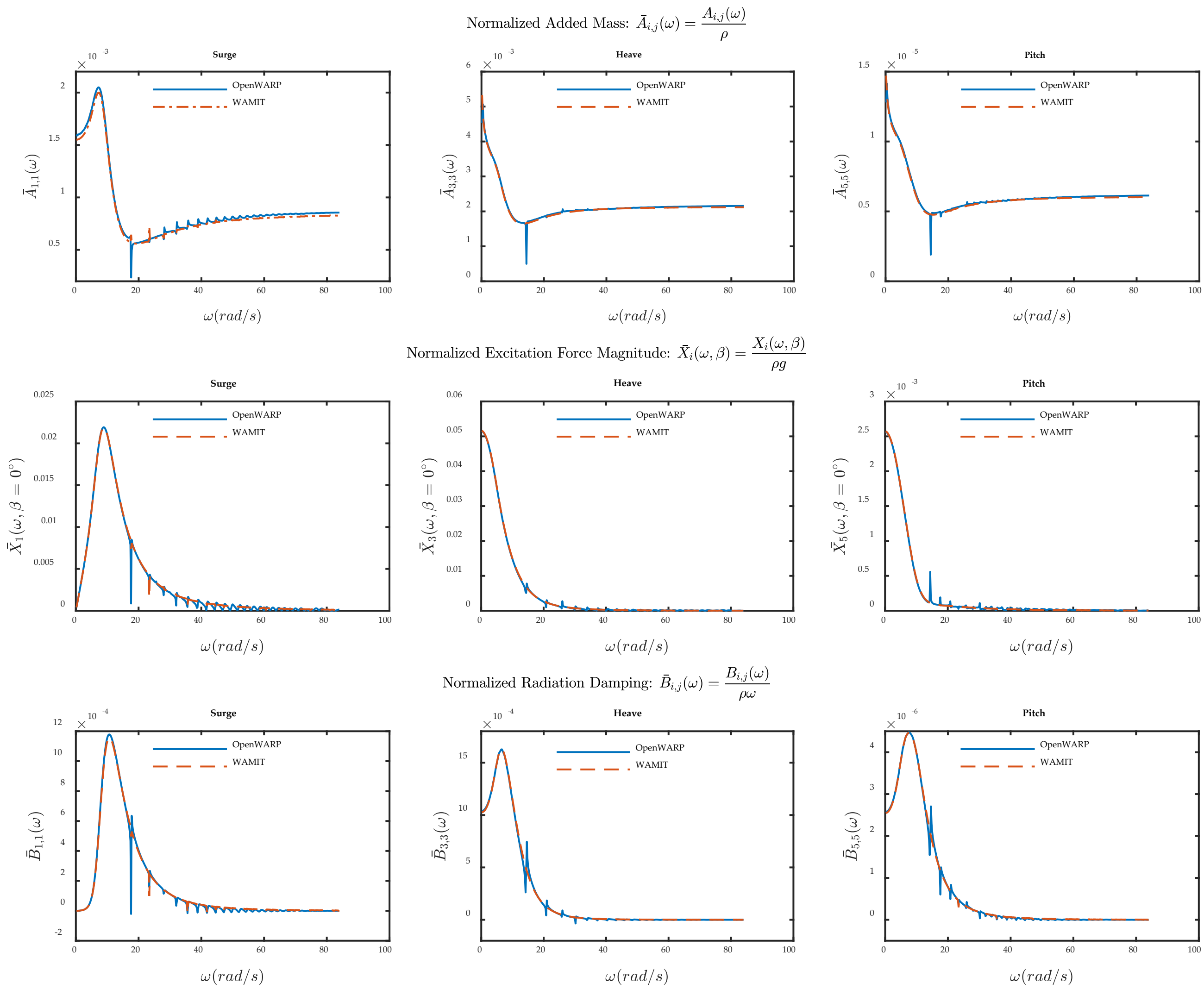

Fig. 4. BEMIO comparison between OpenWARP and WAMIT (a) Normalized added mass. (b) Normalized radiation damping. (c) Normalized excitation force.

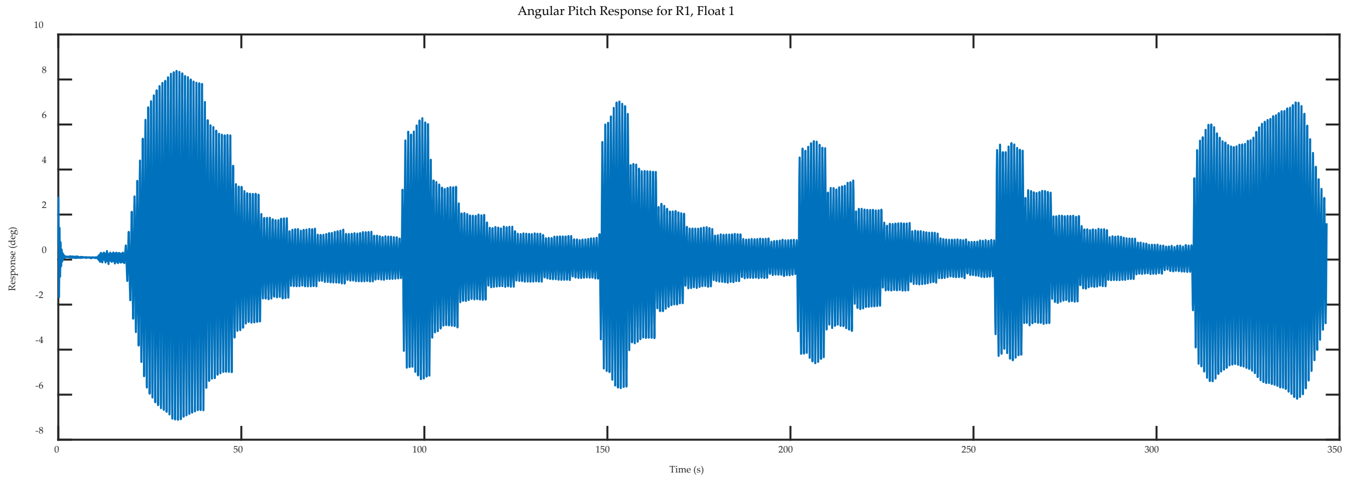

Fig. 5. Complete time history of pitch response for float 1. Data selected for the 5-second time interval was 30.44 – 35.44 seconds.

TABLE V
RESPONSE AMPLITUDE OPERATOR (RAO) BETWEEN WEC-SIM AND THE EXPERIMENTAL WEC RESPONSES WITH A 0.03 M WAVE AMPLITUDE [M/M]

	R1			R2			R3		
Float	Wec-Sim	Exp	% Error	Wec-Sim	Exp	% Error	Wec-Sim	Exp	% Error
1	4.235	4.457	5.25	3.752	3.787	0.92	2.837	3.036	7.01
2	4.235	3.785	10.63	3.752	3.584	4.49	2.837	2.815	.80
3	2.896	2.930	1.17	3.648	3.791	3.91	2.785	3.252	16.77
4	2.496	3.008	20.54	3.698	2.737	25.98	2.816	3.357	19.23
5	2.896	3.272	12.98	3.648	3.975	8.95	2.785	2.462	11.58
Avg. Error			10.11 %			8.85 %			11.08 %

3) *Array separation study*

To further investigate the body-to-body interaction of WEC arrays in WEC-Sim, a separation study was conducted to see how the WEC interactions change. The row separation for the array in the experimental comparison is 6.25D, so for the purposes of this study the row separations were decreased. Table IV describes the positions of the second row for the three cases. The wave state being used in this investigation is R2 from Table III. The goal of this investigation is to assess the body-to-body interactions of the WECs as they are moved forward.

III. BEM CODE VERIFICATION

OpenWARP was executed to calculate the hydrodynamic coefficients of one WEC for frequencies ranging from 0.2 to 84.0 rad/s. Using parallel computing reduced computational time, which was comparable to the WAMIT computational time. After running the BEM outputs through BEMIO, six plots were produced.

For Figures 4a-c, the results show little variation between the normalized added mass, normalized radiation damping, and normalized excitation force magnitude. The spikes in the three sets of data represent the irregular frequencies associated with NEMOH and OpenWARP.

Fig. 4a shows more variation from the WAMIT output for the range of frequency values. The differences in added mass are negligible due to the small magnitude of the output. Frequency values are also unlikely to go to 84.0 rad/s when modeling sea states. The full-scale frequency is 376 rad/s, which is outside the range of interest. It can be observed that the majority of the irregular frequency spikes for Figures 4-6 recorded are above 20 rad/s. These spikes occur due to the effect of irregular frequencies [17], and WAMIT includes a method to remove them [1], which has not yet been incorporated into NEMOH/OpenWARP.

IV. EXPERIMENTAL COMPARISON RESULTS

After the verification of the BEM code, OpenWARP was used to calculate the hydrodynamic coefficients for the WEC array. The array was gradually increased in size by one WEC until reaching five WECs. This was done to avoid potential input errors that would arise from modeling one device and scaling directly up to five devices. In total, there are 25 bodies being simulated in WEC-sim with corresponding constraints and PTO for the five WECs. As mentioned before, Fig. 3 shows the simulated WECs and the 25 bodies that make up the array.

Of the 25 bodies being simulated, only the five floats were inputted into OpenWARP. This is because the floats have a hydrodynamic interaction with the water, unlike the other simulated bodies. In addition to expanding the input file to include the 25 bodies, the Simulink file was also expanded for the five devices.

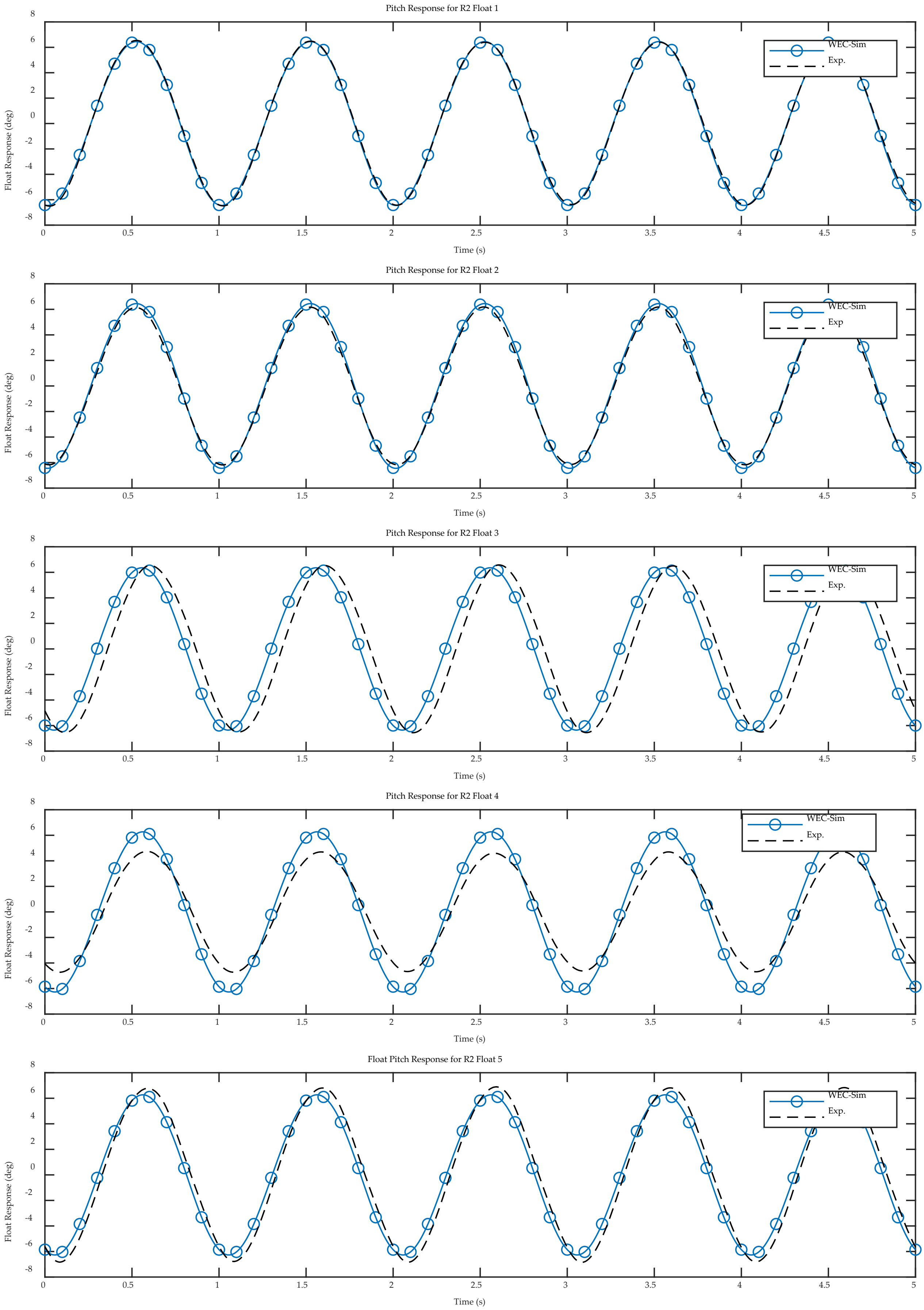

Fig. 6. Angular pitch comparison between simulated and experimental tests for the R2 wave condition. Row one consists of floats one and two while row two contains WECs three, four, and five.

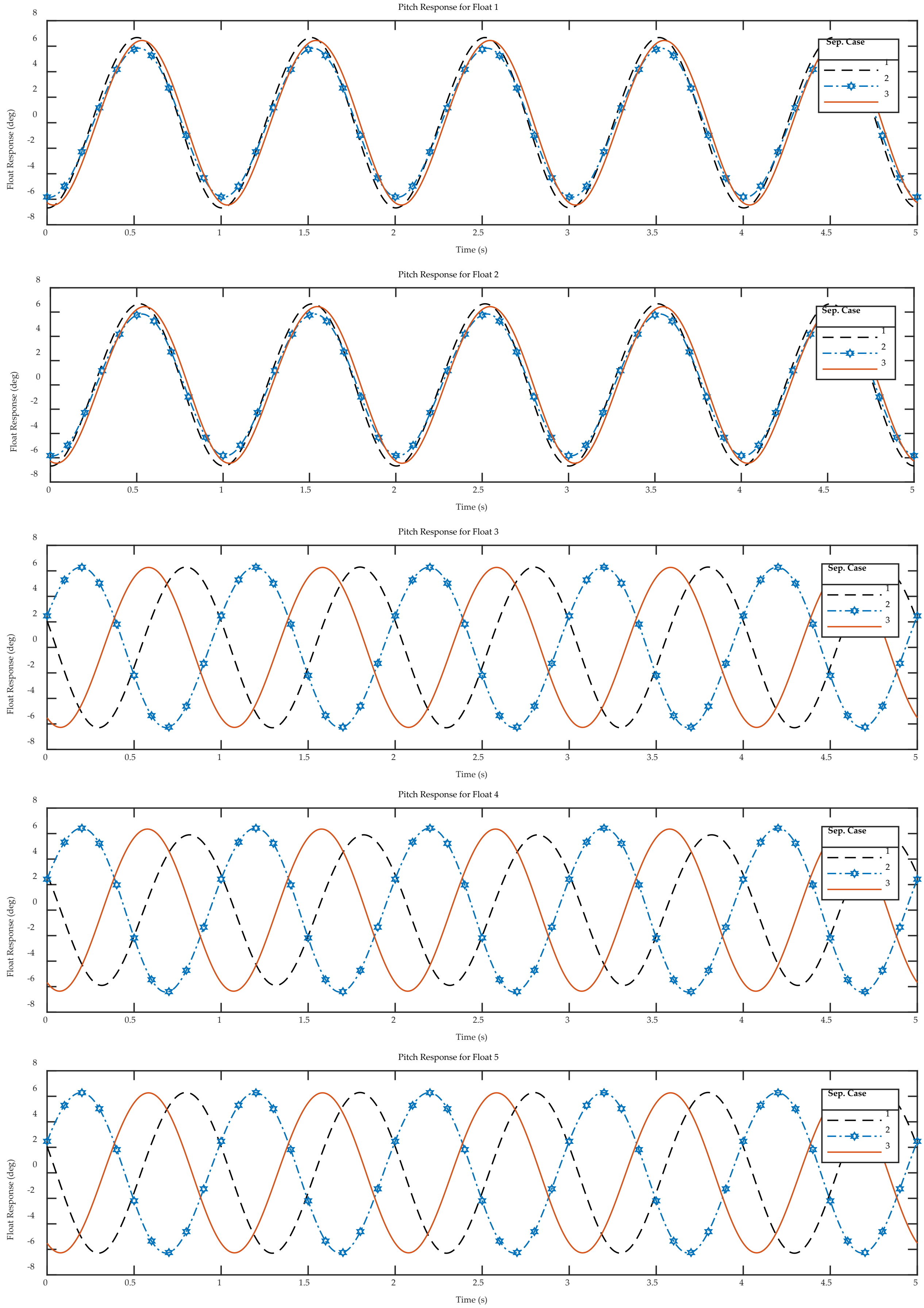

Fig. 7. Angular pitch comparison between three array configurations. The array separation cases are in ascending order with case three corresponding to the distance used in the experimental comparison. The locations for row two of the array can be found in Table IV.

The three waves states in Table III were then simulated in WEC-Sim for the array of devices. To represent the data, a 5-second interval of the angular pitch response was chosen to better understand how each float was behaving. The pitch response for the WEC-Sim results were uniform for the simulated time so the 5-second time frame was chosen to match the 5-second interval of the experimental responses. The experimental results for the three wave states had larger variability in each dataset. One of the more distinguished differences is the total test time for each of the experimental wave conditions, which varied from 350 to 900 seconds. To compare against the WEC-Sim results, the 5-second intervals chosen needed to be uniform in response with little pitch response variation as well as little to no PTO force acting on the device. Fig. 5 shows the total time history for one float under the R1 wave conditions.

A summary of the comparisons for the simulated array responses under the three wave conditions can be found in Table V. A response amplitude operator (RAO) was used to compare WEC-Sim to the experimental test. The RAO was obtained by taking the ratio of the response amplitude to the wave amplitude of 0.03 m.

The WEC-Sim responses have a general trend for all three cases. The first row shares the same RAO as well as experiencing a larger response than the second row of WECs. For the RAOs in the second row, float 3 and 5 share the same value. For the results in R1 floats 3 and 5 have a greater RAO than float 4, however, float 4 had a larger RAO for the R2 and R3 wave states.

The total error for the three cases was 10.04% when compared against the experimental RAO. The experimental pitch responses do show more variability between the three cases, but also follow the trend found within the WEC-Sim data. Fig. 6 shows the five response comparisons for R2 which had the lowest error. The largest error in this case is found in the float 4 response. The simulated response is shown to have a larger response than the response found in the tank test.

For both R1 and R3—which had errors above 10%—the amplitude of the second row is where a significant amount of the error is located.

V. Array separation study results

Fig. 7 shows the response comparison between three array simulations run through WEC-Sim with varying row separation. The goal of this investigation was to better understand how WEC-Sim models body-to-body interactions between WECs. In this investigation, case 3 was the control case due to the experimental comparison conducted in Section IV.

TABLE VI
RESPONSE AMPLITUDE OPERATOR FOR ARRAY SEPARATION CASES WITH A 0.03 M WAVE AMPLITUDE [M/M]

Float	Case 1	% Increase	Case 2	% Increase	Case 3
1	3.885	3.54	3.397	-9.46	3.752
2	3.885	3.54	3.397	-9.46	3.752
3	3.665	0.46	3.656	0.22	3.648
4	3.433	-7.13	3.738	1.12	3.697
5	3.665	0.46	3.656	0.22	3.648
Avg. Error		0.17 %		-3.47 %	
Std. Dev		4.36		5.48	

The assessment used for this comparison was the percent increase of the RAO of the two cases moved in towards the first row of WECs. Moving up the second row for both cases resulted in symmetric responses for the array.

In case 1 there was a 3.54 % increase in the row one RAO and a 0.46 % increase in RAO for floats 3 and 5. Float 4 in case 1 likely falls into a wave minimum with a 7.13% decrease. The large increase in RAO in the first row of this case is likely due to positive interaction with the second row of devices.

For the second case however, the first row experiences a lower RAO with a 9.46 decrease. This case does however yield an increase in response for all three devices in row two.

The first separation case had an overall average increase in the five-float RAOs while the second case has an average decrease . As a result of the small RAO experienced by float 4 in case one, the standard deviation of case one is higher than case two.

VI. Conclusion

Implementing WEC arrays is the first step towards investigating power fluctuations in larger, more complex WEC networks. By conducting this study, we have expanded off current WEC-Sim studies that have only included one to two WECs. The primary objective of this paper has been to verify the array modeling capabilities of WEC-Sim. In this effort, we have conducted three separated comparison studies to assure the implementation of arrays will provide users with a baseline for creating more complex WEC networks
within the toolset. As an expansion off the WECCCOMP single Wavestar device validation, the comparisons include the validation of array implementation of five Wavestar WECs in WEC-Sim and the validation study of OpenWARP, a NEMOH inspired BEM code.

By calculating the hydrodynamic coefficients of the Wavestar in OpenWARP, we have validated the open source BEM code against WAMIT. The simulated results of the five-float responses have also shown that the simulated results follow the same trends found in the experimental results all while being under 11% error. After also investigating the body-to-body functionality of WEC-Sim in the separation study, there was evidence of greater interaction as the array rows were moved closer together.

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