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 Lab (NREL) and Sandia National Laboratory (SNL) have contributed to this by creating WEC-Sim, an open-source 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 WEC hydrodynamic performance.**

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

I. Introduction

Wave energy is still considered to be in the early development phase. The large expenses of prototyping and deploying devices have led to researchers and developers to look for early design options to 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 WEC arrays [4-12]. 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 for wave energy converter (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 how WECs will behave in arrays, but most are study specific. The model for the array may not be used again in future studies. By creating a baseline for simulating WEC arrays, the 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 Laboratory (SNL) have jointly developed the modelling tool WEC-Sim to assist with early design decisions for WECs [13]. 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 is the first step of the code development and validation efforts for research on power management and control for WEC arrays – which aims on reducing the power fluctuation and the integration impacts of WEC plants in both distribution and transmission grids and in the standalone isolated power systems. Previously, NREL has investigated methods to reduce the overall power fluctuations for a single WEC. In the study, 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 fluctuation 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, SNL, 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 to support 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 this 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 BEM code 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 SNL and NREL with funding from DOE's Water Power Technology 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, power take-off 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. 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 commonly used. Commercial codes include WAMIT, AQWA, Aquaplus, and WADAM [18]. Another code is NEMOH – an open-source BEM code was developed in 2014 by Ecole Centrale de Nantes [2]. The primary use of BEM codes over methods like CFD modeling is due to the 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. For the purposes of this study the WEC moorings are not included, and the PTO remains constant throughout the study. OpenWARP is a BEM code developed by NREL through a coding competition in 2014 [17]. 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:

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

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:

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

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

$$\bar{X}_i(\omega,\beta) = \frac{X_i(\omega,\beta)}{\rho g} \tag{3}$$

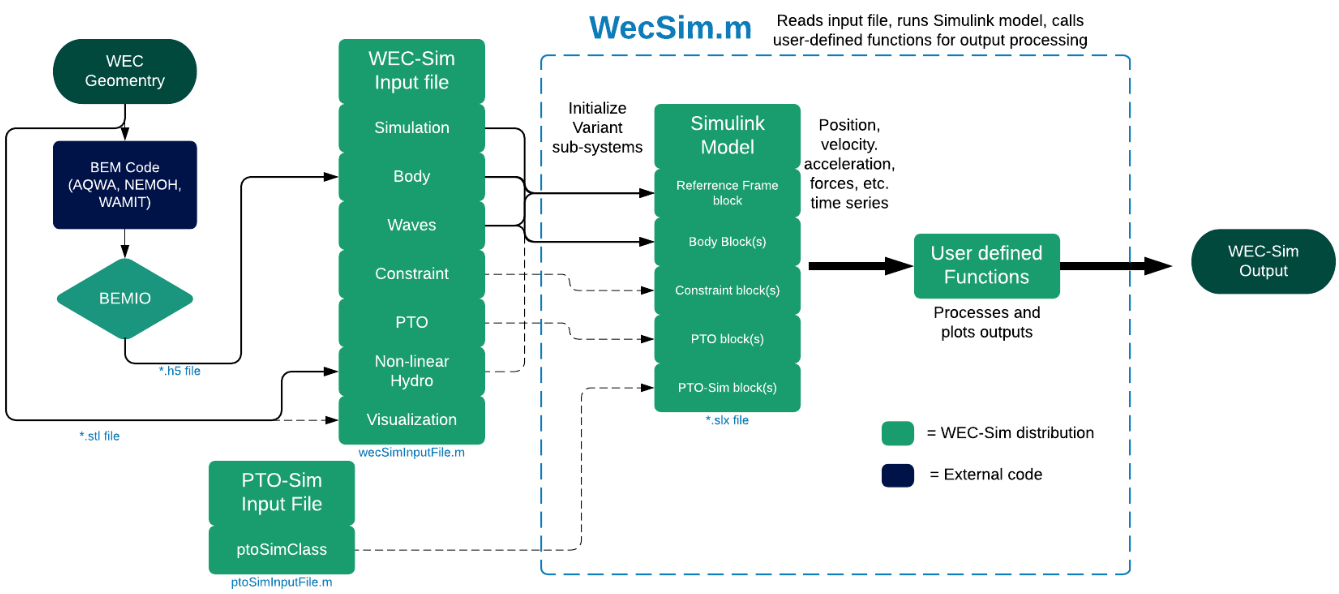

Fig. 1. WEC-Sim workflow diagram.

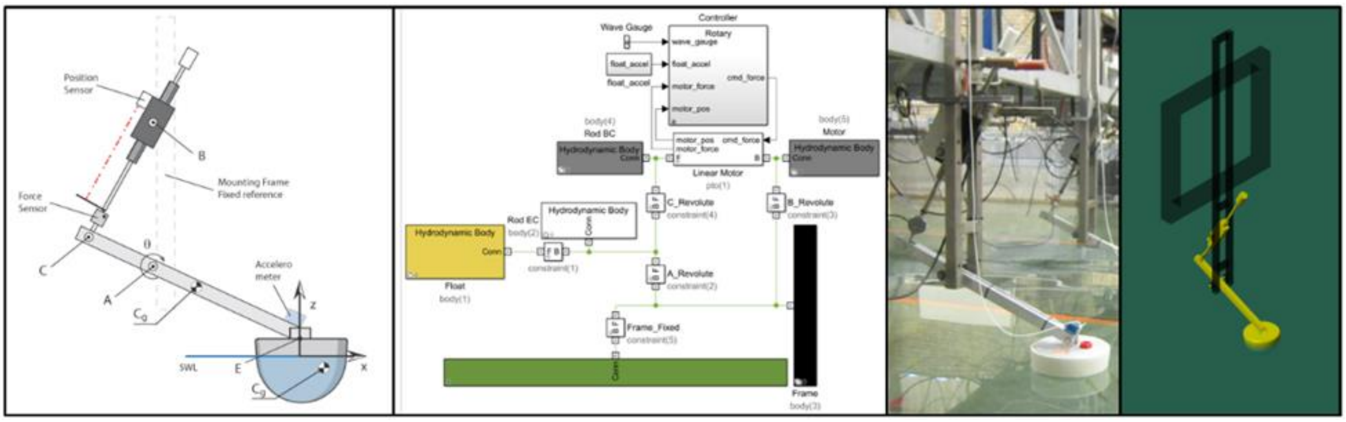

Fig. 2. (a) Diagram of Wavestar device experimental setup. (b) WEC-Sim model of the device. (c) experimental setup of the WEC. (d) WEC-Sim simulated device [16].

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

These three outputs were used to assess the validity of OpenWARP because the results from these equations would be the first indication if the BEM outputs were off. When comparing two different BEM codes, there should be the consistent water displacement and excitation force magnitude because the float geometry is constant for both methods. The OpenWARP BEM run was replicated to match the inputs from the WAMIT run provided on the WECCOMP repository. The test includes 420 frequencies with a range of 0.2 to 84.0 rad/s to match the data collected from the WECCCOMP verification [16].

B. *Model Set Up*

1) *WEC Device*

The Wavestar WEC is being developed by Wavestar Energies and was originally patented in 2003 [17]. A 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 [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.

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]

2) *Array implementation*

The array set up replicates the unpublished experimental tests completed by SNL and AU. Fig. 3 displays the array layout of five devices used while Table II describes the location of each WEC.

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

This study will compare three regular wave states of varying periods. To fully investigate the modeling capabilities of WEC-Sim, the wave states were chosen to give a large range for the size of WEC being modeled. These waves 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.

TABLE III
REGULAR WAVE STATES

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

Time intervals of five seconds were therefor used to compare the results to the simulated WEC responses.

3) *Array separation study*

To further investigate the body-to-body interaction of WEC arrays, a separation study will be conducted to see how the WEC interactions change. This will be completed by decreasing the distance of the between the two rows of the array in Fig. 3. Table IV describes the positions of the second row for three cases. The distance of the original layout is 6.25D so by decreasing the distance there should be an increase in the float response. The wave state being used in this investigation is R2 from Table III. The goal of

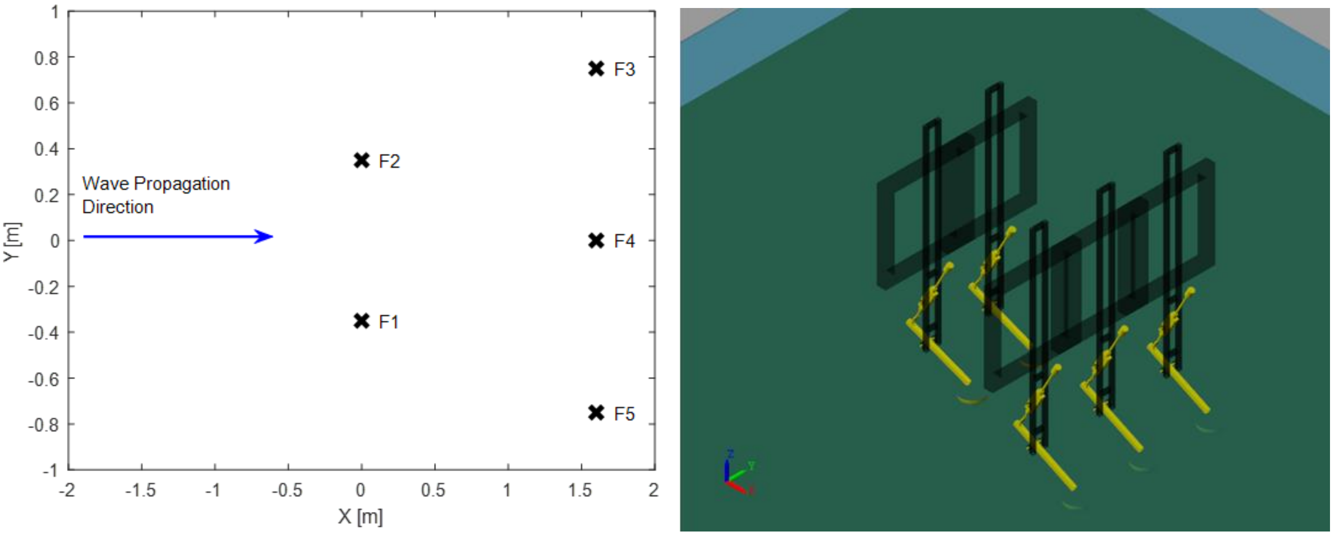

Fig. 3. (a) WEC location for the five Wavestar devices. (b) The isometric view of the simulated WEC-Sim array.

TABLE IV
ARRAY SEPARATION CASES

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

this investigation is to access 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

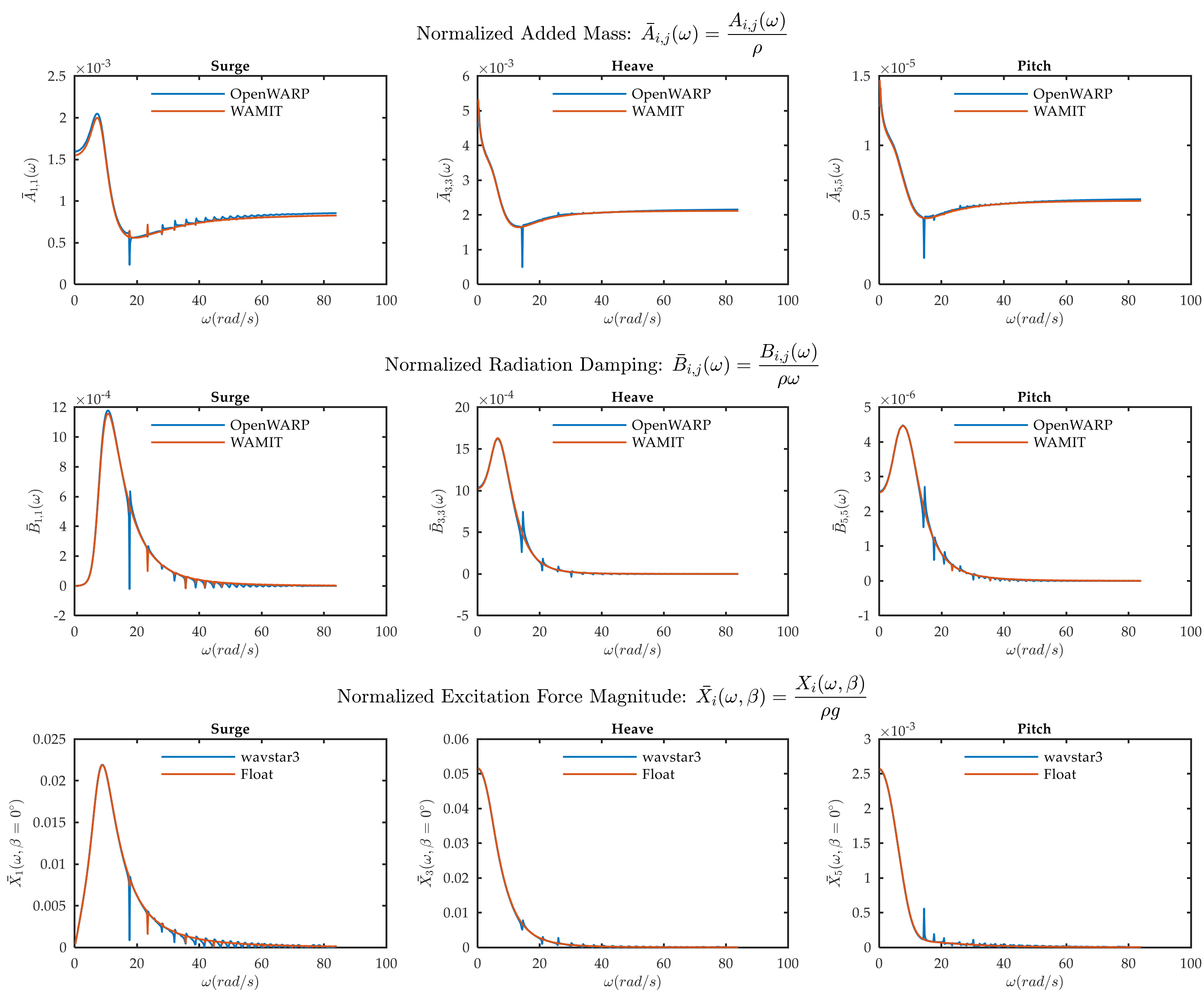

Fig. 4. (a) Normalized added mass. (b) WEC-Sim model of the device. (c) experimental setup of the WEC. (d) WEC-Sim simulated device.

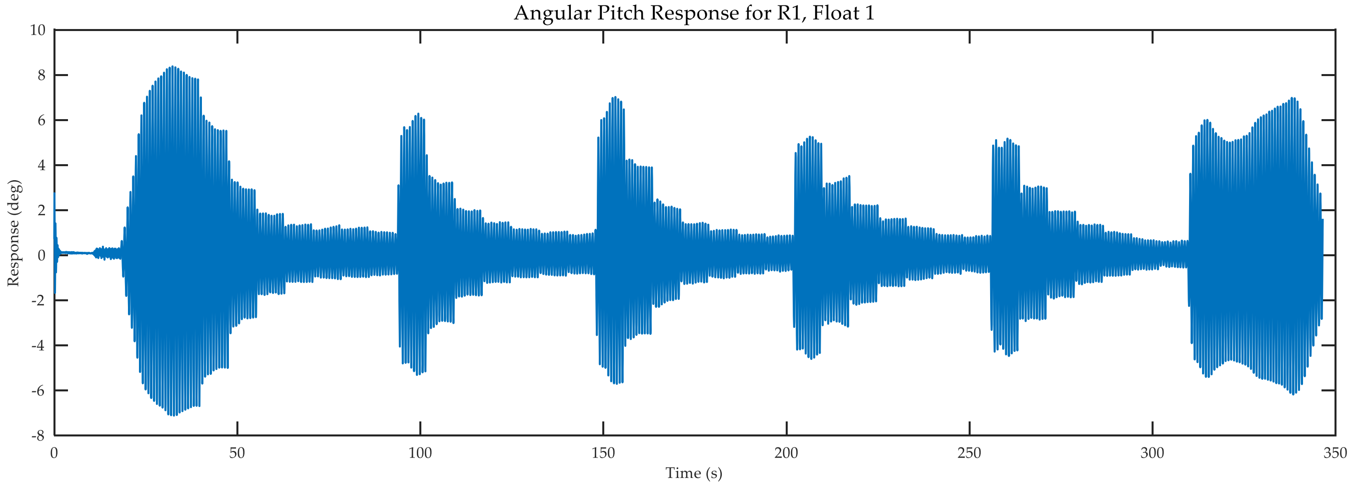

Fig. 5. Complete time history of pitch response for float 1. Data selected for the five-second time interval was 30.44 – 35.44 seconds.

TABLE V
FLOAT RESPONSE ERROR

	R1			R2			R3		
Float	Wec-Sim	Exp	% Error	Wec-Sim	Exp	% Error	Wec-Sim	Exp	% Error
1	14.558	15.33	5.25	12.9	13.019	0.92	9.753	13.019	7.01
2	14.558	13.011	10.63	12.9	12.321	4.49	9.754	9.676	.80
3	9.994	10.072	1.29	12.542	13.032	3.91	9.574	11.18	16.77
4	8.58	10.342	20.54	12.712	9.409	25.98	9.679	11.54	19.23
5	9.994	11.248	13.24	12.542	13.665	8.95	9.574	8.465	11.58
Avg. Error			10.19 %			8.85 %			11.08 %

ranging from 0.2 to 84.0 rad/s. Using the core reduced computational time and was comparable to the WAMIT computational time. Once running the BEM outputs through BEMIO, there were six plots outputted.

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. It can be observed that the majority of the irregular frequencies' spikes for Figures 4-6 recorded are above 20 rad/s.

IV. EXPERIMENTAL COMPARISON RESULTS

After the verification of the BEM code, OpenWARP was used to calculate the hydrodynamic coefficients for the WEC array. To simplify moving towards a five-WEC array, the array increased in size by one WEC until reaching five WECs. This was conducted to avoid potential input errors that would arise from modeling one device and scaling directly up to five devices. In total, there are twenty-five bodies being simulated in WEC-sim with corresponding constraints and PTO for the five WECs.

Only the five floats were inputted into OpenWARP for hydrodynamic interactions, but all bodies were needed to accurately portray the system in WEC-Sim. In addition to expanding the input file to include the twenty-five bodies, the Simulink file was also expanded for the five devices. The three waves states in Table III were then simulated in WEC-Sim for the array of devices. To represent the data, a five-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 five-second time frame was chosen to match the five-second interval of the experimental responses. The experimental results for the three wave states had larger variability in each data set. One of the more distinguished differences is the total test time for each of the experimental wave conditions – which varied from 350 seconds to 900 second. To compare against the WEC-Sim results the five-second intervals chosen needed to be uniform in response with little pitch response variation. Fig. 5 shows the total time history for one float under the R1 wave conditions.

A summary of the comparison for the simulated array responses under the three wave conditions can be found in Table V. The WEC-Sim responses have a general trend for all three cases. The first row shares the same response amplitude as well as experiencing a larger response than

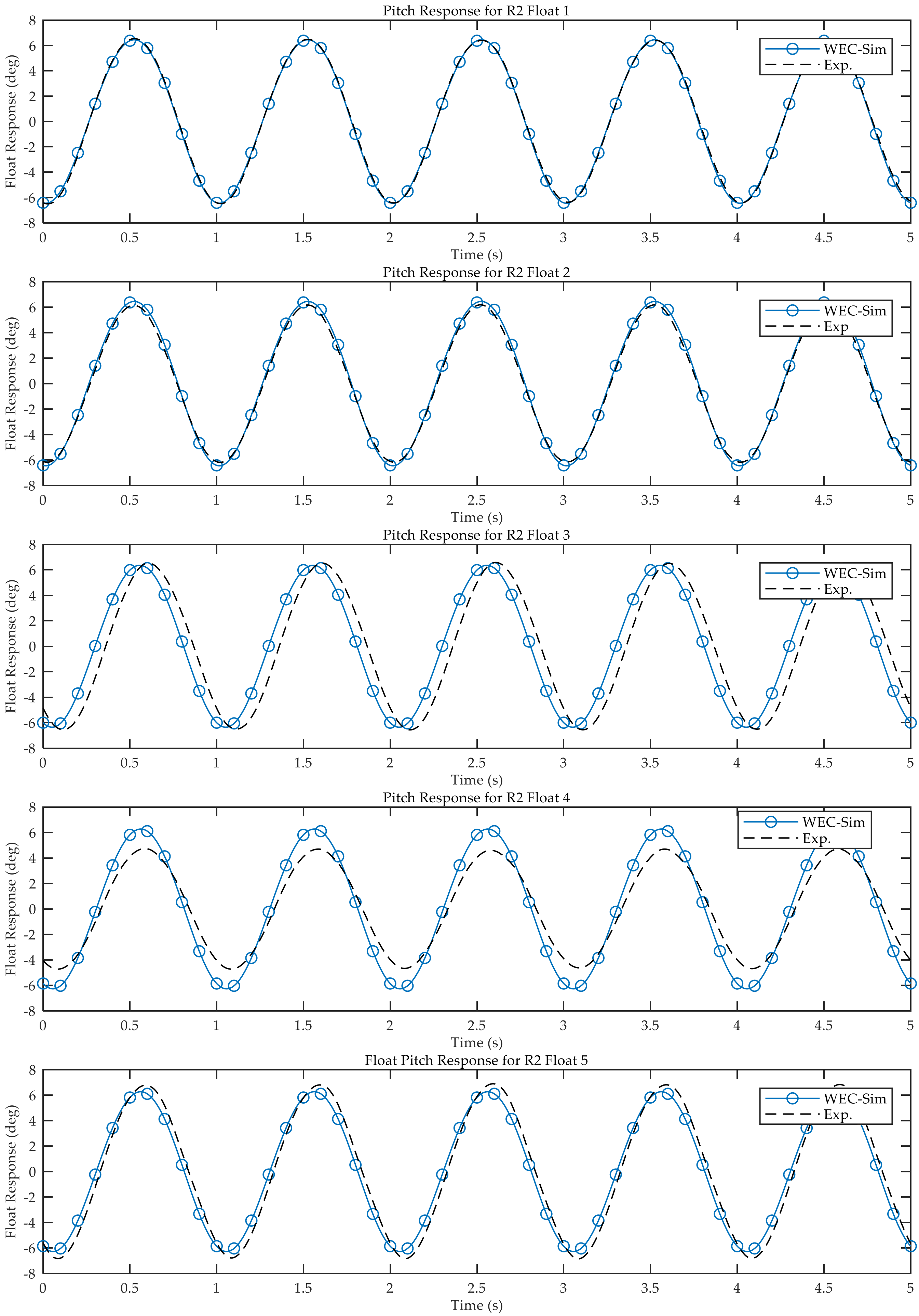

Fig. 6. Angular pitch comparison between simulated and experimental tests for the R2 wave condition. Row one consists of floats one and two while row two contains WECs three, four, and five.

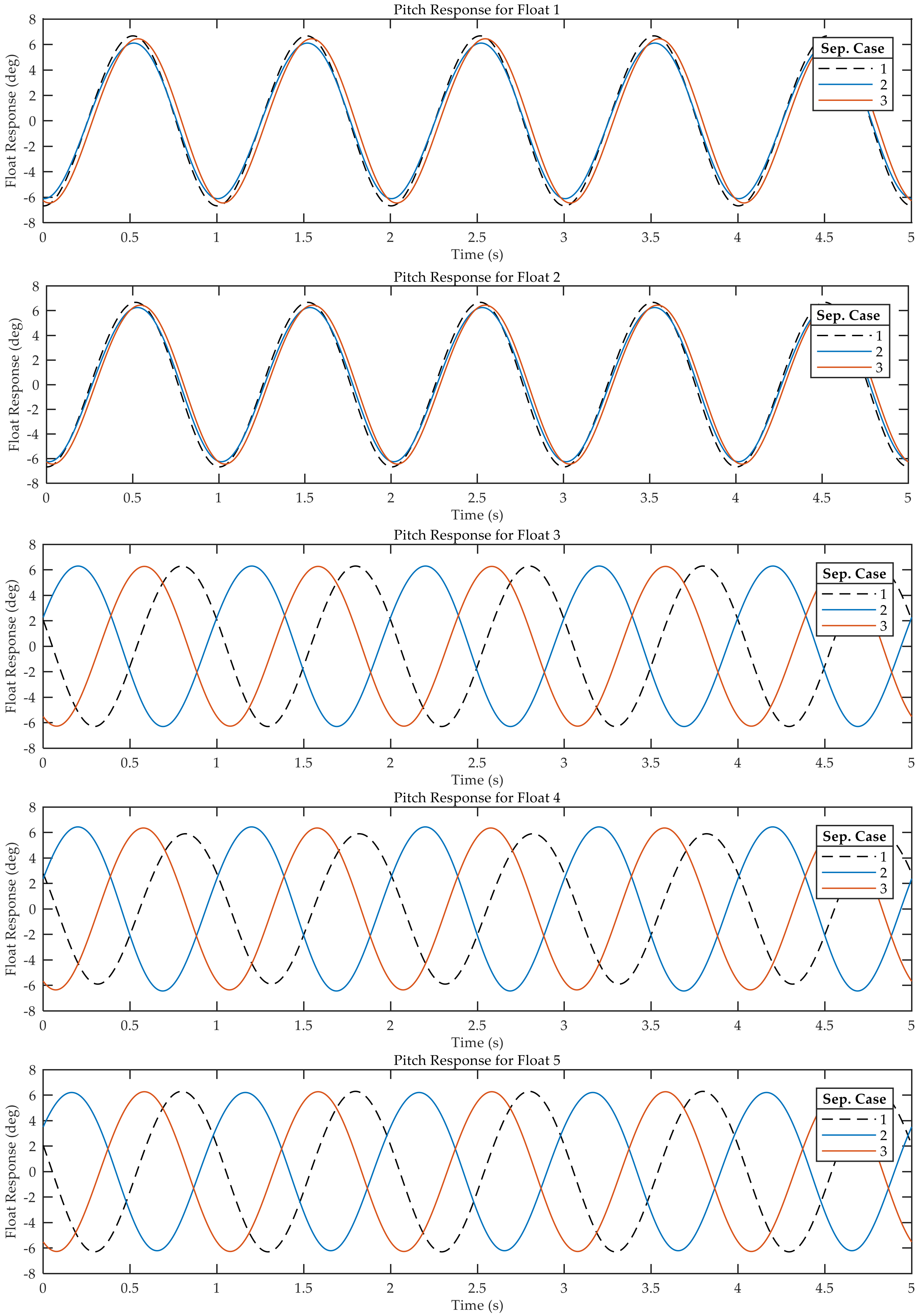

Fig. 7. Angular pitch comparison between three array configurations. The array separation cases are in ascending order with case three corresponding to the distance used in the experimental comparison. The locations for row two of the array can be found in Table V.

the second row of WECs. For the responses in the second row, float 3 and 5 share the same response. For the response in R1 floats 3 and 5 have a greater responses amplitude than float 4, however float 4 had a larger response amplitude for the R2 and R3 wave states.

The total error for the three cases was 10.04% when compared against the experimental responses. The experimental pitch responses do show more variability between the three cases, but also follow the trend found with 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 arrays with different row separation. The goal of this investigation is to better understand how WEC-Sim models body-to-body interactions between WECs. In this investigation Case three is the control case due to the experimental comparison conducted in Section IV.

The assessment used in this comparison is the percent increase of the pitch response amplitude of the two cases moved in towards the first row of WECS. In case one there is a 3.54 % increase in the row one response amplitude and a 0.46 % increase in amplitude for floats 3 and 5. Float 4 in case one falls into a wave minimum with a 7.13% decrease. The large increase in amplitude in the first row of this case is likely due to positive interaction with the second row of devices.

Case two also shows a response increase for float 2, however float 1 experienced a 5.26 decrease in amplitude. As shown in Table VI, the second case did not have symmetric results like case one. This case does show that float 3 experiences a wave maximum.

The first separation case had an overall average increase in the five-float responses while the second case has an average decrease in response. Due to the small response experienced by float 4 in case one the standard deviation of case one is higher than case two.

TABLE VI
FLOAT PITCH RESPONSE COMPARISON FOR ARRAY SEPARATION CASES

Float	Case 1	% Increase	Case 2	% Increase	Case 3
1	13.354	3.54	12.22	-5.26	12.9
2	13.354	3.54	13.12	1.72	12.9
3	12.598	0.46	12.596	0.45	12.54
4	11.802	-7.13	12.88	1.35	12.71
5	12.598	0.46	12.418	-0.97	12.54
Avg. Error		0.17		-0.54	
Std. Dev		4.36		2.84	

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 network 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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REFERENCES

[1] Tobergte, D. R., & Curtis, S. (2013). WAMIT User Manual. *Journal of Chemical Information and Modeling*, *53*(9), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

[2] Jamet, S. (n.d.). NEMOH-Presentation - LHEEA. Retrieved from https://lheea.ec-nantes.fr/logiciels-et-brevets/nemoh-presentation-192863.kjsp?RH=1489593406974

[3] ANSYS Aqwa | Hydrodynamics Simulation & Diffraction Analysis. (n.d.). Retrieved from https://www.ansys.com/products/structures/ansys-aqwa

[4] Penalba, M., Kelly, T., & Ringwood, J. (2017). Using NEMOH for modelling wave energy converters: A comparative study with WAMIT. *Proceedings of the Twelfth European Wave and Tidal Energy Conference*, {631\hyphen 1}--{631\hyphen 10}.

[5] Balitsky, P., Fernandez, G. V., Stratigaki, V., & Troch, P. (2017). *Assessing the Impact on Power Production of WEC array separation distance in a wave farm using one-way coupling of a BEM solver and a wave propagation model*. Retrieved from https://biblio.ugent.be/publication/8530166/file/8530168

[6] Penalba, M., Giorgi, G., & Ringwood, J. V. (2017). Mathematical modelling of wave energy converters: A review of nonlinear approaches. https://doi.org/10.1016/j.rser.2016.11.137

[7] Penalba, M., Touzón, I., Lopez-Mendia, J., & Nava, V. (2017). A numerical study on the hydrodynamic impact of device slenderness and array size in wave farms in realistic wave climates. https://doi.org/10.1016/j.oceaneng.2017.06.047

[8] Sharp, C., & DuPont, B. (2018). Wave energy converter array optimization: A genetic algorithm approach and minimum separation distance study. *Ocean Engineering*, *163*, 148–156. https://doi.org/10.1016/j.oceaneng.2018.05.071

[9] Cruz, J., Sykes, R., Siddorn, P., & Taylor, R. E. (2010). Estimating the loads and energy yield of arrays of wave energy converters under realistic seas. *IET Renewable Power Generation*, *4*(6), 488. https://doi.org/10.1049/iet-rpg.2009.0174

[10] Göteman, M., McNatt, C., Giassi, M., Engström, J., & Isberg, J. (2018). Arrays of Point-Absorbing Wave Energy Converters in Short-Crested Irregular Waves. *Energies*, *11*(4), 964. https://doi.org/10.3390/en11040964

[11] Yang, Z., Neary, V. S., Wang, T., Gunawan, B., Dallman, A. R., & Wu, W. C. (2017). A wave model test bed study for wave energy resource characterization. *Renewable Energy*, *114*, 132–144. https://doi.org/10.1016/j.renene.2016.12.057

[12] López-Ruiz, A., Bergillos, R. J., Raffo-Caballero, J. M., & Ortega-Sánchez, M. (2018). Towards an optimum design of wave energy converter arrays through an integrated approach of life cycle performance and operational capacity. *Applied Energy*, *209*(June 2017), 20–32. https://doi.org/10.1016/j.apenergy.2017.10.062

[13] WEC-Sim (Wave Energy Converter SIMulator) — WEC-Sim documentation. (n.d.). Retrieved November 26, 2018, from https://wec-sim.github.io/WEC-Sim/

[14] Yu, Y.-H., Tom, N., & Jenne, D. (2018). Numerical Analysis on Hydraulic Power Take-Off for Wave Energy Converter and Power Smoothing Methods. Retrieved from http://proceedings.asmedigitalcollection.asme.org

[15] Tom, N., Ruehl, K., & Ferri, F. (n.d.). *Numerical Model Development and Validation for the WECCOMP Control Competition Preprint Suggested Citation*. Retrieved from www.nrel.gov/publications.

[16] Wavestar. (n.d.). Retrieved from http://wavestarenergy.com/

[17] Welcome to the OpenWARP website — OpenWARP 0.1 documentation. (n.d.). Retrieved December 7, 2018, from http://nrel.github.io/OpenWARP/

[18] Alves, M. (2016). Frequency-Domain Models. Retrieved from https://doi.org/10.1016/B978-0-12-803210-7.00002-5