Numerical Model Development and Validation for the WECCOMP Control Competition

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NUMERICAL MODEL DEVELOPMENT AND VALIDATION FOR THE WECCCOMP CONTROL COMPETITION

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ABSTRACT

This paper details the development and validation of a numerical model of the Wavestar device developed in WEC-Sim. This numerical model was developed in support of the wave energy converter (WEC) Control Competition (WECCCOMP), a competition with the objective of maximizing WEC power production through innovative control strategies. WECCCOMP has two stages: numerical implementation of control strategies, and experimental implementation. The work presented in this paper is for support of the stage one numerical implementation, where contestants are provided a WEC-Sim model of the Wavestar device to develop their control algorithms. This paper details the development of the numerical model in WEC-Sim and of its validation through comparison to experimental data.

INTRODUCTION

In order for ocean wave energy to be a viable solution for our energy future, the levelized cost of electricity (LCOE) must be cost-competitive with other energy generation sources. LCOE is defined as the ratio of total cost to the total electrical energy produced over a wave energy converter's (WEC's) lifetime, often reported in units of $/kWh. Accordingly, there are two mechanisms to reduce LCOE: reduce the costs over the lifetime of the device, or increase its overall electrical energy production. While these two LCOE reduction mechanisms can be done independently, the most advantageous approach taken by many device developers and researchers is to simultaneously reduce cost and increase performance.

Competition is often used to promote innovation and reduce technical and market barriers. In the wave energy field, one such competition is the U.S. Department of Energy (DOE) Water Power Technologies Office-sponsored Wave Energy Prize [1]. The Wave Energy Prize was an 18-month design-build-test competition designed to increase the diversity of organizations involved in WEC technology development, with the aim to double the energy captured from ocean waves [2]. Upon completion of the Wave Energy Prize, four teams surpassed the goal of doubling energy captured, and the winner (AquaHarmonics) demonstrated a five-fold technology improvement. Similarly, a hydrodynamic modeling competition for numerical modeling and simulation of a rigid body subject to incident waves was presented by Garcia-Rosa at OMAE 2015 [3]. This code competition was run by the Center for Ocean Energy Research at Maynooth University, the basis of which was detailed in an OMAE 2014 publication by Costello on numerical model comparison to experimental data for a submerged horizontal cylinder [4, 5]. Related to competitions are international code comparison efforts, such as the International Energy Agency (IEA) Ocean Energy Systems (OES) Task 10 effort on modeling WECs, and the IEA OES Offshore Code Comparison Collaboration (OC3) through Offshore Code Comparison Collaboration, Continued with Correlation (OC5) efforts on modeling floating offshore wind turbines [6, 7].

The work presented in this paper is in support of the international WEC Control Competition (WECCCOMP), a competition with the objective of maximizing WEC power production through innovative control strategies. The first stage of WECCCOMP is implementation of WEC control in a numerical simulation at model scale using the WEC-Sim code. Contestants will

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then be down selected, and the second stage involves implementation of WEC control in an experimental wave tank. This paper details development and validation of the WECCCOMP numerical model of a WEC at scale model in WEC-Sim. The WEC selected for WECCCOMP is a scale model of the Wavestar WEC, a device that is currently operating in Denmark [8]. Prior to WECCCOMP, the Wavestar device was tested in the wave tank at Aalborg University; data from which has been used to validate the numerical model of the Wavestar decive developed in WEC-Sim. For more information on the details of WECCCOMP, refer to the EWTEC 2017 publication by Ringwood et al. on the announcement of the competition and the WECCCOMP website [9, 10].

WEC-SIM CODE

For the first stage of WECCCOMP, a simulation of the Wavestar device with control will be implemented in WEC-Sim. WEC-Sim is an open-source code jointly developed by Sandia National Laboratories (Sandia) and the National Renewable Energy Laboratory (NREL), through funding from DOE's Water Power Technologies Office [11]. The WEC-Sim code is developed in MATLAB/Simulink, uses Simscape Multibody to solve for a WEC's rigid body dynamics, and requires the toolboxes listed in Table 1 [12, 13]. WEC-Sim's implementation as a collection of MATLAB scripts (**.m* files) and Simulink libraries (**.slx* files) is hosted on an open-source GitHub repository [14]. The original v1.0 release of WEC-Sim was in June 2014, and the current v3.0 version was released in November 2017.

TABLE 1. WEC-Sim TOOLBOX REQUIREMENTS, AND WECCCOMP SUPPORTED VERSION

Required Toolbox	Supported Version
MATLAB	Version 9.2 (R2017a)
Simulink	Version 8.9 (R2017a)
Simscape	Version 4.2 (R2017a)
Simscape Multibody	Version 5.0 (R2017a)

WEC-Sim is a time-domain open-source code that solves for the system dynamics of WECs consisting of a combination of rigid bodies, power-take-off (PTO) systems, mooring systems, and control systems. The dynamic response in WEC-Sim is calculated by solving the WEC's equation of motion for each rigid body about its center of gravity C_g in 6 degrees-of-freedom (DOF) based on Cummins' equation [15]. A WEC's equation of motion can be written as:

$$(m+A_\infty)\ddot{X} = -\int_0^t K_r(t-\tau)\dot{X}(\tau)d\tau + F_{exc} + F_{vis} + F_{hs} + F_{pto} \quad (1)$$

where A_∞ is the added mass at infinite frequency, X is the body displacement (a dot denotes a time derivative), m is the mass, K_r is the radiation impulse response function, F_{exc} is the wave-excitation force, F_{pto} is the force from the PTO system, F_{vis} is the quadratic viscous drag term, and F_{hs} is the hydrostatic restoring force. While the WEC equation of motion often includes F_m for the mooring force, this term has been omitted in Eq. 1 since the Wavestar device does not include a traditional mooring system. The WEC-Sim source code includes a preprocessing boundary element method input/output (BEMIO) code that imports hydrodynamic data generated by the potential flow solvers WAMIT, NEMOH, or AQWA, and parses the BEM data into a (*.h5) data structure that is read by WEC-Sim. The *userDefinedFunctions.m* script can be used to postprocess WEC-Sim results in the form of time-series plots of position, loads, and power. For more information about WEC-Sim theory, implementation, functionality, and application, refer to the WEC-Sim website [11].

EXPERIMENTAL SETUP

For the second stage of WECCCOMP, a scale model of the Wavestar device with control will be tested in the University of Aalborg wave tank. The Wavestar is a single DOF WEC, consisting of a float rigidly connected to an arm (linkage EC) that rotates around hinge A (see LHS of Figure 1). While the experimental setup includes multiple DOFs connected by kinematic linkages, the hydrodynamic response of the float-arm can be defined as pitch motion around hinge A. The scale model includes linear position and linear force measurements, and upstream wave gauges can then be used as inputs to the controller. The experimental WEC's mass properties are listed in Table 2, and an image of the experimental setup is shown in the mid-RHS of Figure 1.

NUMERICAL MODEL DEVELOPMENT

The WEC-Sim model of the Wavestar device was developed to accurately represent the physical model that will be tested during the experimental stage of WECCCOMP. The numerical model includes the float's hydrodynamic response as well as the physical linkages and joints. The model of the Wavestar device model in WEC-Sim is shown in the mid-LHS of Figure 1, along with a visualization of the model shown in the RHS of Figure 1. The WEC-Sim Simulink model provided in mid-RHS of Figure 1 includes the float as a yellow block labeled *body(1)*. The connection between the float and arm (point E) is modeled as fixed connection, labeled *constraint(1)*. Similarly, hinge (revolute) joints

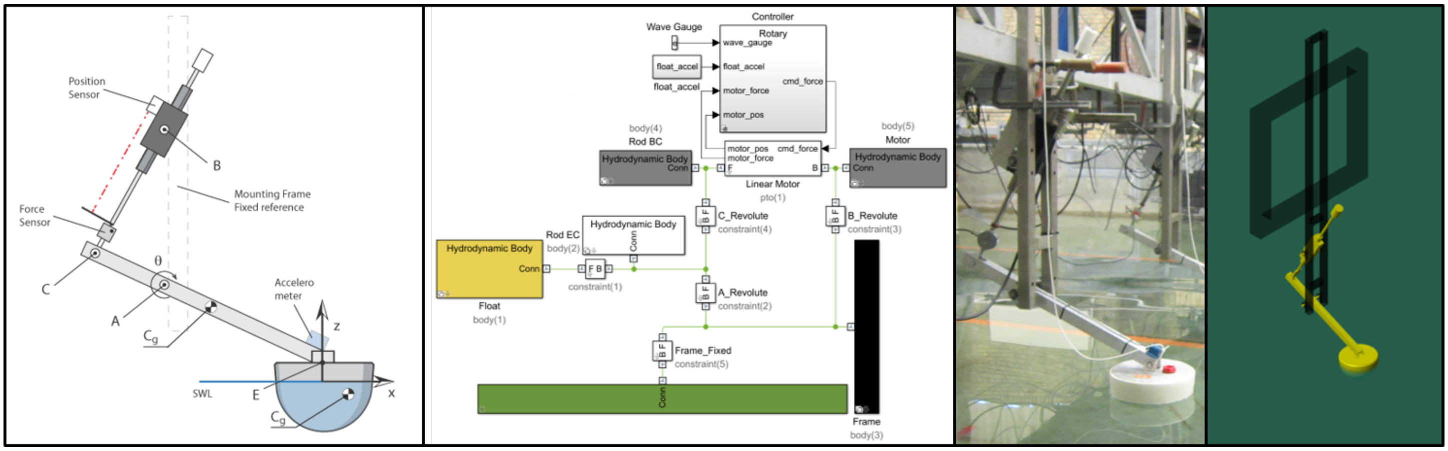


FIGURE 1. LHS: DIAGRAM OF WAVESTAR EXPERIMENTAL SETUP. MID-LHS: WEC-SIM MODEL OF WAVESTAR DEVICE. MID-RHS: IMAGE OF WAVESTAR EXPERIMENTAL SETUP. RHS: WEC-SIM SIMULATION VISUALIZATION.

TABLE 2. WAVESTAR MODEL DIMENSIONS AND MASS PROPERTIES RELATIVE TO ORIGIN AT THE STILL WATER LINE (SWL).

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 (at SWL)	0.256 [m]
Arm Mass	1.157 [kg]
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, 0.302) [m]
Hinge B (x,z)	(-0.438, 0.714) [m]
Hinge C (x,z)	(-0.621, 0.382) [m]

A, B, and C are labeled *constraint(2)*, *constraint(3)*, and *constraint(4)*, respectively. The WEC's nonhydrodynamic rigid bodies are labeled the following: arm (Rod EC) is *body(2)*, mounting frame is *body(3)*, Rod BC is *body(4)*, and motor linear actuator mass is *body(5)*. The movement of Rod BC is modeled by a translational PTO (Linear Motor) labeled *pto(1)*, which is actuated based on the algorithm written in the controller block. The WECCCOMP controller is to be developed using inputs from the upstream wave gauge(s) and either the linear force and displacement of the motor, or the rotary torque and displacement of the float. The controller linear/rotary implementation may be changed by selecting the appropriate variant subsystem in the model. This numerical model of the Wavestar device is provided to the WECCCOMP contestants for development of their controller through a GitHub repository [16]. In addition, the hydrodynamic boundary element method (BEM) solution obtained from WAMIT [17] was provided to the contestants to limit discrepancies between competitor numerical models. A mesh with 3952 panels was used to calculate the hydrodynamic radiation added mass, radiation wave damping, and wave-excitation forces and torques. The hydrodynamic coefficients were calculated at ∞ rad/s and between 0.2 rad/s and 40 rad/s with an angular frequency spacing of 0.2 rad/s. Details on the validation of this numerical model based on preliminary wave tank tests are provided in the following sections. Results from the WEC-Sim model are compared to experimental results in terms of the linear motor power, force, and displacement.

WECCCOMP Evaluation Criteria

WECCCOMP submissions will be compared against one another using the following evaluation criterion (EC):

$$EC = \frac{\text{avg}\,(P)}{2 + \frac{|f|_{98}}{F_{max}} + \frac{|z|_{98}}{Z_{max}} - \frac{\text{avg}|P|}{|P|_{98}}} \quad (2)$$

where avg (P) is the average (electrical) absorbed power (in W), $|f|_{98}$ is the 98$^{\text{th}}$ percentile of the absolute motor force time history (in N), F_{max} is the motor force constraint on the PTO (60 N), $|z|_{98}$ is the 98$^{\text{th}}$ percentile of the absolute motor displacement time history (in m), Z_{max} is the motor displacement constraint on the PTO (0.08 m), avg$|P|$ is the mean absolute electrical power (in W) , and $|P|_{98}$ is the 98$^{\text{th}}$ percentile of the absolute power time history (in W). The WECCCOMP evaluation criteria are used in this paper to assess the validity of the numerical model.

EXPERIMENTAL MODEL VALIDATION: FORCED MOTION

The WEC-Sim model was first validated against experimental tests of the Wavestar device using data from forced motion tests. In these tests, Wavestar motion is driven by a predetermined input force from the linear motor without waves. These input force signals are useful for system identification of both linear and nonlinear dynamics as the signals can be designed to cover the range of allowable amplitudes and periods expected during operation [18]. The rotational response about point A, of the rigidly connected float and arm, for three forced motion tests were completed in this analysis: a chirp test, a random amplitude, random period (RARP) test, and a multisine test. The force input time series for each test is shown in Figure 2.

In order to have a single value statistic to compare the time series between the Wavestar experiments and the WEC-Sim model, the coefficient of determination was calculated. The coefficient of determination ranges from 0 to 1, with 1 being a perfect match between signals. The calculation of coefficient of determination is given by:

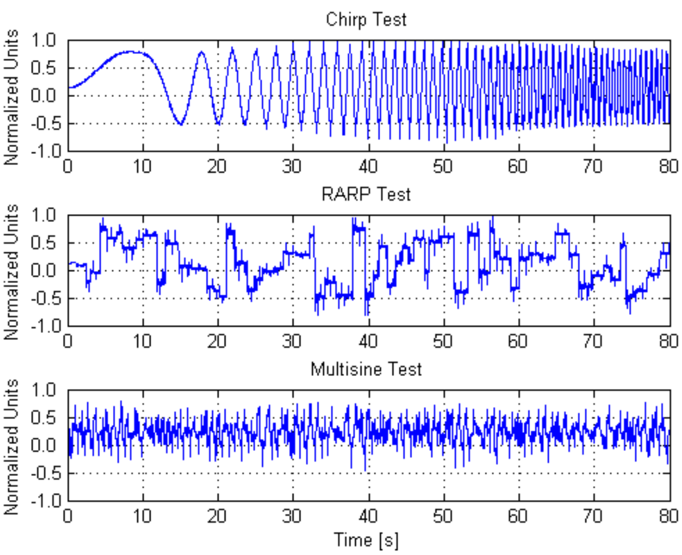


FIGURE 2. TIME HISTORY COMPARISON OF THE INPUT FORCE TESTS.

$$SS_{tot} = \sum_i \left(\theta_i - \bar{\theta}\right)^2 \quad (3)$$

$$SS_{res} = \sum_i \left(\theta_i - \hat{\theta}_i\right)^2 \quad (4)$$

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad (5)$$

where θ is the Wavestar experimental time series, $\bar{\theta}$ is the mean of the Wavestar experimental time series, $\hat{\theta}$ is the WEC-Sim time series, and R^2 is the coefficient of determination. Note that the signal length of all time series is equal, so there is no need to normalize by number of samples in this comparison.

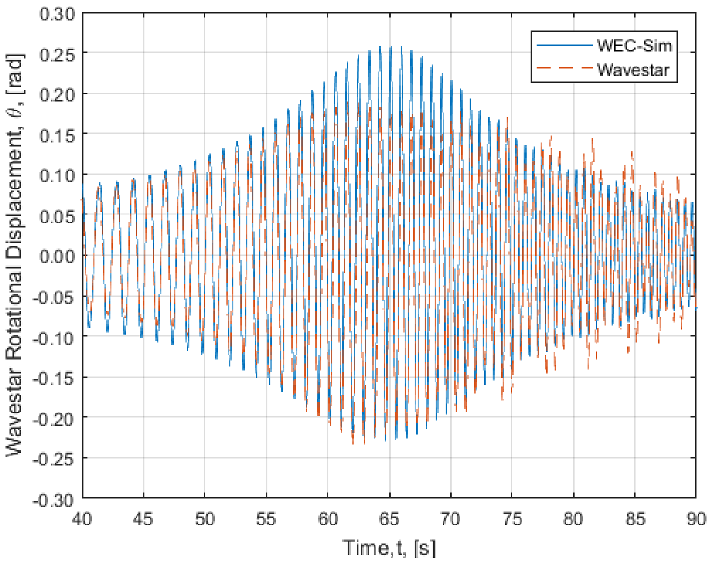
The comparison between the WEC-Sim model and the experimental data set for a chirp time series is shown in Figure 3. A linear rotational damping coefficient, located at point A, was used to tune the response of the Wavestar to account for unmodeled bearing friction and fluid viscosity in the system. After model tuning, a value of 0.4 was selected, which led to a coefficient of determination of 0.89, with the main discrepancies occurring because of an overprediction by the WEC-Sim model in the rotational displacement—see Figure 3(a) and Figure 3(b)—while WEC-Sim is able to capture the phase response fairly well.

The comparison between the WEC-Sim model and the Wavestar experiments for the RARP time series is shown in Figure 4. The same linear pitch rotational damping coefficient used to tune the chirp response of the Wavestar has been maintained for consistency. The resulting RARP coefficient of determination was calculated to be 0.95, which is an improvement over the chirp time series. As indicated from the time series in Figure 4(a), there is good visual agreement that is supported by the magnitude and phase frequency response of WEC-Sim and Wavestar experiments; see Figure 4(b). The improved time series match may be a result of the reduced amplitude of motion observed in the RARP test compared to the chirp test, which allows the assumption of linear hydrodynamic theory to be more accurate.

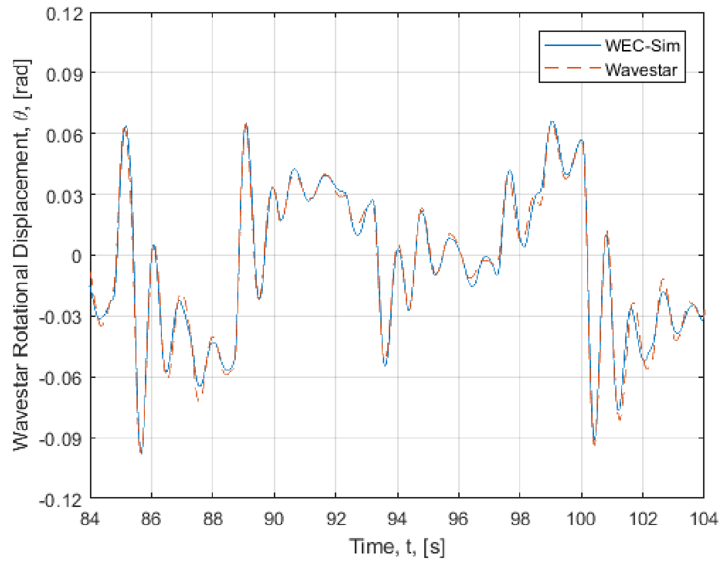
The comparison between WEC-Sim and the Wavestar experimental data set for the multisine time series is shown in Figure 5. The multisine input is the test most similar to the eventual irregular sea states used for WECCCOMP. The same linear damping coefficient from previous tests was maintained. WEC-Sim had a coefficient of determination of 0.92, which sits between the chirp and RARP simulations. It can be observed from Figure 5(b) that the WEC-Sim rotational magnitude response slightly overpredicts the Wavestar displacement for wave frequencies below 7.5 rad/s while underpredicting at higher frequencies. Overall, the authors consider the current WEC-Sim Wavestar model to provide sufficient accuracy in predicting the motion response in forced motion tests. These tests assisted in validating the models for the linear motor force response, Wavestar hydrostatic forces/torques, Wavestar hydrodynamic radiation forces/torques, and frictional forces.

EXPERIMENTAL MODEL VALIDATION: WAVE MOTION

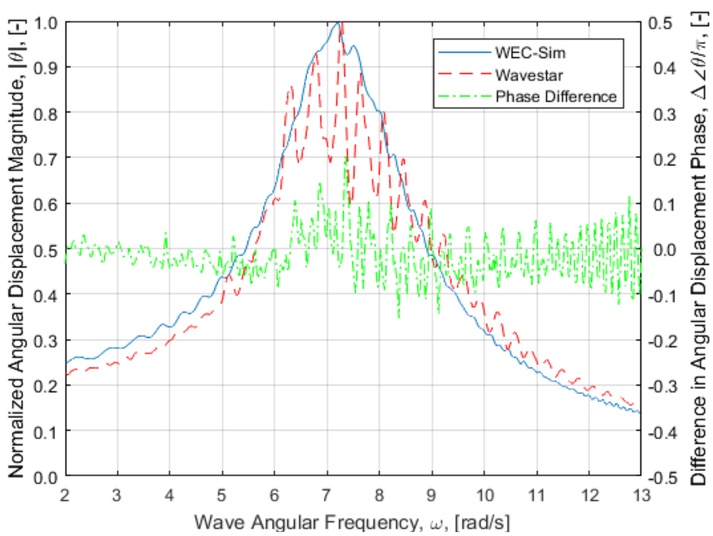
The next step in the validation study was the use of WEC-Sim to simulate the Wavestar device under irregular wave excitation. In these simulations, the Wavestar device is excited by incident waves described by a Jonswap spectrum with a signifi-



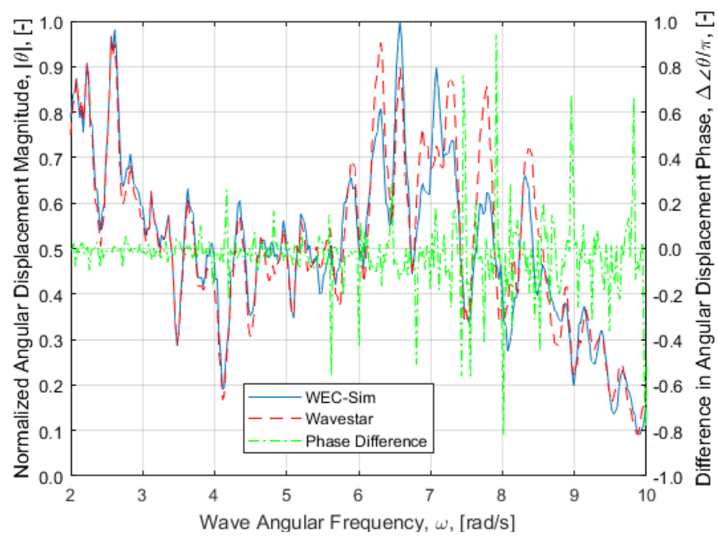
(a) WAVESTAR ROTATIONAL DISPLACEMENT CHIRP TIME SERIES



(a) WAVESTAR ROTATIONAL DISPLACEMENT RARP TIME SERIES



(b) WAVESTAR ROTATIONAL CHIRP MAGNITUDE AND PHASE RESPONSE



(b) WAVESTAR ROTATIONAL RARP MAGNITUDE AND PHASE RESPONSE

FIGURE 3. A FAST FOURIER TRANSFORM WAS APPLIED TO THE MODEL AND EXPERIMENTAL CHIRP INPUT FORCE TIME SERIES TO OBTAIN THE WAVESTAR ROTATIONAL MAGNITUDE AND PHASE RESPONSE.

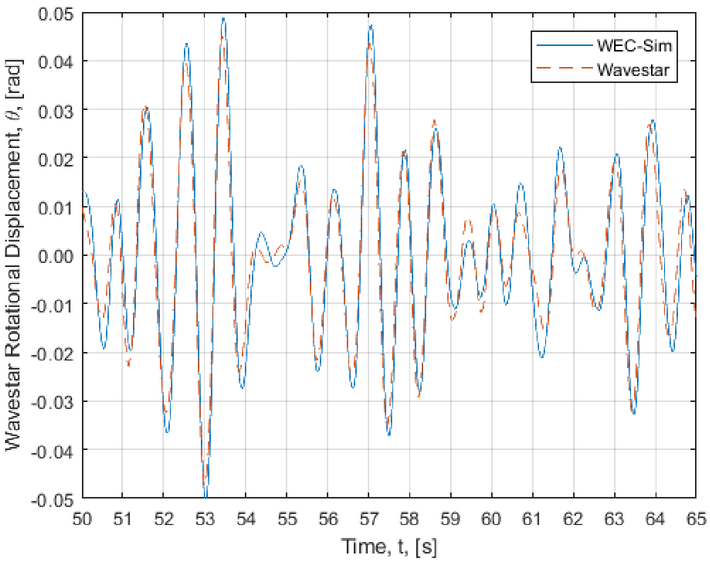
FIGURE 4. A FAST FOURIER TRANSFORM WAS APPLIED TO THE MODEL AND EXPERIMENTAL RARP INPUT FORCE TIME SERIES TO OBTAIN THE WAVESTAR ROTATIONAL MAGNITUDE AND PHASE RESPONSE.

cant wave height, H_s, of 6 *cm*, a zero-crossing period, T_{02}, of 1.2 *s*, and peak enhancement factor of 1.

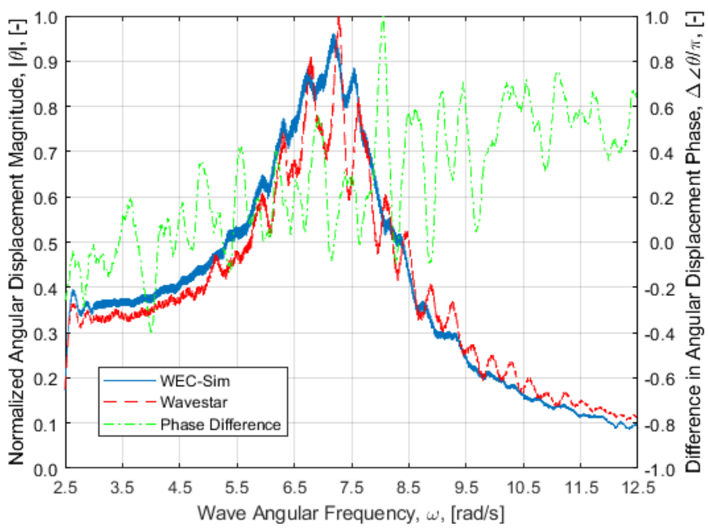
Wave Motion: No Control

The first simulation was run without implementing any linear motor control force and allowing the WEC to oscillate naturally under irregular wave excitation. Because there are no control forces implemented, the simulation results can be used to help verify the hydrodynamic wave-excitation forces. The simulation was run with the same constant linear pitch rotational damping coefficient determined during the forced motion simulations. The comparison of the linear motor displacement between WEC-Sim and Wavestar is shown in Figure 6.

Figure 6(a) plots the time history of the linear motor displacement for WEC-Sim and Wavestar experiments, which provides a coefficient of determination, R_m^2, of 0.94. This can be confirmed from good visual agreement in Figure 6; however, this metric is not used in the evaluation criteria described in Eq. (2). Therefore, the 98th percentile of the absolute value of the linear



(a) WAVESTAR ROTATIONAL DISPLACEMENT MULTISINE TIME SERIES



(b) WAVESTAR ROTATIONAL MULTISINE FREQUENCY RESPONSE

FIGURE 5. A FAST FOURIER TRANSFORM WAS APPLIED TO THE MODEL AND EXPERIMENTAL MULTISINE INPUT FORCE TIME SERIES TO OBTAIN THE WAVESTAR ROTATIONAL MAGNITUDE AND PHASE RESPONSE.

motor displacement, $|z|_{98}$, was calculated for comparison. The absolute value of the linear motor displacement was sorted in ascending order and plotted in Figure 6(b). There is very good agreement between the simulation and experiments with WEC-Sim providing a 98th percentile value that is 97% of the Wavestar experiment. It can be observed from Figure 6(b) that WEC-Sim slightly underestimates the absolute value of the linear displacement for the data points between the 80th and 98th percentile and the maximum linear motor displacement is larger for the Wavestar experiments.

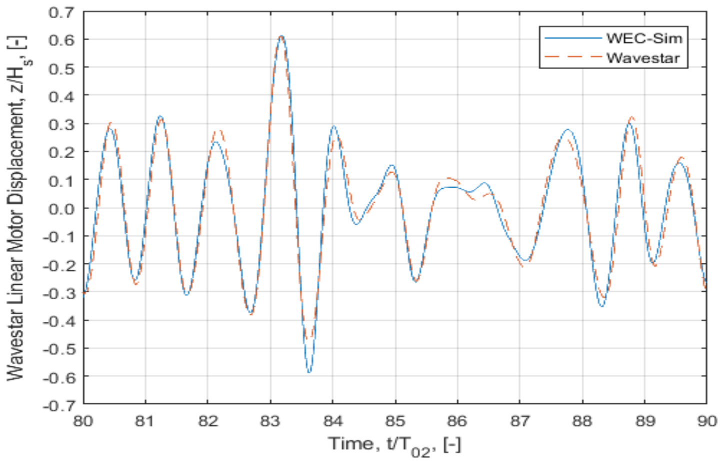
The comparison of the frequency response between WEC-Sim and the Wavestar experiments has been plotted in Figure 6(c). Overall, the phase difference is minimized at the most energetic frequencies, while the Wavestar appears to have a slightly larger response in the wave frequencies above 5.5 rad/s. The discrepancy at higher wave frequencies might be explained by the pitch linear damping coefficient, which has a greater influence in the high-frequency regime. The pitch linear damping coefficient might also have been overpredicted, as it was tuned in forced motion tests (there is no control force applied in this test case). However, results show there is good overall agreement between WEC-Sim and the Wavestar experiments for the unforced response in irregular waves.

Wave Motion: Controller Response

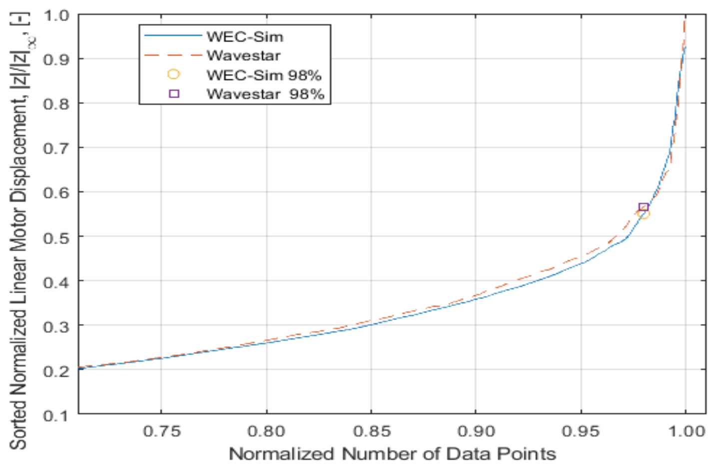
Using the same wave elevation time series, four tests were completed to validate the ability of WEC-Sim to simulate the force generated by the linear motor during control experiments. For these tests, a resistive control law was implemented that generated a motor command torque that was equal to the product of the Wavestar angular velocity and a linear rotational damping coefficient. The tests are labeled as 2, 3, 4, and 5, which correspond to rotational damping coefficients of 5, 10, 15, and 20 $N \cdot m \cdot s$, respectively. A rotational-to-linear conversion block has been added to the WEC-Sim Simulink model to calculate an equivalent linear motor force to match the commanded control torque.

A comparison of the performance metrics used to calculate the evaluation criteria between WEC-Sim and the Wavestar experiments can be found in Table 3 and Table 4. There is good agreement between simulations and experiments with the difference in EC between WEC-Sim and Wavestar peaking at 7%. However, as the PTO rotational damping coefficient is increased, WEC-Sim predicts greater peaks in motor power, motor force, and motor displacement. The overprediction may be the result of unmodeled motor controller dynamics that are not accounted for in WEC-Sim. As the PTO rotational damping coefficient increases the linear rotational drag coefficient can be increased to improve matching between WEC-Sim and the Wavestar experiments. The linear rotational drag coefficient tuned in the forced motion tests led to a significant overprediction by WEC-Sim in average power and needed to be increased to 1.8 for improved matching during control tests.

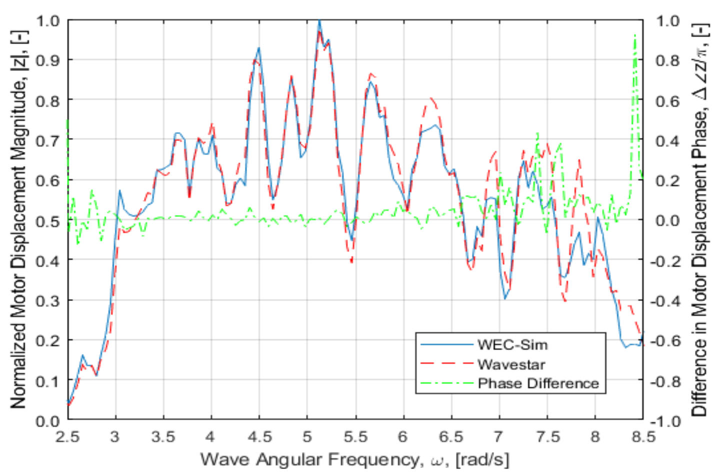
The time histories the from WEC-Sim and Wavestar experiments for test case 3 have been plotted in Figure 7. As expected from the performance metrics in Table 3 and Table 4, there is good visual agreement between WEC-Sim and the Wavestar experiments for the linear motor instantaneous power, force, and displacement. In Figure 7(b), there are two signals from WEC-Sim and Wavestar that correspond to the commanded and measured linear motor force. The control law calculates the desired



(a) WAVESTAR LINEAR MOTOR DISPLACEMENT



(b) SORTED NORMALIZED ABSOLUTE VALUE OF THE WAVESTAR LINEAR MOTOR DISPLACEMENT



(c) WAVESTAR LINEAR MOTOR DISPLACEMENT FREQUENCY RESPONSE

FIGURE 6. TIME HISTORY COMPARISON OF THE LINEAR MOTOR DISPLACEMENT BETWEEN THE WEC-SIM AND WAVESTAR EXPERIMENTS FOR SIMULATION WITHOUT CONTROL.

TABLE 3. WAVESTAR EVALUATION CRITERIA METRICS

Test	avg(P)	$\frac{\lvert f\rvert_{98}}{F_{max}}$	$\frac{\lvert z\rvert_{98}}{Z_{max}}$	$\frac{\text{avg}\lvert P\rvert}{\lvert P\rvert_{98}}$	EC
2	0.076	0.161	0.272	0.145	0.033
3	0.084	0.242	0.214	0.145	0.036
4	0.080	0.292	0.178	0.140	0.034
5	0.073	0.328	0.149	0.135	0.031

TABLE 4. WEC-SIM EVALUATION CRITERIA METRICS

Test	avg(P)	$\frac{\lvert f\rvert_{98}}{F_{max}}$	$\frac{\lvert z\rvert_{98}}{Z_{max}}$	$\frac{\text{avg}\lvert P\rvert}{\lvert P\rvert_{98}}$	EC
2	0.072	0.152	0.266	0.156	0.032
3	0.086	0.241	0.218	0.148	0.037
4	0.085	0.302	0.182	0.141	0.036
5	0.079	0.342	0.155	0.137	0.033

motor force while there is a separate motor controller that is responsible for meeting the commanded motor force. However, the motor controller does not provide a perfect match between commanded and measured force. A transfer function was created from the Wavestar experimental data and implemented in the WEC-Sim Simulink model. Results show that the transfer function realization performs well at modeling the physical response of the motor.

The absolute values of the linear motor instantaneous power, motor force, and motor displacement were sorted in ascending order for test case 3 and plotted in Figure 8 to compare the 98th percentiles. Of the four test cases, test case 3 had the best matching between WEC-Sim and the Wavestar experiments so it is not surprising that the 98th percentiles for the three evaluation criteria metrics are within a few percent. However, it can be observed that at the tail of the plots, between the 99th and 99.9th percentiles, WEC-Sim produces greater peaks in motor power, force, and displacement. The 98th percentile was chosen as it was considered a better statistical representation of the expected peak value. Larger peaks observed during the simulations could be dependent on constructive interactions between wave components because of the random phase angles selected to reconstruct the irregular wave elevation. The tail end of the sorted time series starts to grow exponentially and the peak value can be significantly larger than the 98th percentile. The plots show the ratio of the peak value to the 98th percentile is 3, 1.8, and 2 times greater for the linear motor power, force, and displacement, respectively.

The frequency response of the linear motor instantaneous power, motor force, and motor displacement are plotted in Figure 9. Overall, there is good agreement in the magnitude and phase response between the WEC-Sim and Wavestar experiments. In the frequency range with the greatest energy concentration, between 4.0 rad/s and 6 rad/s, WEC-Sim does appear to slightly overpredict the magnitude response for each metric, but the phase difference is minimal. While in the high-frequency range, above 6 rad/s, the WEC-Sim begins to underpredict the magnitude response; however, because the motion is only 30% of the peak, this should not have as large an impact on the average electrical power and 98^{th} percentile calculations.

CONCLUSION

The work presented in this paper describes the validation of a numerical model of the Wavestar device developed in WEC-Sim. This numerical model was developed in support of the WEC Control Competition (WECCCOMP), a competition with the objective of maximizing WEC power production through innovative control strategies. WECCCOMP has two stages: numerical implementation of control strategies and experimental implementation. The WEC-Sim model was developed for stage one, numerical control implementation, where contestants are provided a WEC-Sim model of the Wavestar device to develop their control algorithm. The simulated response of the WEC-Sim model provided in this paper was compared against Wavestar wave tank experiments provided by Aalborg University. The validation study began with forced motion tests that did not include wave excitation, where the Wavestar motion was driven by a predetermined input force from the linear motor. These tests assisted in validating the linear motor force response, hydrostatic forces, hydrodynamic radiation forces, and frictional forces. Next, the validation study included wave-excitation forces and implemented a linear-resistive control strategy. Four different linear PTO damping coefficients were tested and the performance metrics used to calculate evaluation criteria were reported, with discrepancies in the evaluation criteria staying within 7%. Comparisons of the time histories, 98^{th} percentile, and frequency response between WEC-Sim and the Wavestar experiments were all in good agreement with small discrepancies identified; however, these discrepancies are not expected to affect the evaluation criteria. The validation study between the simulations and wave tank experiments demonstrated WEC-Sim's ability to accurately simulate device response and power performance. Future work will include verification of the device natural frequencies and free decay behavior that was not included in this work, but is important for further verification of the dynamic model. Further evaluation of WECCCOMP contestant control algorithms is also needed, with review of submissions for stage two to follow.

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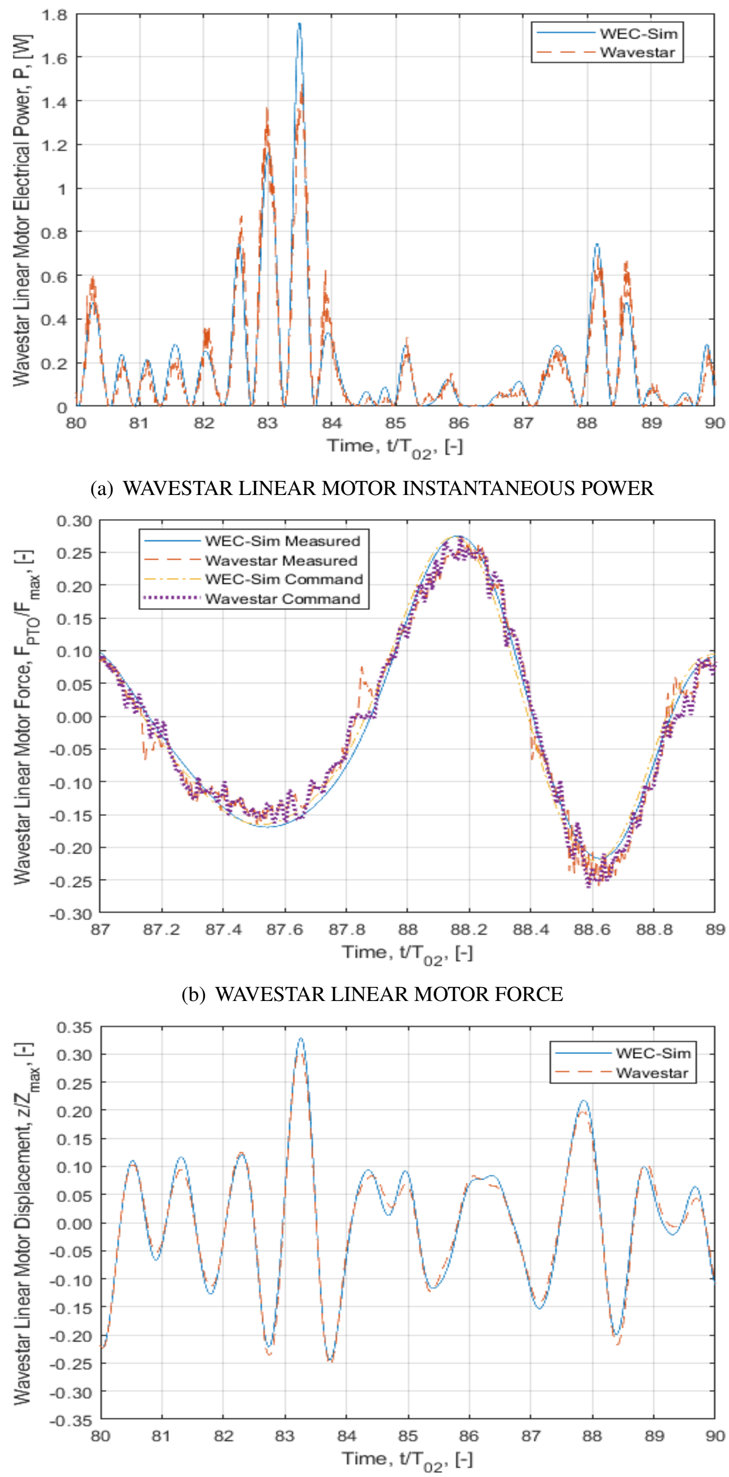
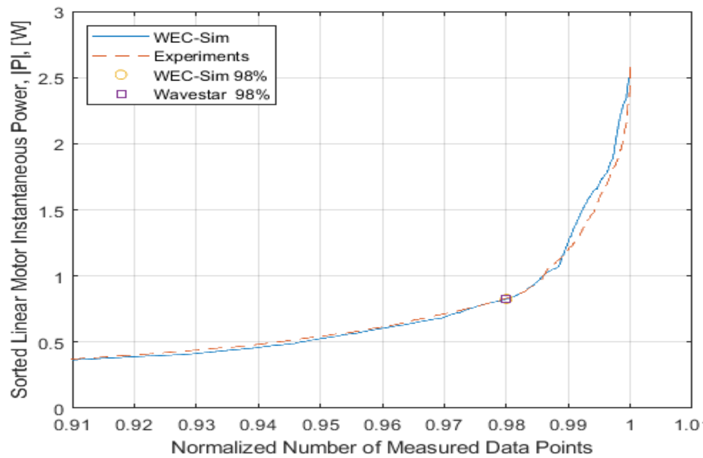


(a) WAVESTAR LINEAR MOTOR INSTANTANEOUS POWER

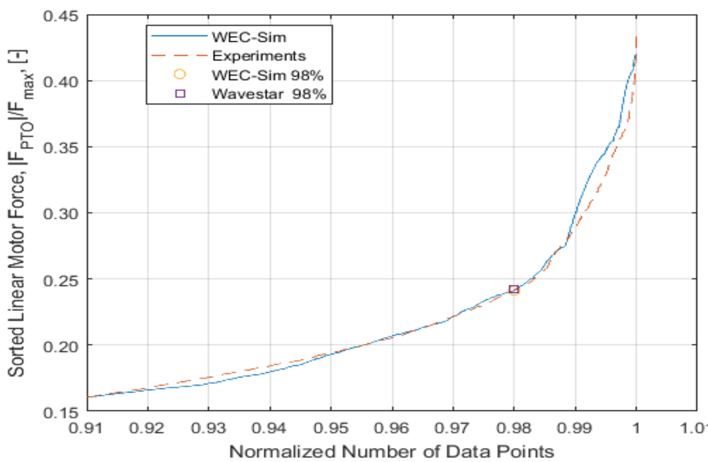
(b) WAVESTAR LINEAR MOTOR FORCE

(c) WAVESTAR LINEAR MOTOR DISPLACEMENT

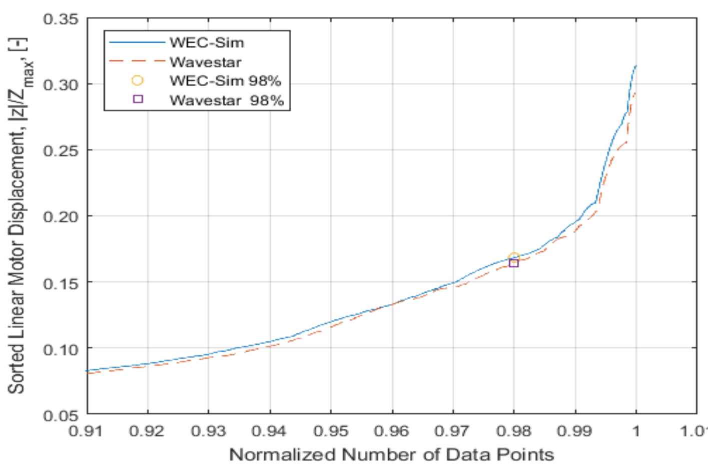
FIGURE 7. TIME HISTORY COMPARISON OF LINEAR MOTOR INSTANTANEOUS POWER, LINEAR MOTOR FORCE, AND LINEAR MOTOR DISPLACEMENT BETWEEN WEC-SIM AND THE WAVESTAR EXPERIMENTS FOR TEST CASE 3.



(a) SORTED WAVESTAR LINEAR MOTOR INSTANTANEOUS POWER

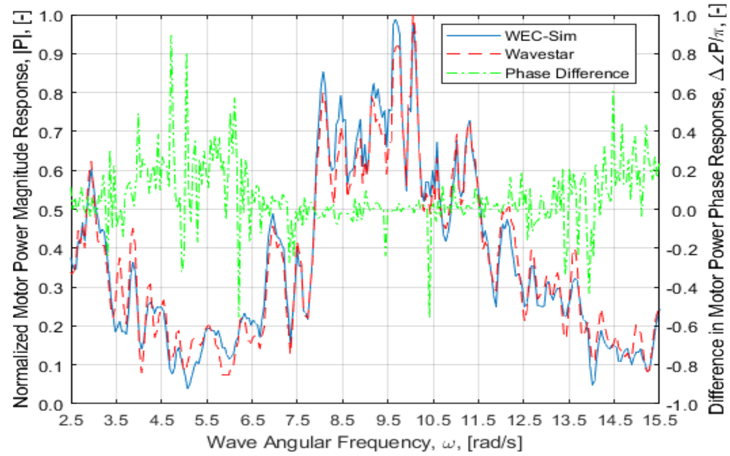


(b) SORTED WAVESTAR LINEAR MOTOR FORCE

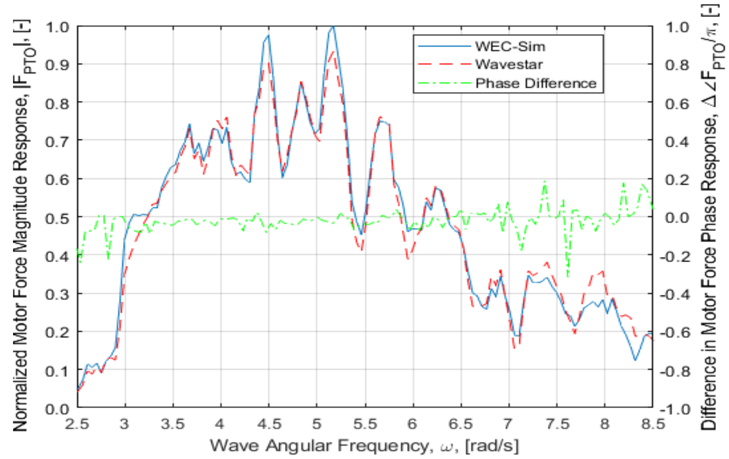


(c) SORTED WAVESTAR LINEAR MOTOR DISPLACEMENT

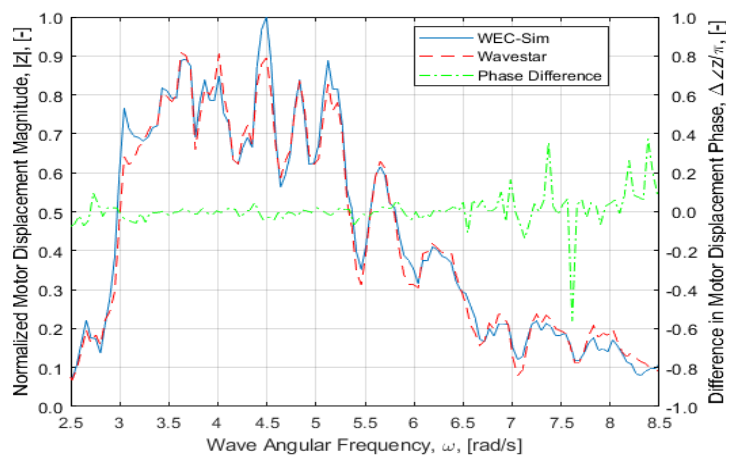
FIGURE 8. COMPARISON OF 98th PERCENTILE OF LINEAR MOTOR INSTANTANEOUS POWER, LINEAR MOTOR FORCE, AND LINEAR MOTOR DISPLACEMENT BETWEEN WEC-SIM AND THE WAVESTAR EXPERIMENTS FOR TEST CASE 3.



(a) MOTOR INSTANTANEOUS POWER FREQUENCY RESPONSE



(b) MOTOR FORCE FREQUENCY RESPONSE



(c) MOTOR DISPLACEMENT FREQUENCY RESPONSE

FIGURE 9. COMPARISON OF THE FREQUENCY RESPONSE OF LINEAR MOTOR INSTANTANEOUS POWER, LINEAR MOTOR FORCE, AND LINEAR MOTOR DISPLACEMENT BETWEEN WEC-SIM AND THE WAVESTAR EXPERIMENTS FOR TEST CASE 3.

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