Preliminary Wave Energy Converters Extreme Load Analysis

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PRELIMINARY WAVE ENERGY CONVERTERS EXTREME LOAD ANALYSIS

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ABSTRACT

Wave energy converter (WEC) devices are designed to sustain the wave-induced loads that they experience during both operational and survival sea states. The extreme values of these forces are often a key cost driver for WEC designs. These extreme loads must be carefully examined during the device design process, and the development of a specific extreme condition modeling method is essential. In this paper, the key findings and recommendations from the extreme conditions modeling workshop hosted by Sandia National Laboratories and the National Renewable Energy Laboratory are reviewed. Next, a study on the development and application of a modeling approach for predicting WEC extreme design load is described. The approach includes midfidelity Monte-Carlo-type time-domain simulations to determine the sea state in which extreme loads occur. In addition, computational fluid dynamics simulations are employed to examine the nonlinear wave and floating-device-interaction-induced extreme loads. Finally, a discussion on the key areas that need further investigation to improve the extreme condition modeling methodology for WECs is presented.

KEYWORDS

Wave energy; extreme condition modeling; design load; time-domain numerical model; computational fluid dynamics simulation

INTRODUCTION

A successful wave energy converter (WEC) design requires a balance between the power output and the cost to generate that power [1,2]. Because WEC technologies are still in the early stages of development, their cost of energy is high. Therefore, finding an efficient pathway to reduce that cost is essential for the WEC industry to be successful [3]. Generally, a WEC is designed to optimize its motion so it can produce the maximum system power output [4]. However, the design loads, including fatigue loads and extreme loads, must be carefully examined during the device design process as the structural constraints imposed by these loads are often a key cost driver for WEC designs. In particular, the extreme loads are often caused by the complex nonlinear wave-structure interaction, and the prediction of these loads is a critical step in the design process. Additionally, the extreme wave load does not always occur at the largest wave. Instead, it is often a series of specific wave trains that cause extreme loads. Therefore, it is essential to develop a systematic approach to identify the critical sea states that are likely to cause an extreme wave load.

Researchers from Sandia National Laboratories and the National Renewable Energy Laboratory hosted a workshop on WEC extreme conditions modeling (ECM) in Albuquerque, New Mexico, in which the current state of knowledge on how to numerically and experimentally model WECs in extreme conditions was reviewed. A summary on the workshop key findings and recommendations are presented in this paper. More details of the workshop findings, including the breakout session discussions and notes are described in the workshop report [5].

As discussed in the workshop, although high-fidelity computational fluid dynamics (CFD) methods have become available for design application because of the rapid development of high-performance computing technology, the application of CFD is still relatively uncommon because of the prohibitive computational time needed to simulate all the necessary cases. Therefore, ship designers [6–8] and the wind energy industry often use a modeling approach that first identifies the likely extreme loading scenarios using a simple low/midfidelity method and then investigates those scenarios by using CFD simulations or experimental wave tank tests.

In this paper, researchers from the National Renewable Energy Laboratory and Sandia National Laboratories first review the key findings and recommendations from the ECM workshop. Then, we focus on the development and application of a design process for predicting WEC extreme loads. A study on using a linear time-domain numerical model to simulate a point absorber WEC design under a 100-year extreme sea state was conducted. The simulation was carried out through extensive Monte-Carlo-type calculations to determine maximum loads and the sea state at which those loads occurred. Based on the linear model results, the CFD simulations were performed at the extreme loading sea states to further examine the WEC design loads. The results from the midfidelity time-domain model and CFD simulations are included in this paper, as well as a discussion on the key areas that need further investigation to improve the extreme condition modeling methodology for WECs.

ECM WORKSHOP SUMMARY

The objective of the ECM workshop was to review the current state of knowledge related to numerical and experimental modeling of WECs in extreme conditions and suggest how additional research could be performed to improve ECM methods. More than 30 U.S. and European WEC experts from industry, academia, and national research institutes attended the workshop, which consisted of presentations from WEC developers and subject matter experts, breakout sessions, and a final plenary session. The key findings and recommendations from the workshop include the following [5]:

- Numerical and experimental ECM methods developed by the offshore oil and gas and shipping industries are useful; however, WEC-specific ECM methods are needed because the device is designed to maximize its motion and wave-induced load at the dominant sea states, and offshore oil and gas platforms and ships are not.
- It is not always the largest wave that causes the largest load. The largest load often happens when the WEC device is subjected to a series of waves that do not have the largest wave height but result in the maximum load because of the instantaneous WEC position and wave elevation. In addition, for different WEC components, the largest load may happen at different wave environments, which can occur in operational sea states as well.
- Because of the nature of the irregular sea states, a risk-based design approach is being used for certification. The occurrence of extreme loads can be studied as a stochastic event, which is similar to the design process used for ship and offshore structure design.
- Open-source experimental data sets are needed to validate WEC device design and analysis methods, and the development of a set of guidelines and best practices that describe how to numerically model WECs—particularly in extreme conditions—would benefit the WEC community.

HEAVING SPHERE TEST CASES

The following sections will present a study that was conducted to aid in the development of a practical methodology to predict WEC extreme loads. The method was applied to model a heaving sphere. The test case setup and the extreme sea states at a reference site used in the study are described in this section.

Case Setup

The heaving sphere and its schematic are shown in Figure 1. The floating body has a radius of 5 m and is at its equilibrium position with its origin located at the mean water surface. The body was only allowed to move freely in heave, and the incoming extreme wave was assumed to be unidirectional.

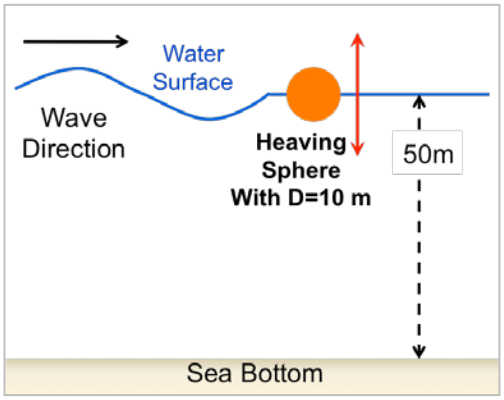

Figure 1. SCHEMATIC (SIDE VIEW) FOR THE HEAVING SPHERE TEST CASE.

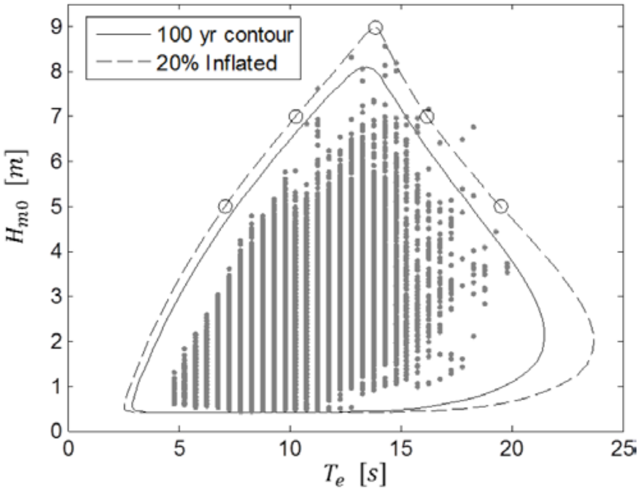

Figure 2. 100-YEAR CONTOUR FOR THE NATIONAL DATA BUOY CENTER BUOY #46212 [9].

Extreme Sea States

A typical 100-year significant wave height during storms for the West Coast of the United States is generally between 8 and 13 m. We used data from the National Data Buoy Center #46212 buoy near Humboldt Bay, California, as the reference wave environment for the extreme sea conditions [9]. Figure 2 shows the scatterplot of measured conditions from 2004 to 2012, which contains specific extreme wave conditions during storms. Also shown in the figure are the 100-year and 20% inflated contours, accounting for the approximations in the extreme load simulations. Table 1 shows the selected wave environments of the 20% inflated contour (open circles in Figure 6), which were used for the design load analysis in the following WEC-Sim simulations to search for the extreme events.

Table 1. WAVE ENVIRONMENTS ALONG THE 20% INFLATED 100-YEAR CONTOUR

Case Number	**Significant Wave Height H_s (m)**	**Energy Period T_e (s)**	**Peak Period T_p (s)**
1	5.0	7.1	8.2
2	7.0	10.3	11.9
3	9.0	13.8	16.0
4	7.0	16.2	18.8
5	5.0	19.5	22.6

EXTREME CONDITION MODELING METHODOLOGY

The following sections will present a study that was conducted to aid in the development of an approach for predicting WEC extreme loads. The methodology for the preliminary approach and the two numerical models employed are described.

Approach for Searching Extreme Events

Based on the experience from the ship design and wind energy industries, a preliminary using a simple midfidelity method to identify the likely extreme loading scenarios and a higher-fidelity method (CFD simulations) to then investigate those scenarios has been utilized (Figure 3).

The approach first solves the WEC device system dynamics and estimates the corresponding forces using a time-domain numerical model known as WEC-Sim. A set of sea states were defined to be of interest for the fictional device studied here. Using WEC-Sim, each sea state, identified by a significant height (H_s) and peak period (T_p), was simulated in a Monte-Carlo fashion with different random phase seeds to search for the maximum peak load. The identified extreme wave environment was then modeled using high-fidelity CFD simulations, thus allowing the detailed flow field and nonlinear wave-body-interaction-induced extreme loads to be analyzed. The CFD simulations were performed using a single design wave (regular) with a wave height of H = K×H_s and a period of T=T_p, where H_s and T_p were identified from the WEC-Sim simulations and K is equal to 1.9. The value was given by assuming the distribution of the extreme wave height follows a Rayleigh distribution, and the maximum 100-year individual wave height H_{100} for sea states is most likely 1.9 times of the significant wave height for the 100-year wave (H_{s100}), assuming the storm lasts for 3 hours with 1,000 waves [10].

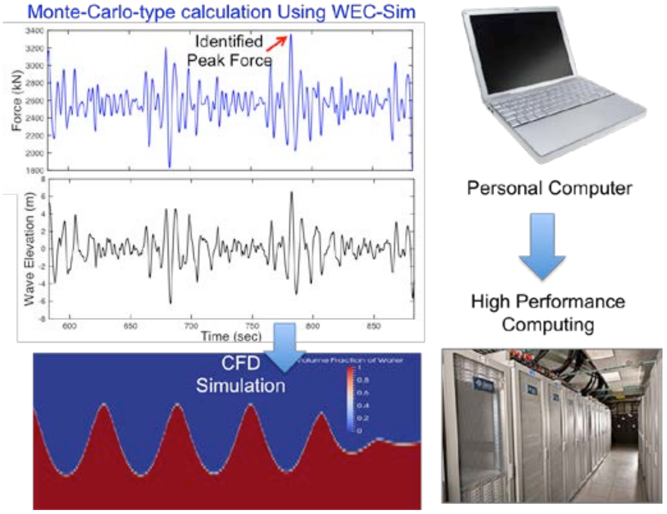

Figure 3. PROCESS CONCEPT FOR PREDICTING THE DESIGN LOAD.

WEC-Sim Model

WEC-Sim solves the multibody system dynamics of WECs in the time domain, based on the radiation and diffraction method and a simple power take-off (PTO) model [11,12]. Figure 4 shows the WEC model and developed WEC-Sim hydrodynamic blocks.

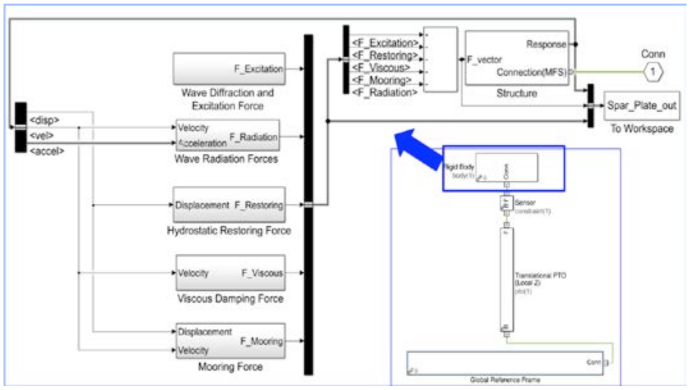

Figure 4. MODEL SETUP IN WEC-SIM AND THE PREBUILT BLOCKS TO MODEL HYDRODYNAMICS.

The equation of motion (Cummins equation) for the floating-body system is solved in WEC-Sim around the center of gravity for each body, can be given as

$$(m+m_\infty)\ddot{x} = -\int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau - F_{hs} + F_e + F_v + F_{ext} \quad , \qquad (1)$$

where m is the mass matrix and m_∞ is the added mass matrix at the infinite frequency. The term $-\int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau$ is the convolution integral that represents the resistive force on the body from wave radiation, and K is the impulse response function. F_{hs}, F_e, F_v, and F_{ext} are the hydrostatic restoring force, the wave excitation force, the viscous drag force, and the external force, respectively. The convolutional integral, m_∞, F_{hs}, and F_e represent the forcing terms induced by the inviscid wave and floating-body interaction. A viscous drag coefficient of 1 was used for the sphere in the WEC-Sim simulation. All of the inviscid hydrodynamic terms were calculated using linear coefficients obtained from a potential-flow boundary-element-method (BEM) simulation known as WAMIT [13]. Mesh sensitivity studies were performed for the WAMIT simulations to ensure that the BEM-based hydrodynamic coefficient solutions were converged. More details on the WEC-Sim model methodology, validations, and applications are described in [11,12].

RANS Model

A finite-volume, method-based, unsteady Reynolds-averaged Navier-Stokes (RANS) model (StarCCM+ [14]) was applied in this study to model the extreme events identified by the Monte-Carlo-type WEC-Sim simulations. The RANS model discretizes RANS and continuity equations over the computational domain and solves the system of linear equations in the time domain. The numerical schemes used in the study are listed in Table 2. An overset model was applied by implementing two layers of meshes, one for the floating body and a second one for background wave field to encounter movement of the body caused by the wave and floating body interaction. The computational domain was 90 m wide, 90 m high (with a water depth of 50 m), and 6 wavelengths long. A fifth-order Stokes wave was specified at the inflow boundary, and the volume of fluid method was used to capture the wave elevation. To absorb the outgoing and reflecting waves without creating additional numerical disturbance, a two-wavelength-long sponge-layer-damping zone was used in the simulations.

Table 2. NUMERICAL SETTINGS IN THE RANS MODEL.

Pressure-velocity coupling	Transient SIMPLE algorithm
Turbulence model	k-ω SST (with a two-layer all y+ wall treatment model)
Time marching	Second-order implicit scheme
Water surface capturing	Volume of fluid method
Mesh and body motions	Overset
Wave absorber	Sponge-layer wave damping zone

RESULTS

This section presents the results from the test case study through the use of WEC-Sim and CFD simulation.

Search for Extreme Events

The design approach was initiated by performing WEC-Sim simulations under the irregular wave environment with the given significant wave height and peak period listed in Table 1. For each given sea state, the WEC-Sim simulations were performed repeatedly with 200 random wave phase seeds to search for the extreme wave condition that would result in the maximum response or force. Each simulation was performed in the time domain for the duration of $200T_p$, with a ramp time of $20T_p$ and a time-step size of $0.005T_p$. Two quantities of interest were considered here:

- Maximum heave response: related to end-stop limitations in PTO systems
- Peak surge force: indicates the likely large force and moment at the foundation.

Figures 5 and 6 show the density distribution for the peak heave response and surge force for the two extreme cases, resulting from each WEC-Sim simulation with different random seeds.

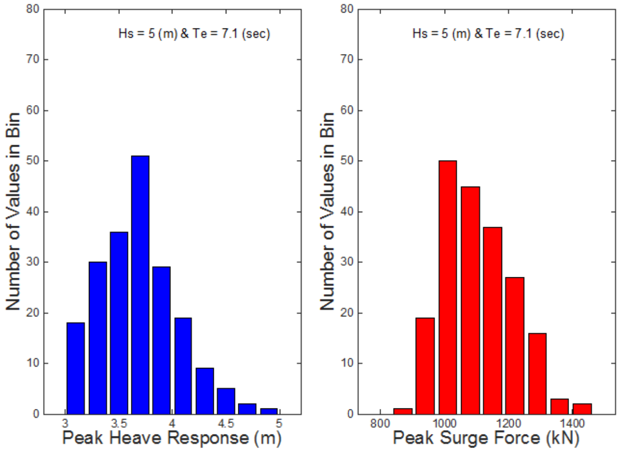

Figure 5. DENSITY DISTRIBUTIONS FOR THE PEAK HEAVE RESPONSE AND SURGE FORCE IN CASE 1 (H_S=5 M AND T_E=7.1 S).

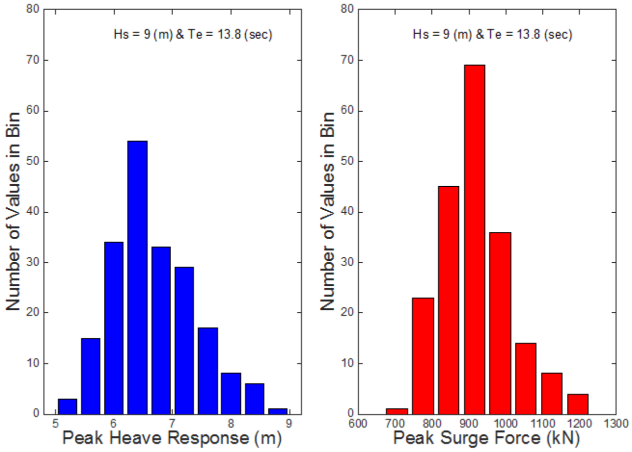

Figure 6. DENSITY DISTRIBUTIONS FOR THE PEAK HEAVE RESPONSE AND SURGE FORCE IN CASE 3 (H_S=9 M AND T_E=13.8 S).

Figure 7 plots the peak response and surge forces against the energy period for the five selected wave environments. For reference, the significant wave height is also plotted against the energy period.

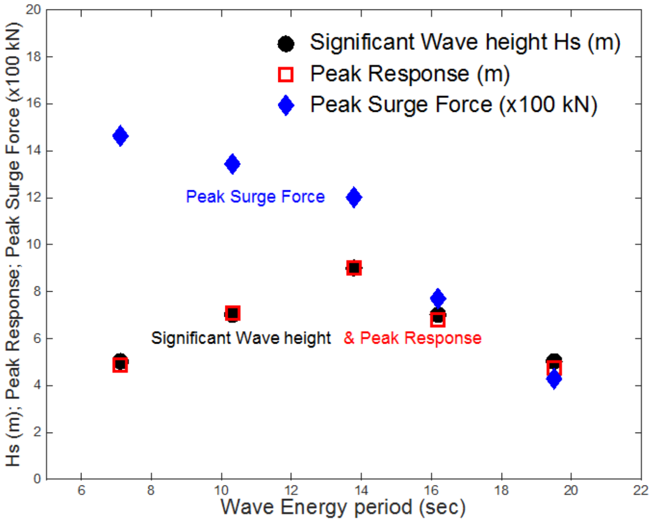

Figure 7. PEAK RESPONSE AND SURGE FORCE FOR EACH EXTREME SEA STATE.

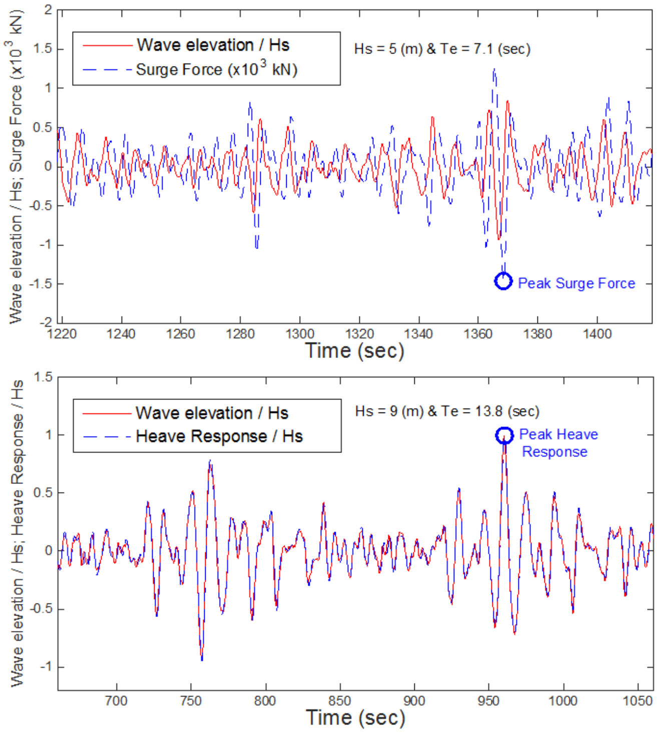

Figure 8. IDENTIFIED EXTREME CONDITION CASES: (TOP) CASE 1 AND (BOTTOM) CASE 2.

Based on the results from the 200 random-seeded WEC-Sim simulations, the sea states in which the maximum heave response and peak surge force occurred were identified. The maximum heave response was observed when the wave was the largest, which is case 3, where $H_s = 9$ m and $T_e = 13.8$ s. For this device, the results also showed that it is not the largest wave that causes the largest surge load, as the peak surge force occurred in case 1, where $H_s = 5$ m and $T_e = 7.1$ s.

The values from the identified sea states with corresponding random seed that resulted in the maximum force and response values are plotted against time in Figure 8. The identified extreme surge force and heave response are shown as open circles. Also shown in the figure is the wave elevation. Based on Morsion equation, the normal force to the body in an oscillating flow is the sum of an initial force and a drag force. The initial term is most likely the dominant force, which is the sum of the Froude–Krylov force and the hydrodynamic added-mass force, which are in phase with the flow acceleration. Therefore, the crest and trough for the surge force history occur when the wave elevation is close to the mean water surface (Figure 8, top), where the wave-induced flow acceleration is at its maximum in the horizontal direction. On the other hand, the heave response followed the wave elevation (Figure 8, bottom) on all the tested cases because the wave period in all cases was larger than the natural period of the sphere, which is around 4 s.

RANS Simulations

As presented in the Search for Extreme Events section, the wave events that caused the maximum heave response and surge force were identified from a series of Monte-Carlo-type WEC-Sim simulations with different random seeds. The identified critical scenarios were then investigated using the RANS model. This section will present a mesh sensitivity study and the results from the RANS simulations.

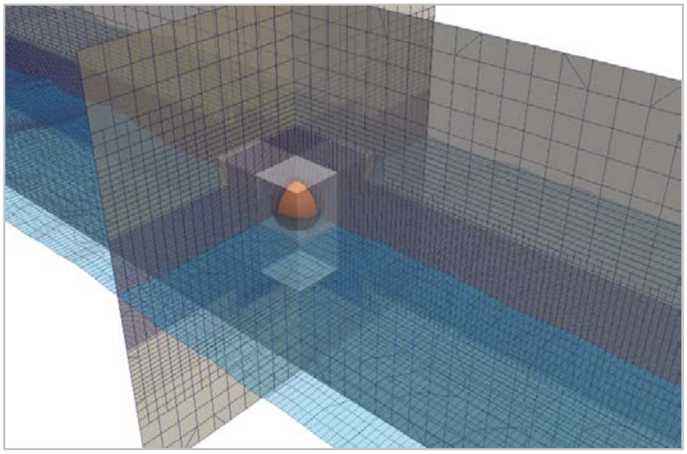

Figure 9. MESH AROUND THE FLOATING BODY IN THE RANS SIMULATION.

Figure 9 shows the mesh around the floating WEC body in the RANS model. Two sets of overlapping (overset) meshes were applied: one for the background and one for the floating WEC body, and the grid resolution was finer near the free surface and around the body to capture both the wave dynamics and details of the flow. Grid resolution for the mesh around the body was determined based on the grid sensitivity study presented by Yu and Li [15]. In addition, a mesh sensitivity study was conducted for the background mesh to ensure that the RANS model captured the wave propagation accurately for these large amplitude and steep waves, and the RANS solutions reached convergence and were sufficient for the following studies.

To determine the mesh resolution for capturing the wave propagation in a numerical wave tank, the wave elevation from the RANS simulations were compared to the analytical solution from the fifth-order Stokes wave theory. The comparison of a regular wave with a wave height of $H = 13.1$ m and a wave period of $T = 10.3$ s is presented in Figure 10, and the RANS simulation result agrees well with the analytical solution. Note that because a sponge layer was implemented in the RANS model, waves were damped out near the outflow boundary ($x >$ 320 m). Based on the mesh-resolution sensitivity analysis, a mesh with total cells numbered on the order of 8 million and a resolution of $\Delta x < \lambda/160$ m and $\Delta z > H/20$ m near the free surface, was used in the following RANS simulations. To keep the Courant number small and preserve the numerical stability, a small time step of T/500 was used in the study, which ensured that the wave was propagating less than half a cell per time step in the simulation.

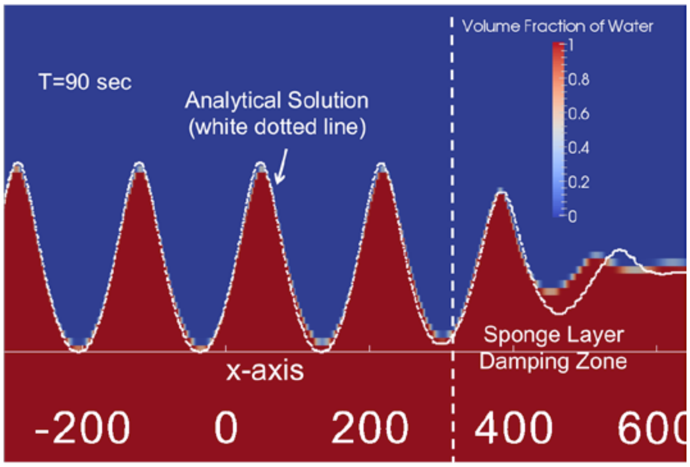

Figure 10. WAVE ELEVATION COMPARISON BETWEEN RANS AND THE ANALYTICAL SOLUTION.

The two extreme cases that were simulated using the RANS model are listed in Table 3. The RANS simulations were performed in regular waves, with a wave height of $H = 1.9H_s$ and a period of $T = T_p$. An example of the free-surface elevation and the hydrodynamic distribution from the RANS simulation at a selected time instant is shown in Figure 11.

Table 3. IDENTIFIED SEA STATES FOR THE RANS SIMULATIONS

Case Number	**H_s (m)**	**T_p and T (s)**	**H (m)**
1	5	8.25	9.5
2	9	16.0	17.1

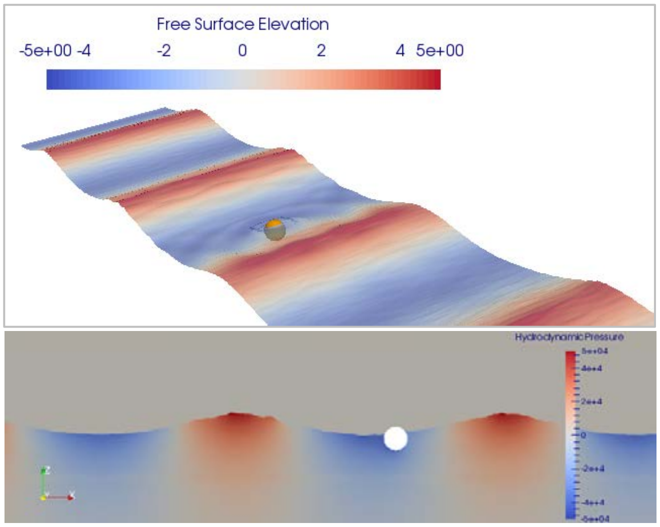

Figure 11. FREE-SURFACE ELEVATION (TOP) CONTOUR AND HYDRODYNAMIC PRESSURE DISTRIBUTION (BOTTOM) FROM THE RANS MODEL (AT TIME=78.4 S; H=9.5 M; T=8.25 S)

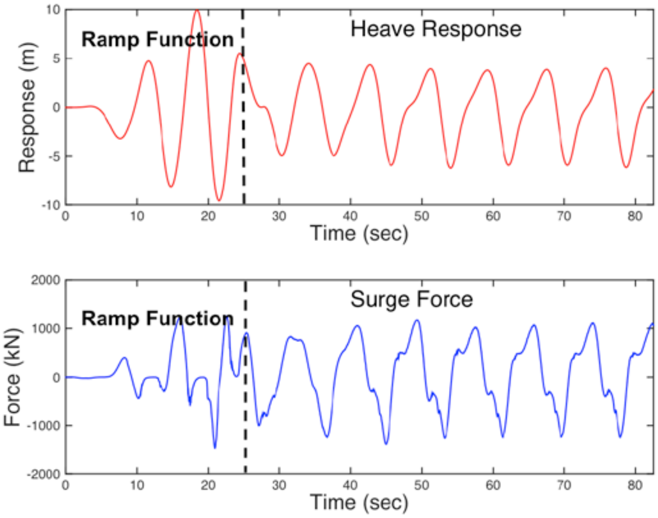

Figure 12. TIME HISTORY OF THE HEAVE RESPONSE (TOP) AND SURGE FORCE (BOTTOM) FROM THE RANS MODEL (H=9.5 M; T = 8.25 S).

Figures 12 and 13 plot the time histories of the sphere heave response and corresponding surge force on the sphere predicted from the RANS simulations. A ramp function was applied to the wave-induced load for the first three wave periods, when solving the system dynamics of the sphere, to reduce the transient oscillation of the body caused by the shock wave loads. To study the hydrodynamics under the identified extreme wave environment, we compared the heave response and surge force predicted from the RANS model to those from the WEC-Sim Monte-Carlo simulations. The values for the two critical sea states obtained from both WEC-Sim and the RANS model are listed in Table 4. Because the transient response damped out after the fifth wave period in the RANS simulations and only the steady-state response remained, the peak heave response and surge force were determined by selecting the peak oscillation from the time history of the last five wave periods.

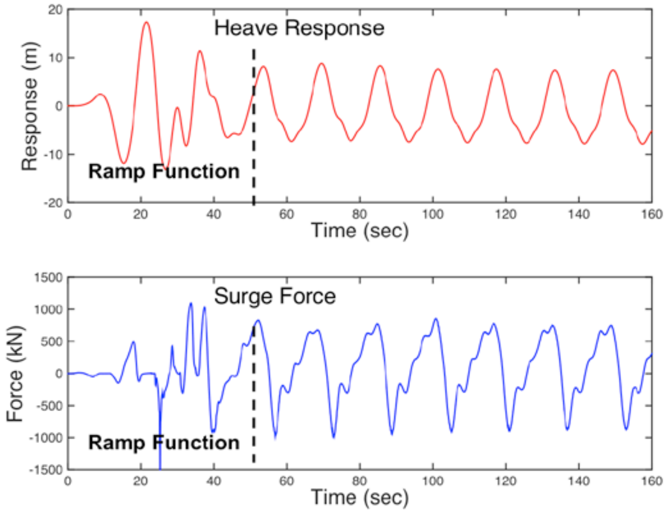

Figure 13. TIME HISTORY OF THE HEAVE RESPONSE (TOP) AND SURGE FORCE (BOTTOM) FROM THE RANS MODEL (H=17.1 M; T=16.0 S).

Table 4. EXTREME RESPONSE AND FORCE COMPARISONS FROM THE WEC-SIM AND RANS SIMULATIONS.

Cases		**WEC-Sim Peak Scenario**	**RANS Prediction**
Heave Response	Case 1	4.8 m	5.2 m
	Case 2	9.0 m	8.7 m
Surge Force	Case 1	1460 kN	1370 kN
	Case 2	1200 kN	980 kN

DISCUSSION

The design process often heavily depends on the specifics of a WEC's design. As shown in Figure 7 and mentioned by the developers and researchers at the workshop, it is not always the largest wave that causes the largest wave load. Each of the WEC components, such as the buoy structure for the point absorber, power take-off system, and the mooring and anchor, may be subject to an extreme wave load at different extreme wave environments. In addition, the occurrence of an extreme load should be studied as a stochastic event because of the nature of the irregular sea states. The extreme wave load can be predicted from a brute-force, very long, time-domain irregular wave simulation or many short-term Monte-Carlo-type simulations, as performed in this study. Therefore, it is still uncommon to directly use CFD simulations to search for the extreme sea states because of the prohibitive computational time for the WEC design application. In this study, we presented a preliminary methodology for searching the extreme wave events that are likely to result in the maximum load through Monte-Carlo-type simulations and modeling the identified sea states with a single wave series in the RANS model.

As shown in Figures 12 and 13, both the heave response and surge force were nonlinear. The RANS simulation was able to capture these complex wave and floating-body interactions, and the simulation results can be used further to determine the WEC device design load. To determine the peak heave response and surge force, the values predicted from the WEC-Sim Monte-Carlo-type simulations are close to those obtained from the RANS model. The simple midfidelity model provided a good estimate on the extreme response and force; however, the sphere that was studied had a small natural period of 4 s, which was much less than the tested wave environment. As a result, the body's heave response followed the wave elevation in all of the tested cases (i.e., Figure 8). It is expected that nonlinear wave and floating-body interaction will become more essential when the WEC is at resonance. In addition, WEC devices are often designed to have a resonant frequency that is close to the dominant wave frequency to maximize it power performance. Further studies are needed to investigate these more critical scenarios.

Because the extreme load is often a matter of chance created by the instantaneous position of the device and a series of random waves, it is most likely that modeling the extreme load of the WEC design under regular waves will underestimate the extreme load if a smaller coefficient for $K=H_{100}/H_{s100}$ is used, particularly for the scenarios at the WEC device resonant frequency. Studies in naval architecture have shown that a statistically derived short-term design wave approach, by constructing an ensemble of short design wave profiles that identify the design extreme events of a floating system, can provide a more accurate prediction of the extreme load based on the design requirement and avoid overdesigning the system. Defining the parameters for the short-wave profile to be used as a design event has been a subject of many studies in naval architecture. Several methods have been proposed, and detailed literature reviews were presented in [16,17].

Studies have also shown that most of these short-term design wave methods could be less accurate for a flexible hull because the load response heavily depends on the instantaneous wave profile, hull position, and deformation, in which the memory of the wave and floating-body interaction is essential. For WECs, most of the designs are stiff and can be considered as a rigid body; however, they often consist of multiple bodies and are allowed to move in multiple degrees of freedom to generate power. In addition, they are generally designed to have a resonant period around the dominant sea state to maximize the power output. Ultimately, these methods may work well for some types of WEC devices, but not for others. Further analysis and development of WEC-specific ECM methods are needed because of the nature of the system design, the complex nonlinear wave, and WEC body interaction and mooring. For simplicity, the mooring was not considered in this paper and would also have a significant influence on the WEC's hydrodynamic response and the corresponding forces on the body. Yet, the mooring configuration also needs to be carefully examined during the WEC design process.

Table 5 lists the physical and computational time simulated by WEC-Sim through Monte-Carlo-type simulations (with 200 random seeds), and by the RANS model for a single sea state. Although the high-fidelity CFD simulations have become available because of the rapid development of high-performance computing (HPC) technology, the application of the method still requires massive computing power to run even a short-term regular wave series. Nevertheless, the RANS model is capable of predicting the complex nonlinear interaction between waves and the floating WEC design, including wave breaking, slamming, and overtopping, which are often essential for the extreme design load case. In addition, the CFD simulations can be fully coupled with a finite-element-analysis numerical model to evaluate the design load based on the dynamic stress analysis and structure deformation [8].

Table 5. NUMERICALLY SIMULATED PHYSICAL AND COMPUTATIONAL TIME FOR DIFFERENT NUMERICAL METHODS USED IN THE STUDY.

Model	**Category**	**Simulated Time**		**Computer**
		Physical	**CPU**	**Type**
WEC-Sim	Midfidelity model	412000 s	4 h	Desktop
RANS	High-fidelity CFD runs	100 s	10 h	HPC system with 384 cores[1]

CONCLUSIONS

In this paper, a summary of the key findings and recommendations from the extreme conditions modeling workshop and a preliminary study on the development of a numerical approach to predict the design load for the WEC system under extreme wave conditions were presented. The workshop was hosted to identify the current state of knowledge on how to numerically and experimentally model WECs in extreme conditions. The numerical approach was developed as the first step to investigate the methodology for estimating WEC extreme design loads. The results from the WEC-Sim Monte-Carlo-type simulations confirmed that it is not always the largest wave that causes the largest load, and each WEC component can be subjected to an extreme wave load at different extreme wave environments, depending on the WEC design. Because the nature of the irregular sea states and the WEC is generally designed to maximize the device's motion and wave-induced load at dominant sea states, it becomes more challenging to identify extreme sea states and predict the extreme load accurately and efficiently. Experience from the wind energy, offshore oil and gas, and shipping industries are useful and can be used as a starting point, but further analysis and development of a WEC-specific ECM is essential to creating a more cost-efficient WEC design.

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