Design Load Analysis for Wave Energy Converters

Preprint

Jennifer van Rij and Yi-Hsiang Yu
National Renewable Energy Laboratory

Ryan Coe
Sandia National Laboratories

Presented at 37th International Conference on Ocean, Offshore, and Arctic Engineering
Madrid, Spain
June 17–22, 2018

Suggested Citation
van Rij, Jennifer, Yi-Hsiang Yu, and Ryan Coe. 2018. "Design Load Analysis for Wave Energy Converters: Preprint." Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-71213. https://www.nrel.gov/docs/fy19osti/71213.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Conference Paper
NREL/CP-5000-71213
October 2018

Contract No. DE-AC36-08GO28308

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

DESIGN LOAD ANALYSIS FOR WAVE ENERGY CONVERTERS

Jennifer van Rij
National Renewable Energy Laboratory
Golden, CO, USA
E-mail: jennifer.vanrij@nrel.gov

Yi-Hsiang Yu
National Renewable Energy Laboratory
Golden, CO, USA
E-mail: yi-hsiang.yu@nrel.gov

Ryan G. Coe
Sandia National Laboratories
Albuquerque, NM, USA
E-mail: rcoe@sandia.gov

ABSTRACT

This study demonstrates a systematic methodology for establishing the design loads of a wave energy converter. The proposed design load methodology incorporates existing design guidelines, where they exist, and follows a typical design progression; namely, advancing from many, quick, order-of-magnitude accurate, conceptual stage design computations to a few, computationally intensive, high-fidelity, design validation simulations. The goal of the study is to streamline and document this process based on quantitative evaluations of the design loads' accuracy at each design step and consideration for the computational efficiency of the entire design process. For the wave energy converter, loads, and site conditions considered, this study demonstrates an efficient and accurate methodology of evaluating the design loads.

KEYWORDS

Wave energy converter; design loads; extreme condition modeling.

INTRODUCTION

Wave energy converters (WECs) are a promising renewable energy technology, with many new WEC concepts being explored. At present, however, there are very few design standards or technical specifications specific to WEC design. Methodologies for evaluating WEC design loads have not been well-defined previously, due to the immaturity and variability of WEC designs, the stochastic nature of the load conditions, and WECs' unique functional requirements in comparison to traditional offshore structures. Nonetheless, WEC design standards are emerging, with the recently released International Electrotechnical Commission TS 62600-2 [1] being the first such technical standard specific to WECs. Furthermore, guidelines and standards for related systems, such as ships and offshore structures, are also often applicable, as reviewed in [2,3]. However, it has not yet been clearly established when these guidelines may be used directly, and when WEC-specific design methods must be further developed.

Design loads are the limiting load scenarios that define a WEC's structural strength requirements, and an accurate evaluation of the design load cases should enable an optimized structural design, ensure survival, and reduce overall WEC costs. Offshore structural design loads are evaluated for site-specific environmental conditions; typically, characterized by the joint probability distribution of significant wave heights, H_s, and wave energy periods, T_e. The probability of extreme sea states within the joint probability distribution is customarily indicated with contours of typical return periods, i.e., design life, such as 25, 50, or 100 years (as illustrated in Fig. 2).

There are several prevailing methods for calculating design loads for a given wave environment. The simplest approach is the one-dimensional design load method, wherein loads are evaluated at the peak H_s on the selected design life contour for a range of T_e [1,4]. Alternatively, the contour design load method may be used, wherein loads are evaluated at intervals along the design life contour and the maximum response/load obtained is used as the design load [4,5]. Although the one-dimensional and contour design methods are typically applied in conjunction with correction or safety factors, implicit in both methods is the assumption that the design load is the same as the extreme wave condition load. Although this is often the case, it is not always true, particularly for WECs, which are designed for resonance at operational sea states. Alternatively, the most rigorous and accurate design method is the long-term, all-sea-state approach [4,5]. Using the all-sea-state method, short-term extreme responses, typically 3 hours, are obtained at points throughout the entire (H_s, T_e) design space. The short-term responses are then weighted by their probabilities and summed to estimate the long-term design load for the specified design life (i.e., 25, 50, or 100 yr). This method is clearly more arduous but has several advantages. First, power and fatigue loads, which typically must be calculated in the design process anyway, can be estimated using the same simulations. Second, no assumptions are made on when the design load conditions occur. Third, by obtaining the full sea-state response surface, decisions on the WEC design life, survival modes, and so on, are better informed. And finally, as will be explored in this study, the all-sea-state approach can be used in conjunction with low- to mid-fidelity models to inform and reduce the computational expense of higher fidelity models to more accurately determine the design loads.

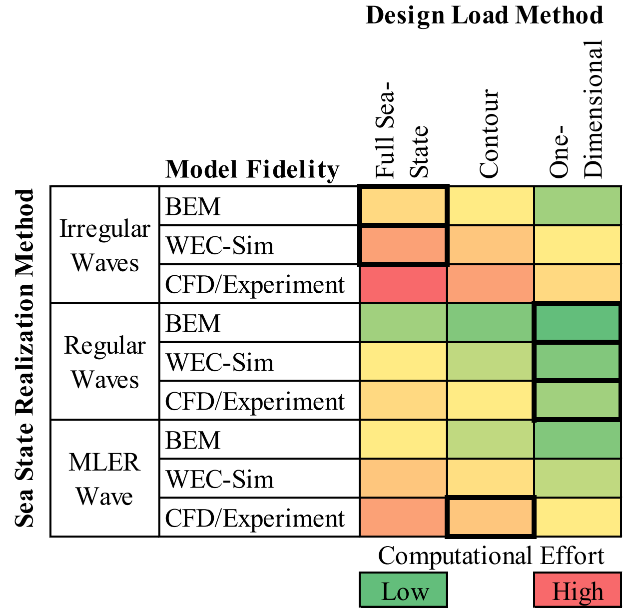
While the design load methodology provides guidance on *what* sea states should be considered in calculating the design loads, it does not specify *how* these stochastic sea states should be realized. Irregular ocean waves are typically quantified in terms of a site-specific empirical or idealized wave spectrum. As such, the most direct method of simulating a specified sea state, and a WEC's response to it, is to use the wave spectrum to create an irregular wave time series for the timeframe of interest. This approach, however, is often too computationally expensive when the timeframe of interest is on the order of 3 hours, particularly for high-fidelity models. Alternatively, assuming the wave heights follow a Rayleigh distribution, the extreme wave heights for a given sea state may be estimated with regular wave heights of $H = 1.9H_s$ to approximate the maximum WEC responses [4].

Or, another simplified sea-state realization approach, is the use of a design, or focus wave, which uses broadband wave theory to define a series of wave amplitudes and phases that will produce the most-likely extreme response (MLER) [6].

Irrespective of design load method, or sea-state realization method, a modeling method is also necessary to simulate the sea state and the WEC response to the sea state. To achieve this, there are a wide range of modeling fidelities available. The simplest modeling approach is the linear frequency-domain, boundary-element-method (BEM)-based potential flow codes (e.g., WAMIT [7], and Nemoh [8]). Frequency-domain BEM codes calculate the hydrodynamic loads and resulting hydrodynamic coefficients based on linear radiation and diffraction theory. With this approach, the system dynamics are solved directly in the frequency domain, with simulation times often two orders of magnitude less than real time. At the next level of modeling fidelity are the linear time-domain, BEM-based codes, such as WEC-Sim [9]. These types of models use the frequency-domain, BEM hydrodynamic coefficients to solve the system dynamics in the time domain and may also include weakly nonlinear quadratic damping and restoring and Froude–Krylov forcing terms. Simulation times for linear time-domain-type models are typically on the order of real time. To predict highly nonlinear effects, such as boundary layer viscous flow separation, turbulence, wave breaking, and overtopping, models based on the Navier-Stokes equations are generally employed. Navier-Stokes-based computational fluid dynamics (CFD) have a large range of possible simulation times, roughly ~10^4–10^8 times real time, depending on the model complexity, particularly the turbulence model.

Potential combinations of the design load method, sea-state realization method, and modeling fidelity are summarized in Table 1. Each potential combination is valid but may make more, or less, sense depending on the design stage and modeling resources available. For example, it would be reasonable to use a one-dimensional design load method, with regular wave sea-state realizations, along with a BEM model, to obtain proof-of-concept estimates in the initial stages of a WEC design. However, in the latter stages of design, where extremely accurate design loads must be obtained, a full sea-state design load method, with irregular wave time series realizations, utilizing high-fidelity CFD would be highly desirable. Unfortunately, this combination of design load analysis methods is currently far too computationally expensive and time consuming to be feasible. Because of this computational limitation, an extreme condition/design load analysis framework has been loosely suggested in the past for analyzing WEC design loads [6,10–13]. The crux of this framework is to use low- to mid-fidelity models to inform high-fidelity models, such that accurate design loads may be obtained, without having to perform a full long-term, all-sea-state loads analysis using high-fidelity models.

TABLE 1. DESIGN LOAD ANALYSIS APPROACHES AND THEIR RELATIVE COMPUTATIONAL EFFORT (BOLD OUTLINED CELLS ARE CONSIDERED IN THIS STUDY).



This study is an attempt to formalize and validate the previously suggested extreme condition/design load analysis framework and demonstrates a systematic methodology for establishing the design loads of a WEC. The proposed design load framework incorporates existing design guidelines, where they exist, and follows a typical design progression—namely, advancing from many, quick, order-of-magnitude, accurate, conceptual stage design computations to a few, computationally intensive, high-fidelity design validation simulations. The goal of this study is to streamline and document this process based on quantitative evaluations of the design loads' accuracy at each design step and consideration for the computational efficiency of the entire design process. The WEC selected to demonstrate the design load methodology is the Reference Model 3 (RM3) WEC, a two-body point absorber [14]. And, the design "loads" evaluated are the surge, heave, and pitch motions. Four design stages are employed in this study, wherein the results of each stage are utilized to identify the conditions under which the design loads are statistically most likely to occur, thereby reducing the number of evaluations necessary in the subsequent, more computationally intensive design stages. The first set of design load estimates are calculated using the BEM code WAMIT. The second set of design load estimates are obtained using the linear time-domain code WEC-Sim, in which irregular seas are simulated, and statistically representative values of the design loads are calculated. The third set of design load estimates are, again, obtained using WEC-Sim, but with the inclusion of nonlinear restoring and Froude-Krylov forcing terms. And, in the final set of design load calculations, CFD models, which are first validated with regular wave experimental data, are used to simulate the most-likely extreme response to focused waves, tuned to the response and sea states indicated by the lower-fidelity models. The design load analysis methods implemented in this study are outlined in bold in Table 1.

DEVICE CONFIGURATION

As stated previously, the WEC selected to demonstrate the design load framework is the RM3 WEC [14]. And, the design loads evaluated are the surge, heave, and pitch motions. As one of the reference models, RM3 is well-documented and experimental results are already available. The 1:100-scale variation of this model is used, because this was the scale at which extreme conditions were experimentally evaluated. The 1:100-scale RM3 model (with the motion tracking device) is illustrated in Fig. 1, and the basic model properties are provided in Table 2. A full description of the model and the tank tests conducted are provided in [14] and the references therein. During the 1:100-scale RM3 tank tests, surge, heave, and pitch motions were measured, as well as the mooring tension and axial spar forces (with a force transducer between the float and spar-plate). Regular waves were used, corresponding to, nominally, 3, 9, and 15 m, at full scale.

FIGURE 1. RM3 1:100-SCALE MODEL [14].

TABLE 2. RM3 1:100-SCALE MODEL PROPERTIES [14].

Property	Value	Units
m	0.313	kg
I_x	8.89×10^{-3}	$kg \cdot m^2$
I_y	8.89×10^{-3}	$kg \cdot m^2$
z_{cg}	-0.214	m
$z_{mooring,top}$	-0.051	m
$z_{mooring,bottom}$	-0.213	m
$k_{mooring}/8$	0.7	N/m

ENVIRONMENTAL CONDITIONS

The environmental conditions assumed for the study are those measured by National Data Buoy Center (NDBC) Buoy 46022, as presented in Fig. 2. The design life/return contours plotted in Fig. 2 are calculated using the WEC design response toolbox [12], using the principle component contour method [15]. The 15-m experimental tank test data [14] roughly equates to a one-dimensional design load method, with regular wave sea-state realizations applied at the 1-yr contour (15 m ÷ 1.9 = 7.89 m ≈ 1 yr $H_{s,max}$, as shown in Fig. 2). Consequently, although a 1-yr design life is not likely, at least intentionally, for the purposes of model comparison and validation, 1 yr will be used as the design life in the following studies.

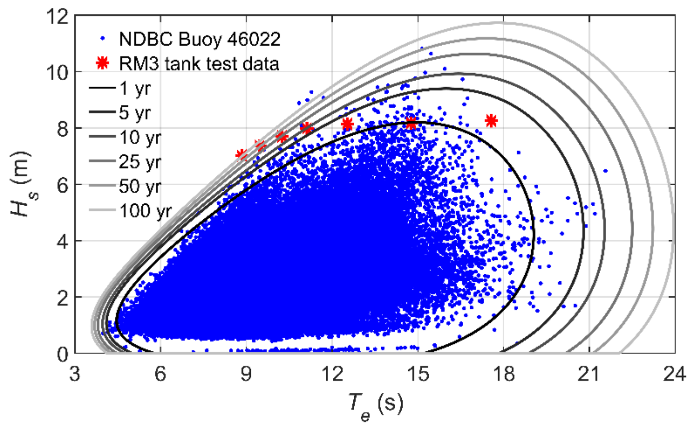


FIGURE 2. JOINT PROBABILITY DISTRIBUTION FOR NDBC BUOY 46022.

DESIGN LOAD ANALYSES

The following studies demonstrate the extreme condition/ design load framework for establishing the design loads of a WEC. Four design stages are employed. The first set of design load estimates are calculated using BEM theory. The second set of design load estimates are obtained using the linear time-domain code WEC-Sim. The third set of design load case estimates are, again, obtained using WEC-Sim, but with nonlinear terms. And, the final set of design load simulations, validated with experimental data, are realized using CFD focus waves. All of the following results, unless otherwise indicated, are reported at full scale.

WAMIT Simulations

The BEM code used in this study is WAMIT [7]. For the 1:100-scale RM3 WAMIT model, an average panel size of 2.6 x 2.6 mm^2 was used, resulting in 13,800 total panels, as shown in Fig. 3. WAMIT results were obtained with all radiation, diffraction, and response amplitude operator (RAO) solutions calculated. Although, it is possible to solve the BEM system of equations with additional stiffness and damping forces, representative of the mooring and viscous damping, respectively, these forces were not considered at this level, as they are typically more efficiently included at the WEC-Sim level of modeling. This will be a known inaccuracy in the BEM model results.

FIGURE 3. RM3 WAMIT MODEL.

To calculate short- and long-term loads using the WAMIT model results, the procedure outlined by Faltinsen is used [16]. The variance of the response, σ_r^2, for a given significant wave height and period is approximated using Eq. (1). Where $S(\omega)$ is the sea spectrum and $H(\omega)$ is the response transfer function (i.e., RAO):

$$\sigma_r^2 = \int_0^\infty S(\omega)|H(\omega)|^2 d\omega \quad (1)$$

For $S(\omega)$, the Bretschneider spectrum is assumed, both here and in the subsequent WEC-Sim simulations. By assuming that the probability density function of the response peaks can be approximated as a Rayleigh function, the most probable maximum short-term response, R_{max}, is then given by Eq. (2). Where t is the short-term timeframe of interest, 3 hr, and T_2 is the mean wave period.

$$R_{max} = (2\sigma_r^2 \log(t/T_2))^{1/2} \quad (2)$$

The long-term probability, Q, that the maximum response exceeds R is found by the summation across the joint probability distribution, given in Eq. (3). Where, p_{jk} is the joint probability for each significant wave height (*j*) and period (*k*).

$$Q(R) = \sum_{j=1}^{M} \sum_{k=1}^{K} exp\left(-0.5R^2/\sigma_{r,jk}^2\right) p_{jk} \quad (3)$$

The resulting short-term maximum responses, R_{max}, for surge (*x*), heave (*z*), and pitch (*Θ*), as calculated with Eq. (2), are presented in Figs. 9(a)–9(c), respectively, where they are compared to the results of the higher-fidelity modeling methods. And, the long-term design loads for *x*, *z*, and *Θ*, as calculated with Eq. (3), are given in Figs. 9(j)–9(l), respectively, where, again, they are compared to the results of the higher-order modeling methods.

WEC-Sim Simulations

The second and third sets of load analyses are obtained using the linear time-domain, BEM-based code WEC-Sim [9], in which irregular sea states are simulated and statistically representative values of the design loads are calculated. Fundamentally, WEC-Sim solves Cummins' equation [17] to determine the WEC's system response in the time domain. For a floating-body system, with its origin defined about its center of gravity, the equation of motion is given in Eq. (4).

$$(m + m_\infty)\ddot{x} = -\int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau + F_e - F_{hs} + F_v + F_{ext} \quad (4)$$

Where, m is the mass matrix, m_∞ is the added mass matrix at infinite frequency, x is the position vector, the term $\int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau$ is the convolution integral, which represents the resistive force on the body caused by wave radiation, K is the impulse response function, and F_e, F_{hs}, F_v, and F_{ext} are the wave-excitation force, hydrostatic restoring force, viscous drag force, and external forces, respectively. The linear force coefficients m_∞, K, F_{hs}, and F_e are from the WAMIT results. By solving Eq. (4), WEC-Sim can simulate devices with six degrees of freedom that are made up of rigid bodies, their constraints, simple power-take-off mechanisms, and mooring systems.

A WEC-Sim model is comprised of a Simulink model and a MATLAB input file, as detailed in [9], in which the simulation and wave parameters, BEM hydrodynamic coefficients, mass properties, viscous drag coefficients, mooring stiffness, and power-take-off properties are specified. The Simulink model, as shown in Fig. 4, was created using prebuilt WEC-Sim blocks. The WEC-Sim block used to model rigid bodies, such as the RM3 model, contains modules for calculating the wave radiation, excitation, hydrostatic restoring, viscous drag, and mooring forces. Using this model setup and inputs, time-varying wave forces may be applied, and the 3-degrees-of-freedom equation of motion is solved for each WEC body in the time domain using a fourth-order Runge-Kutta time-marching algorithm to obtain the system's dynamic response.

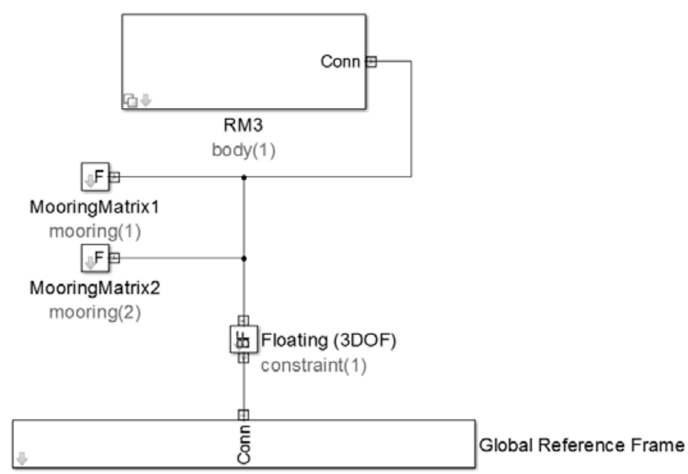


FIGURE 4. RM3 WEC-SIM SIMULINK MODEL.

WEC-Sim is run for each nonzero probability sea state in the joint probability distribution, which results in 201 irregular sea-state simulations. For each of the 201 simulations, a time-step size of $dt = T_p/200$ ($T_p = 1.1667T_e$) is used; a startup ramp for the input wave of $10T_p$ is used, and the total simulation time is set at $200T_p$. The simulation results are then used to calculate the short-term, 3-hr (18 min at 1:100 scale) extreme responses using an all-peaks Weibull fit, as detailed in [12,18]. Where, the short-term extreme is calculated at the 99th percentile of the 3-hr extreme Weibull fit distribution. The full sea-state long-term design loads are calculated using a summation of the 201 probability weighted short-term extreme Weibull fits, as described in [12,19].

The second and third sets of load simulations, both using WEC-Sim, utilize the same model and setup. However, the third set, the "nonlinear" WEC-Sim simulations, include nonlinear restoring and Froude-Krylov forcing terms. These weakly nonlinear forcing terms are calculated and integrated across a discretized RM3 body surface of 2314 panels at each time step. Consequently, although the nonlinear WEC-Sim simulations are expected to be more accurate, these simulations take significantly longer than the linear simulations (~150 times longer in this case). To save computation time, the nonlinear simulations could potentially be done only for the region of interest, i.e., the regions of maximum load, based on the WAMIT- and linear- WEC-Sim-predicted results. However, in this study, the nonlinear simulations are run for the full probability distribution so that the full sea-state long-term loads may be calculated.

The short-term extreme responses for x, z, and Θ, calculated with linear and nonlinear WEC-Sim models, are presented in Figs. 9(d)–9(f), and 9(g)–9(i), respectively; where these results are compared to the results of the WAMIT results. The resulting long-term design loads for x, z, and Θ, are plotted in Figs 9(j)–9(l), wherein they are also compared to the results of the BEM modeling methods.

STAR-CCM+ Simulations

STAR-CCM+ [20], which is fairly representative of many of the currently available commercial CFD codes, is utilized in this study for the high-fidelity simulations. STAR-CCM+ models are used to 1) estimate the drag coefficients used in the WEC-Sim studies, 2) validate the STAR-CCM+ model setup and parameter selection in comparison to experimental data for regular waves, and 3) calculate the design loads using the MLER focus wave approach. All of the following CFD simulations are run with an implicit, unsteady, three-dimensional, Reynolds-averaged Navier-Stokes model. For the turbulence closure model, the SST k-ω model, with "all $y+$ wall" treatment, is utilized. The free surface is modeled using the Eulerian multiphase, volume of fluid method, utilizing the fluid properties noted in Table 3. Second-order temporal accuracy, with time steps corresponding to a Courant number ($C = u\Delta t/\Delta x$) of 0.5 or less, are used for all simulations to ensure numerical stability and accuracy.

TABLE 3. STAR-CCM+ MODEL FLUID PROPERTIES.

Parameter	Setting	Units
ρ_{water}	1000	kg/m^3
μ_{water}	8.887×10^{-4}	$Pa \cdot s$
ρ_{air}	1.184	kg/m^3
μ_{air}	1.855×10^{-5}	$Pa \cdot s$

Drag Coefficients: In addition to linear BEM hydrodynamic coefficients obtained from WAMIT, the WEC-Sim models require estimates of the viscous drag coefficients, C_D, for each body and degree of freedom. Heave, surge, and pitch C_D are calculated for the 1:100-scale RM3 model based on forced oscillation simulations in STAR-CCM+. Although C_D values typically vary with both oscillation amplitude and frequency, viscous drag forces are generally much smaller than linear hydrodynamic forces, thus, it is a reasonable simplification to use constant C_D's for all WEC-Sim simulations. C_D values are obtained at an oscillation H of 1 m (full scale) and T of 7.4 s (the probability-weighted average T for the joint probability distribution shown in Fig. 2).

The forced oscillation response is modeled in STAR-CCM+, with the RM3 model initially hydrostatically centered in quiescent water with x-z plane symmetry applied. The mooring lines are not applied for the C_D evaluations. The computational domain is sized with one wavelength, at the model's oscillation frequency, 1λ, above and below the free surface, and 3λ to each side of the model, with 1.5λ of wave damping at the domain periphery to minimize wave reflections. Because the oscillation motions are predominantly linear (e.g., no wave breaking, or overtopping), a morphing mesh is used to model the motion, rather than an overset mesh, thereby avoiding possible overset mesh interpolation errors. An illustration of the C_D surge simulation is given in Fig. 5.

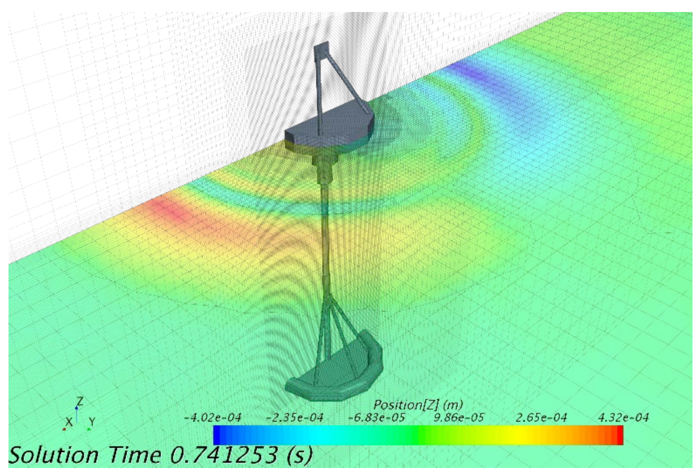


FIGURE 5. RM3 MESH FOR SURGE C_D EVALUATION.

The mesh shown in Fig. 5 was obtained via mesh resolution and convergence studies. The mesh refinement zones are based on minimizing the average $y+$ on the RM3 model surface, as well as sufficiently resolving the velocity gradients surrounding the model, while attempting to keep the total number of cells at a minimum. The resulting grid resolution at the water surface is

$\lambda/\Delta x \approx 60$ in the horizontal direction, $H/\Delta z \approx 8$ in the vertical direction, and an average y^+ of 3.25 on the model surface. The resulting number of cells used for each of the drag coefficient simulations is 8.35 x 10^6. Each simulation is run for $15T$, where T is the oscillation period, during which the model position and resulting hydrodynamic forces and moments are recorded. The forces are then fit to the Morison equation, and least squares are used to find C_D. The resulting C_D values, as implemented in WEC-Sim, are 2.56 for surge (A = 9.85e-3 m^2), 3.21 for heave (A = 2.75e-2 m^2), and 2.17 for pitch (A = 2.50e-5 m^5). Heave and pitch C_D calculated directly from the experimental decay tests [14] are 2.66 (T = 9.03 s) and 3.95 (T = 7.93 s), respectively. Despite the oscillation frequency and amplitude differences, these C_D values are comparable in magnitude, thereby, at least qualitatively, validating the CFD C_D simulations.

Model Validation: The final, and most accurate, set of design load simulations are accomplished with CFD models of MLER focus waves for each load of interest. However, before MLER simulations are run, it is useful to validate the CFD model with the experimental tank test results reported in [14] for the regular wave conditions specified in Table 4. Furthermore, this validation provides additional design load comparison points for a one-dimensional design load approach, with regular wave sea-state realizations, for each of the modeling fidelities.

The regular waves are modeled in STAR-CCM+ for the 1:100-scale RM3 model using the experimental wave tank depth (1.5 m) and width (2.4 m), with *x-z* plane symmetry applied. The computational domain length is adjusted such that there is 3λ in front of and behind the RM3 model, with 1.5λ wave damping at the channel outlet to minimize wave reflections, and a fifth-order regular wave specified at the inlet. To accurately model the resulting large amplitude motions, as well as the mooring system, using a reasonably sized mesh, STAR-CCM+'s DFBI overset method is used. An example of the mesh and simulation results for Test Number 15 are given in Fig. 6. The mesh pictured in Fig. 6 was obtained via mesh resolution and convergence studies. The resulting grid resolutions at the water surface, for all validation simulations, are $\lambda/\Delta x \approx 200$ in the horizontal direction, $H/\Delta z \approx 32$ in the vertical direction, and an average y^+ of 4.89 at the model surface. The average number of cells used for each of the validation simulations is 12.6 x 10^6. Each of the simulations are run for $15T$. In addition to each response simulation conducted, an equivalent wave-only simulation is conducted, with identical simulation parameters and mesh distribution, but without the RM3 body. The wave-only simulation is used to obtain an accurate "input" wave for calculating the RM3 RAOs.

TABLE 4. REGULAR WAVE VALIDATION POINTS [14].

Test Number	H (m)	T (s)
15	15.67	17.58
16	15.52	14.76
17	15.47	12.53
18	15.17	11.12
19	14.63	10.25
20	13.97	9.47
21	13.32	8.84

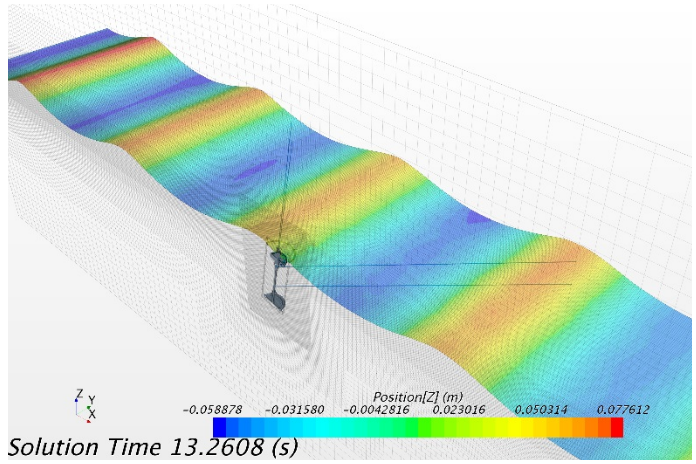


FIGURE 6. RM3 MESH FOR TEST NUMBER 15 VALIDATION.

The resulting surge, heave, and pitch RAOs are plotted in Fig. 7(a)-7(c), respectively. In addition to the experimental- and CFD-determined RAOs, RAOs calculated with the WAMIT, linear WEC-Sim, and nonlinear WEC-Sim models are also plotted and compared. The average, absolute RAO error for each of the computational models—in comparison to the experimentally measured RAOs—are reported in Table 5. Although the CFD simulations do not reproduce the experimental results precisely, they do reproduce the trends well; better than the lower-fidelity models. Based on this validation, the same CFD model setup and parameters are used for the subsequent MLER focus wave design load simulations.

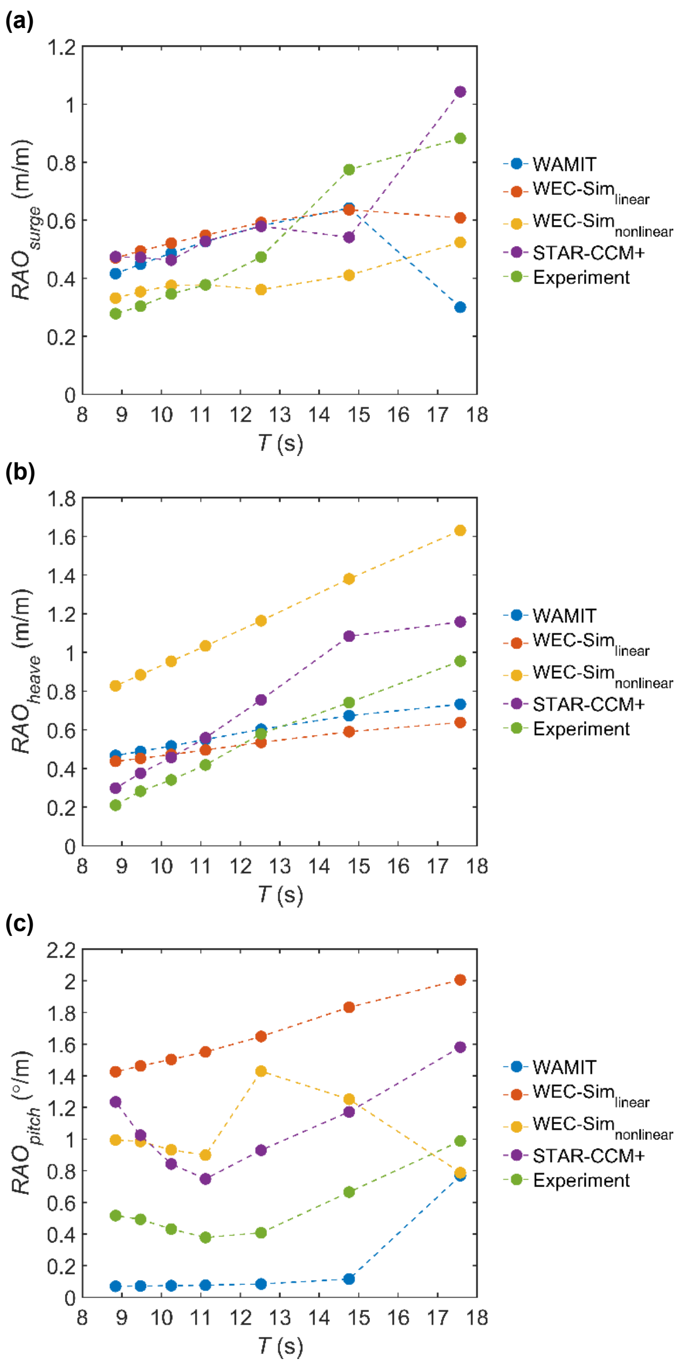


FIGURE 7. SIMULATED VERSUS EXPERIMENTALLY MEASURED RAOS: (a) SURGE, (b) HEAVE, AND (c) PITCH.

TABLE 5. AVERAGE ABSOLUTE RAO ERROR.

Model	Surge	Heave	Pitch
WAMIT	0.199	0.155	0.374
Linear WEC-Sim	0.180	0.160	1.079
Nonlinear WEC-Sim	0.138	0.622	0.543
STAR-CCM+	0.162	0.166	0.522

MLER Simulations: A full description of the MLER method and its application is provided in [6,12] and the references therein. Required MLER inputs are the sea state (H_s, T_p), at which the maximum load is expected to occur, the wave spectrum, and the load RAO. Outputs are the linear superposition waves that comprise the focus wave. The MLER waves for surge, heave, and pitch are calculated in this study using the WEC design response toolbox [12]. The sea state at which the maximum loads are expected is obtained from the nonlinear WEC-Sim results, as indicated in Fig. 9(g)–9(i) and listed in Table 6. The Bretschneider spectrum is, again, assumed. The RAOs are also calculated using the nonlinear WEC-Sim model, such that the mooring, drag coefficients, and nonlinear effects are accounted for. Once the MLER subwaves are generated, the same CFD model parameters (as described for the validation simulations) are used for the MLER simulations. Except, instead of a fifth-order regular inlet wave, the linear superimposed first-order MLER waves are specified at the inlet. The resulting MLER waves, ζ, and responses, *x*, *z*, and *Θ*, are given in Fig. 8.

TABLE 6. MLER SEA STATES.

Load	H_s (m)	T_p (s)
Surge	7.03	20.888
Heave	8.19	17.649
Pitch	8.19	17.591

RESULTS AND DISCUSSION

The WAMIT and WEC-Sim load results are given in Fig. 9. Loads obtained by all the modeling methods are summarized in Table 7. For all but the WAMIT pitch loads, the various modeling methods give comparable results. The pitch loads predicted by WAMIT differ, because mooring stiffness and viscous drag forces are not included in the model. In future studies, these forces will be included in the BEM model, such that the resulting load comparisons are more relevant.

It is known that linear-based models cannot accurately predict loads for extreme, nonlinear conditions. However, to verify the proposed extreme condition modeling framework, an objective of this study is to determine if the linear-based models can accurately predict the sea state conditions at which the maximum loads are likely to occur, such that higher-fidelity models can be efficiently used at these points. Comparing results from the WAMIT, linear WEC-Sim, nonlinear WEC-Sim, STAR-CCM+ and experimental results, provided in Figs. 7(a)–7(c) and Figs. 9(a)–9(i), it appears that the linear-based models can accurately predict the *regions* of maximum load. The 1-yr, 3-hr maximum loads, and the (T_e, H_s) conditions at which they occur, are indicated in Figs. 9(a)–9(i) for each model. For the loads considered, all the maximum loads occur on the 1-yr contour in roughly the same region. Furthermore, although the various modeling methods presented in Figs. 7(a)–7(c) give varying RAO results, the trends are similar, with the maximum response for each method generally at the largest wave period.

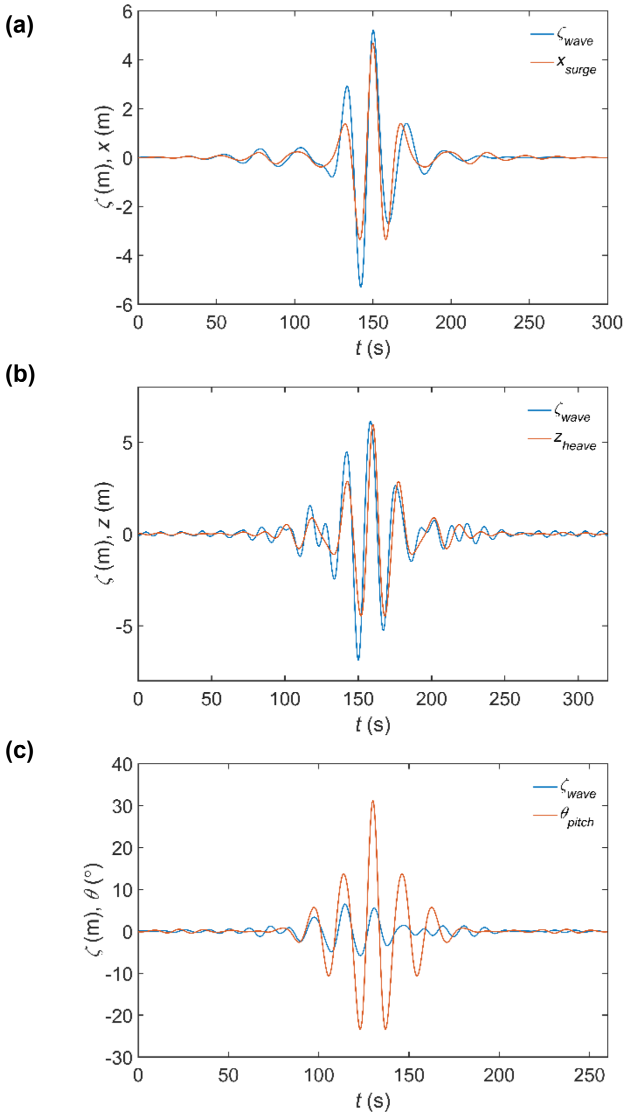


FIGURE 8. MLER SIMULATIONS: (a) SURGE, (b) HEAVE, AND (c) PITCH.

For each of the linear-based models, the 1-yr, long-term loads, given in Figs. 9(j)–9(l), are larger than the 1-yr, 3-hr maximum loads, given in Figs. 9(a)–9(i). Because the full sea-state, long-term approach accounts for the load responses at all the probable sea-states, these results are considered more accurate. In future studies, the accuracy of the linear and nonlinear WEC-Sim results may be improved upon with a finer T_e, H_s discretization of the joint probability distribution, longer simulations times, and smaller simulation timesteps.

Although the CFD model validation results in Figs. 7(a)–7(c) show similar trends to the experimental data, the CFD model should, ideally, reproduce the experimental data more accurately. Future studies will continue to refine the CFD model parameters and mesh to achieve a better model validation. Towards this end, the experimental results will also be reevaluated, to verify consistent numerical and experimental data analysis methods.

TABLE 7. COMPARISION OF 1-YR DESIGN LOADS, AS CALCULATED BY THE VARIOUS METHODS.

Load Analysis Method	x (m)	z (m)	θ (°)
WAMIT, 3-hr extreme	6.6	5.0	6.7
Linear WEC-Sim, 3-hr extreme	5.7	6.3	20.4
Nonlinear WEC-Sim, 3-hr extreme	5.8	6.8	19.4
WAMIT, long-term	7.6	5.9	7.8
Linear WEC-Sim, long-term	6.2	7.1	25.4
Nonlinear WEC-Sim, long-term	6.8	9.3	23.3
WAMIT, 1D, regular wave	5.0	5.7	6.0
WEC-Sim, 1D, regular wave	4.9	5.0	15.7
Nonlinear WEC-Sim, 1D, regular wave	4.1	12.8	11.0
STAR-CCM+, 1D, regular wave	8.2	9.1	12.4
Experiment, 1D, regular wave	6.9	7.5	7.7
STAR-CCM+, MLER wave	4.7	6.0	31.3

Finally, it is possible that the differences in loads calculated by the various methods, as presented in Table 7, are smaller for a more realistic design life, such as 25, 50, or 100 years. Since, at a longer design life, there will be more extreme loads that may dominate the resulting extreme load solution(s).

SUMMARY AND CONCLUSIONS

This study demonstrates a systematic framework for establishing the design loads of a WEC. The proposed design load methodology incorporates existing design guidelines, where they exist, and follows a typical design progression; namely, advancing from many low-fidelity conceptual stage design computations to a few computationally intensive, high-fidelity, design validation simulations. The goal of this study is to document and verify this process based on quantitative evaluations of the design loads' accuracy at each design step and consideration for the computational efficiency of the entire design process.

The WEC selected to demonstrate the design load case methodology is the 1:100-scale RM3 WEC and the loads considered are the surge, heave, and pitch motions. Four design stages are employed, wherein the results of each stage are utilized to identify the conditions under which the design loads are statistically most likely to occur, thereby reducing the number of evaluations necessary in subsequent, more computationally intensive design stages. The first set of design load case estimates are calculated using the linear, frequency domain, BEM-based, potential flow code WAMIT. The second set of design load case estimates are obtained using WEC-Sim, a linear time-domain, BEM-based code. The third set of design load case estimates are, again, obtained using WEC-Sim, but with the inclusion of weakly nonlinear terms. And, the final set of design load case simulations are realized using CFD and are validated with experimental data.

This study was conducted for an example WEC with example loads and example environmental conditions. For the WEC, loads, and site conditions considered, this framework appears to be an efficient and accurate methodology of

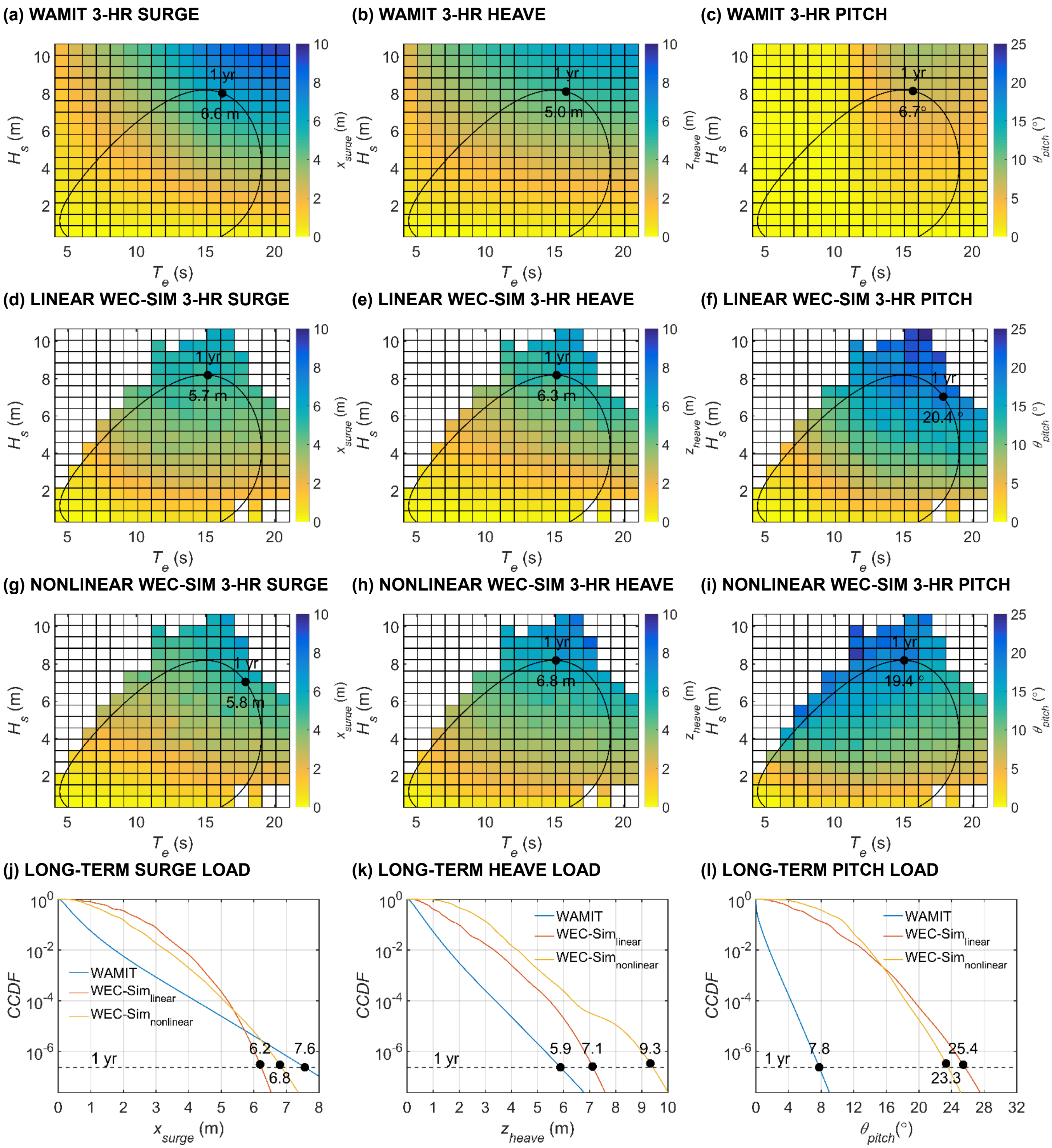


FIGURE 9. WAMIT-CALCULATED 3-HR EXTREME LOADS: (a) SURGE, (b) HEAVE, AND (c) PITCH; LINEAR WEC-SIM-CALCULATED 3-HR EXTREME LOADS: (d) SURGE, (e) HEAVE, AND (f) PITCH; NONLINEAR WEC-SIM-CALCULATED 3-HR EXTREME LOADS: (g) SURGE, (h) HEAVE, AND (i) PITCH; LONG-TERM FULL SEA-STATE EXTREME LOADS: (j) SURGE, (k) HEAVE, AND (l) PITCH.

evaluating the design loads. Given these results, we suggest that a similar procedure could be followed for other WECs (e.g., design variations, and optimizations), other loads (e.g., structural loads, and fault conditions), and other environmental conditions (e.g., wind, current, and directionality). However, the method's validity should be evaluated further in future studies, possibly using structural design loads and loads that occur at resonance.

ACKNOWLEDGMENTS

The Alliance for Sustainable Energy, LLC (Alliance) is the manager and operator of the National Renewable Energy Laboratory (NREL). NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. This work was authored by the Alliance and supported by the U. S. Department of Energy under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. Department of Energy Office Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the U.S. government. The U.S. government retains, and the publisher, by accepting the article for publication, acknowledges that the U.S. government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. government purposes.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

REFERENCES

[1] International Electrotechnical Commission, 2016, *Marine Energy – Wave, Tidal and Other Water Current Converters – Part 2: Design Requirements for Marine Energy Systems*, IEC TS 62600-2, IEC, Geneva, Switzerland.

[2] Coe, R. G., Yu, Y.-H., and van Rij, J., 2018, "A Survey of WEC Reliability, Survival and Design Practices," Energies, **11**(1), p. 4.

[3] Wave Energy Scotland, Ove Arup & Partners Ltd, and Cruz Atcheson Consulting Engineers, Lda., 2016, *Structural Forces and Stresses for Wave Energy Devices*, WES_LS02_ER_Forces and Stresses, Wave Energy Scotland.

[4] NORSOK, 2007, *Actions and Action Effects*, N-003, Standards Norway, Oslo, Norway.

[5] Det Norske Veritas, 2007, *Recommended Practice: Environmental Conditions and Environmental Loads*, DNV-RP-C205, DNV, Oslo, Norway.

[6] Quon, E., Platt, A., Yu, Y.-H., and Lawson, M., 2016, "Application of the Most Likely Extreme Response Method for Wave Energy Converters," *35th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE2016, Busan, South Korea.

[7] Lee, C., and Newman, J., 2015, *WAMIT® User Manual Version 7.1*, Chestnut Hill, MA, USA.

[8] "Nemoh – Open Source BEM" [Online]. Available: https://lheea.ec-nantes.fr/logiciels-et-brevets/nemoh-presentation-192863.kjsp?RH=1489593406974.

[9] "WEC-Sim" [Online]. Available: https://wec-sim.github.io/WEC-Sim/.

[10] van Rij, J., Yu, Y.-H., Edwards, K., and Mekhiche, M., 2017, "Ocean Power Technology Design Optimization," International Journal of Marine Energy, **20**, pp. 97–108.

[11] Coe, R. G., Neary, V. S., Lawson, M. J., Yu, Y.-H., and Weber, J., 2014, *Extreme Conditions Modeling Workshop Report*, NREL/ TP-5000-62305, SNL/ SAND2014-16384R, National Renewable Energy Laboratory & Sandia National Laboratory.

[12] Coe, R., Michelen, C., Eckert-Gallup, A., Yu, Y.-H., and van Rij, J., 2016, "WDRT: A Toolbox for Design-Response Analysis of Wave Energy Converters," *Proceedings of the 4th Marine Energy Technology Symposium, METS2016*, Washington, DC, United States.

[13] Yu, Y.-H., van Rij, J., Coe, R., and Lawson, M., 2015, "Preliminary Wave Energy Converters Extreme Load Analysis," *34th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE2015, St. John's, Newfoundland, Canada.

[14] Yu, Y.-H., Lawson, M., Li, Y., Previsic, M., Epler, J., and Lou, J., 2015, *Experimental Wave Tank Test for Reference Model 3 Floating-Point Absorber Wave Energy Converter Project*, NREL/TP-5000-62951.

[15] Eckert-Gallup, A. C., Sallaberry, C. J., Dallman, A. R., and Neary, V. S., 2016, "Application of Principal Component Analysis (PCA) and Improved Joint Probability Distributions to the Inverse First-Order Reliability Method (I-FORM) for Predicting Extreme Sea States," Ocean Engineering, **112**, pp. 307–319.

[16] O.M. Faltinsen, 1993, *Sea Loads on Ships and Offshore Structures*, Cambridge University Press, Cambridge, UK.

[17] Cummins, W. E., 1962, *The Impulse Response Function and Ship Motions*, Department of the Navy, David Taylor Model Basin.

[18] Michelen, C., and Coe, R., 2015, "Comparison of Methods for Estimating Short-Term Extreme Response of Wave Energy Converters," *Oceans 2015*, IEEE, Washington, DC, United States.

[19] Coe, R. G., Michelen, C., Eckert-Gallup, A., and Sallaberry, C., 2018, "Full Long-Term Design Response Analysis of a Wave Energy Converter," Renewable Energy, **116**, pp. 356–366.

[20] "STAR-CCM+" [Online]. Available: http://mdx.plm.automation.siemens.com/star-ccm-plus.