Extreme Load Computational Fluid Dynamics Analysis and Verification for a Multibody Wave Energy Converter

Preprint

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EXTREME LOAD COMPUTATIONAL FLUID DYNAMICS ANALYSIS AND VERIFICATION FOR A MULTIBODY WAVE ENERGY CONVERTER

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ABSTRACT

A wave energy converter (WEC) must be designed to survive the extreme sea states that it will be subject to throughout its lifetime. Although there are many analysis methods and codes available to accomplish this, there are currently several engineering challenges to WEC survival design. Foremost, the computational design approach will typically involve a trade-off between accuracy and computational efficiency. Additionally, most computational fluid dynamics (CFD) codes are not ideally suited to modeling extreme events for WECs with multibody dynamics, power-take-off systems, and mooring systems. Finally, although WEC design standards and CFD guidelines are emerging, with the current immaturity of the WEC industry, they are not yet well established. In this study, loads on a 1:35-scale, moored, multibody WEC are evaluated with CFD. The CFD results are compared with results obtained from a computationally efficient, midfidelity model based on linearized potential flow hydrodynamics. For these model verification comparisons, both operational and survival configurations are considered. The extreme load results obtained, using both codes, indicate that the survival configuration successfully sheds loads during extreme sea states. It is also found that WEC-Sim, when appropriately applied, can provide reasonable load results, at a fraction of the computational expense of CFD. However, for the more extreme sea states, and for higher-order effects not included in the WEC-Sim model, the linear-based results have significant errors in comparison to the CFD-based results, and should be used judiciously.

Keywords: wave energy converter, extreme/design loads, computation fluid dynamics.

INTRODUCTION

A commercially viable wave energy converter (WEC) must be designed to survive the extreme sea states that it will be subject to throughout its established lifetime at a reasonable cost. Although this is conceptually straightforward and there are many computational analysis methods and codes available to accomplish this, in practice, there are several significant engineering challenges to accurately, efficiently, and economically evaluate extreme WEC loads.

First, the computational design approach will typically involve a trade-off between accuracy and computational efficiency. The simplest, and most commonly used, modeling approaches for hydrodynamic loads are the linear, frequency-domain, boundary-element-method (BEM)-based potential flow codes (e.g., WAMIT [1] and Nemoh [2]). With BEM methods, the system dynamics are solved in the frequency domain, with simulation times often 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 [3]. These codes rely on the frequency response functions obtained via BEM to solve the system dynamics in the time domain and may include weakly nonlinear quadratic damping, restoring and Froude–Krylov forcing terms, arbitrary mooring dynamics and control input. Simulation times for linear time-domain-type models are typically on the order of real time. However, to accurately predict highly nonlinear extreme loading events, including boundary layer viscous flow separations, turbulence, wave breaking, overtopping, etc., models based on the Reynolds averaged Navier-Stokes (RANS) equations are typically employed. RANS-based computational fluid dynamics (CFD) codes have a large range of simulation times, often ranging from 10^4 to 10^8 times real time, depending on the model complexity [4]. And, for structural load evaluations, the RANS solver must also be coupled with a finite element analysis (FEA) solver, or similar,

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which even further increases the computational requirements, both by adding to the computational load and by introducing stability and time-step constraints. Additionally, most CFD codes are not ideally suited to modeling WECs with multibody dynamics, power-take-off (PTO) systems, and mooring systems. Typically, these physics must be modeled with highly simplified systems, user-defined functions, and/or coupling to other codes, which again increases the computational requirements. These trade-offs in modeling accuracy versus computational cost are discussed in further detail in [4].

Also, although WEC design standards and CFD guidelines are evolving, with the current immaturity of the WEC industry, they are not yet well established. Offshore design loads are generally evaluated with the use of a site-specific 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 indicated with contours of typical return periods, such as 25, 50, or 100 years [5]. As reviewed in [6–8], there are several common methods to calculate the design loads for a given wave environment and design life, including: the one-dimensional design load method, where loads are evaluated at the peak H_s on the selected design life contour, for a range of T_e [9,10]; the contour design load method, where loads are evaluated at intervals along the design life contour [10,11]; and, the long-term, all-sea-state approach [10,11], where short-term extreme responses, typically 3 hours, are obtained throughout the entire (H_s, T_e) design space and then weighted and summed to estimate the total long-term design load. Furthermore, there are also several common approaches on how the specified design sea states are realized. The most direct method of simulating a stochastic sea state and a WEC's response to it is to use a site-specific empirical or idealized wave spectrum to create an irregular wave time series for a statistically significant timeframe. However, with timeframes on the order of 3 hours or more, this is often too computationally intensive to be feasible. Alternatively, a simplified sea state realization approach may be used. Assuming the wave heights follow a Rayleigh distribution, extreme wave heights may be estimated with regular waves of $H = 1.9H_s$ [10]. Or, a design or focused wave, which uses broadband wave theory to define a series of wave amplitudes and phases that will produce the most likely extreme response, may also be used [12]. The design and sea state realization methods used, however, are typically dictated by computational resources rather than known methodology limitations, and consequently must be offset with large safety factors and conservative design practices.

In this study, extreme wave loads on a moored, multibody WEC, with simplified mooring and PTO systems, are evaluated with RANS CFD, as well as the computationally efficient, midfidelity model, WEC-Sim. The objectives are to develop mid and high-fidelity models that can predict the operational loads and the extreme design loads for a 1:35-scale model WEC. The loads that are evaluated are the effective PTO force, F_{PTO}, the mooring force, $F_{mooring}$, and the spar bending moment, M_{spar}. In future studies, these numerical models will be further validated with experimental extreme wave tank test data. For the present verification comparisons, both baseline and survival configurations are considered. The results of this study provide valuable design and load data for the specific WEC configuration considered. However, this study also contributes to the knowledge base for general WEC design load analyses, the convergence of which will result in proven design standards and CFD analysis guidelines for WECs. In particular, the validity and limitations of using midfidelity models for extreme condition loads are considered. And, the CFD model settings and resources required for convergence are ascertained.

EXPERIMENTAL DEVICE

The WEC device considered in this study is a 1:35-scale version of the Dehlsen Associates, LLC [13] multipod Centipod, as shown in Fig. 1. The envisioned full-scale Centipod device is a horizontally stable floating platform. The 1:35-scale Centipod model evaluated here was tested at the MASK facility at the Naval Surface Warfare Center Carderock Division (NSWCCD) in West Bethesda, Maryland, in late 2018. The MASK is an indoor basin with an overall length of 110 m, a width of 73 m, and a depth of 6 m. The primary objectives of the experimental tests were to validate the design models and characterize the extreme condition loading performance. As illustrated in Fig. 2, this model has two configurations, a baseline configuration and a survival configuration. The survival configuration is used in extreme sea states to shed loads and thereby improve survivability. During NSWCCD testing, both operational and extreme sea states were considered, as specified in Table 1. For operational sea states, irregular waves were generally used. To estimate the extreme design loads, regular waves representative of sea states along a 100-year joint probability contour were used. Following [9–11, 14], regular wave heights of $H \approx 1.9H_s$ were used (i.e., a contour design load approach with a simplified regular wave sea state realization approach was used for design load evaluations). Recorded measurements during the tests

FIGURE 1: IMAGE OF THE DEHLSEN ASSOCIATES, LLC 1:35-SCALE CENTIPOD WEC

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TABLE 1: EXPERIMENTALLY EVALUATED SEA STATES

	Run	H or H_s (m)	T or T_p (s)	Θ_{wave} (°)	Wave
Operational	O1	0.067	1.240	35	Irregular
	O2	0.075	1.670	45	Irregular
	O3	0.153	1.950	-25	Irregular
	O4	0.059	2.150	35	Irregular
	O5	0.167	2.570	45	Irregular
	O6	0.093	2.790	45	Irregular
	O7	0.102	1.670	45	Irregular
	O8	0.178	2.150	35	Regular
Extreme	E0	0.548	2.359	0, 45	Regular
	E1	0.625	2.749	0, 45	Regular
	E2	0.652	2.946	0, 45	Regular
	E3	0.678	3.142	0, 45	Regular
	E4	0.695	3.340	0, 45	Regular
	E5	0.705	3.536	0, 45	Regular

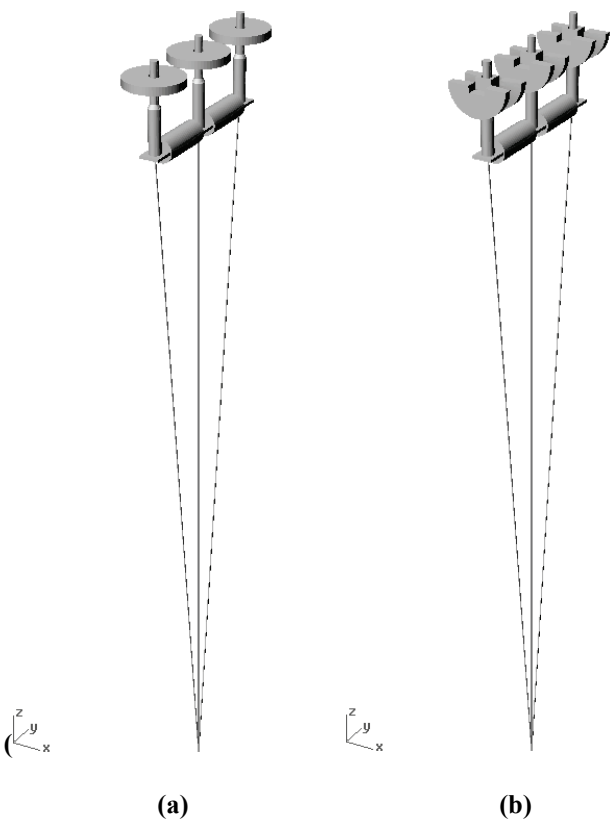

FIGURE 2: 1:35-SCALE CENTIPOD MODEL WITH MOORING: (a) BASELINE CONFIGURATION, (b) SURVIVAL CONFIGURATION

included the transient kinematics of the structure, the axial forces and moments in the spars, and the mooring line tension. At a later date, the numerical models developed in this study will be validated with these experimental data. As such, the simulations will reproduce the described experimental wave tank, geometries (Fig. 2), and sea states (Table 1).

NUMERICAL MODELS

Two types of models are developed and compared in this study: the midfidelity, linear-based WEC-Sim models and the high-fidelity RANS-based CFD models. Additionally, to supply WEC-Sim with the necessary hydrodynamic coefficients, BEM models are also created, as described below.

3.1 BEM Models

The linear frequency-domain BEM code used in this study is WAMIT [1]. For the baseline configuration, 4,250 panels are used for the backbone-spar body, and 3,840 panels are used for each of the three floats (pods), for a total of 15,770 panels, as pictured in Fig. 3(a). For the survival configuration, 4,250 panels are again used for the backbone-spar and 4,955 panels are used for each of the three pods for a total of 19,115 panels, as shown in Fig. 3(b). WAMIT results are obtained for the radiation and diffraction solutions for both configurations at all relevant frequencies and wave headings, Θ_{wave}. WAMIT was run on a workstation and used 12 CPUs, requiring ~18 hr. for each simulation to complete.

3.2 WEC-Sim Models

WEC-Sim is the midfidelity computationally efficient numerical model verified in this study. A detailed description of the theory and application of WEC-Sim is given on the WEC-Sim website [3]. However, the governing equation WEC-Sim solves to determine a WEC's system response in the time domain is Cummins' equation [15]. For a floating-body system with its origin defined about its center of gravity, this equation of motion is given in Eq. (1).

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

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, representative of 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 supplied by the previously discussed WAMIT models for these geometries. WEC-Sim then relies on Simscape Multibody, which uses a Lagrange multiplier approach, to solve for the six degrees-of-freedom (DOF) dynamics.

A WEC-Sim model comprises the Simulink model and a MATLAB input file where the simulation and wave parameters, BEM hydrodynamic coefficients, mass properties, viscous drag coefficients, mooring stiffness, and PTO properties are all specified. The Simulink model for the operational Centipod configuration, as shown in Fig. 4, was created using prebuilt WEC-Sim blocks. For the survival Centipod configuration, the PTO blocks in Fig. 4 are replaced with fixed joints. The WEC-

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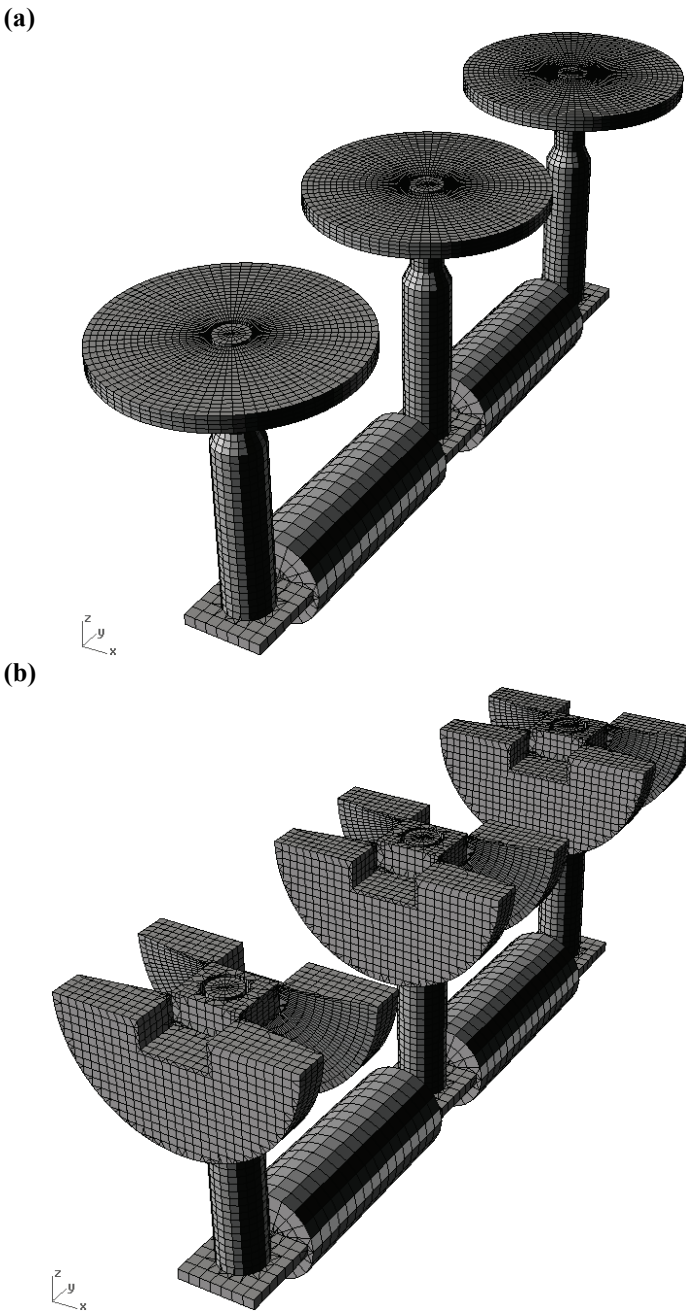

FIGURE 3: WAMIT MODELS: (a) BASELINE CONFIGURATION, (b) SURVIVAL CONFIGURATION

Sim block used to model rigid bodies, such as the pods and backbone, contains modules for calculating the wave radiation, excitation, hydrostatic restoring, viscous drag, and mooring forces, i.e., Eq. (1). Using this model setup and inputs, time-varying wave forces may be applied, and the six DOF 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 total system's dynamic response.

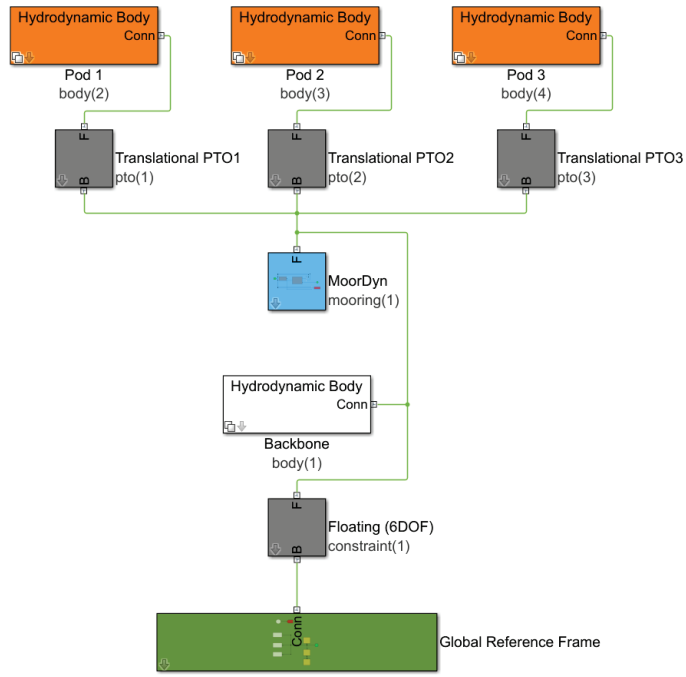

FIGURE 4: WEC-SIM CENTIPOD SIMULINK MODEL

In addition to the linear BEM hydrodynamic coefficients, WEC-Sim requires estimates of the viscous drag coefficients, C_D, for each body and DOF. These coefficients may be obtained from experimental measurements, numerical simulations, or previously reported values. In this case, C_D for the backbone and pods are estimated to be within the range of $2 \leq C_D \leq 3$ for all DOF. These C_D values may require tuning in comparison to the experimental and CFD results; however, they can serve as a reasonable first estimate.

Mooring forces in WEC-Sim may be modeled using either a simple spring matrix or by coupling WEC-Sim to the open-source code MoorDyn [16]. MoorDyn is a lumped-mass mooring line model, which allows arbitrary line interconnections, with different line properties, and clump weights and floats. The model accounts for the mooring lines' internal axial stiffness and damping, weight and buoyancy forces, hydrodynamic forces using Morison's equation, as well as vertical spring-damper forces from contact with the seabed. Because the Centipod's experimental mooring system is made up of taut mooring lines (Fig. 2), which are subject ot snap and slack loading events, particularly during extreme sea states, the MoorDyn model is used for these simuilations to more accurately capture the maximum tension in the mooring system.

Given an initial nonzero wave heading, the Centipod will yaw to an approximately 0° steady-state wave heading. However, because WEC-Sim is a linear-based code in which it is assumed that all motions are small, these large transient yaw motions cannot be accurately captured without modifying the WEC-Sim code. Consequently, for the initial model setup and verification done in this study, all of the sea states specified in

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Table 1 are run in WEC-Sim with a 0° wave heading. For the irregular wave simulations, WEC-Sim is run with a Bretschneider wave spectrum ($T_p = 1.1667T_e$, $T_{avg} = 0.711T_p$). For each simulation, a time-step size of $dt = T/1000$ is used. For the irregular wave cases, a startup ramp for the input wave of $60T$ is used, and the total simulation time is set to 3 hr. at full scale (~30 min at 1:35 scale). For the regular wave cases, a startup ramp of 3T is used, and a simulation time 20T is used, which is the same simulation time used in the regular wave CFD simulations and thus will be directly comparable. The WEC-Sim models were run on a laptop with eight 2.7-GHz processors. The regular wave cases each took ~3 min to run, and the irregular wave simulations each took ~3.5 hr. to run, meaning that simulation times were roughly equivalent to real time. The irregular simulation results are then used to calculate the short-term, 3-hr, extreme responses using an all-peaks Weibull fit, as detailed in [17, 18] where the short-term extreme is calculated at the 90th percentile of the 3-hr. extreme Weibull fit distribution.

3.3 CFD Models

STAR-CCM+ [19] is utilized in this study for the high-fidelity CFD simulations. The Centipod, with its large backbone-spar body and multiple pods, results in a computationally very large CFD model, which limits the number of simulations that can be reasonably completed. Consequently, assuming that the most extreme design loads are produced by the most extreme wave, Extreme Run 5 in Table 1, models are developed for this sea state for both the baseline and survival configurations and for both 0° and 45° initial wave headings, for a total of four extreme load CFD simulations. For the extreme load simulations, the pods are assumed to be locked into position on the spars, and the Centipod's backbone-spar body and three pods are modeled as a single rigid body, which greatly simplifies these cases.

All the CFD simulations are run with an implicit, unsteady, three-dimensional, RANS 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 2, with an example of the resulting free surface for the baseline configuration and 0° initial wave heading given in Fig. 5. To accurately model the large amplitude extreme wave motions, as well as the mooring forces, using a reasonably sized grid, STAR-CCM+'s DFBI overset method is used. The mooring lines are modeled with simple linear spring couplings with no repelling force, such that snap and slack mooring loads ($F_{mooring}$) are simulated. To model the structural loads (F_{PTO} and M_{spar}), a one-way FEA coupling approach is used. At each timestep, the pressure, shear, and mooring loads are mapped to a separate STAR-CCM+ FEA simulation of the Centipod. Example results are shown in Fig. 6 for the baseline configuration and 0° initial wave heading. The one-way FEA coupling approach is acceptable for these simulations because the structural components are nearly rigid, and any response of the structure on the fluid dynamics is negligible.

The STAR-CCM+ computational domain and grid refinement zones are pictured in Fig. 7. Regular waves are modeled for the 1:35-scale Centipod model using the experimental wave tank depth and a width twice the depth, which is approximately 10 times the Centipod width. Any blockage effects should be negligible. The computational domain length is adjusted such that there is ~2λ in front of, and ~4λ behind, the Centipod model. A velocity inlet with a fifth-order regular wave is specified at the channel inlet and side walls. A pressure outlet, with 2λ wave damping to minimize wave reflections, is specified at the channel outlet. Slip walls are specified at the top and bottom walls. The grid shown in Fig. 7 is obtained via mesh resolution and convergence studies. The grid refinement zones are based on minimizing the average $y+$ on the WEC model surface, as well as sufficiently resolving the velocity gradients

TABLE 2: 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}	$Pa \cdot s$

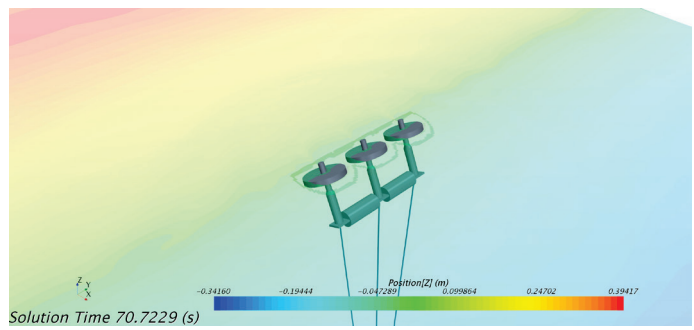

FIGURE 5: STAR-CCM+ EXTREME WAVE SIMULATION 5, FOR BASELINE CONFIGURATION WITH 0° WAVE HEADING

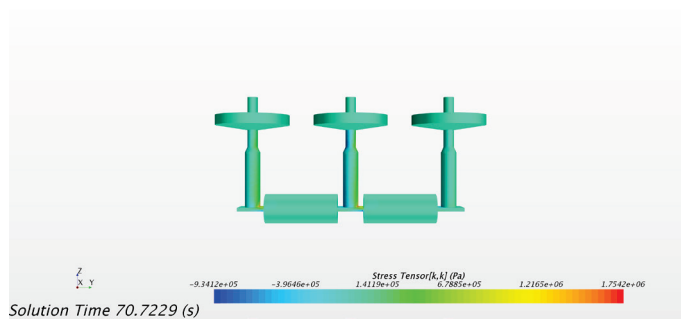

FIGURE 6: STAR-CCM+ COUPLED FEA FOR EXTREME WAVE SIMULATION 5, FOR BASELINE CONFIGURATION WITH 0° WAVE HEADING

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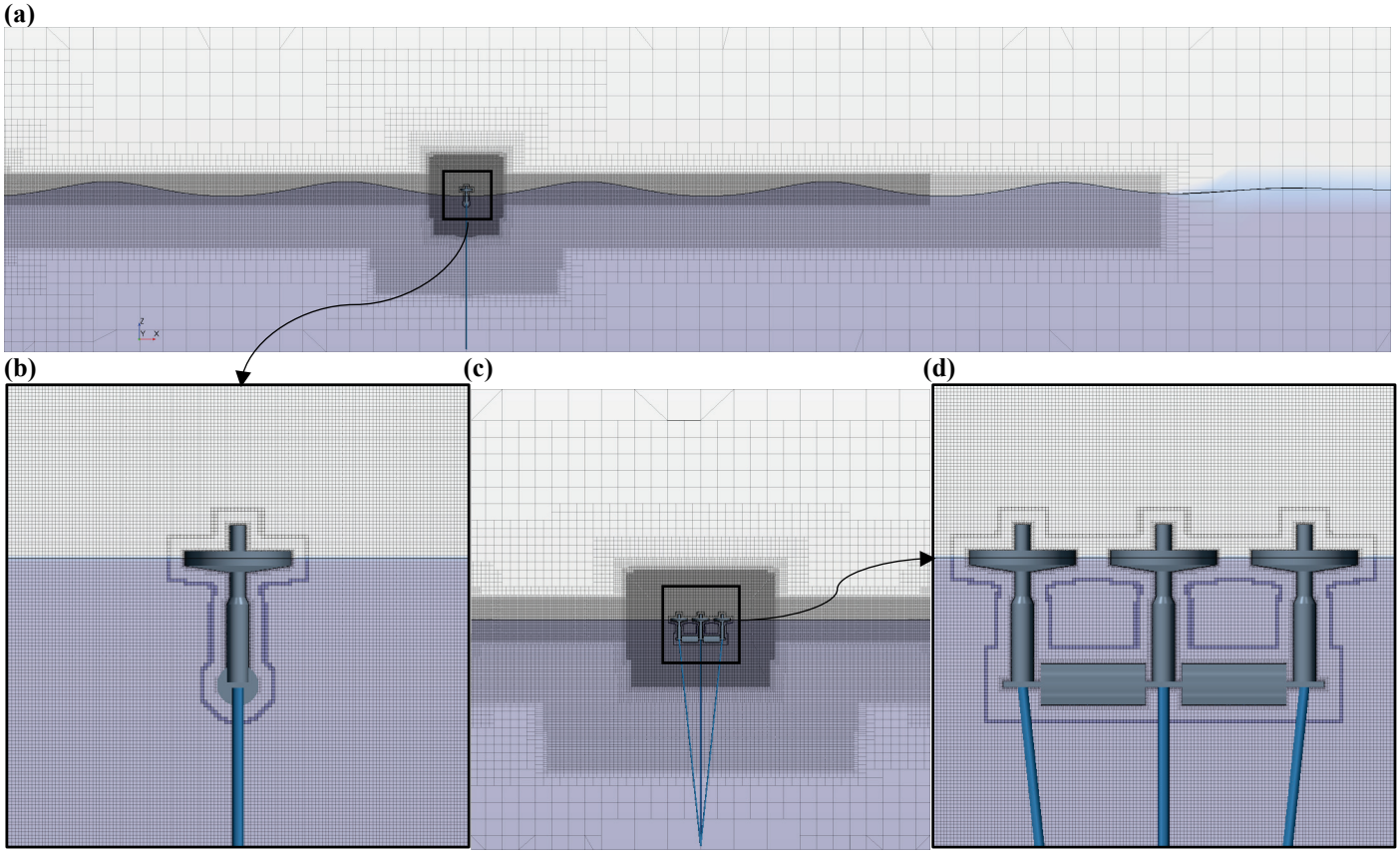

FIGURE 7: STAR-CCM+ COMPUTATIONAL DOMAIN AND GRID REFINEMENT ZONES FOR THE OPERATIONAL CENTIPOD CONFIGURATION: (a) SIDE VIEW, (b) SIDE VIEW DETAIL, (c) FRONT VIEW, (d) FRONT VIEW DETAIL

surrounding the model, while keeping the total number of cells at a minimum. The resulting grid resolution at the water surface is $\lambda/\Delta x = 138$ in the horizontal direction, $H/\Delta z = 40$ in the vertical direction, and an average y^+ of 19.2 on the model surface. The average number of cells used for each of the validation simulations is 18.8 x 10^6. Each of the simulations is run for $20T$ using second-order temporal accuracy, and time steps corresponding to a Courant number ($C = u\Delta t/\Delta x_{min}$) of 0.5 to ensure numerical stability and accuracy. Each of the CFD simulations was run at a high-performance computing center. On average, each simulation required 17 days and used 672 CPU, for a total of ~2.8 x 10^5 CPU·hr. With these computing resources, the ratio of simulation time to real time is ~2.1 x 10^4.

RESULTS

For Extreme Run 5, WEC-Sim and STAR-CCM+ surface elevation results, $\eta(t)$ at the initial Centipod position are plotted and compared in Fig. 8 for the first 10 wave periods. The corresponding time series kinematic results for surge, $x(t)$, sway, $y(t)$, heave, $z(t)$, roll, $\Theta_x(t)$, pitch, $\Theta_y(t)$, and yaw, $\Theta_z(t)$, are

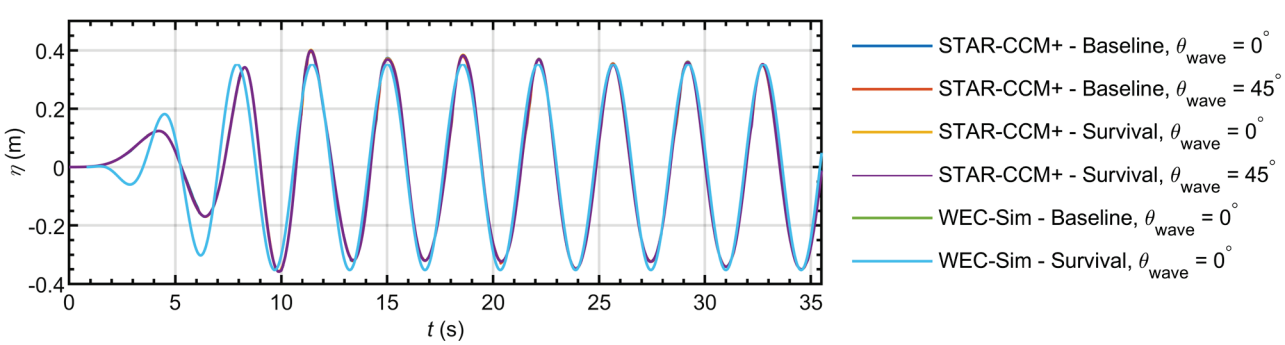

FIGURE 8: COMPARISON OF SURFACE ELEVATION RESULTS, $\eta(t)$

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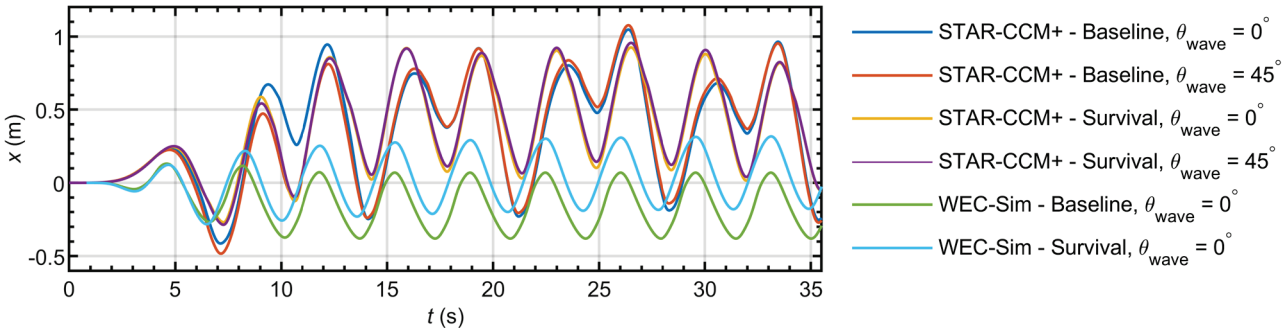

FIGURE 9: COMPARISON OF SURGE RESULTS, $x(t)$

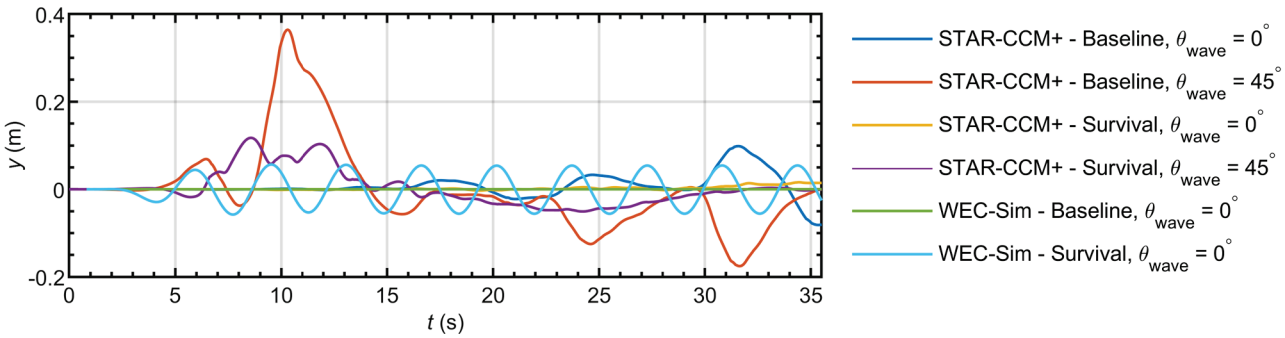

FIGURE 10: COMPARISON OF SWAY RESULTS, $y(t)$

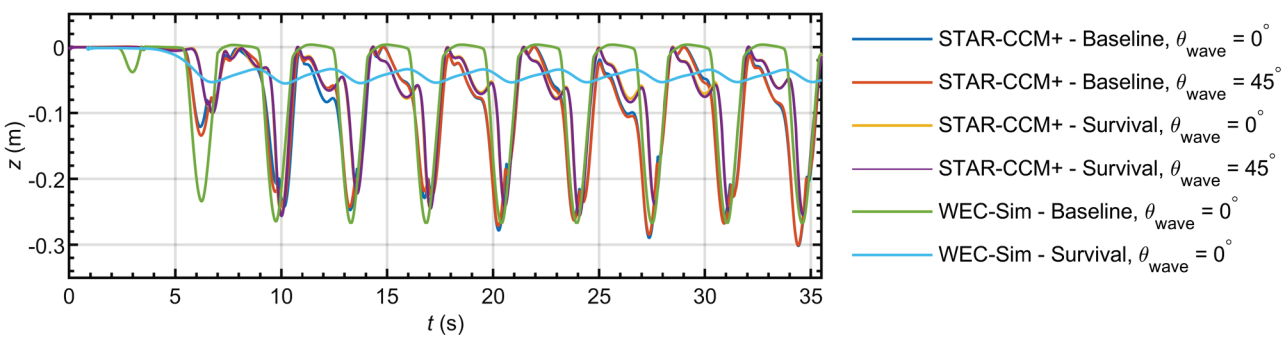

FIGURE 11: COMPARISON OF HEAVE RESULTS, $z(t)$

plotted in Figs. 9-14. The WEC-Sim surface elevation is the specified regular wave with a $2T$ startup ramp. The surface elevation in STAR-CCM+, which propagates from the inlet 2λ upstream, agrees well with the analytic solution after ~$2T$, thereby verifying the grid resolution utilized.

In the surge comparison, Fig. 9, the predicted dominant responses are similar, but STAR-CCM+ generally predicts more significant steady-state drift downstream than WEC-Sim does. The simulated sway response, Fig. 10, is relatively small for all the models except the STAR-CCM+ baseline configuration with Θ_{wave} = 45°, where there appears to be some large initial lateral motions that damp out with time. Fig. 11 gives the heave comparisons, where there is reasonable agreement between all the simulations except the WEC-Sim survival configuration. Surprisingly, given the extreme sea state and WEC-Sim's linear basis, even the results for the WEC-Sim baseline configuration predict the total magnitude and phase of the heave response well in comparison to the STAR-CCM+ results. The WEC-Sim survival configuration heave response, however, is better understood in conjunction with the pitch response, given in Fig. 13. Fig. 13 shows that WEC-Sim prediction is large, steady-state pitch response for the survival configuration, which reduces the predicted heave response. Also evident in Fig. 11 is the effect of the mooring configuration on the Centipod motion. Tension in the mooring lines prevents any significant upward displacements while the mooring lines are slack for the large negative displacements.

As shown in Fig. 12, for the 0° wave heading simulations, in both STAR-CCM+ and WEC-Sim the predicted roll responses are negligible. The STAR-CCM+ baseline configuration with Θ_{wave} = 45° has a large, roughly symmetric roll response, while the STAR-CCM+ survival configuration with Θ_{wave} = 45° has a

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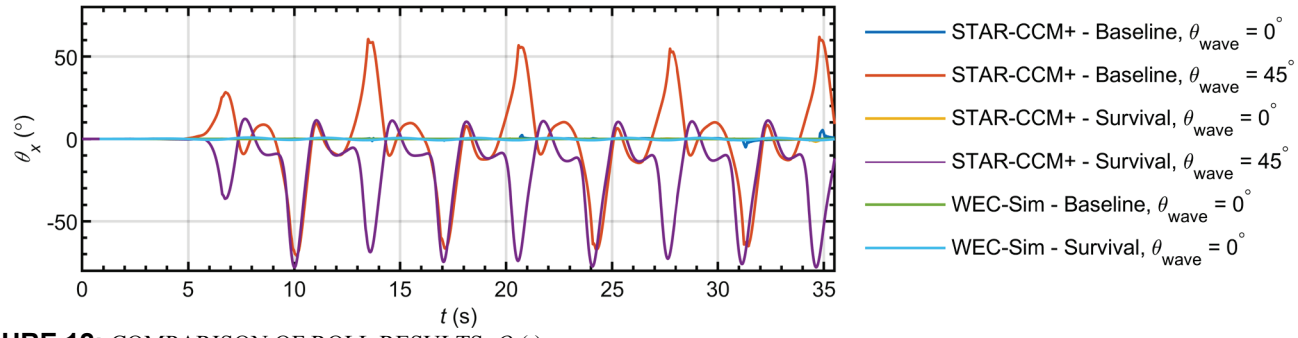

FIGURE 12: COMPARISON OF ROLL RESULTS, $\Theta_x(t)$

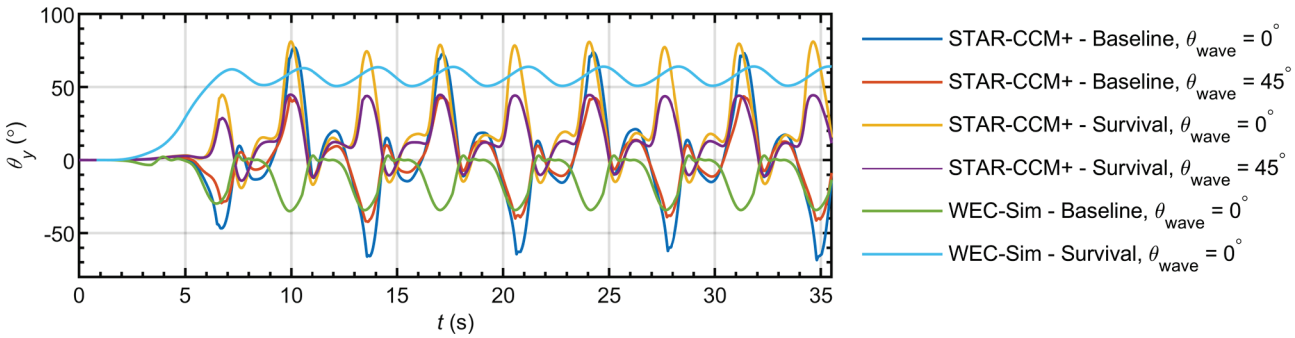

FIGURE 13: COMPARISON OF PITCH RESULTS, $\Theta_y(t)$

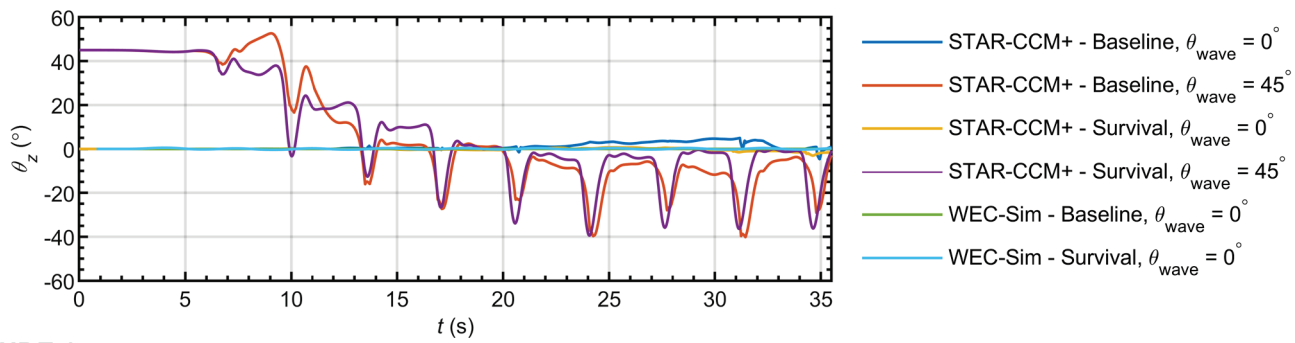

FIGURE 14: COMPARISON OF YAW RESULTS, $\Theta_z(t)$

large, predominantly negative roll response. The STAR-CCM+ baseline configurations have a large, roughly symmetric pitch response, as shown in Fig. 13, while the STAR-CCM+ survival configurations have a predominantly positive pitch response. The WEC-Sim baseline simulation does not predict the positive pitch motions predicted by STAR-CCM+, and as discussed previously, the WEC-Sim survival simulation gives a large steady-state positive pitch displacement, which does not correspond to the STAR-CCM+ simulation. In the STAR-CCM+ simulations with initial wave headings of 45°, the Centipod yaws to an approximately 0° steady-state wave heading within several wave periods, as shown in Fig. 14. The initially 0° wave heading simulations do not show any significant yaw motion. Interestingly, the rotational motions induced by the initial yaw displacement, Θ_x, Θ_y, and Θ_z, do not converge to the Θ_{wave} = 0° values, at least over the time period evaluated here.

WEC-Sim and STAR-CCM+ for F_{PTO}, $F_{mooring}$, and M_{spar}, are compared in Figs. 15–17, respectively. Only results for the first pod/spar/mooring line (on the negative y-axis) are presented. Although there is some variation among the three pod/spar/mooring line results, they are not significant enough to present separately. The F_{PTO}, $F_{mooring}$, and M_{spar} loads are plotted with respect to the average wave period: T for regular waves, and $0.711T_p$ for irregular waves. Additionally, the loads plotted in Figs. 15–17 are the maximum response wave amplitude, not the response wave height.

Based on the F_{PTO} and $F_{mooring}$ results, it appears that WEC-Sim significantly overpredicts these loads in the baseline configuration and slightly under predicts F_{PTO} and $F_{mooring}$ in the survival configuration. However, both WEC-Sim and STAR-CCM+ results indicate a significant load reduction in F_{PTO}, $F_{mooring}$, and M_{spar} for the survival configuration. The initial 45°

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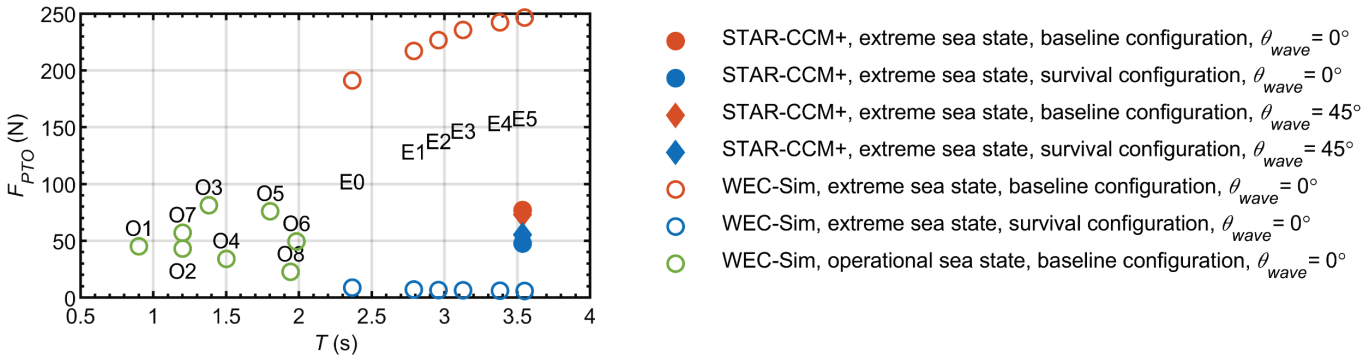

FIGURE 15: COMPARISON OF PTO FORCE RESULTS, F_{PTO}

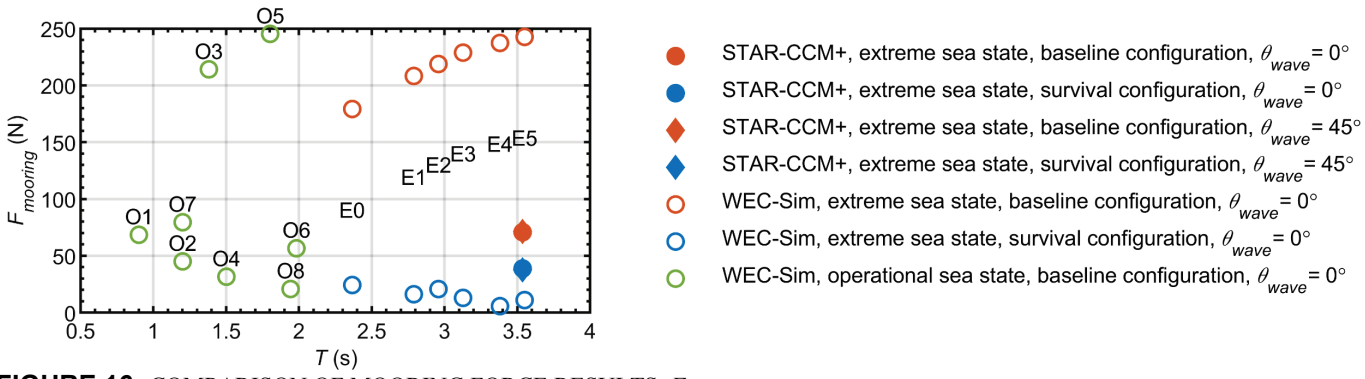

FIGURE 16: COMPARISON OF MOORING FORCE RESULTS, $F_{MOORING}$

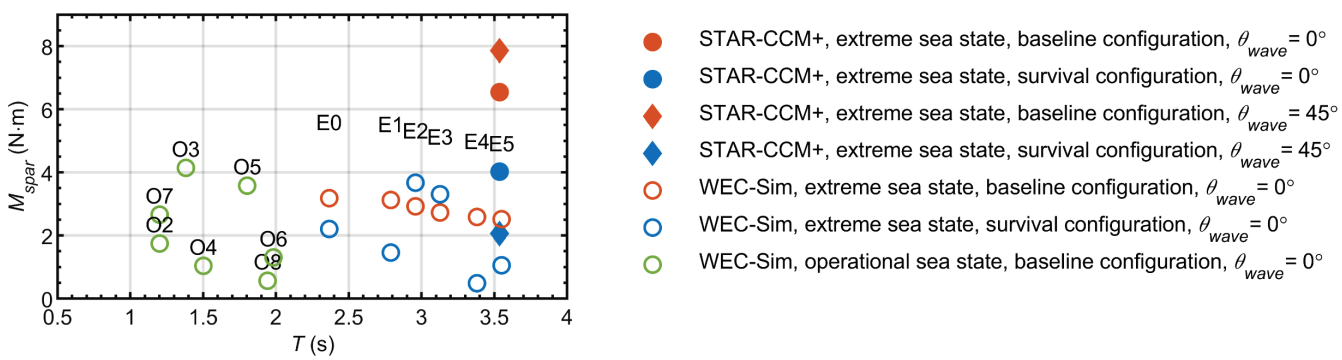

FIGURE 17: COMPARISON OF SPAR BENDING MOMENT RESULTS, M_{SPAR}

wave heading has little impact on F_{PTO} and $F_{mooring}$ in the STAR-CCM+ simulations, but increases M_{spar} in the baseline configuration, and decreases M_{spar} in the survival configuration. Given that the 45° wave heading affects the rotational DOFs more significantly than the translational DOFs, these results appear to be reasonable.

DISCUSSION

In this study, extreme wave loads on the moored, multibody Centipod WEC are evaluated and compared using both RANS CFD (STAR-CCM+) and the potential flow-based model WEC-Sim. These models are created and verified as a first step in ongoing verification and validation actives for this WEC. For the verification study presented here, both baseline and survival configurations are considered. The extreme load results obtained for F_{PTO}, $F_{mooring}$, and M_{spar} in both WEC-Sim and STAR-CCM+ indicate that the survival configuration successfully sheds loads during extreme sea states when compared to the baseline configuration.

The STAR-CCM+ versus WEC-Sim comparison of the heave response for the baseline configuration is an encouraging indication of WEC-Sim's capabilities to simulate a WEC's first-order response in extreme sea states. These results indicate that WEC-Sim models can provide reasonable design results at a fraction of the computational expense of CFD/FEA. However, the STAR-CCM+ versus WEC-Sim comparison of the heave response for the survival configuration is indicative of the challenges of linear-based models. Generally, linear-based

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models, particularly in extreme sea states, require significant tuning to CFD and experimental data, which may not always be available.

It is likely that the WEC-Sim models developed in this study can be improved in comparison to the CFD results by including weakly nonlinear Froude–Krylov forcing terms and adjusting the viscous drag coefficients. Future studies will consider these improvements. It may also be useful to modify WEC-Sim to account for the large transient yaw motions. Furthermore, with CFD simulations for only one sea state, it is difficult to draw any general conclusions on WEC-Sim's limitations compared to CFD. Consequently, it may also be useful in future studies to develop an operational CFD model of the Centipod that includes relative motions between the backbone-spar body and pods. Following these model improvements, both the STAR-CCM+ and WEC-Sim models will be validated against the experimental tank test data. Based on the validation comparisons, the validity and limitations of using midfidelity models for extreme condition loads will be further considered.

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