An Efficient Three-Dimensional CFD-Based Numerical Wave Tank for a Wave Energy Converter in Extreme Irregular Waves

Preprint

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AN EFFICIENT THREE-DIMENSIONAL CFD-BASED NUMERICAL WAVE TANK FOR A WAVE ENERGY CONVERTER IN EXTREME IRREGULAR WAVES

Will Wiley[1], Thanh Toan Tran[1], Thomas Boerner [2], Collin Weston [2], Lu Wang [1]

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ABSTRACT

A numerical wave tank approach for computational fluid dynamics (CFD) modelling of an extreme irregular seastate is presented. The technique couples a potential flow solution with a CFD solver for more efficient numerical predictions. This method has recently become attractive both for the research community and the industry working with offshore structures. The model is used to determine the response of a submerged pressure differential wave energy converter (WEC) in a fully nonlinear irregular wave condition using the high-fidelity CFD code, STAR-CCM+. Potential flow based numerical models are commonly used to predict motions and performance of wave energy converters. Wave kinematics can deviate from potential flow predictions for extreme wave conditions; the excitation loads on an absorber can also be increasingly influenced by viscous effects, not predicted by potential flow engineering level models. In these extreme conditions, a Reynolds-averaged Navier-Stokes CFD model can better predict motions and loads for a WEC. Long time series with varying random seed numbers can be used to identify singular extreme wave events from a stochastic irregular sea state. This approach simulates a more realistic wave series for a given sea state than a regular wave or a focused wave. However, it is computationally infeasible to run these long time series for three-dimensional (3D) CFD simulations. In this work, two-dimensional (2D) CFD simulations with a long domain allow the full development of an extreme nonlinear wave condition. The results are used to identify extreme events from a 50-year storm condition for the PacWave site off the coast of Oregon. A relatively short time window including this extreme event is then mapped to a 3D simulation using a user defined wave methodology. Convergence studies for domain length, wave forcing lengths, and time before the extreme event were conducted.

1. INTRODUCTION

Wind, solar, and hydropower are established renewable energy technologies that are currently installed on a utility scale. There is no single solution which is ideal for every situation, and a diverse clean energy portfolio is more robust and dependable. Marine energy has the potential to provide sustainable and reliable power to coastal communities. Marine energy resources include wave, tidal, river, and ocean thermal energy.

The United States continental shelf has a recoverable wave energy resource of 1170 TWh/year, which is over a quarter of the country's electricity consumption [1]. There are several types of wave energy converters that have been designed to most efficiently capture this resource. Point absorbers have been early leaders in the wave energy category. CalWave performed a 10 month open water deployment of their X1 device in 2021-2022 off the coast of California, demonstrating its power production and storm survival capabilities [2].

WECs often feature buoyant floating bodies that are actuated by incident waves. The motion of the absorber in some way actuates a power take off device creating usable energy. Small amplitude and long wavelength seastates can be well captured by potential flow models, and are typically the waves with the highest occurrence. This makes potential flow based models useful for predicting the power production performance of a wave energy converter. However in certain water depths or extreme storm conditions, waves can become steep and highly nonlinear and potentially break. In these conditions potential flow is not able to capture the dynamics of the wave particle motions. These wave conditions also can cause forces on the body which cannot be captured in potential flow models. While extreme storm conditions may not dominate annual energy production, they can be critical ultimate load cases, which determine the survivability of a device. It is important to have accurate predictions of extreme loads to reduce project risk and optimize design, ultimately lowering the levelized cost of energy.

Modeling extreme waves is computationally challenging. Computational fluid dynamics (CFD) approaches can capture the complex dynamics of these waves, but come with a high computation cost. Romanowski et al. from the University of Strathclyde performed a set of simulations to guide the spatial and temporal refinement necessary for accurate modeling of an irregular seastate [3]. Their work used a built-in irregular wave formation in the commercial CFD software STAR-CCM+, and looked at the required length of time to converge on the a time series with the desired statistical parameters. They decided that between 100 - 300 wave periods was required, leading to very high computation costs [3]. Running a full CFD simulation for this long, in order to model an extreme wave event to predict ultimate limit state loads, is not practical. Some have suggested using a focused wave to represent an extreme event from an irregular seastate, such as WEC modeling work done by van Rij et al. in 2020 [4]. A focused wave is easier to generate in many CFD codes, but does not necessarily match the profile that would come from an irregular wave.

Oggiano et al. in 2017 proposed a method to use a specified wave profile as an input for a CFD simulation, also run in STAR-CCM+ [5]. This approach allowed them to make comparisons to data from physical experiments for validation. They used a commercial wind turbine modeling tool developed by IFE, 3Dfloat, to take the recorded time series and generate boundary conditions which were fed to the CFD solver [5]. The process used only a first order wave formulation, and a physical time of 25.0 s for the simulation, and saw good agreement to loads on a structure measured in a tank test [5].

Also in 2017, Gatin et al. used a higher order spectral (HOS) method, which they describe as a psuedo-spectral potential flow method, to generate a developed wave field for a CFD simulation [6]. The CFD model in their work used a level-set free surface, where the HOS code was coupled at every time step [6]. In their findings, they emphasized the importance of capturing a fully developed nonlinear wave field for extreme loads.

2. OBJECTIVE

The goal of this work is to improve the efficiency of accurate numerical modeling of extreme wave conditions on a WEC. This will be done by simulating a specified wave field in CFD. The WEC studied was designed by CalWave, an early leader in the wave energy field. A photo of their X1 device provided by CalWave is shown in Figure 1; this is not the exact device modeled in this work, but is similar. CalWave's technology is designed to operate fully submerged, leading to effective load shedding in storm conditions, while maintaining good energy production characteristics [2].

In order to protect proprietary information about CalWave's device, all plots in this paper pertaining to the WEC have the axis labels removed, and no dimensions are specified. The focus is on the numerical approach, and normalized descriptions are used.

3. METHOD

The commercial CFD code, STAR-CCM+ version 2022.1 was used for the analysis. Three operational regular wave cases were used for validation of the power take-off (PTO) behavior and WEC response. The extreme wave case is based on the 50-year storm condition for the PacWave site off the coast of Newport, Oregon. Figure 2, adapted from a Pacific Marine Energy Center report, shows a description of this condition including a 50-year contour.

FIGURE 1: CALWAVE X1 DEVICE OFF THE COAST OF SAN DIEGO [7]

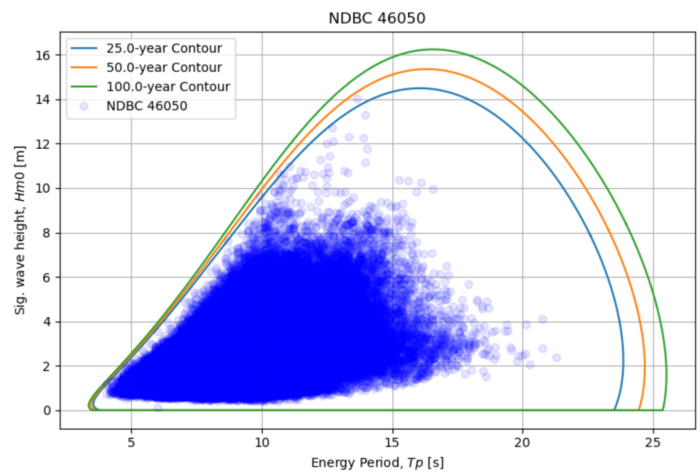

FIGURE 2: EXTREME WAVE CONTOUR PLOT AT PACWAVE SITE, ADAPTED FROM [8]

The WEC uses multiple tethers for mooring and power generation. The PTO system is modeled with user defined forces, which align with CalWave's control algorithms, and utilize various states of the system. The forces are calculated at each time step, and applied to the rigid body.

3.1 Numerical Schemes

An unsteady Reynolds-averaged Navier-Stokes model is used. The two-phase flow was modeled using the volume of fluid (VOF) method, based on an air and a water phase. Second order implicit time discretization was used with second order upwind convection for velocity and turbulence and the high-resolution interface-capturing scheme was used for the volume fraction convection. Turbulence was modeled with the $k-\omega$ SST model; this is a typical approach for marine applications. This model is good for capturing flow along walls and is less sensitive to the free stream dissipation rate than the standard $k-\omega$ model. The detailed boundary layer flow is not expected to drive the loads on the WEC, and all y^+ treatment wall functions are used. In 3D simulations a symmetry plane is used to reduce computation cost; the plane is at the center of the WEC. It is expected that for long crested waves with zero heading, limited roll, yaw, and sway should be induced, so this simplification should be acceptable.

The motion of the WEC is modeled using the overset grid method. The motions are potentially large, and the hexahedral medium aspect ratio cells work best when their orientation is maintained. A mesh morpher would distort these cells potentially interfering with the wave propagation near the body. The overset method keeps the same background free surface mesh in tact, and also keeps the boundary layer mesh on the WEC body consistent.

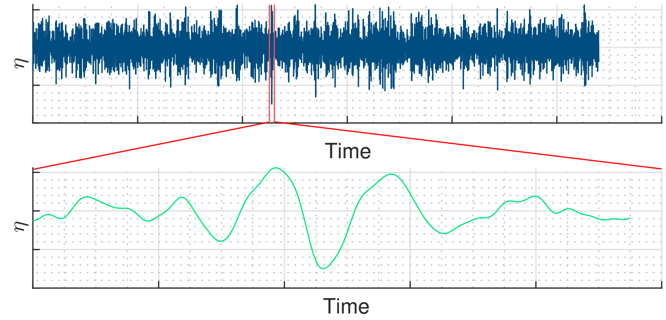

FIGURE 3: EXTREME WAVE EVENT SELECTION

3.2 Workflow

A workflow was developed to efficiently predict the ultimate loads from an extreme wave event on a wave energy converter. This workflow is largely based on the user defined wave feature introduced to STAR-CCM+ in the 2021.1 release. The new capability allows the mapping of a solution from one simulation to use as inputs for another simulation, via a CFD General Notation System (CGNS) file. The mapped field data can be used to define wave properties, for boundary conditions and forcing zones [9]. This method can allow improvements in wave modeling efficiency, by using a 2D domain for the first simulation, and mapping the solution to a 3D domain. The computationally inexpensive 2D domain can be very long and run for a long physical time, allowing a fully developed wave field with fully nonlinear and viscous influenced motions. The two-dimensional simulation does not include the WEC body. This developed field can then be brought into a shorter 3D domain, where the body of interest can be modeled [9]. The wave field forced at the boundaries of the 3D domain is already fully developed, so extended time and length are not needed for a physically accurate wave. For a wave which falls fully into the linear theory regime, this method does not improve efficiency, but it can be very helpful for steeper nonlinear and possibly breaking waves.

STAR-CCM+ has built in tools to model different wave profiles; however, custom spectra and phases for an exact desired wave profile are not possible at this time. Instead, user defined boundary conditions and initial conditions were used to generate the desired and repeatable wave profile. In this study, the wave profile was externally calculated using a discrete fast Fourier transform only including first order components. Any input time series could be used, including recorded data from tank test or field measurement. Here, a three hour time series was generated using a repeatable seed number, and the most extreme event was selected based on the maximum trough to crest amplitude. A certain time before and after this event is prescribed in the modeled time series, and this length is based on a convergence study described below. Figure 3 shows an example three hour irregular wave time series and the down-selected extreme event time range.

After the time range is chosen the necessary inputs are calculated for the 2D simulation. The initial condition for every cell center is found for volume of fluid phase fraction, x-direction velocity, z-direction velocity, and hydrostatic pressure following the STAR-CCM+ convention (x-direction is the direction of wave propagation and z-direction is vertical). A cosine squared damping zone was also incorporated in the initial condition over the last wavelength to the outlet, matching the setting used in the CFD. This limits the transient and potential for numerical instability at the start of the run. The inlet boundary condition was calculated for every cell face center on the inlet boundary, for every planned time step. This was done for the volume of fluid phase fraction, x-velocity, and z-velocity. This process can also work with a recorded wave series, either from field data or from a model tank test, allowing direct validation for a complex input.

The initial and inlet boundary conditions were then imported as tables into the 2D CFD simulation. STAR-CCM+ has the ability to set boundary conditions directly from imported tables, allowing direct manual implementation [9]. The 2D domain used was six peak wavelengths in length, with two wavelengths upstream of the planned body location, and four wavelengths downstream of the planned body location. This length is expected to be sufficient to have a fully developed extreme wave profile by the point of interest, and long enough to not feel the influence of the damping zone which minimizes wave reflection. Links are set up to record the necessary field data projected on to surfaces; velocities are recorded on the side of the domain (parallel to the x-z plane) and wave elevation is recorded on the floor of the domain (parallel to the x-y plane) [9]. It is important to realize that with this process in STAR-CCM+, the discretization of the wave elevation data is only as fine as the cells on the bottom of the domain. A coarse mesh is often used in deep water, where wave motions are expected to be negligible, but this cannot be done using this method, as short wavelengths can't be conveyed, acting like a low-pass filter on the wave spectrum.

A 3D simulation is then set up. An import link is created pointing to the CGNS solution from the 2D simulation aforementioned. STAR-CCM+ data mappers extrude the information across the y-direction (only works for long-crested waves), and spatially interpolate for the new mesh [9]. Time interpolation is also now available with a built-in option, allowing the use of an adaptive time step [9]. After the data is mapped, it is used to create a user defined wave. This wave can be used for typical functions, including: initial condition, boundary condition, and forcing zone. Figure 4 schematically shows the workflow used in the project.

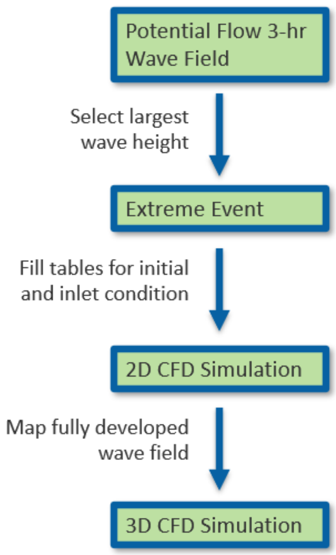

FIGURE 4: WORKFLOW DIAGRAM

4. CONVERGENCE STUDY

Detailed convergence studies were performed for several parameters unique to this workflow. This is done to make sure the solution is independent of their values, especially as best practices have not been established for similar modeling. This is also done to evaluate the possible gains in computational efficiency.

4.1 Mesh Resolution

A mesh sensitivity study was performed to determine the necessary free surface discretization to correctly capture the wave motions. This was done using a 2D domain, with one cell in the y-direction. Two parameters were studied, the number of cells per significant wave height in the vertical direction, and the aspect ratio of the cells. If the waves of interest were not as long relative to their wave height, the number of cells per wavelength in the propagation direction could be a governing parameter. However in this study, all of the waves were long compared to their wave height, and the cell aspect ratio is thus the limiting factor.

It was found that using 20 cells per significant wave height, and a maximum cell horizontal to vertical aspect ratio of 2, produced sufficiently accurate wave fields. This study was done using a long regular wave which falls into the first-order wave theory regime, allowing simple verification of the wave profile.

Volumetric refinements were used around the wave energy converter body, and a boundary layer mesh was formed with prism layer cells extruded from the surface. It is expected that separation will always occur, and always at the sharp corners of the WEC, so capturing a precise boundary layer will likely not significantly improve the results. The total thickness of the prism layers was chosen to match the thickness of the boundary layer on an equally sized flat plate with a relative velocity equal to the expected wave particle velocities. The first cell thickness falls in the logarithmic-law region, and wall models are used with all y^+ treatment. The cells around the WEC are cubes with a length equal to one fourth of the free surface cell height. This report focuses on the numerical wave tank approach, and a specific convergence study for the mesh refinement surrounding the wave energy converter has not yet been performed. In future work, the influence of this could be examined, but it is not expected to change the resulting method for extreme wave modeling.

With the overset grid technique, cells in the background region can take on three types, active, inactive, and acceptor. The inactive cells are fully covered by the overset region, and calculations are not performed. The active cells are fully exposed, and the calculations are performed as normal. The acceptor cells are at the interface and use a blend of solutions from the two regions [9]. For a smooth flow transition between regions, it is important that cells from both regions near the interface have a similar size and aspect ratio. To achieve this, an extra refinement zone is used in the background mesh, in the area where overlap could occur with the moving mesh region. This overset boundary can cross through the free surface refinement area, and thus the refined cell size needs to be similar to the free surface cells. The aspect ratio is also limited here, due to the expected pitching of the overset region with the WEC motions. Figure 5 shows a section of an example mesh, with free surface and overset matching refinements shown for the background mesh.

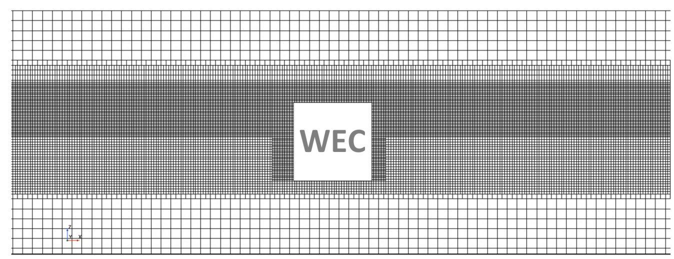

FIGURE 5: EXAMPLE MESH REFINEMENT

4.2 Time Step

The time step was also considered in the 2D domain. The International Towing Tank Conference (ITTC) gives guidelines on the best CFD practices for marine applications. They suggest using a minimum of 60 time steps per shortest wave period [10]. For the wave spectrum used in this project 99% of the wave energy is at wave periods above 5.85 s, which would allow a time step of 0.10 s based on the ITTC standard. Romanowsi et al. suggest that the maximum vertical Courant number should be 0.4; this corresponds to a time step of 0.06 s [3].

When using these recommended times, the turbulent kinetic energy of the $k - \omega$ SST model became unstable and diverged. Reducing the time step to 0.02 s eliminated the turbulence instability. This smaller time step was used in all the following simulations. It should be noted that this instability is dependent on the turbulence model, and could potentially be avoided with a different model. Larsen and Fuhrman focused on this problem with CFD surface wave simulations, and they found that all traditional two-equation turbulence models for RANS codes are unconditionally unstable for flows with finite strain [11]. Larsen and Fuhrman developed a stabilized version of the $k\omega$ model, but this version or a similar model is not yet available in STAR-CCM+ [11]. The use of a one-equation model could also possibly help mitigate this turbulent instability.

In the 3D simulations, when using the overset method for mesh motion, it is also important to consider the velocity of the overset region. The cells at the interface should not move far relative to their size in a single time step. In the following tests the cells at the overset interface never moved more than one twentieth of their height in a time step.

4.3 3D Domain Length

The 2D domain was six peak wavelengths long to allow for full development of the extreme wave field, and to avoid the influence of a damping zone at the point of interest. Unlike in a 3D simulation, this long domain is not prohibitive in two dimensions. Once the wave solution is found, it can be leveraged to use a shorter more efficient domain for 3D simulations, where a fully developed solution can be forced at the boundaries.

Four 3D domain lengths were tested. In all 3D domains, the point of interest, the WEC's equilibrium point, is at the center of the domain in the x-direction. Lengths of 1.0, 2.0, 3.0, and 4.0 peak wavelengths were tested. The mesh sizes for each of the tested lengths are shown in Table 1.

TABLE 1: DOMAIN LENGTH STUDY MESH SIZE

Domain Length	Cell Count [millions]		
n λ	Background	Overset	Total
1.0	1.54	0.15	1.69
2.0	3.06		3.22
3.0	4.58		4.73
4.0	6.11		6.26

A key concern is reflected waves, which can impact the desired wave elevation profile. This problem can be addressed with either a damping or forcing zone, which forces the solution either to a flat surface, or a specified wave solution at the boundary. Here a forcing zone, one quarter peak wavelength long, is used both at the inlet and the outlet. The forcing zone applies a momentum source term. This source term is opposite the difference between the measured momentum and the prescribed momentum (only based on velocity for this incompressible model) [9]. The momentum source is only applied over a selected length, and uses a cosine squared factor to attenuate the forcing at the end of the zone [9].

The radiated waves from the WEC motions drive its hydrodynamic linear damping, creating important loads. It is important that any forcing or damping zone is far enough away from the WEC as to not interfere with the radiation effects.

Figure 6 shows the free surface elevation throughout the simulation for the different domain lengths. The elevation is recorded at the x-position of the WEC equilibrium, and at the furthest extent of the domain in the y-direction, in order to have as little influence from the WEC radiation as possible. In the plot, the elevation recorded in the two-dimensional run, which is the input for the 3D run, is shown with a dashed black line. All domain lengths show strong agreement to this solution. All time plots show dashed vertical lines at the same times marking off the extreme event for comparison.

Figure 7 shows the resulting WEC motions for a chosen PTO controller gain set with the different domain lengths. There is again strong agreement between the four runs.

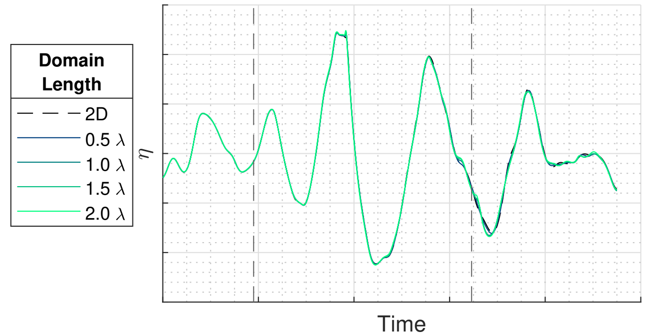

FIGURE 6: DOMAIN LENGTH IMPACT ON WAVE ELEVATION

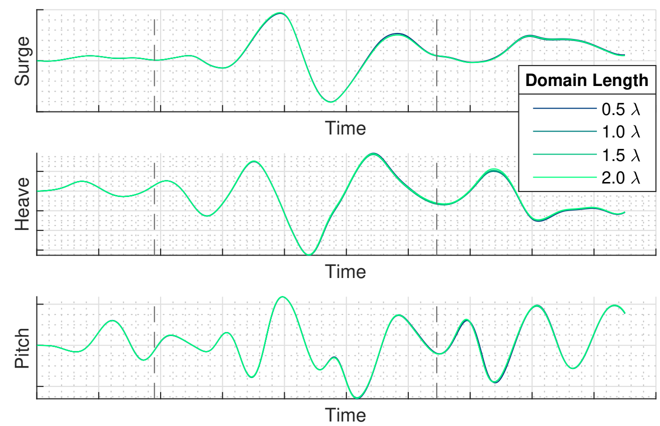

FIGURE 7: DOMAIN LENGTH IMPACT ON WEC MOTIONS

Down to the shortest domain tested, with half a peak wavelength on either side of the WEC, the solution is insensitive to the domain length. The shortest domain was used for following tests. In future work even shorter domains could be tested to further reduce computation cost. It is important to note that the required length is dependent on the size of the body compared to the wavelength and wave height. For this particular body and wave, the dominant radiated waves are short compared to the incident waves, allowing a shorter domain.

4.4 3D Domain Wave Forcing Length

The same wave was run in the shortest domain with varying forcing zone lengths at both the inlet and the outlet. The best forcing zone length is a function of the domain length. A long enough forcing zone is required to ensure that the diffracted and radiated waves from the body are not reflected by the boundaries. In addition, a large enough distance between the forcing zone and the WEC is needed to ensure that the WEC radiation and diffraction forces are not influenced.

Unlike the domain length, the forcing zone length has minimal impact on computation cost. The number of cells does not change, only a small increase in calculations for the momentum source terms in the zone. Three forcing lengths were tested: 0.25, 0.1, and 0.0 peak wavelengths.

Figure 8 shows the wave elevation for the three runs. There is strong agreement between the results, especially up to the time of the largest extreme wave event. Even with no forcing zone there seems to be negligible wave reflection.

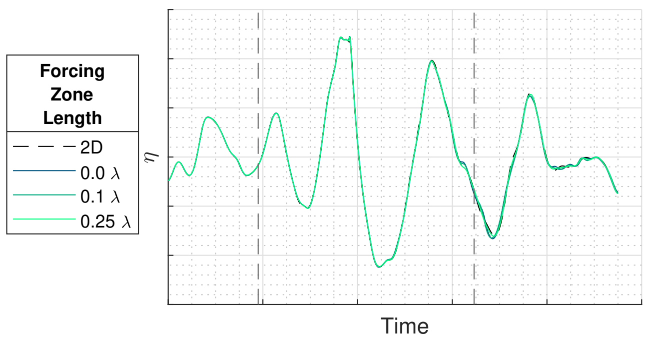

FIGURE 8: FORCING ZONE LENGTH IMPACT ON WAVE ELEVATION

Figure 9 shows the resulting WEC motions for the three runs. Again there is strong agreement between the forcing zone lengths. It should be noted again, that the required forcing zone length is a function of the specific WEC relative to the wave condition. In this condition there is a small amount of wave radiation, making it easier on the boundary condition to maintain the correct elevation profile, and less likely for the forcing zone to impact the WEC motions. This variable should be checked on a case-by-case basis.

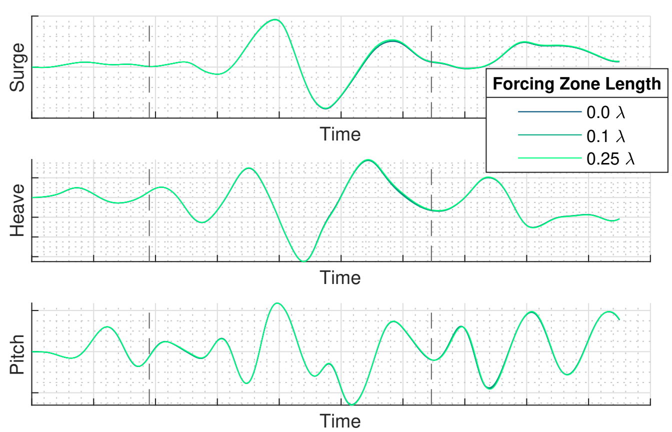

FIGURE 9: FORCING ZONE LENGTH IMPACT ON WEC MOTIONS

4.5 Time Before Extreme Event

Modeling a commonly used three-hour sea state using CFD is extremely computationally expensive. Wang et al. modeled a floating offshore wind platform in a three-hour irregular wave field in a 2022 study [12]. They focused on the low-frequency response of the platform, so this long simulation time was required. Using their baseline discretization, they found that 2.6e5 core-hours were required for a one-hour simulation [12]. The method used here allows a much shorter simulation time to determine ultimate loads from an extreme wave event. However, if a run is started just before the extreme event, the transient start-up of the WEC motion will impact the loads observed. A certain time before this event needs to be modeled for the body to reach a realistic position, velocity, and acceleration leading into the largest wave.

In addition to the WEC transient, some time is also needed for a fully developed nonlinear wave field. The use of an efficient two-dimensional CFD simulation is effective for achieving a physical extreme wave profile, but some criteria must be met. As mentioned in Section 4.3, the domain needs to be long enough upstream of the point of interest for the full nonlinear and possibly rotational wave to develop. Analogously, a certain length of time is needed for full wave development.

The domain length study and forcing zone length study both included three times the peak wave period prior to the extreme event. Additional time lengths were tested for both the convergence of the WEC transient and the wave development. All runs included two peak periods after the extreme event. The computation cost scales linearly with the physical time simulated.

The convergence of the wave field is shown first. This was done only using the efficient 2D domain. Twelve different time periods were used ranging from two peak periods to fifty peak periods before the extreme event. The resulting free surface elevation time series are shown in Figure 10. The top plot shows the full modeled time for all time lengths. The bottom left plot shows only the time surrounding the extreme event. The bottom right tracks the trough and crest elevations for the two waves around the extreme event as a function of modeled time.

Overall there is strong agreement in period and phase even with only two peak periods modeled prior to the extreme wave. However there is some apparent variability in the exact profile. With ten peak periods or more the time series are much more consistent, although some uncertainty is still present. There is no clear trend in trough or crest elevation as a function of increasing simulation time.

The convergence of the WEC transient was tested with four different simulation times. For each of the simulations the exact same 2D wave solution was used; this solution came from the 2D case with twenty peak periods before the extreme event. In the 3D runs, the waves were not run prior to the release of the WEC, so there is no diffraction effect on the wave profile at the start. The body was released with zero velocity at the same position for each variation.

The resulting WEC motions are shown in Figure 11. The surge and heave motions both appear to converge quickly, with consistent motions across all four runs prior to the extreme wave. The pitch motion has strong dependence on the transient for longer. The motions in all three degrees of freedom are well aligned between simulations at the start of the first extreme wave. This wave is dominant enough to cover the influence of the release time. Interestingly, the heave and surge motions deviate slightly between start times after the second extreme wave.

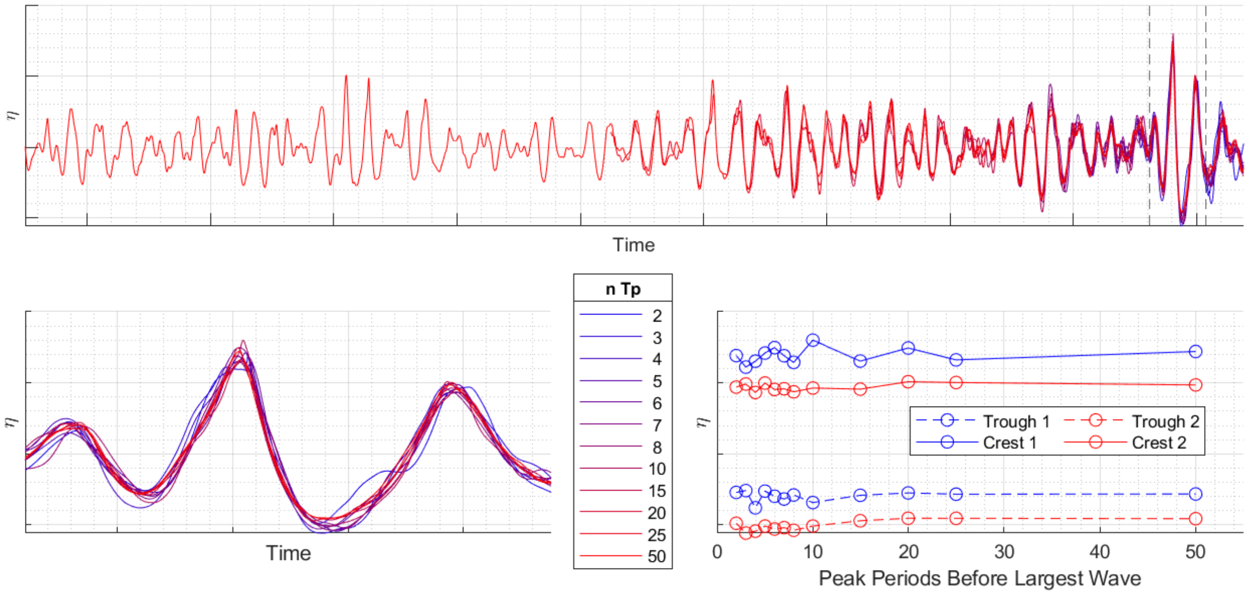

FIGURE 10: TIME BEFORE EXTREME EVENT IMPACT ON WAVE ELEVATION

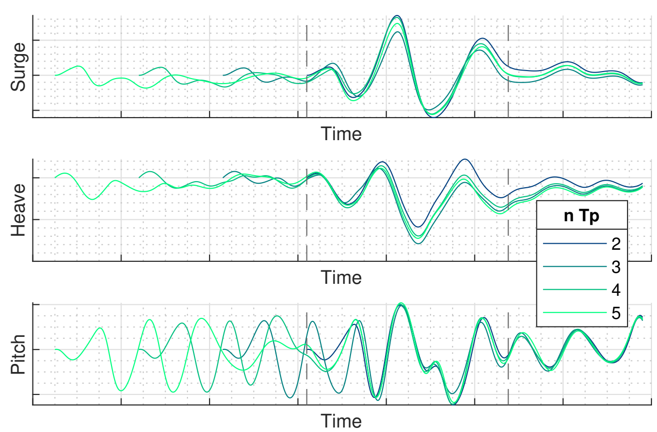

FIGURE 11: TIME BEFORE EXTREME EVENT IMPACT ON WEC MOTIONS

5. DISCUSSION

A method and workflow for extreme wave modeling was created and demonstrated. The new STAR-CCM+ user defined wave feature was tested, with use of CGNS simulation coupling. The approach allows the use of any defined wave field. In this case, the wave field was externally selected by isolating the largest waves from a potential flow irregular wave sea state. The wave time series could also come from field data or model test data, and be used in this same process.

Specifically selecting the wave field allows one to model a realistic extreme event from a stochastic wave signal, without the need for a prohibitively long simulation. This decrease in required solution time correlates directly to a decrease in computation time.

Spatial efficiency was also gained. By first calculating a fully developed wave field in a two-dimensional domain, the expensive 3D domain can be much smaller in size. For this specific wave and body combination, a 3D domain length of one peak wavelength was sufficient. When using the described method, a forcing zone at the inlet and outlet may be needed to avoid wave reflection, but this work found that it may not always be necessary. Both the domain length and forcing zone length for the 3D domain are a function of the relative body size and motions compared to the wave size, and should be evaluated on a case-by-case basis.

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