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Review of TEAMER Awards for WEC-Sim Support

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Abstract—**Testing Expertise and Access for Marine Energy Research (TEAMER) is a U.S. Department of Energy Water Power Technologies Office sponsored program, overseen by the Pacific Ocean Energy Trust, which aims to advance the state of marine energy technologies. The program connects technology developers with experts at U.S. facilities, including numerical modeling and analysis facilities, like WEC-Sim. The WEC-Sim facility is supported by the WEC-Sim development team at Sandia National Laboratories and the National Renewable Energy Laboratory. WEC-Sim (Wave Energy Converter SIMulator) is an open-source software for simulating wave energy converters. WEC-Sim can model the multi-body dynamics of devices comprised of bodies, joints, power take-off systems, and mooring systems. Since TEAMER's first request for technical support in 2020, there have been 18 TEAMER awards focused on numerical model development in WEC-Sim. TEAMER awards for WEC-Sim support have modeled a wide range of wave energy converter archetypes, including point absorbers, attenuators, oscillating water columns, and many other novel architectures. A wide variety of studies have been conducted, leading to important insights for TEAMER partners and software improvements for WEC-Sim. This article highlights several successful WEC-Sim TEAMER awards. The awards described herein include TEAMER recipients Ocean Motion Technologies, AquaHarmonics, iProTech, East Carolina University, the University of Michigan, Maiden Wave Energy, and the University of Massachusetts Dartmouth. The awards of these seven partners contain a wide range of investigations and cover the creation of baseline hydrodynamic models, Power Take-Off (PTO) modeling, geometry optimization in both boundary element methods and WEC-Sim, and model tuning and validation.**

Index Terms—**WEC-Sim, TEAMER, Wave Energy, Numerical Modeling, Industry Support**

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I. Introduction

Established in 2020, the Testing Expertise and Access for Marine Energy Research (TEAMER) program, is sponsored by the U.S. Department of Energy Water Power Technologies Office and directed by the Pacific Ocean Energy Trust. The TEAMER program aims to advance the state of marine energy by connecting technology developers, both within the U.S. and internationally, with experts at U.S. facilities. Applicants apply to receive a wide range of technical support from a TEAMER facility in the following categories:

- numerical modeling and analysis
- laboratory and bench testing
- tank, flume, tunnel and basin testing
- open-water testing

The Wave Energy Converter SIMulator, WEC-Sim, was established as one of TEAMER's first numerical modeling and analysis facilities. WEC-Sim is an open-source software for simulating wave energy converters, developed jointly by Sandia National Laboratories (Sandia) and the National Renewable Energy Laboratory (NREL), and the WEC-Sim facility is supported by the WEC-Sim development team at Sandia and NREL [1]. WEC-Sim is commonly used in the field of offshore renewable energy [2] to model the multi-body dynamics of devices comprising bodies, joints, power take-off systems, and mooring systems using potential flow-based hydrodynamic coefficients in the time domain [3]. Refer to the WEC-Sim documentation for an in-depth description of the methodology and implementation [3]. While originally developed to model wave energy converters (WECs), WEC-Sim has also been used to simulate a broad range of devices, including floating offshore wind turbines, hybrid systems, and floating platforms [4].

Due to the desire for technology developers to simulate their innovative technologies, and the broad applicability of the WEC-Sim software, requests for WEC-Sim support have grown substantially. Since TEAMER's first request for technical support (RFTS) in 2020 through RFTS 9 in 2023, there have been 17 TEAMER awards focused on numerical model development through the WEC-Sim facility, accounting for approximately 15% of all TEAMER awards. One additional award outside of the WEC-Sim facility completed a WEC-Sim analysis. There are now 75 TEAMER facilities available, making WEC-Sim one of the single most requested TEAMER facilities. TEAMER awards for WEC-Sim support have modeled a wide range of wave energy converter archetypes including point absorbers, attenuators, oscillating water columns, and many other novel architectures.

This paper reviews a subset of those TEAMER awards including support for the following recipients: Ocean Motion Technologies, AquaHarmonics, iProTech, East Carolina University, the University of Michigan, Maiden Wave Energy, and the University of Massachusetts Dartmouth. The TEAMER awards with these seven partners include a wide range of numerical modeling and analysis, covering development of baseline hydrodynamic models, modeling power take-off systems, geometry optimization, and model verification and validation. For each project, the company and device, the scope of work in the award, type of study or analysis conducted, and a key result are discussed. Upon completion, TEAMER awards submit project data to the U.S. DOE Marine and Hydrokinetic Data Repository (MHKDR). Project submissions to MHKDR are noted if available.

II. Ocean Motion Technologies

Ocean Motion Technologies (OMT) has participated in three TEAMER awards for WEC-Sim support, covering baseline model creation, geometry optimization in Capytaine [5] and WEC-Sim, and model validation with experimental data. OMT targets applications for powering ocean observation, maritime monitoring, offshore aquaculture monitoring, and surveillance and reconnaissance for defense and coastal security. OMT's WEC is a hardware attachment that can be installed on commercial data buoys. The Adaptive Point Attenuator (APA) can include a set of one, two, three or more mechanical levers that are positioned to provide omnidirectional energy capture on existing ocean platforms. A render of a 2-arm APA from WEC-Sim is shown in Figure 1. As waves interact with the buoy, the lever arms are excited and move relative to the buoy. This motion is converted into electricity through OMT's power take-off (PTO) system, which consists of a combination of mechanical and electrical components.

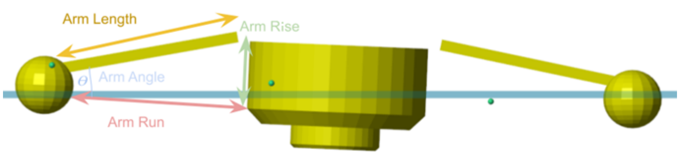

Fig. 1. Simulink render of a 2-arm OMT WEC mounted to a commercial data buoy, modeled in WEC-Sim.

During the first iteration of TEAMER support, researchers at Sandia and NREL supported OMT with the creation of baseline boundary element method (BEM) hydrodynamic data and a baseline WEC-Sim model. The WEC-Sim model was expanded to cover several iterations of the OMT device and include the ability for OMT to add their custom artificial intelligence controller in the simulation loop. Figure 2 shows a portion of the WEC-Sim model in Simulink, including the various bodies, joints, mooring system and custom controller.

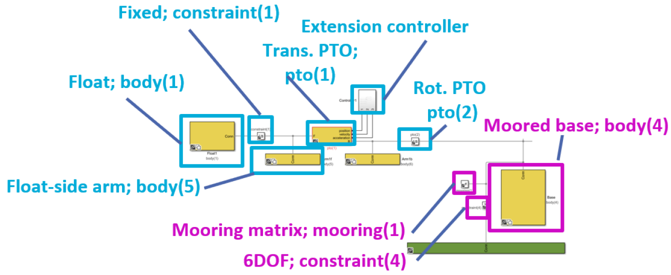

Fig. 2. Sample of the Simulink diagram showing the schematic of how a OMT device is connected to a moored oceanographic data buoy

The second award built upon the RFTS 1 modeling to create a simulation system where geometrical properties (e.g., float radius, arm length, float ballast) can be varied. Capytaine and a custom-built meshing tool were used to iteratively create hydrodynamic data for various float radii, arm lengths, etc. WEC-Sim was used to model these geometry variations in a variety of sea states. The overarching goal was to create a power matrix for each geometry variation and discover which geometrical configurations resulted in the greatest power generation.

Simulation results indicate that both changing the arm length and increasing the radius of the float can greatly impact the device's performance in a given sea state. A larger float radius increases wave excitation and thus the force exerted on the float, causing increased device/buoy motion and increased power output. OMT's current PTO and control system uses a constant resistive torque. In some sea states, a shorter arm length increases the rotational velocity of the arm, increasing power output, while in other sea states the greater range of motion of a longer arm increases power output. It was also discovered that device performance depends heavily on the steepness of incoming waves. Increased wave steepness always resulted in greater power output (within the linear wave theory assumptions of WEC-Sim). Wave steepness was found to be as or more important than arm length and float radius in determining device power output. Figure 3 shows how the device power generation changes with arm length and wave steepness. As the wavelength becomes more closely aligned with the arm length, the device acts more like an attenuator and absorbs more power.

As a result of this collaboration, the TEAMER facilities successfully developed several working WEC-Sim models of OMT's APA device. The simulations are robust and enable easier design iteration in the future. OMT's third TEAMER award is validating the WEC-Sim model with experimental data by incorporating tuned moorings and damping coefficients. WEC-Sim can provide precise information on the mechanical, hydrodynamic, and PTO response and loading of the device. The data and workflow for this work can be utilized to iterate and improve the device and allow it to reach a higher technology readiness level. Through

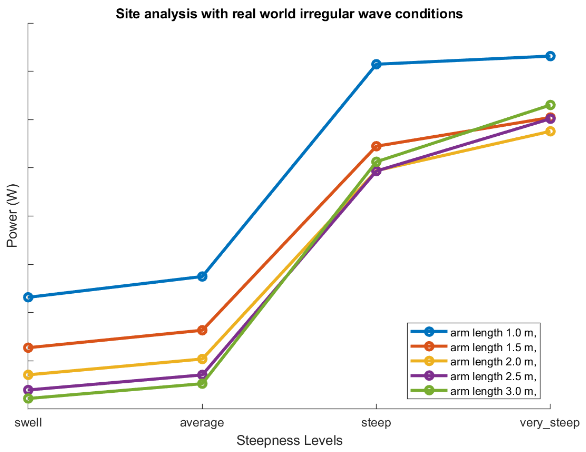

Fig. 3. Power generation of the OMT device with various arm lengths in various wave conditions. Y-axis scale is intentionally redacted.

these awards, the WEC-Sim facility was able to apply WEC-Sim to a new device and PTO design, furthering the adoption of WEC-Sim for marine energy research.

The TEAMER work with Ocean Motion Technologies is available through the MHKDR [6].

III. AquaHarmonics

The AquaHarmonics wave energy converter concept is an axisymmetric point absorber that operates in a tension-only condition over a large stroke to eliminate the need for end stops in normal operating conditions. The device consists of a floating hull with an interior PTO that uses an impedance-matching control scheme, matching with the wave environment to maximize electrical power capture, improving capture over a similarly sized passive device. The PTO has a large hydraulic brake integrated into the assembly that can be used for latching-type control, as well as a service brake for in situ repairs of the device and PTO.

The AquaHarmonics wave energy converter PTO module includes the main PTO drum, which is fixed to a shaft with rotary seals, and is supported by bearings in a sealed compartment. The compartment is integrated around a pneumatic return spring assembly, which provides the restoring force during operation. The pneumatic return spring connects to the spring return belt, which passes over a return drum, and terminates at the spring return shaft. The spring return shaft is connected to the main PTO drum via a synchronous belt. Connected in parallel with the spring return system to the PTO drum is a second synchronous belt that connects the main PTO drum shaft to the PTO generator, which is used to generate electrical power. The main PTO mooring belt terminates at the PTO drum on one end and is connected at the opposite end to a guided sliding termination assembly (GSTA), which allows the belt to terminate and pass loads to an electrical-optical-mechanical (EOM) cable connected via a pass-through-type connection. The EOM cable passes through and is constrained laterally by a fairlead integrated into the lower spar section. The EOM cable connects at standard dive depths to a buoyant EOM connection assembly, attached to a second EOM cable that finally connects to the device mooring anchor on the seafloor. A second pass-through-type termination allows the electrical and optical part of the EOM cable to continue to a subsea junction box connected to the end user's subsea cable, which can then proceed to shore in a grid tie connection or standalone condition. In the event of a large storm, the GSTA also engages an attenuator at the bottom of the device stroke, which passes large loads from the EOM cable directly to the hull structure, bypassing the device PTO. A schematic of a 1:7 PTO is shown in Figure 4.

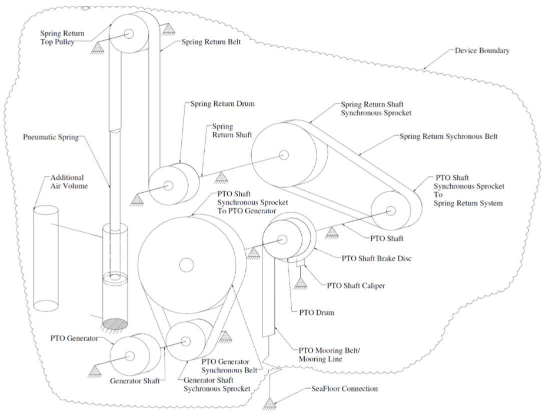

Fig. 4. 1:7 scale AquaHarmonics PTO.

The main objectives of this project were to develop a WEC-Sim numerical model of the 1:7 scale AquaHarmonics device, couple a parametric PTO model to the WEC-Sim simulation, and couple an energy storage model to the PTO and WEC-Sim simulation.

Figure 5 compares the high-level schematic of the device with the WEC-Sim Simulink model, including the hydrodynamic simulation from WEC-Sim, the PTO model, and the energy storage model. This model was used to determine the optimal spring and damping coefficients to maximize grid power for different wave conditions. The results for the optimized grid power are presented in Figure 6.

The time-series results from the simulation are useful to determine how the dynamics of the device are affecting the power generation. The time-series results for the AquaHarmonics WEC are presented in Figure 7.

A challenging aspect of this project was the accurate determination of hydrodynamic coefficients. The AquaHarmonics WEC has a flooded hull chamber exposed to water, which complicates the BEM model. The approach to handle this complexity was to simulate different defeatured versions of the device with special methods to modeling flooded WECs, including a model in which the bottom of the enclosure was fully open rather than modeling individual small flood holes. Also, thin walls (0.01 m) can be used for the hull of the device but require increased thickness at the bottom of the hull (about 0.1 m) to avoid unexpected results such as a negative added mass. The WEC-Sim team's analysis found that a hull thickness of approximately 0.03 m eliminated the negative added mass problem.

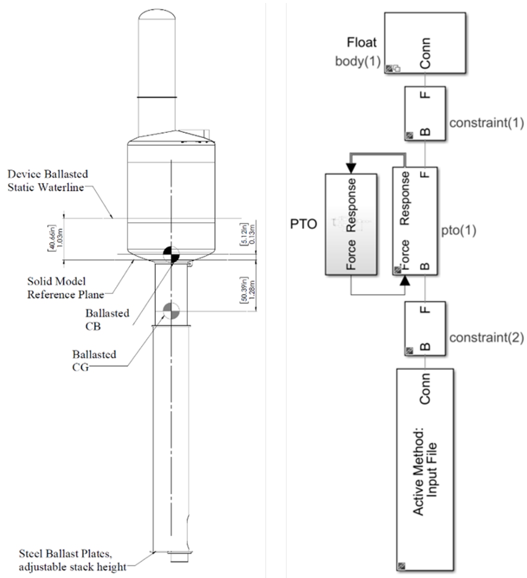

Fig. 5. Schematic of the 1:7 scale device with hydrostatic and mass property details (left). High-level WEC-Sim model in Simulink (right).

Fig. 6. Optimized grid power for the AquaHarmonics system

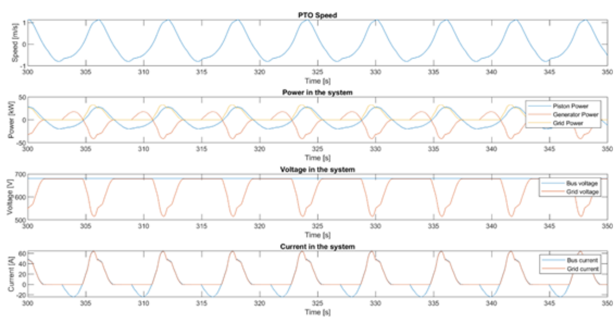

Fig. 7. Optimized grid power for the AquaHarmonics system

The TEAMER work with AquaHarmonics is available through MHKDR [7].

IV. iProTech

This section presents the development of numerical models for a novel WEC concept called the Pitching Inertial Pump (PIP), developed by iProTech. The goals of this project include exploring the PIP's design space and understanding its characteristics. Two types of models were developed to achieve these goals:

- A fast WEC-Sim model with a linear PTO model.
- A separate WEC-Sim model with a detailed component-level model of the hydraulic PTO circuit (using PTO-Sim).

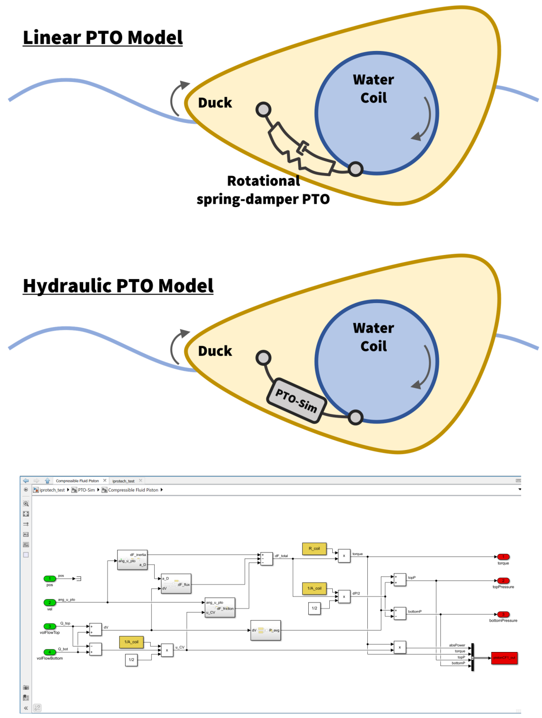

Fig. 8. Sketches of the PIP WEC; two approaches were taken to modeling the PTO; a rotational spring-damper with fixed coefficients and a hydraulic component-level model using PTO-Sim. The PTO-Sim model in Simulink is shown in the bottom image.

The ultimate aim was to assess the performance of the PIP system, identify parameters for optimization, and improve the understanding of the PIP WEC's behavior.

Python scripts were developed to take descriptions of the PIP's geometry (i.e., draft, nose angle of attack, etc.) and turn them into a series of vertices in 3D space. The connections between each vertex were also defined in order to create quadrilateral panels. The points and panels were saved to a .nemoh mesh format. Cosine spacing was used to refine the mesh close to its edges. These Python scripts enabled the modeling team to easily and quickly generate meshes of the PIP WEC for a range of geometry variables.

The open-source Python package Meshmagick was used to take the .nemoh mesh file and compute properties such as the hydrostatic stiffness matrix, center of buoyancy and shell inertia properties, which are necessary for the time-domain simulations. The open-source Python package Capytaine was used to compute hydrodynamic coefficients (excitation, added mass, and radiation damping) for each geometry across a range of frequencies. The MATLAB tool BEMIO was used to convert the Capytaine output files into WEC-Sim inputs.

All of the mass, geometry, and hydrodynamic properties for each design iteration were read into MATLAB/Simulink for WEC-Sim batch runs, generating power response curves for each design case. Various studies investigated PIP variables, such as nose angle of attack, draft, PTO stiffness and damping, and center of gravity.

The linear and detailed PTO models were compared to verify the accuracy of the simpler, linear model (Figure 9). Good agreement was observed for the damping coefficient, $C_{damping} = 3.5 \times 10^7 \frac{N \cdot s}{rad}$, although the second peak of power is at a consistently longer period for the PTO-Sim model.

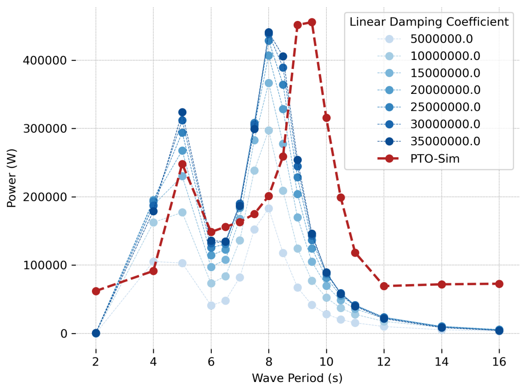

Fig. 9. Comparison of the linear PTO model results (varying the damping coefficient) and the component-level PTO-Sim model.

With the faster, linear PTO model, power response curve comparisons for PIP variable investigations were conducted. The impact of each variable on the PIP WEC's performance was quantified. Parameters such as device draft, nose length/angle of attack, center of gravity were all varied to explore their influence on the PIP's performance. This has offered insights into potential optimization strategies.

The development of a numerical model for the PIP WEC has enabled a comprehensive design space exploration, leading to a better understanding of the system's behavior and potential optimization strategies. Despite some limitations in the current workflow, the results provide valuable insights into the PIP WEC concept.

The separation of meshing, hydrostatics, and hydrodynamic coefficient computations and time-domain hydrodynamic simulation made it difficult to automate the modeling workflow for optimization studies. It is not generally possible to obtain accurate drag coefficients in oscillating flow without performing high-fidelity simulations/experiments, which should be performed to validate particular cases. Hence, the power outputs may overestimate actual performance. Future work my focus on improvement in these areas.

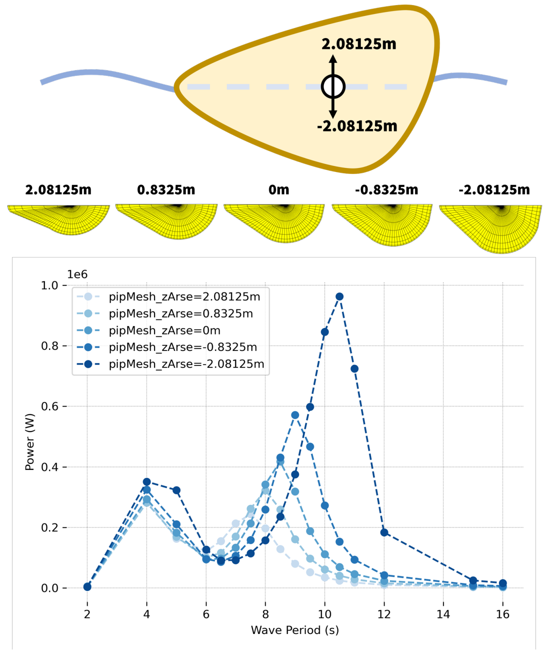

Fig. 10. Example of one of the PIP design space exploration studies; varying the draft of the hull.

The TEAMER work with iProTech is available through MHKDR [8].

V. East Carolina University

The TEAMER award with East Carolina University (ECU) worked to develop a zero-waste, sustainable water desalination system. The zero-waste discharge desalination system is based on reverse osmosis (RO) and supercritical water technology [9]. The device extracts wave energy using an oscillating surge wave energy converter (OSWEC), for a desalination system. This project used numerical models, including WEC-Sim, to verify and validate ECU's design. The numerical models of the supercritical brine recycling from the RO system were implemented using a co-simulation that coupled WEC-Sim, in MATLAB Simulink, with Aspen Plus.

Figure 11 shows a WEC-Sim model with a double-acting rotary actuator PTO system. Figure 11 shows a Simulink model of this PTO and the corresponding WAMIT mesh of the bodies. The design flowchart is shown in Figure 12 with the validation workflow for numerical modeling for the device deployment at Jenette's Pier in Nag's Head, North Carolina. The color of each block represents the main simulation activities—data collection, the development of an analytical solution, and structural properties estimation—to generate a numerical model in WEC-Sim that includes a detailed double-acting rotary PTO with the RO system. Exploration of the design space helped identify the pertinent device configuration with representative PTO parameters. The scope of the numerical modeling efforts were limited to the flap's thickness, which could theoretically increase generated power.

Figure 13 shows the optimal PTO damping for various flap thicknesses and wave periods. Overall, the optimal damping coefficients do not vary significantly

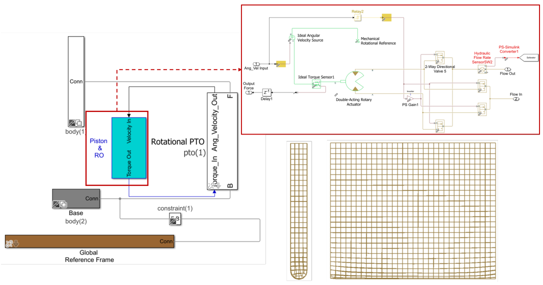

Fig. 11. Sketches of ECU's OSWEC WEC-Sim model (left) with double-acting rotary actuator PTO (top right). An example of WAMIT mesh is shown in the bottom right image.

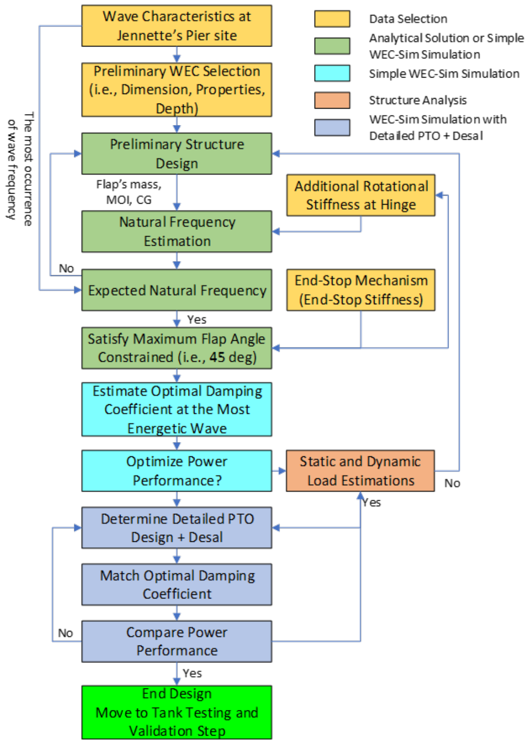

Fig. 12. Design flowchart used for ECU's OSWEC small-scale device

with model thickness for a given wave period. For wave periods of 3.5–8.2 s the optimal damping coefficients are relatively flat-lined. The maximum difference in optimal damping for a given wave period is 1.03 MN·m·s/rad, and occurs at periods of 7 s. While this is only a 16% difference between devices, it is expected that there is a high variability in the designs at this period because it is near the device's resonant period of 7.59 s. Greater damping is required for the thinner OSWECs and generally at lower wave periods. Initially, it was hypothesized that the damping needs of each device could change as the result of different wave heights recorded at the location. Yet there was no apparent correlation to the change in wave height to the overall trends of each device's damping range as seen between the wave periods 11.7–12.8 s.

After the optimal damping range was selected for each period, a power matrix was created by simulating all wave states used in this study. A parametric sweep of flap thickness is shown in Figure 14. The highest device performance was observed at a wave-height of 1.75 m. Furthermore, devices with a flap thicknesses

		Full Model Thickness [m]				
		0.321	0.4815	0.642	0.8025	0.963
Wave Period, Tp	3.5	4.3E+06	4.3E+06	4.3E+06	4.4E+06	4.3E+06
	4.7	3.6E+06	3.4E+06	3.4E+06	3.5E+06	3.5E+06
	5.8	2.7E+06	2.6E+06	2.6E+06	2.5E+06	2.5E+06
	7	2.1E+06	1.9E+06	1.8E+06	1.4E+06	1.1E+06
	8.2	1.6E+06	1.4E+06	1.0E+06	1.0E+06	1.0E+06
	9.3	5.1E+05	4.9E+05	5.5E+05	6.3E+05	7.0E+05
	10.5	8.2E+05	4.9E+05	6.1E+05	6.3E+05	7.0E+05
	11.7	5.1E+05	6.3E+05	6.6E+05	7.2E+05	8.5E+05
	12.8	6.7E+05	7.8E+05	9.7E+05	1.1E+06	1.3E+06

Fig. 13. Estimated optimal damping [N·m·s/rad] range for each device

ranging from 0.321–0.642 m showed peak performance at wave periods of 4.7 s and 9.3 s, while the thicker flaps, with thickness of 0.8025-0.963 m, performed their best at a wave period of 9.3 s. In general, the power performance increased with flap thickness.

		Wave Period, Tp [s]									Flap Thickness
		3.5	4.7	5.8	7	8.2	9.3	10.5	11.7	12.8	
Wave Height, [m]	1.75	24116	32544	22323	22659	21966	26525	28339	29740	26347	0.321
		24913	35033	24512	25829	25604	32458	32730	31607	26752	0.4815
		25422	36984	26332	28663	28746	36412	34810	31653	26828	0.642
		25868	38801	28133	31959	31538	39321	35410	31548	26694	0.8025
		26197	40554	29897	34403	34331	41126	35853	31849	26559	0.963

Fig. 14. Simulated average power with respect to flap thickness and wave period at a wave height of 1.75 m

The TEAMER work with East Carolina University will be available through the MHKDR at a later date.

VI. University of Michigan

This section presents the development of a numerical model for the University of Michigan (UM) floating oscillating surge wave energy converter (FOSWEC).

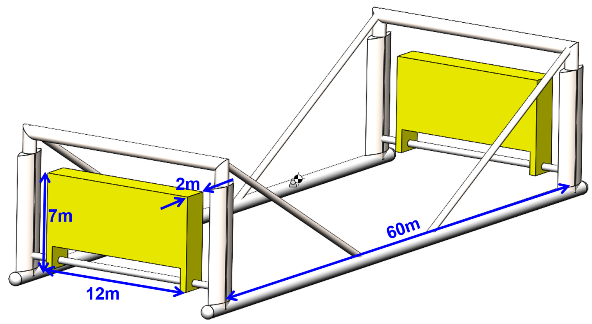

Fig. 15. Sketch of the UM FOSWEC.

Estimates from the Reference Model 5 design have shown the mooring/foundation costs to be about 11.1% of the total capital expenditure [10]. The mooring configuration can also have a large influence on the system performance. Hence, the mooring system is a critical part of the proposed system, which will impact performance and levelized cost of energy. The goal of this TEAMER project was to perform a comprehensive mooring analysis of the University of Michigan's FOSWEC, considering both the technical and economic aspects.

Geometry parameterization and mesh generation were conducted using custom Python scripts, Gmsh, and Meshmagick. Parameterizations of the FOSWEC geometry (e.g., base length, flap width, draft) are defined and iteratively converted into mesh files.

Hydrostatic properties were calculated with the open-source Python package Meshmagick [11], including hydrostatic stiffness matrix, center of buoyancy, and shell inertia properties from the NEMOH mesh, which are necessary for the time-domain simulations. The open-source Python package Capytaine was used to compute hydrodynamic coefficients (excitation, added mass, and radiation damping) for each geometry across a range of frequencies. WEC-Sim's BEMIO module was used to convert the Capytaine output into WEC-Sim inputs. The WEC-Sim model of the VT FOSWEC was developed with a simple linear mooring model (i.e., a linear spring-damper) and with a MoorDyn coupling for a fully nonlinear mooring analysis to assess the performance of the system with both catenary and taut mooring systems.

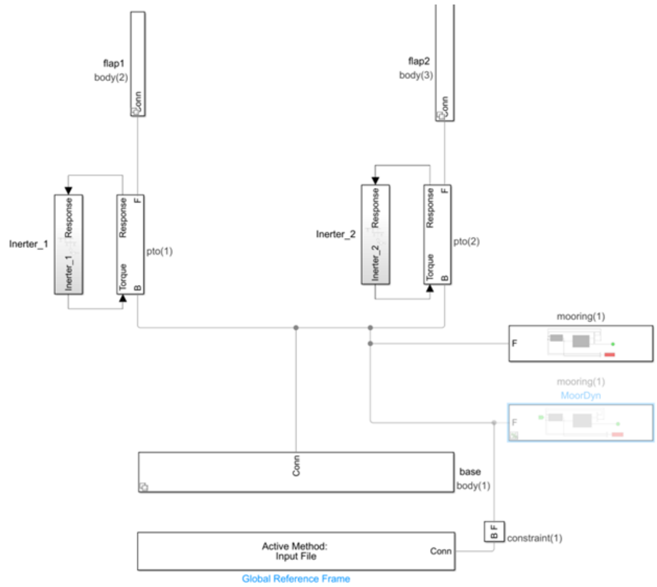

Fig. 16. Schematic of the UM FOSWEC WEC-Sim model, with the MoorDyn block used to couple WEC-Sim and MoorDyn.

The mooring design process involves the use of both NREL's internal, quasi-static mooring design tools and the WEC-Sim/MoorDyn coupling to calculate the dynamics on the floating body and mooring system, respectively. The general design process is shown in Figure 17.

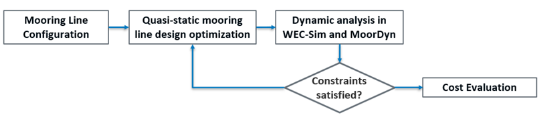

Fig. 17. Mooring system design process for UM FOSWEC.

Power response curves were generated with the UM FOSWEC WEC-Sim model with the linear mooring option for various mooring stiffness values. Figure 18 shows that the stiffness of the mooring had little effect on the WEC-Sim power results. However, the 70 kN/m option gave slightly higher results and became the target stiffness for mooring designs.

The UM FOSWEC's PTO stiffness was also explored to identify an ideal stiffness value. Figure 19 shows that a PTO stiffness of 310 kN/m generally captures the most power over the wave periods over which the flap is excited.

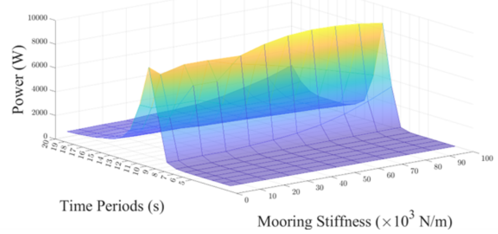

Fig. 18. Power response curves for the UM FOSWEC device with different mooring stiffnesses.

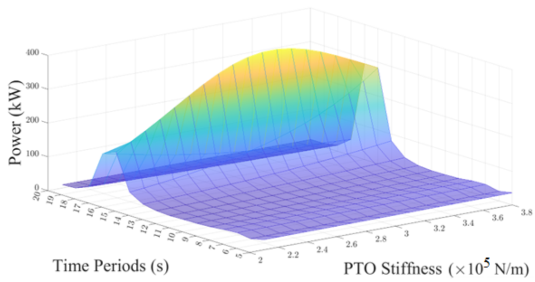

Fig. 19. Power response curves for the UM FOSWEC device with different PTO stiffnesses.

It was assumed that the mooring systems would be designed for one FOSWEC in a single PacWave berth. The physical boundaries of the PacWave berths created maximum anchor spacings for different mooring designs depending on the heading direction of the mooring lines. Figure 20 shows one of the studies performed for catenary mooring systems with different line headings and stiffnesses. Figure 21 shows one of the studies performed for a taut mooring system. The trade-off between stiffness and cost is shown in both figures.

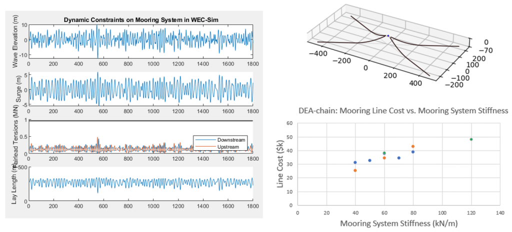

Fig. 20. A catenary-chain mooring system with 27° line headings with dynamic constraint checks in WEC-Sim (a), a perspective view of the mooring system (b), and a graphical representation of the trade-off between mooring system stiffness and mooring line cost (c).

The numerical modeling study offers crucial insights into the performance optimization and design of the FOSWEC concept, emphasizing the need for a comprehensive design approach. The study found low sensitivity of FOSWEC's performance to mooring stiffness, allowing flexibility in material and configuration selection. However, PTO stiffness significantly impacts performance, necessitating careful optimization.

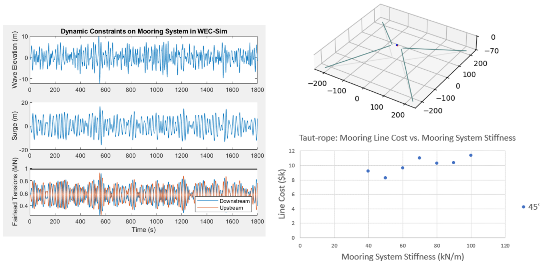

Fig. 21. A taut-rope mooring system with 45° line headings with dynamic constraint checks in WEC-Sim (a), a perspective view of a taut-rope mooring system (b), and a graphical representation of the trade-off between mooring system stiffness and mooring line cost (c).

The importance of evaluating mooring systems under extreme conditions (e.g., 50-year storm scenarios) is highlighted to ensure structural integrity and long-term survivability. The study underlines the trade-offs between mooring cost and performance.

Some limitations of this study can be iterated upon in future work. This analysis only considered material costs and omits other factors like manufacturing, installation, maintenance, and decommissioning. A comprehensive cost analysis can be included to give additional insight. This study also focused on a narrow range of sea states. Future research should assess a broader range of wave conditions. In extreme cases, models based on potential flow theory may not be robust. Simulation can also be validated with higher fidelity data or experimental results.

The TEAMER work with the University of Michigan is available through the MHKDR [12].

VII. Maiden Wave Energy

This section discusses the numerical modeling of a novel WEC being developed by Maiden Wave Energy (MWE), LLC. The MWE WEC comprises a compact array of reciprocating pods oscillating against a floating support structure. The objective of this award was to develop a modeling framework that could simulate, characterize, and assess the different configurations of a compact WEC array based on the multi-pod topology developed by MWE.

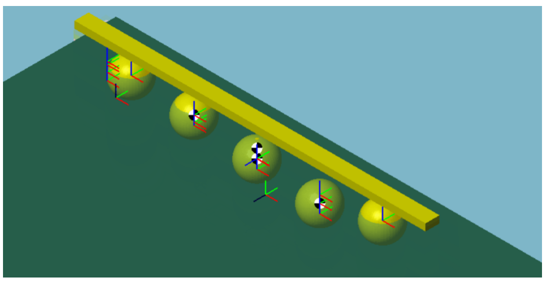

Fig. 22. An example of a five-pod configuration of the MWE device. The overarching rectangular prism represents the spine against which each pod reciprocates.

Figure 22 shows an example of one of the configurations modeled in WEC-Sim. Configurations ranging from 3 to 10 pods were simulated in waves with periods of 2–20 s.

The configuration with 10 pods was investigated in greater detail, with radii ranging from 0.4 m to 4.0 m, and the respective supporting spine ranging from 10 m to 100 m. The spine is assumed to be sufficiently large such that it does not react to pod motions. This simplification reduced the number of design variables,so that the effect of hydrodynamic couplings as a function of array compactness could be understood.

The performance of each configuration was assessed by simulating the system in a wide range of wave periods. Given the large number of configurations, new functionality to programmatically generate WEC-Sim models was developed. Additionally, a Python-wrapper was written so MWE could generate a WEC-Sim model, simulate it, and analyze the post-processed results.

The modeling workflow was automated. In a typical workflow, the user only needs to define the number of pods, their radii, and their spacing distance; the rest of the process is automated. Based on the configuration defined by the user, the pertinent mesh representation of the device is generated using the meshing tools such as pygmsh, or meshmagick, following which hydrodynamics coefficients are generated in Capytaine. These hydrodynamics coefficients are automatically transferred to MATLAB, where the programmatic model generator can then generate the pertinent WEC-Sim model. Finally, running the simulations and post-processing results is also automated, and a user could access the results—all while operating from Python.

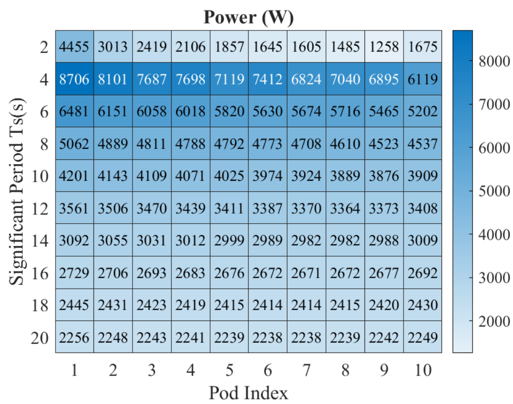

Fig. 23. A power matrix for a configuration with 10 pods each with a radius of 2.4 m, and attached to a spine of length 60 m. This heat-map distributions is showing the mean power generated by each pod (vertical columns), for wave-periods ranging from 2 s to 20 s.

There was variability in performance of each pod across the spine, e.g., in Figure 23, the water-facing pods on the leading edge (with lower pod index) generate more power than the ones on the stern of the device (with higher pod index). Figure 24 shows the total power produced by a configuration normalized by the water-surface area occupied by the configuration, i.e., the footprint of the array. Although, there is convergence in the total power for longer wave periods (> 6 s), the faster natural periods for shorter arrays result in higher power produced by shorter arrays. This is akin to the analysis by Garnaud that showed that compact arrays of smaller buoys produce higher power than an equivalent single buoy [13] with as much as 28% higher power as shown by Husain et al. [14].

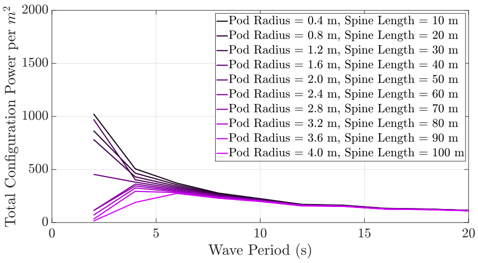

Fig. 24. Total power produced by the 10-pod configurations with different pod sizes and array lengths, normalized by the occupied surface area.

Further investigation into the PTO damping was conducted to understand the effect on dynamic response. The next steps would involve identifying the appropriate configurations for some predetermined sites, based on the corresponding joint probability distributions (JPDs), and the configurations that could be most lucrative given its dynamic characteristics. Future steps would involve identifying the hardware components of a deployable device, simulating the PTO configurations numerically, and eventually validating the numerical models against the dynamic response of physical hardware.

The TEAMER work with Maiden Wave Energy will be available through the MHKDR at a later date.

VIII. University of Massachusetts Dartmouth

This TEAMER award provided technical assistance to the development of a WEC developed at the University of Massachusetts Dartmouth (UMassD). The device is called MADWEC, which stands for maximal asymmetric drag wave energy converter. An artistic rendering is shown in Figure 25. It is a point absorber WEC designed to be low cost, low maintenance, and easily deployable. Guided by cost-saving initiatives, MADWEC uses several "off-the-shelf" parts, including a regular garage door spring, commercially available one-way clutch and electric generators, etc. The MADWEC is a variable-geometry WEC. It contains louvers that open and close with heave motion, dynamically changing the added mass. Through computational simulations, this project optimized the layout of the tethered ballast system, investigated the performance of MADWEC under linear waves, and estimated its power output. Specifically, technical assistance was provided for the following two tasks:

1) Task 1: Optimization of the tethered ballast system design to maximize the heave added mass.
2) Task 2: Building a WEC-Sim model of the MADWEC prototype and analyzing the tethered ballast and PTO performance in linear wave conditions.

Task 1 was a boundary element method study using WAMIT v7.2 [15] and focused on determining the optimal vertical spacing between a series of nested

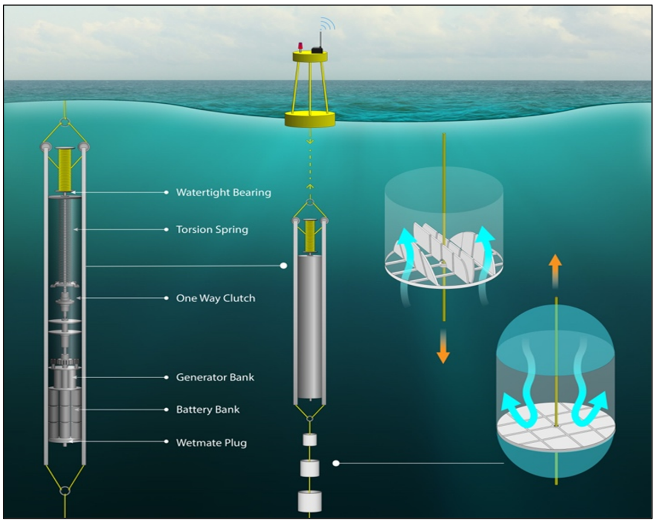

Fig. 25. Schematic rendering of MADWEC deployment (center), with action of tethered ballast component on descent (l) and ascent (r) shown to the right. Details of PTO system are shown to the left. Note that distance between the water surface and first ballast component would be approximately half of the expected dominant wavelength. Figure is used with permission of UMassD who holds its copyright.

hollow cylinders as their radii progressively decrease in order to maximize the total heave added mass of the series. To further illustrate, suppose the added mass of a single hollow cylinder is m_a. The total added of mass of two identical cylinders spaced at a very large vertical distance, L, is expected to be $2m_a$ as there is no interaction between the cylinders. As the spacing decreases, the interaction increases, and the total added mass of the pair is expected to change. UMassD and the WEC-Sim team sought an optimized spacing where the total added mass of the pair is maximized. The cylindrical ballast was represented using WAMIT's higher-order analytical method, "CIRCCYL," which can represent the open-sided cylinder here. Task 1 was broken into several iterative configurations that built off each other to inform the final ballast design. The key parameters quantified in Task 1 were the cylinder size and vertical spacing that maximizes the total heave added mass. The optimized cylinder spacing, investigated through this support, is an important parameter that has not been explored and determined before in the tethered ballast system design.

Task 1 showed that to maximize heave added mass, the cylinder height and diameter should both increase as much as possible, though the diameter has a much stronger influence. The results show that no vertical cylinder spacing creates a positive interaction (cannot increase the total added mass). All interactions between cylinders decreased the total added mass from the maximum of $2 \times m_a$. The cylinders should be spaced by at least one diameter ($L \geq D$) to obtain 95% of the system's possible added mass ($A \geq 0.95 \times A_{max}$). Nesting cylinders does not alter the trends seen with two- and three-cylinder models, but has additional benefits for operation and maintenance.

For Task 2, WEC-Sim was used to model the MADWEC and all solid body components, including the ballast, PTO, and buoy. The PTO was modeled as a bidirectional spring/mass damper system. The WEC-Sim model contains customized source code to allow for a bidirectional added mass.

The parameters measured in Task 2 include the linear stability of the device as well as its response (amplitude and period) to linear waves of various period and height. Additionally, the power output of the device was measured to guide design changes to the MAD-WEC to improve performance. This WEC-Sim modeling was the first extensive numerical simulation of the entire MADWEC system assessing its performance. These investigations will validate various aspects of the MADWEC design and identify areas where the performance can be improved.

The TEAMER work with the University of Massachusetts Dartmouth will be available through the MHKDR at a later date.

IX. Summary

Due to WEC-Sim's broad applicability for marine energy modeling, WEC-Sim support has been and remains one of the most popular types of TEAMER award. From RFTS 1 in 2020 through RFTS 9 in 2023, the Sandia and NREL WEC-Sim facility has supported seventeen TEAMER awards for numerical modeling support, or 15% of all TEAMER awards in that time. One additional award at Florida Atlantic University also utilized WEC-Sim in its analysis.

This paper provided an overview of seven of those TEAMER awards, where WEC-Sim was used to model a wide variety of WEC archetypes, including point absorbers, oscillating surge wave energy converters, attenuators, and other novel concepts. These studies vary greatly in scope, and have involved baseline model creation, geometry defeaturing and meshing with CUBIT and Rhino, boundary element method studies in Capytaine [5] and WAMIT [15], iterative geometry definition, power optimization, variable geometries, model tuning, and more.

WEC-Sim remains a critical TEAMER facility, supporting both domestic and international marine energy developers.

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