Investigating the difference between time-domain and frequency-domain modeling of a small-size two-body point absorber

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Abstract—**In this paper, we conduct a sensitivity study to investigate the difference between time-domain and frequency-domain modeling of small-sized, two-body point absorbers using the modeling software ProteusDS. Frequency domain analysis has an advantage in that it provides fast evaluations and has been used widely in this field; however, its reliance on linearized assumptions may be inadequate for smaller-sized WECs. A nonlinear, time-domain model is able to account for the nonlinear buoyancy variation and nonlinear hydrodynamics, but will increase computational complexity. To compare the fidelity of these models within this context, three float shapes of increasing complexity are evaluated in a full 6 degrees of freedom. It is important to note that the definition of the term 'smaller-size', which refers to WEC devices whose characteristic dimension is of the same magnitude as the mean wave height (around 1 meter). Devices of this size will have short natural periods and will have large wave-driven excursions when exposed to open ocean conditions, and as such will be operating in highly nonlinear conditions. These conditions are analogous to the extreme conditions that a larger-sized WEC would experience—WECs which would typically be designed to have a limited (reduced) response. Our results show that numerically modeling small-size WECs *does* require nonlinear assumptions to accurately capture the nonlinear forces acting on the WECs in large, nonlinear wave conditions the small-size WECs would typically be operating in.**

Index Terms—**Two-body Point Absorber WEC, Small-scale WECs, Numerical Modeling**

I. Introduction

RESEARCH in wave energy technology has largely focused on developing wave energy converters (WECs) to be incorporated into the larger power grid. With global wave energy potential estimated around 2 TW, utility-size WECs could generate a significant amount of energy once commercially viable [1]. One of the main challenges in implementing these technologies into grid systems is the cost. Efforts have been made to find ways to optimize these systems for grid scale, but costs remain high due to the cyclical nature of the design-build-test approach that is currently common for this industry. At a lower cost margin, investigating small-sized WECs could prove useful in emerging markets within the blue economy. Smaller-sized WECs have applications in emerging markets and can include industries that would benefit from local power generation offshore, such as desalination, aquaculture, and remote observation [2].

Mundon provides general definitions for WEC sizes that could be used to power different applications along coasts and within maritime industries [3]. Based on Mundon's definition, *utility-sized* is defined as WECs generating 100s of kW to MW of rated power. *Community-* or *facility-sized* devices have a rated power up to 100 kW. Both of these larger WECs would likely be deployed in arrays to meet energy demand. *Small-sized* WECs are delineated by a range of rated power between a few 100 W to a few kW. Mundon also distinguishes *micro* WECs, which would have a rated power below 100 W. Considering the small size of micro WECs, the devices would likely be deployed in an isolated system to power remote applications [3].

Studies on utility-size WECs typically use frequency-domain codes with linear assumptions to numerically model WECs. Frequency-domain modeling is computationally inexpensive and given the relative size of the utility-sized WEC to the incoming waves, linear wave modeling can accurately predict the performance of the WEC in operational conditions.

There are a number of different WEC archetypes being developed (i.e. [4]). For the purpose of this study a two-body point absorber will be investigated. Falnes details the theory behind this type of WEC, where energy absorption occurs due to relative motion of two bodies [5]. There is a vast range of literature surrounding the research and development of point-absorber WECs, which includes studies on single-body and two-body systems. Al Shami et al. provide an extensive review on the history of these systems [6].

Some more recent studies on two-body point absorbers have ranged in complexity. Studies like Beatty

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et al., Amiri et al., and Giassi et al. all investigate the performance of a two-body system in a heave-limited capacity when numerically modeling the WECs [7]–[9]. Both Beatty et al. and Amiri et al. compare the heave-limited numerical model with heave-limited experimental scaled modeling. Giassi et al. investigate a full six degree-of-freedom (DOF) two-body point absorber in experimental tests and compare the performance to heave-limited numerical models of a single-body and two-body point absorber [9].

Researchers Yu and Li and Xu et al. demonstrate the need for time-domain modeling of utility-size WECs due to the nonlinear effects acting on the WEC in large wave conditions. Yu and Li explore the use of Reynolds-averaged Navier-Stokes (RANS)-based computational fluid dynamic (CFD) modeling with a two-body point absorber [10]. This investigation demonstrates the significance of nonlinear effects on WECs in large waves. Xu et al. is a continuation of this RANS-based approach from Yu and Li. In this study, the authors analyze the RANS-based modeling approach to investigate the behavior of a two-body point absorber in survival conditions, as compared to experimental results [11].

Because most research to-date focuses on the design and verification of utility-size WECs, there is a need for further understanding of how to accurately model and design small-size WECs. Specifically, frequency-domain modeling may not accurately model a small-size WEC due to the increased amount of nonlinear elements required in open ocean conditions. Frequency domain models use linear assumptions to calculate the hydrodynamic coefficients and will likely not capture the nonlinear complexities needed for more accurate representation of a small-size WEC. Additionally, representing the WEC's buoyancy as linear could also lead to further modeling inaccuracies.

Due to their size, small devices will have very short natural periods and will have very large wave driven excursions when exposed to open ocean conditions, and as such will be operating in highly nonlinear conditions. These conditions are analogous to the extreme conditions that a larger-sized WEC would experience and which would typically be designed to have a limited (reduced) response. Yu and Li and Xu et al. have addressed the issue of modeling with linear assumptions for these extreme conditions [10], [11]. Rafiee and Fiévez also discuss the need for including nonlinear assumptions for the modeling of extreme conditions in their study with the CETO WEC. They note linear theory assumes a small wave amplitudes relative to the wavelength and the water depth, which also corresponds to small relative motion of rigid bodies. When looking at interactions where the shape/size of the body significantly disturbs the incoming flow, higher order interactions can occur between the bodies and the waves [12]. These interactions would not be represented with frequency-domain modeling, and the higher order terms would be left out. Penalba et al. also make note that linear assumptions in modeling can lead to overestimation in terms of power production in a nonlinear wave region where power production is still achievable [13].

Understanding the design process of WECs at different sizes will provide key information on how the systems differ from the larger scale-sizes and provide better framework on how to approach the design process for WECs of this scale. Small-size WECs could provide a range of opportunities for low-power maritime applications at low costs from the top down. The cyclical design process requires less overhead spending for prototype testing and iteration and the operation and maintenance costs of commercial technology would be lower. Many maritime applications rely heavily on diesel generation which is both expensive and has high levels of pollution even at a small scale. Switching to small-size WECs could provide a sustainable energy source at a low cost.

In this paper, we conduct a sensitivity study using ProteusDS to investigate the difference between using linear and nonlinear assumptions to model a small-sized, two body point absorber. The goal in this comparison is to better understand how to numerically model small-size WECs for typical open ocean conditions. Numerical modeling can be computationally expensive when incorporating varying levels of nonlinear assumptions. By understanding if small-scale WECs can be accurately modeled using linear modeling assumptions would be beneficial to the design process of this category of WEC-sizes. To date, there is little research on the design and numerical modeling of small-size WECs. A majority of the research conducted on small-size continues to be on scaled prototypes of utility-size devices where the numerical simulations are scaled to match the scaled experimental testing conditions.

II. Methodology

In order to investigate the differences between frequency-domain and time-domain modeling, a number of numerical simulations were conducted to understand how small-scale WECs are numerically represented by these modeling approaches. As mentioned, the device used in this study is a small-scale, two-body point absorber WEC.

The frequency-domain, boundary element method (BEM) code used in this investigation is NEMOH, which was developed by Ecole Centrale de Nantes in 2014 [14]. Much like other BEM codes used for offshore numerical modeling (i.e. WAMIT, AQUA), NEMOH is based on linear wave theory which calculates the first order wave loads. These calculations are based on the assumptions that the fluid is inviscid and the flow is irrotational, as well as the assumption that wave heights and body motion are small relative to the incident wave length.

ProteusDS (PDS) is used for the nonlinear time-domain modeling in this study [15]. This software is a commercial product developed by Dynamic Systems Analysis Ltd. in 2015. PDS models the dynamic responses of offshore structures with a semi-empirical multibody dynamic model. Hydrodynamic loading is calculated using the Morrison method from prescribed metaocean conditions. PDS has taken part of numerous code validation studies since its launch, including a code comparison study. When compared against other numerical modeling tools, the PDS demonstrated overall agreements in the numerical outputs [16].

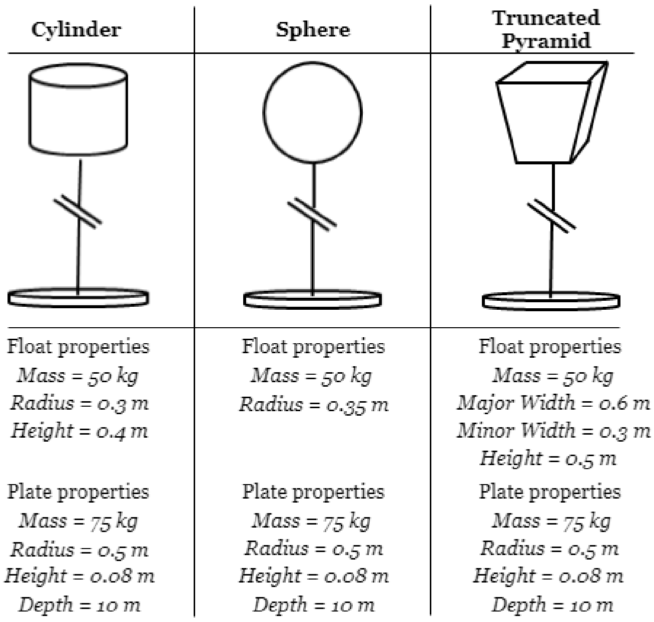


Fig. 1: Diagram of the three float shapes of the two-body point absorber analyzed in this work. Geometric and Mass parameters of both the hull and the reaction plate are included.

A. WEC Model Definitions

We simulate a range of float shapes in PDS that increase in complexity as we investigate the differences between modeling using linear and nonlinear assumptions. The complexity increases from left to right, going from the cylinder float to the truncated pyramid in Figure 1. The cylinder float is considered the baseline float-shape for this study. The cylinder has fewer nonlinear components when calculating the buoyancy due to it's constant profile submerged in the water. The sphere and truncated pyramid were chosen as more complex shapes due to the variation in their profiles as they are submerged in the water.

Based on the scale-size definitions from Mundon [3], each hull-shape is kept under 1 meter and has a mass of 50 kg. For the purpose of this study, the mass distribution for the WEC floats are uniformly distributed. The goal of this paper is to identify if nonlinear modeling assumptions should be used, so the WEC models themselves remained relatively simplistic.

The water depth for these simulations is 50 meters. Each float is connected to a reaction plate located 10 m below the float, with a linear power take off (PTO) between the two bodies. The PTO used for these models was a simple spring and damper system acting in heave (the dominate mode of motion). In the sensitivity analysis, the PTO coefficients are kept constant across the different WEC float shapes and numerical modeling configurations. The damping coefficient used is 200 $\frac{Ns}{m}$ and the stiffness coefficient is 300 $\frac{N}{m}$. These coefficients were chosen based on inital simulations run with the three different hull-shapes.

B. Numerical Model

In total, there are three different simulation setups tested in this investigation for the multiple float shapes. All three numerical setups will be simulated through PDS for modeling consistency. The different simulation setups are differentiated by the type of numerical modeling assumptions used:

- *Nonlinear simulations* - implements nonlinear modeling assumptions integrated into the PDS Software.
- *Linear simulations* - imports hydrodynamic data (coefficients & buoyancy) from NEMOH into PDS for the simulations.
- *Hybrid simulations* - imports hydrodynamic data (coefficients) from NEMOH into PDS for the simulations

The main differences between these different modeling approaches is how the hydrodynamics coefficients and buoyancies are calculated for the small-size WEC.

The first simulation setup uses PDS to model the small-scale point absorbers. For the purposes of this paper, this is our nonlinear, time-domain model. The authors acknowledge this is not a fully nonlinear CDF model, but believe the nonlinear assumptions used should be sufficient enough in early design phases when considering the computational expenses of CDF modeling. Here PDS calculates the nonlinear Froude-Krylov (FK) forcing on the hull. With nonlinear FK forcing assumptions, the effect of the dynamic pressure field is provided for the entire hull shape. This moves away from the linear FK force assumption that the wetted surface remains constant over time. By calculating the FK forces for the instantaneous wetted surface, the hydrostatic pressure field of the hull can also be updated for the changing wetted-surface of the hull. This gives the effect on nonlinear buoyancy which helps provide stability and restoring forces in the model [17]–[19].

The second numerical setup uses NEMOH generated hydrodynamic data to model the point absorbers. This model is a linear system following these general assumptions:

- higher-order terms for Bernoulli's equation are neglected
- only linear waves considered
- hydrodynamic forces are integrated over the mean wetted surface [19].

In this case, the linear FK force for the hull is calculated with the constant mean wetted surface. As mentioned previously, these linear assumptions can lead to inaccuracies with stability and restoring forces in the model [17].

The third numerical modeling setup is a hybrid approach. The linear NEMOH hydrodynamic coefficients are used in the model for the radiation and diffraction loading. PDS is used to calculate the nonlinear buoyancy and incident loading - or in other terms, the nonlinear FK forcing. Generally, the linear approach for radiation force is reasonably accurate for devices that are much smaller than the wavelength [18]. With the small-size WEC interacting with relatively large waves given the size of the device, these hydrodynamic terms calculated with the linear assumptions may result in varying responses from the other two numerical methods, even with the nonlinear FK forcing calculated by proteus for this hybrid approach.

The comparison conducted on the three simulations investigates the WEC responses based on the numerical assumptions used. For this comparison we analyze the normalized root-mean-squared (RMS) wave height against the non-dimensional RMS relative velocity for the different point-absorber geometries. The equation for the RMS wave height is as follows:

$$H_{rms} = \frac{H}{2\sqrt{2}} \tag{1}$$

where, H is the incident wave height acting on the point absorber. Because we are trying to better understand how the different modeling approaches will behave in open ocean conditions, the wave heights included in this study range from 5 cm to 1 m. For the simulations in this sensitivity study, the wave period remains constant at 4 seconds.

As the wave heights acting on the small-scale WEC increase, we should see a linear relationship between the RMS relative velocity and the RMS wave height if there are minimal nonlinear forces. The equations for finding the relative velocity and the RMS relative velocity are:

$$V_{rel,i} = V_{float,i} - V_{plate,i} \tag{2}$$

$$V_{rms} = \sqrt{mean(V_{rel,i}^2)} \tag{3}$$

where $V_{rel,i}$ is the relative velocity over the simulated time series and i represents each time step. The calculation of $V_{rel,i}$ also excludes the initial transient part of the simulation.

To analyze the WEC responses, we have calculated a non-dimensional response values, which is as follow:

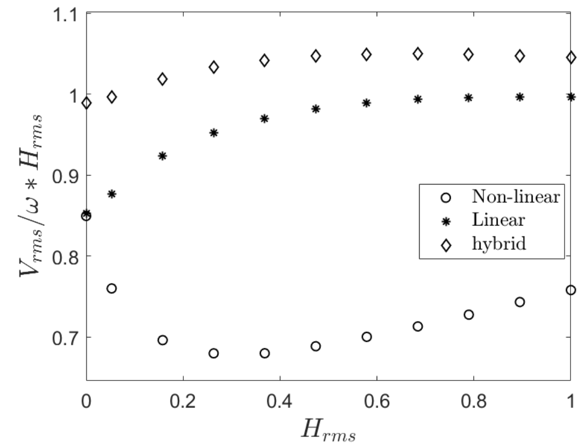
$$\frac{V_{rms}}{\omega H_{rms}} \tag{4}$$

where ω is the angular wave frequency.

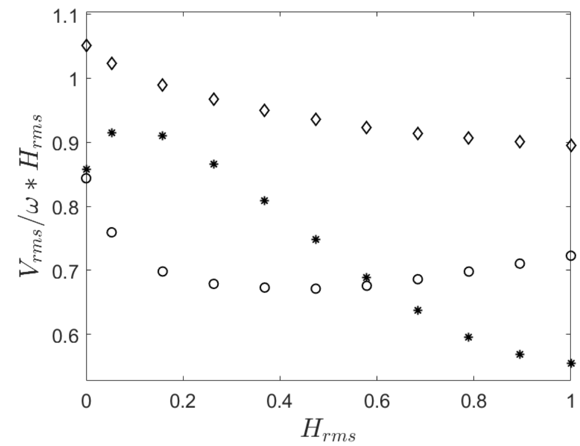
III. Results

The results of the sensitivity study on the different numerical assumptions are presented in this section. Each WEC configuration is modeled using the aforementioned nonlinear, linear, and hybrid modeling assumptions. In this study, we compare a set of non-dimensional relative velocities from the two-body WECs over a range of normalized wave heights. As the wave heights interacting with the point-absorbers increase, the WECs experience more nonlinear forces. This is due to the relative size of the WECs compared to the size of the incident waves. We should see relatively small differences in the simulated velocities for the different numerical methods in the linear wave region.

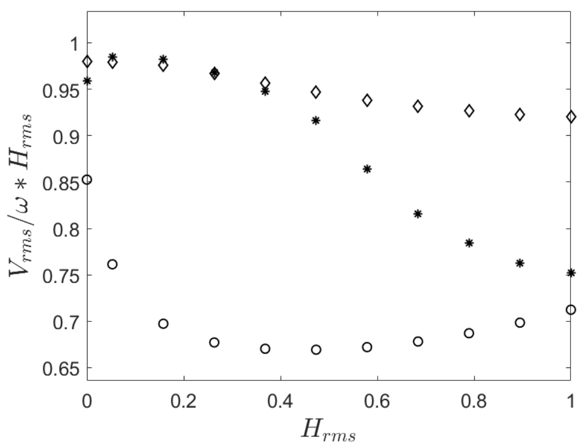
Figure 2 shows the outputs of the three WEC configurations for the different numerical setups. For all three hull shapes, the non-dimensional V_{rms} for simulations with nonlinear assumptions show relatively the same response. All three start with a value around 0.85 with the values immediately decreasing for the following values of H_{rms}. The non-dimensional V_{rms} values do start to increase again at the H_{rms} value of 0.37.



(a) Cylinder



(b) Sphere



(c) Truncated pyramid

Fig. 2: V_{RMS} of two-body point absorbers with different hull-shapes over a range of H_{rms} for different numerical modeling approaches.

The responses from the models with the hybrid and linear assumptions all vary for each hull-shape. The hybrid response in Figure 2a has the most linear response with the larger H_{rms} values. The relative error between the hybrid and the linear assumptions also decrease as the wave heights increase. However, the model using the linear assumptions does not display linear responses as the wave heights increase.

Looking more closely at the non-dimensional velocities the sphere in Figure 2b, none of the three simulations produces linear responses. For the model with linear assumptions, the non-dimensional values have a similar response with the smaller H_{rms} values. As the wave heights increase the V_{rms} starts to decrease with values even lower than the simulation using the nonlinear assumptions.

For the truncated pyramid, shown in Figure 2c, the linear and hybrid outputs have relative error under 10% up until the H_{rms} value of 0.58. Much like the output response of the sphere, the simulations with the linear assumptions start with similar outputs to the simulations with hybrid assumptions. The outputs decrease closer to the outputs of the simulations with nonlinear assumptions as the wave heights increase.

Table I displays the relative error of the smallest H_{rms} and the largest H_{rms}. Here we are setting the nonlinear modeling assumption as the baseline to compare the relative error of V_{rms} across the different normalized wave heights. For the cylinder, the relative error between both the linear numerical model and the hybrid numerical model increases with the H_{rms} value.

The relative error does not increase for the WEC configuration with the sphere float for the linear assumptions with the increased H_{rms}. As shown in Figure 2b, the relationship between V_{rms} and H_{rms} is not linear. The standard deviation for the relative error for this WEC configuration and linear numerical model is 19, which is the highest standard deviation of any configuration in this sensitivity study.

The truncated pyramid has similar relative errors for the smallest H_{rms} values for both the linear and hybrid assumptions. The relative error for the simulation with linear assumptions decreases as the H_{rms} increase. The error for the hybrid assumptions increase for the larger H_{rms} value much like the cylinder float does.

TABLE I: Relative error of V_{rms} between smallest and largest H_{rms} values

		$V_{rms}[m/s]$				
Hull	$H_{rms}[m]$	**N-lin.**	**Lin.**	$\Delta[\%]$	**Hy.**	$\Delta[\%]$
Cyl.	0.01767	0.8496	0.8530	0.40	0.9890	16.40
	0.35345	0.7581	0.9969	31.51	1.0452	37.88
Sph.	0.01767	0.8496	0.8581	1.70	1.0512	24.62
	0.35345	0.7229	0.5553	-23.18	0.8946	23.76
T. py	0.01767	0.8526	0.9593	12.51	0.9800	14.94
	0.35345	0.7124	0.7523	5.60	0.9206	29.21

Overall, the hybrid modeling approaches resulted in higher relative changes across the range of wave heights, but also produced lower standard deviations than the linear numerical models.

IV. Discussion

Small-size WECs will operate in wave fields that will subject the rigid bodies to conditions that are analogous to the extreme conditions utility-size WECs can encounter. Previous studies have shown that the extreme conditions for utility-size WECs are not accurately modeled using the linear modeling assumptions [10]–[13]. Because the small-size WECs will encounter more nonlinearities in the wave field during operational conditions due to their size, the issue of linear modeling inaccuracies carries over for these scale-sizes. As shown in Figure 2, the three modeling approaches for the different WEC configurations resulted in different non-dimensional V_{rms} values. These relative errors in V_{rms} varied depending on the float shape being simulated.

For the baseline WEC configuration (the point absorber with the cylinder float) the relationship between the normalized wave heights and non-dimensional velocity of the hybrid approach demonstrated the closest to a linear response out of the three assumptions. There is large relative error compared to the simulations using nonlinear assumptions, but that is likely due to the difference in hydrodynamic coefficients being calculated by NEMOH and PDS respectively. The simulations with the linear assumptions had relatively low error against the outputs from the hybrid approach for the cylinder float. The linear FK force calculation for this float is likely more similar to the nonlinear FK force calculation because of the constant submerged profile. There is likely less variation in the instantaneous wetted surface compared to the constant mean wetted surface of the linear model. The large relative error between the nonlinear models and the other two numerical setups should also be noted. This is likely due to the calculations of the radiation and diffraction terms based on the constant mean wetted surface of the hull for both the linear and hybrid numerical approach.

Looking at the simulations using linear assumptions for the other two hull shapes, there is more variability in outputs based on the wave height. The hydrodynamic calculations that use the linear assumptions did not maintain the linear relationship across the different wave heights as the small-size WEC experienced more nonlinear forces when using a constant wetted surface calculation. The submerged profiles for both the sphere and the truncated pyramid were not constant like the cylinder, which would lead to more Nonlinearities when taking the instantaneous wetted surface to calculate the nonlinear FK forces. Once the instantaneous wetted surface was included in the FK calculations, like for the hybrid modeling approach, the linear relationship between the V_{rsm} and H_{rms} was restored.

V. Conclusion

Numerical modeling of WECs remains and integral part of the design process for the range of WEC arctypes being developed. A majority of the research to-date has focused on utility-scale WECs and the use of linear, frequency-domain modeling. As discussed, this modeling approach with linear assumptions does not work with smaller-sized WECs. Small-scale WECs have a higher natural frequency and will interact more with higher frequency waves. Additionally, the small-sized WECs normal operation will include interaction with waves that are analogous to extreme conditions for utility-sized WECs. In this paper we investigate the numerical modeling of small-sized point-absorber WECs with different float geometries to better understand the differences between frequency-domain modeling with linear assumptions and time-domain modeling nonlinear assumptions.

Our investigation shows that it is necessary in the design of small-scale WECs to account for the non-linear forces acting on the devices. The comparison between the different modeling assumptions shows the importance of accounting for the changing orientation of the wetted surface of the hull-shape. When the linear assumptions were used, with constant wetted surface, the linear relationship between the non-dimensional V_{rms} and normalized H_{rms} did not hold up. The hybrid modeling approach did maintain a more linear relationship in the plots, but because the hydrodynamic coefficients were calculated using the constant mean wetted surface, the outputs for these models were much larger than the nonlinear approach. Further validation against experimental tests are needed to determine which assumptions are more accurate for the small-size WEC.

This research is part of a larger study to explore the design optimization of small-scale WECs. WEC geometry optimization has been recently explored for utility-sized applications, but it isn't currently clear how design variables, objective functions, and embedded modeling must change in order to optimally design smaller scale WECs. The geometry of a small-scale WEC whose objective is to maximize the response from (relatively) large, nonlinear wave conditions, will likely be quite different to conventional designs that are designed to maximize performance in small linear waves. Future work will investigate the geometry optimization of small-scale WECs.

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