Optimal Parameter Assessment of Linear PTO System for Improved Wave Energy Efficiency

K Aiswaria and Ramakrishnan Balaji

Abstract—**Developing efficient wave energy converters (WECs) tailored to their deployment sites is crucial for economically harvesting power from ocean waves. A key aspect of evaluating WEC performance is the estimation of the power take-off (PTO) parameters. Optimizing the PTO devices to perform effectively in sea states with varying wave amplitude, direction, and frequency is a major challenge. Most previous studies typically use a constant damping coefficient for power calculation across different wave conditions. This approach may lead to inconsistent device performance due to the variations in PTO damping with changing wave characteristics. The analysis of optimal parameters of the PTO system for maximum power extraction offers a foundation for efficient energy utilization.**

This study investigates how the damping coefficient influences the behaviour of a wave energy device under various regular wave conditions. It includes the numerical modelling of a heaving wave energy device with a linear PTO system and assessing the optimal damping coefficients and buoy velocity for maximum power absorption in different wave conditions. The optimum value of PTO damping at the system's natural frequency is estimated and compared to the PTO damping which results in maximum power generation. The study outlines the development of an effective PTO configuration for the wave energy converter model. The results revealed that different wave conditions notably influenced the damping coefficient. Optimal PTO damping varies linearly with wave period and minimally with wave height for the wave conditions considered. Higher damping reduced the buoy velocity with increased PTO force, resulting in more effective wave energy conversion. The study provides important insights for optimising PTO design to improve wave energy conversion efficiency.

Keywords— **Wave energy converter, Linear Power take-off system, Damping coefficient, Buoy velocity, Efficiency.**

I. INTRODUCTION

Marine renewable energy can be promising alternative to conventional renewable energy resources. Marine renewable energy includes wave energy, tidal energy, osmotic energy ocean thermal energy, and current energy, though the majority of the technologies used to harness these energy sources are still in the early stages of development [1]. There are numerous techniques for capturing wave energy, with different devices using distinct approaches to extract and convert it into usable form [2]. Bodies that move in heave and pitch utilize the water surface displacement, while pressure devices take advantage of the changes in hydrostatic and dynamic pressure beneath the waves. Surging bodies harness the energy as waves break in the surf zone, cavity resonators leverage water displacement within a column, and particle motion converters derive power from the motion of water particles [3]. These technologies can be employed individually or in combination to capture wave energy. The majority of installed wave energy projects such as Wavebob, PowerBuoy, Oyster, etc. utilize oscillating body technology, particularly the point absorber (PA) type.

The Power Take Off (PTO) is a major component that extracts the energy from the waves and converts it to usable form [4]. Past research shows that PTO units are a major contributor to the overall cost in the development of wave energy converters (WECs)and any reduction in its cost may result in a huge reduction in the total levelized Cost of Energy (LCOE) [5,6]. Since 2014, the European Commission's Science and Knowledge Service has recognized Power Take-Off systems (PTOs) as a key technological priority for wave energy extraction [7]. Enhancing and demonstrating PTO and control systems remains a significant challenge and a top priority in the design and validation of WECs [8].

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The point absorber is a device that primarily employs heave motion for energy generation, and it is favored for its benefits over other wave energy technologies. Compared to other WECs, PAs are smaller, less mechanically complex, and capable of generating energy from waves approaching from any direction [9]. In PA systems, two main electrical generator types are rotary and linear generators. Traditional rotary generators use hydraulic motors, turbines, or gearboxes to convert slow wave movements into high-speed rotational motion [10]. However, this design involves numerous moving parts, resulting in a relatively complex system that may potentially harm the marine environment through oil leaks from these components [11]. Electromagnetic-based linear generators are implemented in WECs to address this complexity involved. This type of linear generator features a simpler mechanical design, as no gearboxes or any other hydraulic or mechanical conversion systems are required [12].

To maximize the power generation there exists an optimum force that the PTO system produces. PTO damping is the resistive force generated by the PTO system to transfer mechanical power absorbed from the wave-induced motions into useful electrical energy. The PTO damping coefficient is an important metric in determining a WEC's performance since it determines the efficiency of energy extraction from ocean waves under varying wave conditions. Hence, tuning the PTO configurations is essential for improving the performance of point absorber WECs. Optimization algorithms and techniques have been used to identify the best PTO settings that optimize power output while managing device stress and minimizing energy losses [13]. Factors such as wave characteristics, design parameters of the device, and control strategies are to be considered. Most of the past research assumes a constant damping coefficient for the estimation of power performance across varying wave conditions. However, this approximation simplifies the dynamic nature of PTO damping, which varies with wave characteristics. This may result in suboptimal energy extraction and inconsistent device performance. This study aims to address this issue by optimizing PTO damping parameters in response to changing wave conditions, leading to improved efficiency and adaptability of a spherical heaving buoy-type wave energy converter.

The dynamic behaviour of the PTO system determines the applicable control strategies for the WEC, which in turn directly influences its power absorption capability. There are various types of PTO systems such as hydraulic, pneumatic, hydro, direct mechanical drive, direct electrical drive, advanced electric materials, etc based on the energy conversion mechanisms [14]. In the direct-drive systems, the mechanical power generated by buoy oscillations is directly converted into electricity without intermediate energy transformations and has 90% efficiency. Direct-driven linear PTO systems are often used in early-stage WEC modeling due to their analytical simplicity and computational efficiency, though real-world PTO systems may exhibit nonlinearity [15]. In a linear PTO system, the force applied by the PTO is linearly dependent on the velocity of the moving body [14]. The design of linear PTO systems necessitates careful consideration of factors such as the alignment of moving parts and the ability to handle the low-frequency oscillations characteristic of ocean waves.

This study explores the simulation of a linear PTO unit model unit to assess the performance of a spherical buoy under varying wave conditions. Previous studies assumed a constant PTO damping coefficient, ignoring its variability with wave conditions, which overlook the dynamic nature of PTO damping leading to inefficiencies and inconsistent device performance. The study focuses on optimizing the PTO damping parameters under varying test conditions, improving WEC efficiency and adaptability. Section II focuses on the linear modeling of a linear PTO unit. Section III delves into the numerical simulation of the WEC model for understanding the various parameters that are important in the estimation of an ideal PTO unit for the study. Section IV discusses the results obtained. Section V concludes the study.

II. NUMERICAL MODELING OF LINEAR PTO

The model used for the study consists of a spherical heaving buoy connected to the seabed or a fixed structure through the PTO unit. As heaving motion is the most volumetric efficient for small floating buoys, all the other degrees of freedom are disregarded. The model is studied under the influence of regular monochromatic waves to systematically evaluate its dynamic response and energy extraction efficiency under controlled wave conditions. Although regular waves provide an idealized scenario, they serve as a logical starting point for the investigation [16]. This approach is widely employed in early wave energy research to understand fundamental device behavior and establish baseline performance, providing a foundation for future irregular wave analysis.

Assuming the fluid is incompressible and there are no viscous losses, linear wave theory is applied to resolve the governing equations. The resulting equation for the spherical model's motion is as follows:

$$m\ddot{z} = f_z(t) + f_{PTO}(t) \tag{1}$$

where m is the mass of the body, $\ddot{z}$ is the acceleration, $f_z(t)$ is the component of the total wave force in the vertical direction, and $f_{PTO}(t)$ is the vertical component of the PTO force. The wave force consists of the excitation force ($f_E(t)$), the radiation force ($f_R(t)$) and linearized form of the hydrostatic force $f_H(t)$ and can be written as:

$$f_z(t) = f_E(t) + f_R(t) + f_H(t) \tag{2}$$

Wave excitation force refers to the hydrodynamic force exerted on a floating or submerged body due to incoming waves. The wave excitation force is proportional to the amplitude of the incident wave and is given as:

$$f_E(t) = E(\omega)\frac{H}{2}\sin\omega t \tag{3}$$

where $E(\omega)$is the excitation force coefficient which depends on the shape of the buoy and the wave frequency (ω), and H is the incident wave height. Forces arising due to body motions are termed radiation forces. It significantly impacts the dynamic response and power absorption efficiency of WECs. The radiation force consists of the added mass and radiation damping force as follows:

$$f_R(t) = -A(\omega)\ddot{z} - B(\omega)\dot{z} \tag{4}$$

The $A(\omega)$ and $B(\omega)$ are the added mass and radiation damping coefficients respectively and depend on the buoy shape and wave frequency. Both excitation force and radiation force indicate how strongly the body is coupled to the wave environment. The hydrostatic force is given by:

$$f_H(t) = -\rho g S z \tag{5}$$

where ρ is the density of water, g is the acceleration due to gravity, and S is the cross-sectional area of the buoy. PTO force is the force exerted by the PTO system and it counteracts the WEC motion. It influences the WEC dynamics by regulating its motion to efficiently extract energy. PTO force is a linear function of buoy velocity ($\dot{z}$) and can be written as:

$$f_{PTO}(t) = -C\dot{z} \tag{6}$$

where c is the damping coefficient hence (1) can be written as:

$$(m + A)\ddot{z} + (B + C)\dot{z} + (\rho g S)z = f_E(t) \tag{7}$$

The time-averaged power captured by the PTO unit ($\bar{P}$) is given by [17]:

$$(\bar{P}) = \frac{\frac{C}{2}F_E(\omega)^2}{(B + C)^2 + \left(\omega(m + A) - \left(\frac{\rho g S}{\omega}\right)\right)^2} \tag{8}$$

The optimum condition to maximize the power absorption is obtained by equating $\frac{\partial \bar{P}}{\partial C} = 0$. This condition gives:

$$C_{OPT} = \sqrt{(B)^2 + \left(\omega(m + A) - \left(\frac{\rho g S}{\omega}\right)\right)^2} \tag{9}$$

The optimum buoy velocity amplitude (U_{OPT}) to maximize the energy conversion is given by:

$$U_{OPT} = \frac{E(\omega)\frac{H}{2}}{\sqrt{(B + C_{OPT})^2 + \left(\omega(m + A) - \left(\frac{\rho g S}{\omega}\right)\right)^2}} \tag{10}$$

By combining these two optimal conditions, the optimal PTO force amplitude (f_{OPT}) can be determined, expressed as:

$$f_{OPT} = C_{OPT} \times U_{OPT} \tag{11}$$

III. Numerical investigation

The hydrodynamic coefficients of the buoy are estimated in the frequency domain using the potential flow theory tool ANSYS AQWA. It is a Boundary Element Method (BEM) based hydrodynamic simulation solver which estimates the hydrodynamic coefficients by discretizing the model geometry into fine meshes. The BEM solutions are derived by solving the Laplace equation for the velocity potential, based on the assumptions that the fluid flow is inviscid, incompressible, and irrotational.

The hydrodynamic parameters are obtained for each mesh panel, for the required frequency range which is derived by solving the radiation potential. These simulation output files are converted and saved in a standardized human-readable format that uses the Hierarchical Data Format 5 (HDF5) using the bemio code. It estimates the wave excitation and radiation damping impulse response functions (IRFs) and the state space realization coefficients that represent the IRFs.

Then simulations are performed in the time domain using the open-source software WEC-Sim (Wave Energy Converter Simulator) to estimate the power absorption and other relevant parameters [18]. WEC-Sim imports nondimensionalized hydrodynamic coefficients generated by the bemio code. WEC-Sim models wave energy devices that are either fully submerged or floating, along with constraints, mooring systems, PTO mechanisms, etc. The simulations are conducted in the time domain by solving the Cummins equation, considering six degrees of freedom. The numerical model is implemented in MATLAB, utilizing toolboxes such as SIMULINK and SimMechanics. A time-domain multi-body dynamics model of the WEC is constructed using components from the Simulink Library Browser, and simulations are performed across different wave conditions. The wave parameters are then specified either as wave height and period, wave spectrum, or as wave time series.

To ensure the accuracy of the numerical model, the heave response across various wave periods obtained from the experimental study by Li et al. 2024 [19] is compared with the results from the numerical simulations as shown in Fig. 1. The close agreement between the results verifies the proposed model's ability to predict wave-WEC interactions.

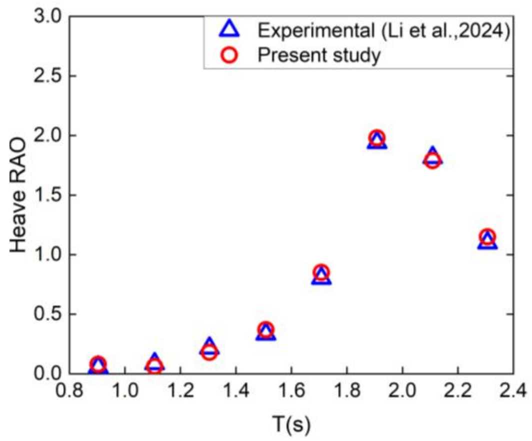

Fig. 1. Validation of the present study Liu et al., 2024

The model used for the study corresponds to the experimental model used by Aiswaria and Balaji to study the performance of a spherical model WEC in irregular waves [20]. They used a constant value of damping corresponding to the experimental value for the numerical study. The model has an outer diameter of 0.1 m, thickness of 0.01 m, mass of 0.8 kg, and draft of 0.075 m. Though small-scale experiments offer key insights, full-scale performance may vary due to Reynolds number effects, structural constraints, etc. The study is conducted to analyze the effect of diameter, wave height, and wave period on the PTO damping, buoy velocity, and the PTO force. The detailed model description is given in TABLE I. The heave response and optimal power extraction of a spherical WEC depend on the wave period, wave amplitude, etc., hence it is vital to optimise the buoy design for the individual sea conditions [21,22]. Hence, the study examines the effect of different wave characteristics on the power performance of the model, which aids in optimising PTO parameters for enhanced energy efficiency.

TABLE I
DESCRIPTION OF THE MODEL

Diameter (m)		0.1	0.15	0.2
Mass (Kg)		0.358	0.74	1.248
Natural frequency (s)		12.26	12.13	12.14
Radiation damping at ω_n (Ns/m)		0.982	2.501	4.283
C_{OPT} (Ns/m)	Theoretical	1.05	2.8	4.47
	Graph	1.05	2.8	4.47

IV. RESULTS AND DISCUSSIONS

(a) Effect of Diameter

To study the influence of the diameter on the optimum values of PTO parameters, the model diameter is varied. Three model diameters of 0.1 m, 0.15 m, and 0.2 m are used. All the models are subjected to a wave height of 0.1 m and a wave period equal to its natural period. The added mass and radiation damping of all three models in heave is shown in Fig. 2 and Fig. 3 respectively. The added mass has a maximum value at the initial frequency of zero rad/s and then decreases and gradually approaches its infinite frequency value. As the diameter increases the added mass value also increases as expected. A larger diameter displaces more water, resulting in an increase in the added mass. The radiation damping increases from a minimum value and then attains a maximum value at the natural frequencies of each model and then again decreases. Similar to added mass, as the diameter increases the radiation damping also increases. As the diameter increases, the water surface area also increases, which generates more waves due to the oscillation of the model when subjected to incident waves. This increases the radiation damping value as more energy is dissipated through the radiated waves.

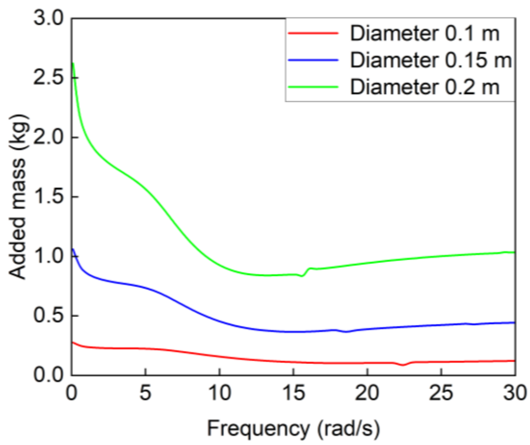

Fig. 2. Heave added mass coefficient of the models of different diameters

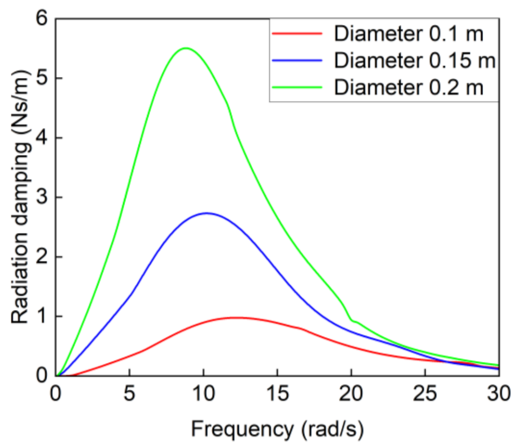

Fig. 3. Heave radiation damping coefficient of the models of different diameters

The power absorbed per squared wave height for various PTO damping values for different diameters is shown in Fig. 4. The maximum power is obtained at a damping value that is the same as the theoretical optimum value for all the diameters. The optimum value and the power performance increase as the diameter increases. As the diameter increases, the water plane area interacting with the waves increases, which may increase the excitation forces. This might result in higher power absorption but also demands higher PTO damping to maintain efficiency and prevent overloading the PTO system. A larger diameter model displaces more water and has a higher added mass which in turn increases the inertia of the system. Thus, the model may require a higher damping force to regulate the motion. Larger buoys may also radiate more waves while oscillating which leads to the requirement of higher PTO damping value for balancing this effect and enhancing power absorption. Large diameters may also increase the viscous drag which increases the total damping.

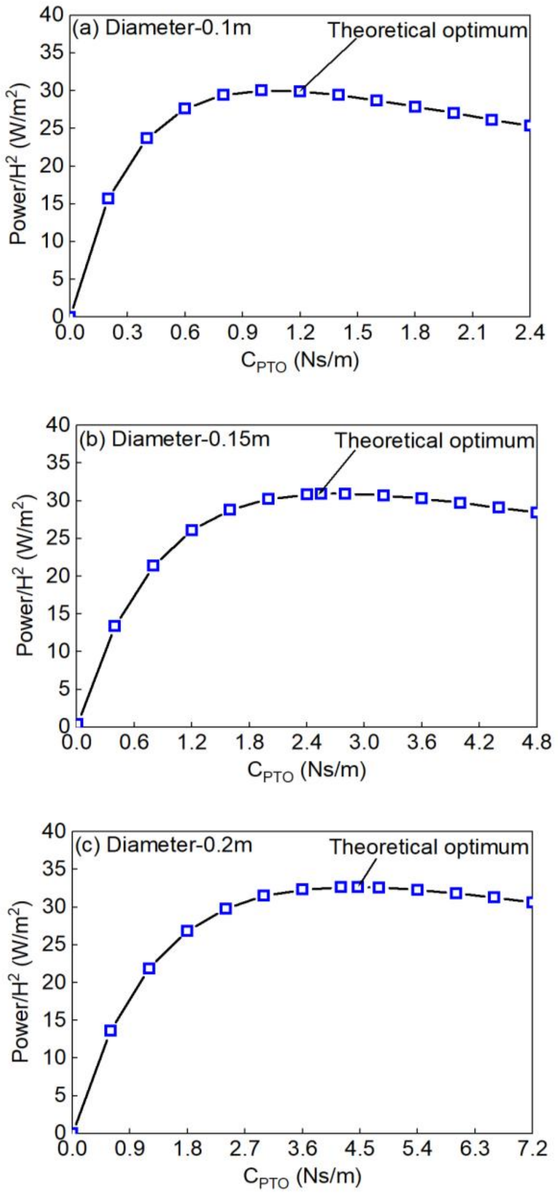

Fig. 4. Power absorbed per squared wave height with PTO damping

The variation of buoy velocity with the PTO damping values is shown in Fig. 5. The velocity has a decreasing pattern for all the diameters. The values increase as the diameter increases. Higher values of PTO damping apply a stronger opposing force to the buoy's motion, limiting its oscillation and thereby reducing velocity. A larger buoy interacts with a larger amount of the wave, which results in stronger excitation forces and higher oscillation amplitudes and velocities.

The variation of PTO force with the PTO damping values is shown in Fig. 6. The force has an increasing trend for all the diameters. The values increase as the diameter increases as higher forces typically call for higher damping values to optimize energy absorption. As the diameter of the WEC increases, the PTO force also increases due to greater interaction with the waves, higher wave excitation forces, and stronger restoring forces.

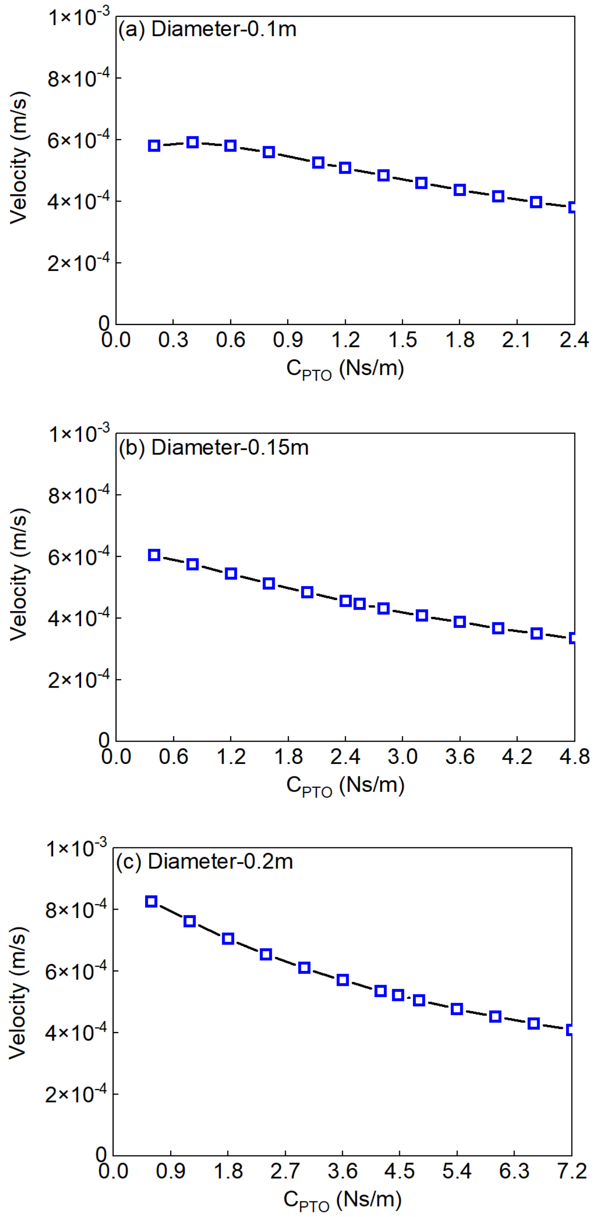

Fig. 5. The variation of velocity with PTO damping

(b) *Effect of Wave height*

The effect of wave height is studied on the model of 0.15 m diameter subjected to a wave period of 0.52 s corresponding to its natural period. Three wave heights of 0.08 m, 0.1 m, and 0.12 m are considered. The power absorbed for various wave heights considered is shown in Fig. 7. which shows that with increasing wave height the power absorbed also rises. As the energy carried by ocean waves is proportional to the square of the wave height, larger waves contain significantly more energy and have a higher potential for energy extraction. Also, larger wave height leads to stronger excitation forces acting on the buoy, causing greater oscillation amplitudes and enhancing power absorption. Hence, WECs exposed to higher waves can capture and convert more energy into useful power which may increase the power output, given the WEC is designed to handle such conditions.

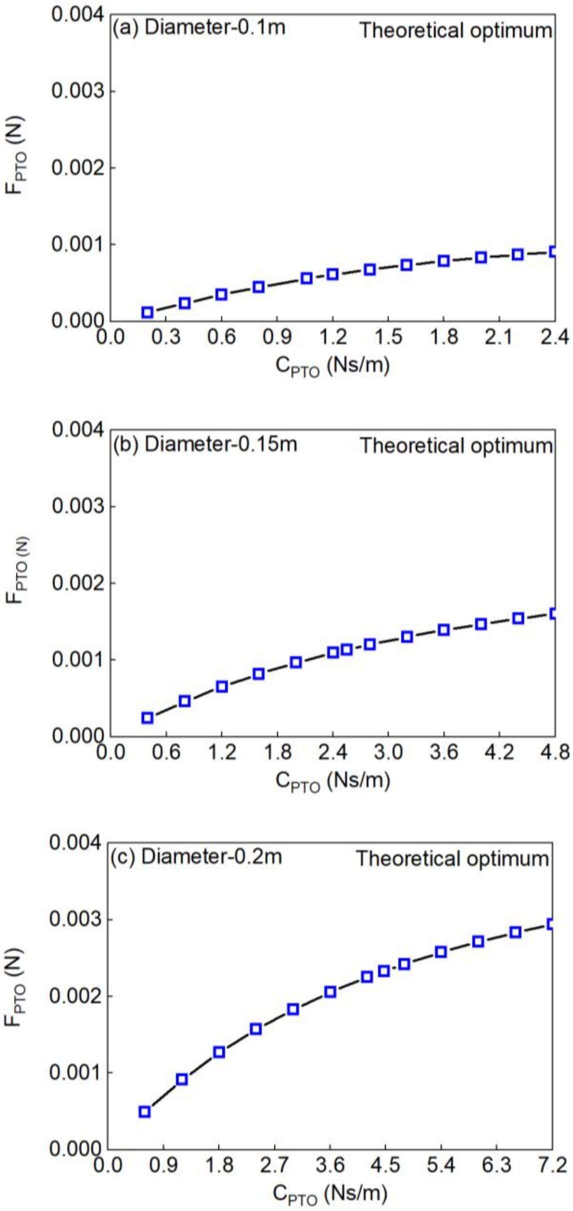

Fig. 6. The variation of PTO force with PTO damping

The power absorbed per squared wave height with various PTO damping for all the considered wave heights is shown in Fig. 8. The variation shows that the power absorbed, when normalized by the square of the wave height, remains constant across different wave heights. As the wave energy is proportional to the square of the wave height, the power absorbed may also have the same variation [3]. Hence dividing the power by H^2 results in a constant value. This indicates that the efficiency of PTO in converting wave energy is consistent across different wave heights.

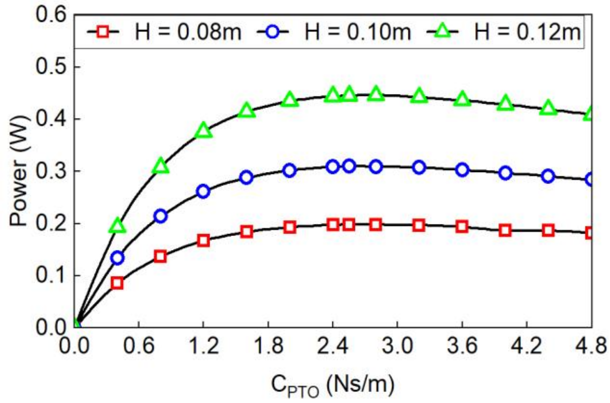

Fig. 7. The power absorbed with PTO damping for different wave heights.

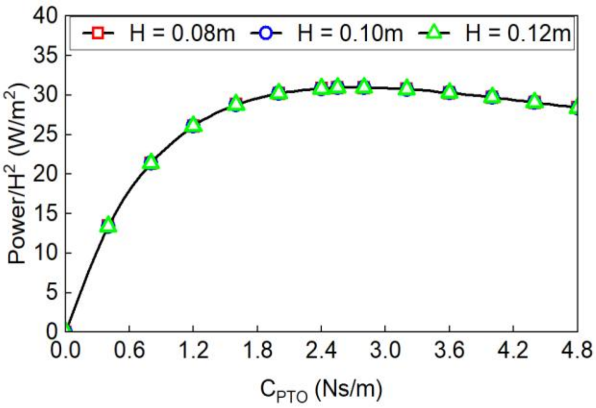

Fig. 8. The power absorbed per squared wave height with PTO damping for different wave heights.

The variation of velocity and PTO force with the PTO damping for various wave heights considered is shown in Fig. 9. And Fig. 10. respectively. The buoy velocity is higher at higher wave height to absorb more power PTO force also increases with the wave height. The buoy experiences a larger external force as the wave height increases, resulting in a higher velocity and a greater amplitude of oscillation. The buoy velocity has a decreasing trend, and the PTO force increases with an increase in the damping values similar to that of the varying diameter case.

(c) Effect of Wave period

The effect of wave period is also studied on the model of 0.15 m diameter subjected to a wave period of 0.1 m Three wave periods of 0.4 s, 0.512 s, and 0.6 s are considered, 0.512 s being the natural period of the model. The power absorbed per squared wave height for various wave periods considered is shown in Fig. 11. As the wave period increases, the power absorbed also increases.

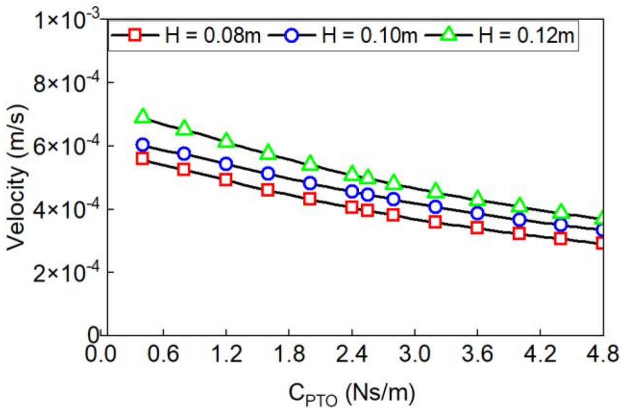

Fig. 9. The variation of velocity with PTO damping for different wave heights.

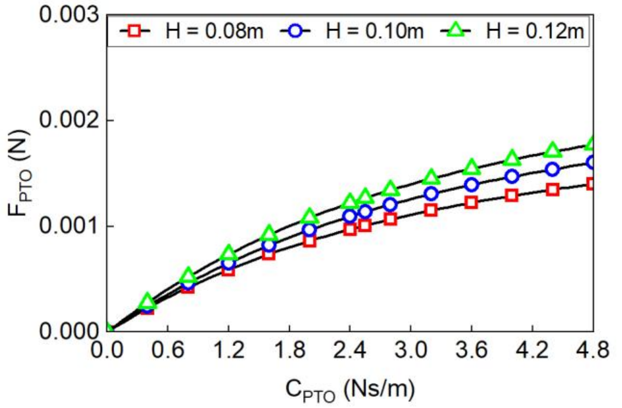

Fig. 10. The variation of PTO force with PTO damping for different wave heights.

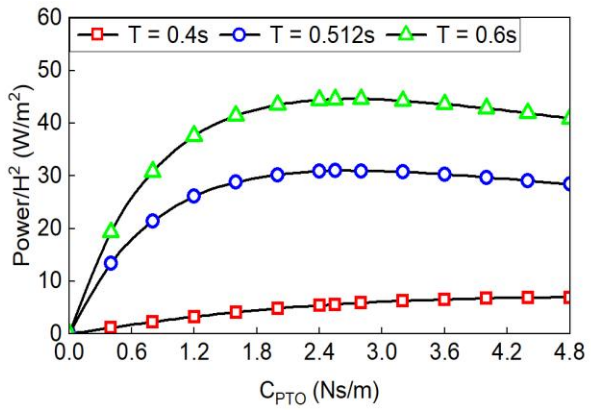

Fig. 11. The power absorbed per squared wave height with PTO damping for different wave periods.

Floating point absorbers are typically designed to absorb maximum power at resonance [23]. Hence maximum power absorption is expected at 0.512 s. But here the maximum power is captured at 0.6 s. This may be because as longer wave periods tend to carry more energy leading to more energy capture [3]. The wave WEC interaction may increase at higher wavelength resulting in greater performance of the WEC. The study must be extended considering more wave periods to analyze its performance.

The variation of buoy velocity and PTO force with PTO damping for various wave periods considered is shown in Fig. 12. and Fig. 13. respectively. Higher velocity and PTO force are obtained at the resonant period. More studies are to be conducted to assess the performance of the model in the resonance frequency range and beyond. For all the cases the optimum value of PTO damping was found to be a constant for the shape considered. Hence studies are to be done to analyze the effect of the shape of the model in the power performance as well as in the value of optimum damping.

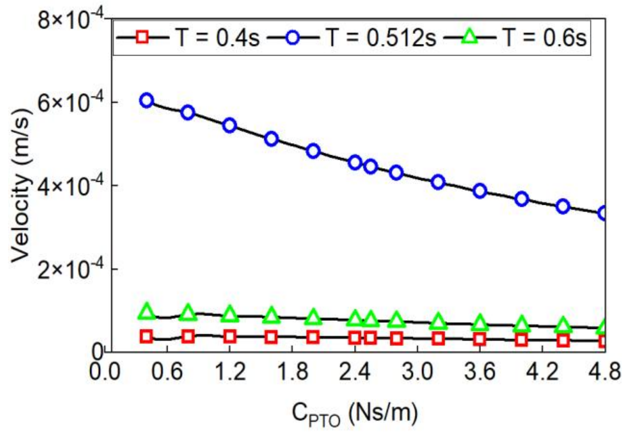

Fig. 12. The variation of velocity with PTO damping values for different wave periods.

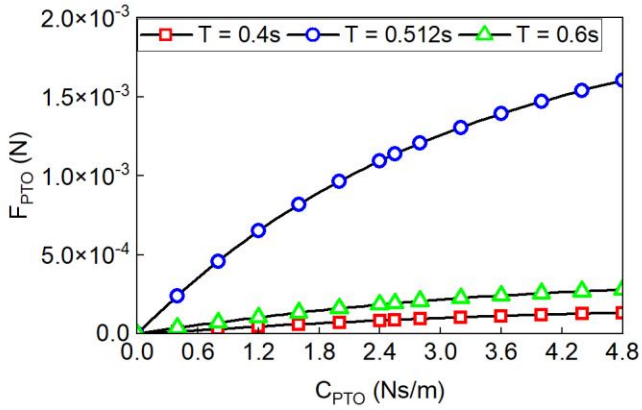

Fig. 13. Variation of PTO force with PTO damping for different wave periods.

The results indicate that wave conditions substantially affect the ideal PTO damping coefficient, which varies linearly with wave period and has negligible reliance on wave height. As damping increases, buoy velocity drops, yet PTO force increases. These findings aid in the optimisation of PTO system design by determining ideal parameters that maximise energy extraction efficiency in wave energy converters.

V. CONCLUSION

The study investigated the numerical modeling of a heaving wave energy converter with a linear PTO system, focusing on determining the optimal damping coefficients and buoy velocity for maximum power absorption under varying wave conditions. The theoretical optimum PTO damping at the system's natural frequency was estimated and compared to the damping that yields the highest power generation after varying the damping values. The theoretical optimum values have a good agreement with the value that yields the highest power.

The findings show that different wave conditions have a significant impact on the optimal damping coefficient. The optimal damping of the PTO unit is linearly related to the wave period and showed only minor variations in the wave height. The buoy velocity showed a decreasing trend with damping values and the PTO force showed an increasing trend.

The results of the study aid in optimizing PTO system design and operation in wave energy devices by identifying optimal PTO parameters for maximum energy efficiency. By understanding how these parameters influence energy extraction under varying wave conditions, the findings support the development of adaptive PTO control strategies, enhancing performance. This insight can guide the designs toward more effective and responsive PTO systems, boosting overall reliability and power production.

The study presented a time-domain analysis of a spherical buoy oscillating in heave with a linear PTO unit in regular monochromatic waves. While real sea waves are not monochromatic, and this simplification may not fully capture their complexities, analyzing WEC devices in controlled conditions provides valuable insights into their operation before testing them in realistic wave environments. More studies are to be conducted to analyze the performance of the model outside the resonant frequency range to have a more comprehensive understanding of its performance. Extending the analysis to irregular waves will enhance the real-world applicability of the findings. Incorporating nonlinear PTO dynamics can improve the model's accuracy and broaden its applicability to real-world wave energy conversion.

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