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Analysis and Optimization of Point Absorber Wave Energy System Buoys Using Ansys

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Abstract

In this study, the hydrodynamic performance of four different point absorber buoy geometries, designed to harness energy from the vertical motion of waves, was analyzed using Ansys AQWA software. The analyses were conducted based on the average wave data of the Black Sea, and key hydrodynamic parameters, including Response Amplitude Operator (RAO), added mass, radiation damping, and excitation force, were evaluated. The results indicate that the P4 buoy geometry exhibits peak RAO values within the dominant wave frequency range of the Black Sea (0.5–0.7 rad/s), demonstrating superior energy absorption performance. In the same frequency range, the added mass values for P4 remained within 40–45 kg, contributing to enhanced energy efficiency. The radiation damping coefficient for P4 was found to range between 20–25 N/s, and its stability was attributed to the presence of a submerged mass and a center of gravity positioned near the ballast. Moreover, the excitation force for the P4 buoy reached the highest value among all geometries, with approximately 1900 N/m in the 0.5–0.7 rad/s frequency range. These findings highlight the P4 buoy as the most efficient and hydrodynamically favorable design for wave energy conversion under Black Sea conditions.

1. Introduction

Rapid development in the global economy and industry has significantly increased the demand for energy, and this demand is expected to continue to grow in the coming decades. According to the International Energy Agency [1], global energy demand increased by 2.2% in 2024, exceeding the annual average of 1.3% observed between 2013 and 2023, largely due to extreme weather conditions and the expanding use of electric vehicles. Furthermore, electricity generation, which currently accounts for over 40% of total energy consumption, is projected to grow substantially. It is estimated that electricity's share of total final energy consumption will rise from 23% in 2023 to 52% by 2050 under the 1.5°C scenario, emphasizing its increasing importance in the global energy mix [2].

The fact that traditional energy sources such as fossil fuels are gradually decreasing cannot be ignored. Environmental climate changes and high CO_2 levels are directing global attention to renewable and clean energy sources. Recent studies emphasize that fossil fuel use remains the primary contributor to anthropogenic greenhouse gas emissions, prompting an accelerated global transition to renewable energy alternatives [3]. In recent years, great efforts have been made to develop alternative energy sources such as solar, wind, and nuclear energy. However, wave energy has increasingly attracted attention due to its high energy density and predictability compared to other renewables [4].

The concept of harnessing wave energy has historical roots. China used ocean and sea wave energy to run mills in the 13th century, one of the earliest examples. Girard in France made the first theoretical application of this energy in 1799. One of the first important steps in this field was a wave-powered navigation buoy developed by Yoshio Masuda. This buoy also contained a turbine mechanism and later became known as the "oscillating water column." Due to the oil crisis in the late 1970s, researchers and universities accelerated their work on wave energy technology. In this period of rising oil prices, scientists such as Stephen Salter and American Michael E. McCormick pioneered wave

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energy technology [5].

Many Wave Energy Converters (WEC) have been developed by various organizations and companies to extract energy from ocean waves. The European Marine Energy Center (EMEC) has classified these systems into eight different types of WECs. These devices, designed to extract energy from both coastlines and offshore, utilize various energy conversion systems [6-7].

WECs are designed to harness energy from waves approaching from various directions, typically by employing symmetrical structures. Two common types of WECs are point absorbers and oscillating wave surge converters. Due to their geometric symmetry, these devices do not require reorientation toward the incoming wave direction [8]. Point absorbers tend to perform better in regions with shorter waves and longer periods, while oscillating devices based on pressure differentials are more effective in environments with higher wave heights and longer wave periods [9].

Point absorbers are axisymmetric oscillating systems that extract energy from the vertical motion of the water surface. Physically, these systems are relatively small compared to the incoming wavelength (λ), and they typically operate within a narrow frequency band. However, their natural frequency often does not align with the dominant frequency of sea states [8]. For optimal performance, it is critical to tune the natural frequency of the buoy to match the wave frequency, enabling resonance conditions in which the system achieves maximum motion and energy absorption [10].

Accurate sizing and design of WECs significantly enhance energy conversion efficiency and reduce the need for complex control systems. Consequently, many studies have focused on optimizing the geometry and dimensions of floating structures to maximize power capture [11]. In this study, the hydrodynamic analysis software Ansys AQWA, which is widely applied in marine and offshore engineering, is used to evaluate the performance of various buoy geometries and identify the configuration offering the highest energy efficiency.

2. Material and methods

To optimize the interaction of floating platforms, especially wave-powered buoys, with the waves to ensure maximum power absorption, there are three main criteria to be considered. First, the diameter of the floating buoy should be proportional to the wavelength of the incoming waves. Such an arrangement allows the buoy to interact more effectively with the wave and control its motion, resulting in increased efficiency [12-14]. Secondly, the natural frequency of the floating buoy should be compatible with the frequency of the incoming waves. Such an arrangement is necessary to maximize power generation in the resonance region. Resonance allows the buoy to absorb more energy by traveling at the same frequency as the wave [15-17]. Thirdly, the draft of the floating buoy should match the wavelength of the incident waves. This step is important to increase the efficiency of the buoy [18-20]. These criteria imply that the geometry and physical properties of the buoy should be optimized to maximize power absorption by allowing it to interact more effectively with the waves. The optimization process involves making the necessary adjustments to the design and configuration of the buoy, taking these criteria into account. Therefore, Figure 1 provides a flowchart to better understand the optimization process. This approach will enhance the effectiveness of analysis planning.

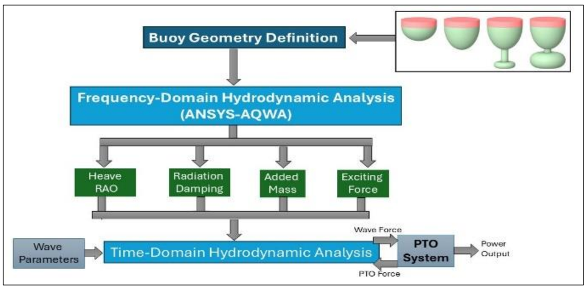

Figure 1: Flowchart of a buoy dynamic model.

In this study, the WEC system operates based on energy conversion from the vertical motion of waves, specifically the heave movement. Therefore, optimal performance requires the buoy's natural heave frequency to be closely aligned with the wave's heave frequency. In this context, four different buoy designs, coded as P1, P2, P3, and P4, were developed at a 1:4 scale and modeled in 3D using Ansys SpaceClaim. While all buoys share identical beam and freeboard dimensions, variations in draft and the addition of different masses affecting sway were introduced to alter their centers of gravity and buoyancy. This approach aims to identify the buoy design that provides the most efficient response to wave frequencies. In the optimization process of the draft value, the focus was placed on parameters such as the center of gravity and center of buoyancy, which directly affect the stability of the buoy. The study tested whether the T2 draft value of the P2 geometry, designed with a higher draft than the T1 draft value of the P1 geometry, would provide a more consistent and stable hydrodynamic response to the selected wave loads. Following the draft optimization, the design process focused on enhancing the buoy's resistance to capsizing under extreme wave conditions through the addition of a keel structure. In this stage, P3 and P4 geometries were modified by adding a keel to improve the righting arm and center of gravity effects. Specifically, in the P4 design, the keel volume and configuration were expanded to investigate the potential for reducing the buoy's roll and pitch motions. In this study, no numerical optimization algorithms such as genetic algorithms or particle swarm optimization were utilized; instead, a parametric variation approach was adopted. In this approach, design parameters were manually adjusted, and key hydrodynamic parameters such as the Response Amplitude Operator (RAO), added mass, radiation damping, and exciting force response were thoroughly examined for each variant. This methodology aimed to identify the potential of the designs to adapt to the Black Sea conditions and to exhibit motion responses close to the targeted resonance conditions. The 3D visualizations of the buoy designs are presented in Figure 2.

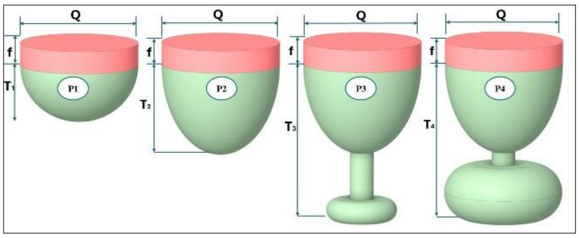

Figure 1. Three-dimensional models of the four buoy geometries used in the analysis.

Ansys AQWA is based on the linear potential flow theory and uses the Boundary Element Method (BEM) to solve for hydrodynamic interactions. The RAO is calculated as the ratio of the buoy's response amplitude to the incident wave amplitude, expressed as:

$$RAO(\omega) = \frac{|\eta(\omega)|}{|\varsigma(\omega)|}$$

Where $\eta(\omega)$ is the buoy's motion amplitude and $\varsigma(\omega)$ is the wave amplitude at a given frequency $\varsigma(\omega)$. The added mass and radiation damping coefficients are derived from the real and imaginary parts of the frequency-domain hydrodynamic coefficient matrix, respectively. These coefficients represent the inertial and dissipative effects of the fluid on the buoy's motion.

Before conducting hydrodynamic analyses, it is essential to define the structural boundary conditions and physical parameters of all designed buoys. While certain physical parameters, such as beam and freeboard, were kept constant across all designs, variations were introduced in the weight and center of gravity. These values were determined as presented in Table 1.

Table 1. Physical Parameters of the Buoys

Structural Properties of Buoys		**P1**	**P2**	**P3**	**P4**	**Unit**
Diameter	Q	0.5				m
Draft	T	0.25	0.40	0.70	0.70	m
Freeboard	f	0.10	0.10	0.10	0.10	m
Displacement Volume	∇	0.033	0.052	0.060	0.09	m^3
Displacement Tonnage	Δ	33.52	53.61	61.60	94.81	kg
Center of Buoyancy	CoB	-0.094	-0.150	-0.210	-0.33	m
Material Density	% 60 PVC Foam %40 Composite Resin	PVC Foam :80 Resin : 1140				kg/m^3
Mass	$M_{1,2,3,4}$	6.11	7.04	8.59	12.25	kg
Center of Gravity	CoG	0.076	0.023	-0.087	-0.18	m
Moment of Inertia	Ixx	0.35	0.51	1.03	1.60	$kg{\cdot}m^2$
	Iyy	0.35	0.51	1.03	1.60	$kg{\cdot}m^2$
	Izz	0.25	0.30	0.32	0.49	$kg{\cdot}m^2$
Structural Properties of the Keel Addes Mass						
Mass Density	p	11340				kg/m^3
Mass	$M_{S1,S2,S3,S4}$	22.41	41.57	48.01	77.56	kg
Center of Gravity	G	-0.225	-0.35	-0.65	-0.61	m
Moment of Inertia	Ixx	0.08	0.17	0.20	0.45	$kg{\cdot}m^2$
	Iyy	0.08	0.17	0.20	0.45	$kg{\cdot}m^2$
	Izz	0.15	0.28	0.32	0.52	$kg{\cdot}m^2$

The hydrodynamic behavior of a buoy varies depending on its shape. Therefore, conducting hydrodynamic analyses on buoys is essential for determining their potential to capture wave energy. However, comprehensive studies in this area remain limited. To simulate surface forces, the Ansys AQWA software was utilized. By analyzing the surface forces acting on four different buoy geometries, their theoretical performance under Black Sea wave conditions was evaluated.

Since the designed buoys generally feature curved surfaces and relatively simple geometries, a tetrahedral mesh type was selected for the analysis of all four geometries. Tetrahedral meshing is considered the most suitable method for less complex structures with predominantly curved surfaces [21]. The element size was set to 0.02 mm. Although reducing the element size below 0.02 mm did not significantly affect the results, it led to a considerable increase in computational time. Therefore, a 0.02 mm element size was chosen to optimize computational efficiency.

The number of mesh elements for the P1, P2, P3, and P4 buoys were calculated as 17,974; 25,125; 29,969; and 35,777, respectively. The mesh structures of the buoys are illustrated in Figure 3.

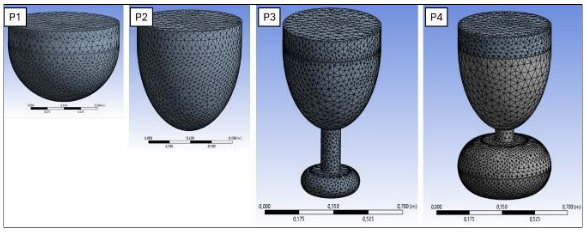

Figure 2. Mesh Structures of P1, P2, P3, and P4 Buoys.

Following the completion of the dimensional design of the buoy geometries, the next step involves defining the input parameters required for the hydrodynamic analysis. According to Aydoğan et al. [22], the wave energy potential of the Black Sea was investigated using wind data obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period between 1996 and 2009, resulting in the creation of a wave atlas for the region. Based on this dataset, wave parameter distributions were updated and scaled down to a 1:4 model scale for use in the present analysis. These updated wave parameter densities are illustrated in Figure 4.

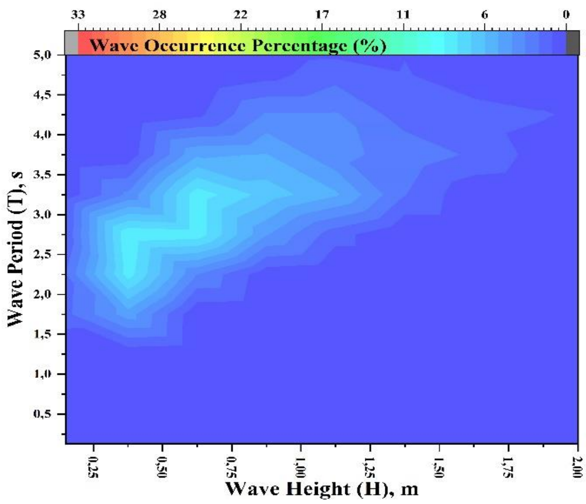

Figure 3. Wave Energy Density Parameter of the Black Sea Region.

According to the wave parameters presented in Figure 4, the conditions with the highest energy density were selected and scaled for the 1:4 buoy models. These values were reduced to numerical inputs suitable for analysis, covering 12 different wave conditions, as presented in Table 2. Figure 5 displays the Ansys AQWA interface along with the visual representations of the buoys under analysis. In these simulations, a water depth of 50 meters was assumed. Additionally, waves were considered linear and propagating perpendicularly to the coastal shoreline.

Table 2. Wave Parameters Used in the Analysis

Sea State	Wave Period T (s)	Wave Frequency w (rad/s)	Wave Height H (m)	Wavelength Lo (m)
1	0,75	1,33	0,125	0,88
2	0,75	1,33	0,250	0,88
3	1,00	1,00	0,375	1,56
4	1,00	1,00	0,125	1,56
5	1,25	0,80	0,250	2,44
6	1,25	0,80	0,375	2,44
7	1,50	0,66	0,125	3,51
8	1,50	0,66	0,250	3,51
9	1,75	0,57	0,375	4,78
10	1,75	0,57	0,125	6,28
11	2,00	0,50	0,250	7,90
12	2,25	0,50	0,375	9,76

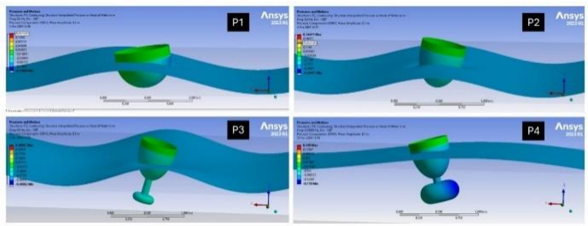

Figure 4. Screenshots of Ansys AQWA simulations for different buoy designs.

3. Results and Discussion

Buoy optimization and design in wave energy systems require accurately modeling the interaction between the buoy and incoming waves to achieve maximum efficiency. In this context, several key hydrodynamic parameters must be considered. In the present study, hydrodynamic parameters of a heaving-type WEC buoy that operates most efficiently under wave conditions characteristic of the Black Sea were calculated and optimized using Ansys AQWA. One of the primary hydrodynamic parameters examined for the four designed buoys is the heave Response Amplitude

Operator (RAO). RAO represents the ratio of the buoy's response amplitude to the amplitude of the incident wave. This parameter is essential for understanding the structure's behavior under wave excitation and plays a crucial role in maximizing energy efficiency during the design process. Figure 6 presents the heave RAO values of the four buoy designs, scaled at 1:4, under Black Sea wave frequencies. Upon comparing the scaled results, it is observed that the RAO curve of the P4 geometry peaks within the frequency range of 0.5 to 0.7 rad/s, which aligns closely with the most dominant wave frequencies in the Black Sea region.

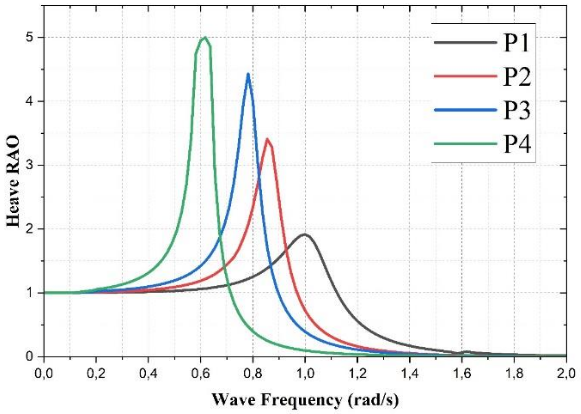

Figure 5. Heave RAO Responses of the Buoys.

Another key parameter in the hydrodynamic analysis of buoys is the added mass. Added mass represents the effective mass of the water surrounding the buoy that resists its motion during wave-induced movement. This hydrodynamic parameter plays a critical role in determining the dynamic response of the buoy, as it contributes to the resistance against motion and must be considered to accurately model the effects of wave action on the structure. In dynamic analyses under wave loading, added mass is particularly important. Studies have shown that buoys with higher added mass coefficients tend to have greater potential to absorb energy from ocean waves compared to those with lower coefficients [15]. Therefore, buoy designs that yield higher added mass values within the most dominant wave frequency ranges are expected to be more energy efficient. Figure 7 presents the added mass curves of the buoys under wave frequency values scaled for the Black Sea region. The dominant wave frequencies in the Black Sea are observed to lie between 0.5 and 1.33 rad/s. The P4 buoy has the highest added mass values and the least decreasing trend in this frequency range. This indicates that it has the best chance of getting energy from waves that are oscillating vertically.

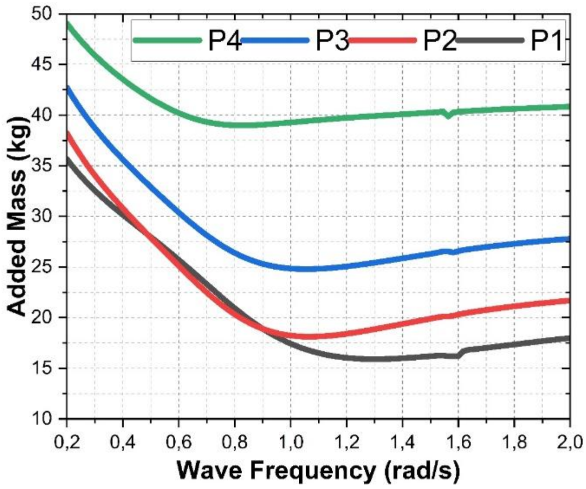

Figure 6. Hydrodynamic Added Mass Responses of the Buoy Designs.

When a buoy moves in response to waves, it transfers energy to the surrounding water, generating new waves on the surface. These newly generated waves, in turn, exert a reactive force on the buoy, creating resistance to its motion. This resistance results in the damping of the buoy's movement, causing it to lose part of its energy. The design of a heaving-type WEC system must consider several critical aspects related to radiation damping. The shape of the buoy directly influences the propagation characteristics of radiated waves and the corresponding damping coefficient. Buoys with broader surface areas typically exhibit higher radiation damping. Therefore, the buoy's dimensions should be optimized relative to the incident wavelength. A buoy that is well-matched to the wave characteristics can help minimize radiation damping and reduce energy losses. Furthermore, the radiation damping coefficient should be compatible with the dominant wave frequency range of the intended deployment region. Figure 8 presents the radiation damping values of the four buoy designs under the scaled Black Sea wave frequency conditions. Although all buoys have the same diameter, differences in draft and center of gravity resulted in varying radiation damping responses. Being heavier and having a lower center of gravity than the other designs, the P4 design was better at resisting radiation damping and kept its performance more stable when waves were excited.

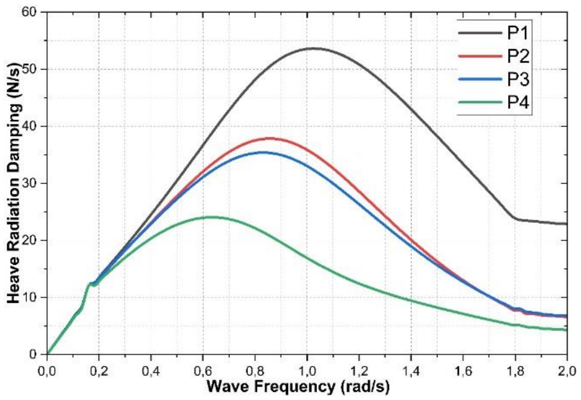

Figure 7. Hydrodynamic Radiation Damping Responses of the Buoy Designs.

Another critical parameter in the hydrodynamic analysis of buoys is the exciting force. This force refers to the pressures and loads exerted by wave motion on the surface of the buoy. In wave energy converters (WECs) that convert heave motion into mechanical energy, the pressure forces acting on the lower surface and surrounding areas of the buoy are particularly important. Higher exciting force values generally result in greater buoy motion. Furthermore, the effect of exciting forces amplifies when the wave frequency aligns with the buoy's natural frequency. Under such resonance conditions, the energy conversion efficiency of the buoy reaches its maximum. Figure 9 illustrates the exciting force values obtained for the four buoy designs across selected wave frequency values. Among them, the P4 buoy demonstrated the highest exciting force values within the dominant wave frequency range observed in the Black Sea.

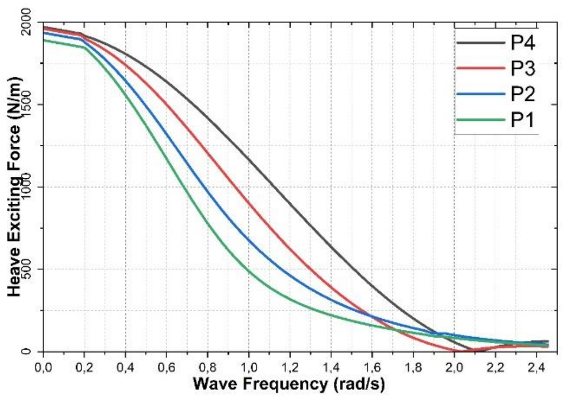

Figure 8. Hydrodynamic Exciting Force Responses of the Buoy Designs

4. Conclusion and Suggestions

This study designed four different buoy geometries for use in heaving-type wave energy converters (WECs) suitable for the Black Sea region. The hydrodynamic analyses of the designed buoys were conducted using Ansys AQWA. Based on the evaluation of the hydrodynamic parameters, it was determined that the buoy coded P4 demonstrated the most favorable performance under the wave conditions characteristic of the Black Sea.

Among the designs, the P4 buoy exhibited higher added mass, lower radiation damping, and greater exciting force values, contributing to optimal energy efficiency. The RAO analysis revealed that the P4 buoy peaked within the 0.5–0.7 rad/s frequency range, which aligns with the dominant wave frequencies observed in the region. Furthermore, the broader ballast configuration and lower center of gravity of the P4 buoy optimized the radiation damping coefficient and improved the system's overall stability. The P4 design also stood out in terms of exciting force values, making it a promising platform for maximizing energy output.

These findings highlight the critical role of buoy geometry optimization in enhancing energy efficiency in wave energy systems. Future studies are recommended to investigate the performance of the P4 design under varying material properties and wave environments. Additionally, the effects of viscous losses and drag forces should be explored in greater detail.

Declaration of Ethical Standards

The author of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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