

Article

Development and Hydrodynamic Performance of an Oscillating Buoy-Type Wave Energy Converter

Yeison Berrio ^{1,2}, Germán Rivillas-Ospina ^{1,3,*}, Gregorio Posada Vanegas ⁴, Rodolfo Silva ^{5,*},
Edgar Mendoza ⁵, Victor Pugliese ⁶ and Augusto Sisa ¹

¹ Department of Civil and Environmental Engineering, Universidad del Norte, Barranquilla 081007, Colombia; ymberrio@uniguajira.edu.co (Y.B.); asisa@uninorte.edu.co (A.S.)

² Faculty of Engineering, Universidad de la Guajira, Riohacha 440002, Colombia

³ PIANC (The World Association for Waterborne Transport Infrastructure)-Colombia, Ecohydrology and Ecohydraulics Research Network (REDECOHH), Barranquilla 081007, Colombia

⁴ Instituto EPOMEX, Universidad Autónoma de Campeche, Av. Héroe de Nacozari 480, Campeche 24079, Mexico; gposadav@uacam.mx

⁵ Institute of Engineering, National Autonomous University of Mexico, Mexico City 04510, Mexico; emendozab@iingen.unam.mx

⁶ Department of Mechanical Engineering, Universidad del Norte, Barranquilla 081007, Colombia; vpugliese@uninorte.edu.co

* Correspondence: grivillas@uninorte.edu.co (G.R.-O.); rsilvac@iingen.unam.mx (R.S.)

Abstract

The development of wave energy converters (WECs) faces several technical challenges, particularly enhancing the capturing efficiency, improving the conversion of mechanical to electric energy, and reducing energy losses in the transmission of electricity to land-based facilities. The present study is an assessment of the interaction between an oscillating buoy-type wave energy converter (WEC) and waves using experimental and numerical methods. A small-scale model was tested in a wave tank to evaluate its energy capturing efficiency, taking wave heights and periods as independent variables. The recorded data were used to validate OpenFOAM (version 9.0) simulations, which provided insights into system response characteristics. The findings highlight the critical role of resonance in optimizing energy capture, with maximum efficiency observed for medium wave periods, and with specific buoy configurations. The study also identified an inverse relationship between the capture width ratio and wave height, suggesting the need for customized buoy designs, tailored to specific sea states. The integrated approach used in this research provides a comprehensive understanding of WEC behaviour and offers valuable insights for advancing wave energy technologies and improving their sustainability and efficiency in diverse marine environments.

Keywords: energy converter (WEC); oscillating buoy device; computational fluid dynamics (CFD); experimental testing; numerical simulations; hydrodynamic efficiency



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1. Introduction

The transition from fossil fuels to sustainable and environmentally friendly energy sources is a central theme of current scientific research [1]. However, more than 72% of global energy comes from non-renewable sources such as natural gas, coal, and oil [2,3]. This dependency on fossil fuel contributes to many environmental problems that are expected to worsen as energy demand increases due to industrialization, population growth, and technological development [4–6].

Waves are a potential energy source, with an estimated availability of 2.15 TW world-wide [7–10]. Several challenges, such as intermittency and low efficiency, remain prevalent in wave energy conversion, as observed in latching control systems and PTO configurations [11,12]. Numerical evaluations of WEC systems confirm that efficiency is highly sensitive to device geometry and wave conditions [13,14]. Moreover, the development of robust power systems remains a limiting factor [15].

In general, wave energy harvesting involves a two-step process. First, the kinetic or potential energy travelling with waves is captured and converted into mechanical energy, using a floating or fixed body. In the second stage, the captured energy is converted into electrical power using power take-off (PTO) systems, which may include air turbines, hydraulic turbines, hydraulic motors, and direct-drive linear generators [16]. Wave Energy Converters (WECs) are commonly classified into three main categories based on their working principles: oscillating water column (OWC) devices [17], overtopping systems [18], and floating-body converters [19,20]. Recent studies have also explored hybrid configurations combining energy extraction and wave attenuation functions, such as WECs integrated with artificial reefs or floating breakwaters [21].

Among the various types of WECs, floating-body systems have attracted growing interest due to their adaptability and feasibility in deep-water environments. However, these devices still face persistent challenges related to energy conversion efficiency and structural optimization [22,23]. Recent studies have focused on optimizing energy capture through improved buoy geometry, system degrees of freedom, and control strategies such as model predictive control [24]. In this context, Computational Fluid Dynamics (CFD) has become an essential tool for evaluating the hydrodynamic performance of floating systems in a controlled, cost-effective manner. Several studies have successfully implemented CFD-based numerical wave tanks to assess the performance of point-absorber WECs under a range of operating conditions [25,26].

CFD implementations using OpenFOAM have enabled detailed investigations into grid motion techniques, wave generation and absorption, and the hydrodynamic behaviour of WECs in extreme sea states [27–29]. For instance, CFD simulations have proven capable of capturing nonlinear effects in WEC arrays and complex free surface flows, as validated against experimental data [30]. Advanced mesh strategies like overset grids and improved mesh morphing methods have also been introduced to handle large-amplitude WEC motions with greater stability and accuracy [27,31]. Furthermore, high-fidelity OpenFOAM models have been validated for extreme wave interaction, accurately predicting dynamic responses and mooring loads for point-absorber systems [32]. These developments underscore the critical role of CFD's in optimizing WEC designs, especially for irregular seas and extreme load scenarios. [31–34].

Research into floating WECs includes the work by [35], who designed and tested a floating breakwater with a vertical PTO, emphasizing the correlation between system efficiency and breakwater characteristics. Later, Ref. [36] applied CFD-based viscous flow simulations to optimize the geometric configuration of the floating breakwater initially proposed by [35]. In turn, Ref. [35] adopted a weakly compressible, smoothed particle hydrodynamic method to demonstrate the effectiveness of an asymmetric, wedge-shaped floating breakwater. Numerical assessments of symmetrical and asymmetrical WEC-type floating breakwaters have been conducted by [36–38]. In their study, Ref. [39] carried out simulations on a hemispherical WEC, known as Wavestar, originally designed by [40], employing a two-phase numerical wave tank (NWT) to exploit the potential of CFD models.

Recently, Ref. [13] used OpenFOAM to estimate the power absorbed by the buoy in order to analyze the interaction between WEC and waves. Their results showed that the power absorbed increases exponentially with the buoy radius and that, for a given radius,

the power absorption is significantly higher for higher frequency waves. Complementarily, recent implementations of OpenFOAM have further explored power capture performance in hybrid and resonant configurations [41], and wave–structure interactions involving porous and irregular geometries using advanced coupling methods such as resolved CFD-DEM [42]. These studies highlight the possibilities of OpenFOAM to simulate realistic scenarios, including nonlinear wave phenomena and energy control systems.

Although considerable research has concentrated on the development of floating-body WECs, the reliability of the numerical outcomes remains uncertain. Validated numerical tools are necessary for low-cost testing of WEC design iterations. The present study thus evaluates the performance of an oscillating buoy-type WEC through small-scale tests in a wave tank. The experimental results were also used to validate a numerical tool that was employed to analyze the system responses (energy capture efficiency) under regular wave conditions. Subsequently, sensitivity analyses were conducted for the parameters of buoy diameter, capture width ratio (CWR), and the impact of flywheel inertia.

This research seeks to identify the nonlinear behaviour of the capture width ratio (CWR) with respect to wave height, revealing a critical trade-off between the total absorbed power and the effective energy capture efficiency. The hypothesis indicates that, while mechanical power increases almost linearly with wave height, the CWR shows a notable decrease in more energetic wave conditions, describing the presence of damping and deformation effects that reduce hydrodynamic efficiency. For this reason, our investigation was focused on the parametric analysis of buoy diameter.

The paper is structured as follows. Section 2 describes the dimensional analysis, efficiency, and other relevant hydrodynamic parameters. Section 3 details the test facilities, the scale model, and the instrumentation used in the experiments, and the setup for both experimental and numerical methods. Section 4 presents the results of the tests and subsequent discussion, and finally, in Section 5 the main conclusions of this research are presented.

2. WEC Hydrodynamics

WEC operation, efficiency, and energy output are strongly dependent on hydrodynamics. It is, therefore, essential to understand the key parameters governing these interactions to optimize the performance of the devices. This section provides a comprehensive overview of the fundamental principles that guide WEC efficiency, capture width ratio (CWR), and the effects of system design on energy absorption. Additionally, the role of the crankshaft and flywheel system in stabilizing energy conversion is discussed, highlighting their influence on maintaining consistent power output in varying wave conditions.

2.1. Hydrodynamic Efficiency Parameters

The available power density, P_{in} , should be directly correlated with the power absorbed by the model, which is determined by its absorption or capture width CWR.

$$CWR = \left(\frac{P_{ab}}{P_{in}} \right), \quad (1)$$

where $P_{ab} = \tau \omega_r$, τ is the torque generated by the device and ω_r is the angular velocity of the drive shaft in the PTO (power take-off) and $P_{ab} = \frac{1}{2} \rho g H^2 c_g L$, where ρ is water density, g is gravitational acceleration, H is wave height, c_g is group velocity, and L is the buoy diameter.

$$CWR = \frac{P_{abs}}{\frac{1}{2} \rho g H^2 c_g L} \quad (2)$$

Furthermore, Ref. [43] established that for asymmetric objects that are subject to monochromatic waves, the maximum theoretical capture width ratio is defined in Equation (3).

$$CWR_{Max} = \varepsilon_{df} \frac{\lambda}{2\pi} \quad (3)$$

where λ is the wavelength of the incident wave and ε_{df} is the degree of freedom for a body with a vertical axis of symmetry that oscillates in vertical motion, as is the case of the proposed oscillating buoy, $\varepsilon_{df} = 1$ [44]. Regarding the potential energy conversion, it is possible to determine different types of efficiency. A simple means of estimating the hydrodynamic efficiency is to divide the capture width, Equation (1), by the characteristic length, Equation (4).

$$e_{w_{abs}} = \frac{P_{ab}}{P_{in}L} = \frac{CWR}{L} \quad (4)$$

In this case, L is the physical length of the WEC. In the proposed model, this would be the diameter of the buoy. On the other hand, WEC efficiency is the ratio of generator output power (P_{out}) to its energy harvesting capacity, Equation (4):

$$e_{WEC} = \frac{P_{out}}{P_{ab}} \quad (5)$$

Equation (6) represents the overall efficiency of the WEC, considering all the equipment in the device and its converted energy:

$$e = \frac{P_{out}}{P_{in}L} = e_{WEC}e_{w_{abs}} \quad (6)$$

The process of converting wave energy into electrical power can be categorized into four distinct stages, as illustrated in Figure 1. The present study focuses on the control requirements of the intermediate conversion stages, with particular emphasis on buoy design and wave energy conversion. While the assessment of available wave resources is beyond the scope of this paper, the literature suggests several methodologies that could be incorporated before the deployment of the device. The reader is referred to [4] for further details.

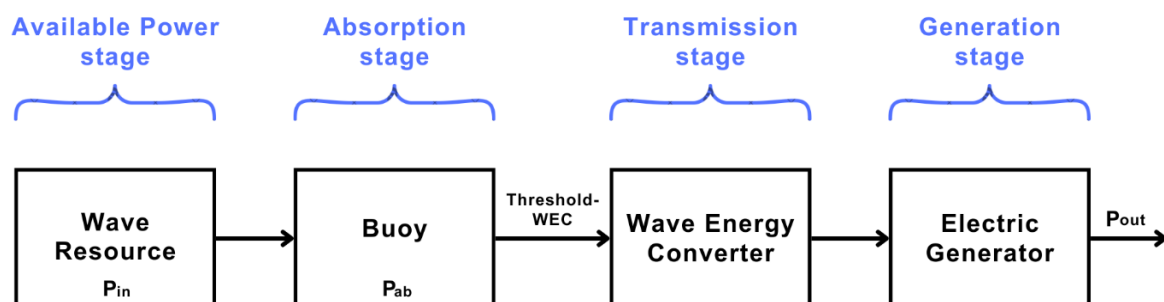


Figure 1. Stages in wave energy conversion with hydraulic power take-off.

2.2. WEC Device Characterization

The prototype under study is a piston-type wave energy converter (WEC) designed to capture the potential energy from the vertical motion of sea waves and convert it into electricity via a generator. The system consists of a submerged buoy linked to a crankshaft mechanism with a connecting rod and a flywheel (Figure 2a). A reinforced cage-like support structure maintains the device's vertical alignment, and additional mass was added to its upper section during laboratory tests to enhance energy capture—conditions also replicated in the numerical model for consistency.

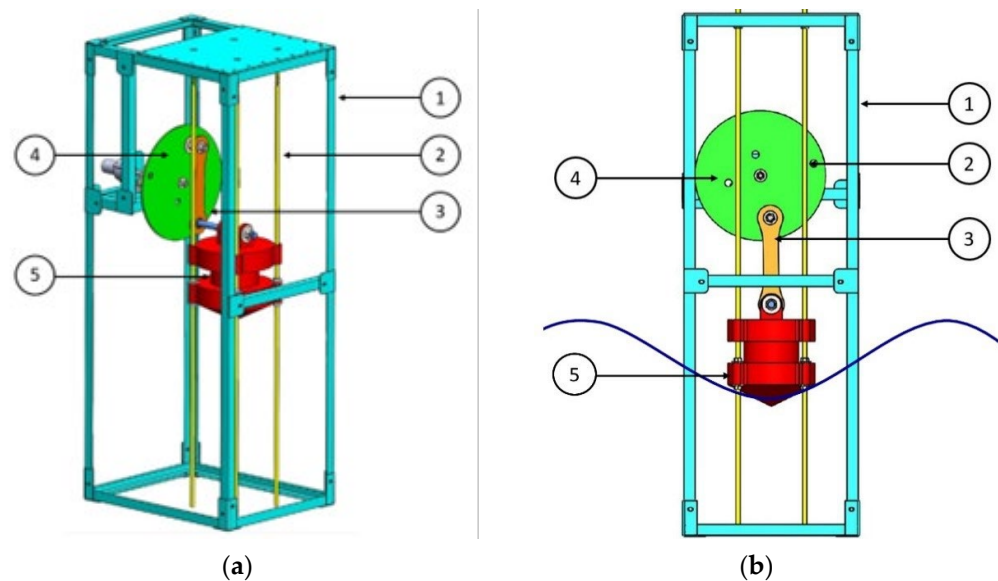


Figure 2. Operation of the oscillating buoy WEC. 1 support; 2 directional guides; 3 connecting rods; 4 flywheel; 5 buoy. (a) Restitution phase. (b) Traction phase.

The WEC operates through the interaction between the buoy and incoming waves. As a wave crest lifts the buoy, mechanical energy is transmitted through the crank mechanism, causing the flywheel to rotate—this is the traction phase (Figure 2b). When the buoy descends into the wave trough, gravity assists the flywheel’s return, initiating the restitution phase. This cyclical motion can sustain continuous flywheel rotation, provided wave heights are sufficient (see Supplementary Material, Animation S1).

However, when waves are too small, the crankshaft may not complete a full rotation, resulting in only oscillatory motion. To ensure efficient and consistent energy conversion, a critical wave height threshold must be identified—one that enables the transition from intermittent to continuous operation [45]. This threshold is essential for optimizing the WEC’s performance and reliability under varying sea conditions.

2.3. Scaling Principles and Limitations

The scaling approach adopted in this study follows the Froude similarity criterion, which is widely used in experimental modelling of WECs to preserve dynamic similarity where inertial and gravitational forces dominate the system behaviour [46,47]. The criterion ensures an accurate reproduction of wave propagation and buoy motion at a reduced scale, particularly when viscous effects are secondary, as is often the case in free-surface wave–structure interactions [48].

It is important to note that applying Froude similarity can modify the relative contributions of force pairs, such as inertia versus viscosity, surface tension, or compressive forces. However, in small-scale wave tank experiments, viscous forces are typically negligible over short distances [49,50], and surface tension effects are minimal when water depth exceeds 20 mm and wave periods are over 0.35 s [49]. Compressional forces, which are more relevant in pneumatic PTO systems, have negligible influence on hydrodynamic performance due to water’s low compressibility at these scales [47].

Although achieving full similarity in both hydrodynamic and aerodynamic behaviour is challenging in laboratory tests [50], the experimental design in this study adheres to geometric and Froude similarity principles. This approach is consistent with previous research on similar WEC configurations and ensures that the observed performance trends remain representative for the analysis of a full-scale model [51–53].

3. Experimental Methodology and Test Setup

The tests were conducted in the 15×9 m wave tank of the Autonomous University of Campeche, Mexico (Figure 3a,b). There, regular or spectral waves of 0.02 to 0.40 m in height, and 1.0 to 6.0 s in period, can be produced. The wave generator is “snake” type, composed of 18 paddles, each of 0.50 m. The paddles have a dynamic absorption system to minimize re-reflected waves [54,55], and the wave generation system is controlled by Awasys software (Version 7.0) [56]. At the other end, the facility has a passive wave absorber of gravel, with D50, of 5.08 cm.

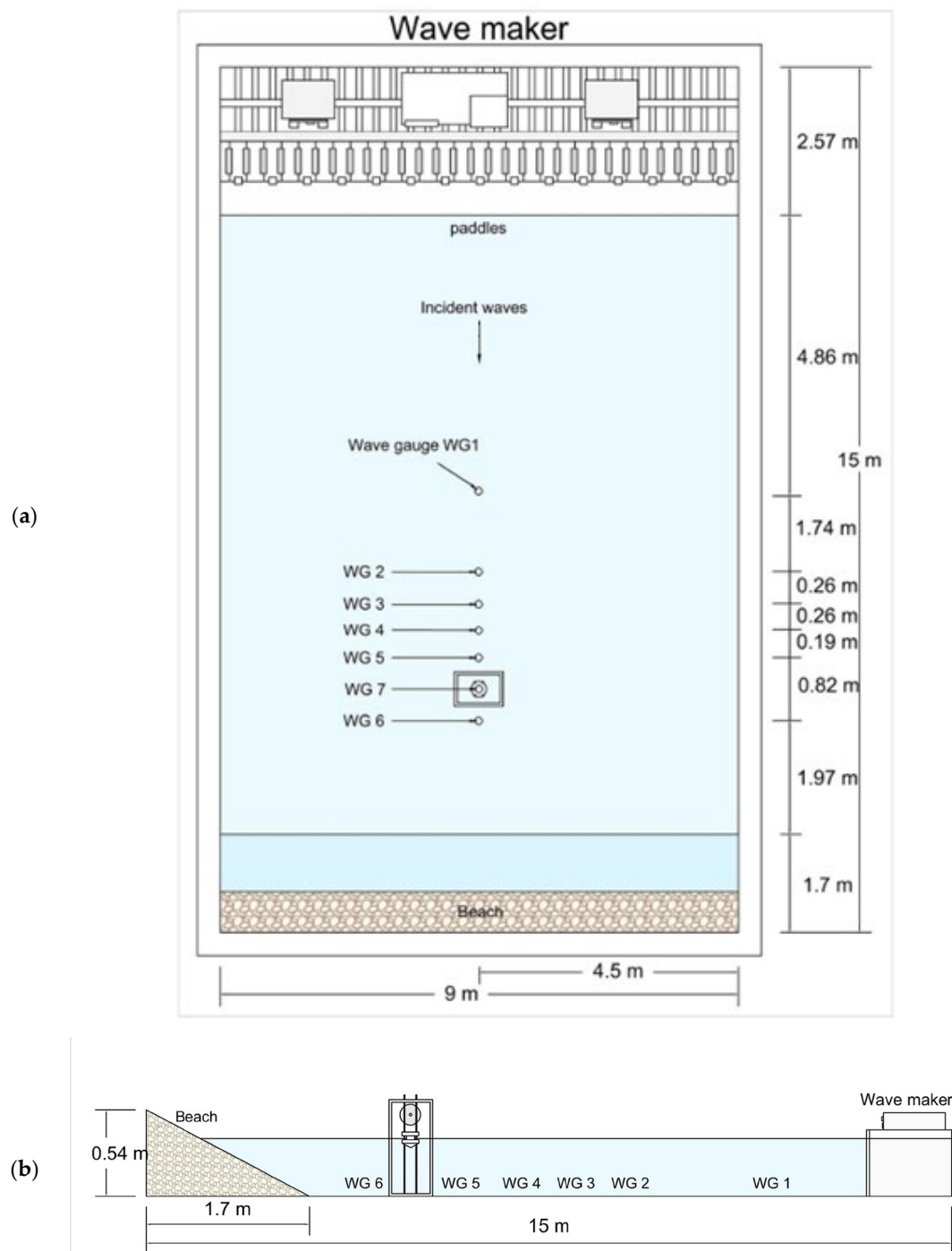


Figure 3. Experimental arrangement for the oscillating buoy device: (a) plan view and (b) profile view and wave gauge positions.

3.1. Instrumentation

The free surface of the water was measured at a frequency of 100 Hz by a network of 6 level sensors, connected to a busdaq IMC datalogger, as seen in Figure 3. Five gauges were located between the paddles and the WEC device, four of which were used to compute wave reflection (WG1, WG2, WG3, and WG4) following [57]. WG5 and WG6 were placed before and after the WEC to evaluate its impact on the hydrodynamics (Figure 4a).

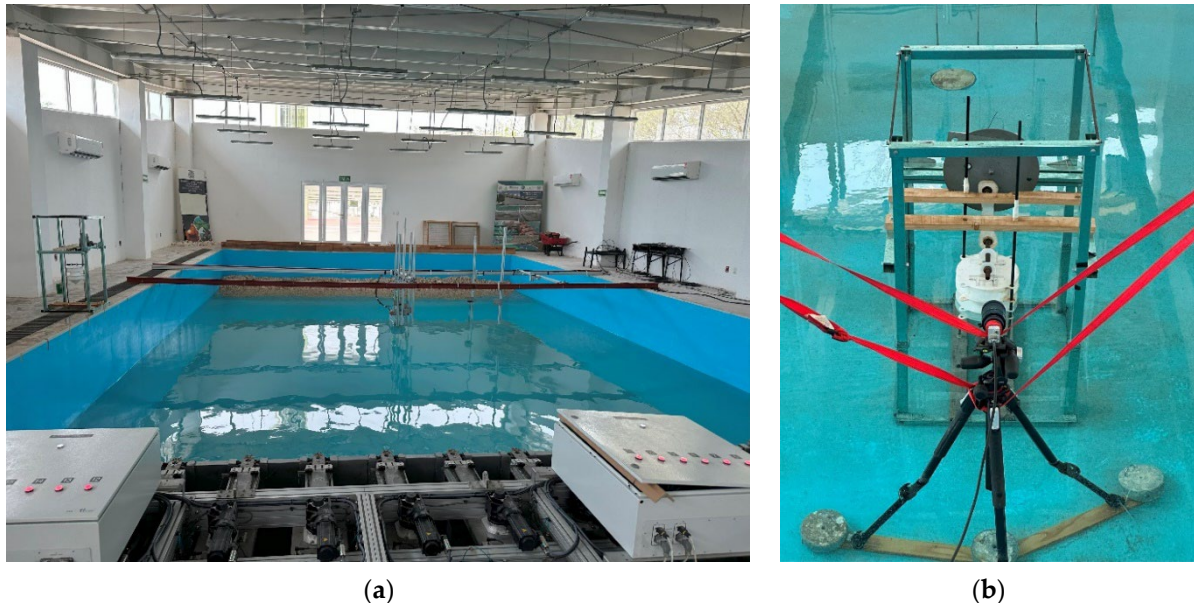


Figure 4. Experimental setup of the oscillating buoy. (a) Wave tank without the device. (b) The oscillating buoy with the high-speed camera.

At 1.0 m from the buoy, a PRONOM U750 high-speed camera from manufacturer: AOS Technologies AG, Baden, Switzerland was located, allowing the buoy movement to be recorded at a frequency of 200 Hz. From these images, using the Tracker (r) software [58], the time series of the total displacement and the speed of movement of the buoy were obtained, Figure 4b [59]. A high-intensity lamp was employed to ensure adequate illumination during the recordings, and a digital counter–tachometer was used to measure the angular velocity of the shaft.

3.2. General Arrangement and Tests Performed

Table 1 shows the wave characteristics of the tests conducted, where H_{sc} is the scaled wave height and H denotes the full-scale wave height. T_{sc} is the scaled wave period, while T is the full-scale wave period. First, a set of preliminary tests were carried out in the absence of the WEC model. These tests determined a test length of 100 waves and evaluated the reflection coefficient of the facility, which was found to be below 5% [60].

The wave heights and the period ranges employed were selected from the full-scale values observed in common sea states in the Caribbean Sea [61], to ensure that the results are relevant for practical applications. The wave periods were selected to cover a broad spectrum of natural wave frequencies, enabling a comprehensive analysis of the WEC performance in different wave conditions. The corresponding small-scale values were calculated using a scale factor of 20 for the selected wave heights and periods.

Table 1. Monochromatic wave tests were evaluated with and without the buoy prototype.

Wave Type	Wave Height (m)		Period (s)	
	Model Scale Hsc	Full Scale H	Model Scale Tsc	Full Scale T
Regular	0.08	1.6	1.0	4.5
			1.2	5.4
	0.10	2.0	1.4	6.3
			1.6	7.2
	0.12	2.4	1.8	8.0
			2.0	8.9
Regular	0.14	2.8	2.2	9.8
			2.4	10.7
	0.16	3.2	2.6	11.6
			2.8	12.5
	0.18	3.6	3.0	13.4

3.3. Numerical Model

In this research, the hydrodynamic interactions between the WEC and the incident waves were simulated using the OpenFOAM numerical model. OpenFOAM solves the Reynolds-averaged Navier–Stokes (RANS) equations [62,63], coupled with the Volume of Fluid (VOF) method, to accurately capture the free surface between air and water [64]. Turbulence effects were modelled using the two-equation κ - ε turbulence model, which is commonly applied in marine and coastal engineering due to its robustness in predicting flow separation and complex boundary layer behaviour. This modelling approach provided a detailed, reliable analysis of wave–structure interactions across a range of sea states, giving valuable insights into the performance and behaviour of the WEC.

3.3.1. Numerical Simulation Configuration

The numerical simulations were focused on studying the dynamics of the buoy. Two libraries, olaDyMFlow and librigidBodyMeshMotion, were used for this purpose. The olaDyMFlow is a dynamic mesh solver for isothermal immiscible fluids. This module combines the Volume Of Fluid (VOF) method with a rigid body motion solver based on the librigidBodyMeshMotion libraries [65].

Since the simulation focuses on solving the propagation of progressive waves in intermediate waters (transition zone $\frac{L}{2} \leq d \leq \frac{L}{20}$), where the orbital velocities describe a circular pattern and the effect of friction with the bottom (between 5 and 10 m depth) is negligible, only losses due to molecular viscosity are considered, and not wave breaking processes (Table 2).

Table 2. Fluid properties analyzed in the modelling process.

Parameter	Units	Water	Air
Kinematic viscosity	$\text{m}^2 \cdot \text{s}^{-1}$	1.0×10^{-6}	1.48×10^{-5}
Density	$\text{kg} \cdot \text{m}^{-3}$	1024	1.0
Surface tension between phases	$\text{N} \cdot \text{m}^{-1}$	0.07	

In the olaDyMFlow solver, both the fluid and WEC motion are combined. During each time step, the implicit motion solver algorithm handles position updates, force calculations, acceleration adjustments, and body movement to its new position. Subsequently, the solver adjusts the mesh to accommodate changes from the previous time step [66]. Next, the fluid

solver begins reconstructing the flow field using the VOF method with a multidimensional universal limiter for explicit solutions. This approach includes a condition limiting the time flow in the solution. The momentum and pressure equations are then solved, using the pressure implicit method for the pressure-bound equations (PIMPLE) algorithm.

3.3.2. Computational Accuracy and Meshing

The rectangular numerical wave tank (NWT) is 12 m long, 2 m wide, and 1.5 m deep. The difference between the width of the physical wave tank and the numerical model is acknowledged. The wave tank has a dynamic absorption system that mitigates reflected waves, allowing OpenFOAM simulations to accurately represent a cross-section of the domain. According to Windt [67], high-fidelity numerical models, such as CFD-based NWTs, can capture relevant hydrodynamic nonlinearities, such as complex free surface elevation, viscous drag, and turbulence. Although NWTs are more computationally expensive, they can provide accurate, high-resolution results, which are essential for investigating specific flow phenomena (small-scale processes) around coastal and marine structures. Numerous studies have demonstrated the effectiveness of NWTs in analyzing marine engineering problems, justifying the use of simplified configurations that do not compromise result accuracy [65–67]. As described in the experimental settings, the buoy was placed 7.05 m from the inlet boundary. Using the open-source programme SALOME <https://www.salome-platform.org> (accessed on 25 September 2023), the buoy was built numerically in a format readable by OpenFOAM (.STL file) and was incorporated into the spatial domain using the snappyHexMesh tool.

To implement the numerical model an appropriate mesh was defined to discretize the wave tank domain, balancing computational cost and accuracy of results. Three areas of progressive refinement were defined: (a) at the beginning of the wave tank (coarse); (b) at the top and bottom of the tank, smoothing between the first area (medium); and (c) where the buoy was located (fine). Figure 5 shows this computational mesh structure, showing the higher spatial resolution in the free water surface area, that ensures that the wave propagation is captured accurately. This refined region extends upstream of the buoy to $4H$ and $8A$, where H represents the regular wave height and A denotes the maximum amplitude [68–70].

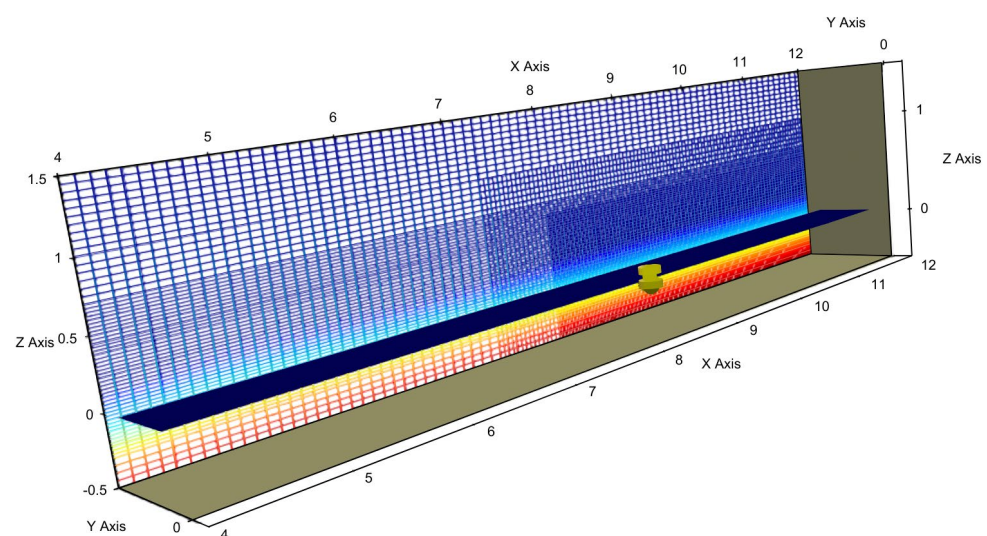


Figure 5. Schematic image of the domain simulated in OpenFOAM. Colors indicate mesh refinement: red (coarse grid), yellow–orange (medium size grid), and blue (fine grid).

A mesh sensitivity analysis was conducted to determine the optimal spatial discretization for accurate simulation of the wave energy conversion processes. This included the

evaluation of key statistical indicators such as root mean square error (RMSE), coefficient of determination (R^2), Bias, and the Willmott index, to quantify numerical errors in the representation of wave crests and troughs. Following the criteria used by [71], the Willmott index ranges from 0 to 1, where a value of 1 indicates perfect agreement between observed and simulated data, while a value of 0 represents complete disagreement. The Bias index provides a measure of average deviation; a Bias of 0 means perfect agreement, while a Bias of 0.05, for example, implies a 5% average underestimation of observed values by the model. RMSE evaluates the magnitude of prediction errors; the lower the RMSE, the more accurate the model. Finally, the coefficient of determination (R^2) indicates the proportion of variance explained by the model, with $R^2 = 1$ indicating perfect predictive performance and $R^2 = 0$ indicating no predictive capability.

In addition to assessing numerical accuracy, the study examined the computational cost associated with each mesh configuration, to ensure a balance between resolution and efficiency. The results, summarized in Table 3 and detailed in Appendix A, show the achievement of a mesh configuration that ensures numerical results regardless of cell size.

Table 3. Discretization level on the x -axis.

Configuration	Discretization Level ΔX (mm)		
	Coarse	Medium	Fine
C1	350	150	50
C2	200	100	35
C3	150	70	20
C4	100	50	10

Based on these results, configuration C3 was selected for the final simulations as it provided an error of less than 1% for the key wave parameters. The configuration H had a progressive refinement, with a minimum cell size of 20 mm in length, along the wave propagation direction, 15 mm width, and 10 mm height, see Table 4.

Table 4. The spatial discretization used in the numerical simulations.

Region	ΔX (mm)	ΔY (mm)	ΔZ (mm)
Coarse	150	200	600
Medium	70	50	30
Finest	20	15	10

For all the numerical tests, the buoy was considered as a rigid cylindrical body with a height of 0.25 m and a radius of 0.10 m. The density of the buoy was $\rho_b = 190 \text{ kg m}^{-3}$. The buoy was modelled as a floating body with two constraints: first, a fixed point at coordinates (7.05, 0, 0, 0) to prevent any pitching motion, due to wave impact, and to allow only translational motion in the z plane. No additional constraints, such as external forces, linear springs, or damping effects, were considered.

It is important to note that the mesh configuration (C3) was chosen as it balances numerical accuracy and computational efficiency, making it well suited for analyzing near-field wave-body interactions over short to moderate simulation timeframes. This level of discretization allowed for an accurate representation of the wave field and buoy motion dynamics, as evidenced by the low RMSE (<1%) and high correlation indices achieved during validation. However, we acknowledge that for simulations involving highly turbulent flow regimes, detailed boundary layer effects, or long-duration analyses, further mesh refinement—particularly near the buoy surface—may be necessary to resolve small-scale processes more accurately. These aspects, while relevant for advanced modelling efforts,

are beyond the scope of the present study, which is focused on the evaluation of the WEC's hydrodynamic response and energy capture efficiency under regular wave conditions.

3.3.3. Boundary Conditions

The boundary conditions specified in the OpenFOAM model are as follows. In the `alpha.water` file, `zeroGradient` is applied to the outlets, sides, buoy, and bottom of the starting field, to eliminate surface tension effects between the wall and the water–air interface. At the inlet and top, `waveAlpha` and `inletOutlet` were set to 0. In the velocity (`U`) file, the inlet boundary was set as `waveVelocity` type, and the outlet boundary was set as `waveAbsorption2DVelocity` type.

At the model inlet boundary, a water velocity profile simulating the wave characteristics was imposed. At the model outlet boundary, an absorption condition was applied to simulate the attenuation of the waves as they propagate out of the numerical domain. The buoy field was set to `movingWallVelocity`, and the upper boundary was set to `PressureInletOutletVelocity`. All other boundary condition fields were set to `noSlip`, as detailed in Table 5.

Table 5. OpenFOAM boundary conditions applied in the NWT.

Boundaries	U	P	Point Displacement	Alpha. Water
Left wall	noSlip	fixedFluxPressure	fixedValue 0	zeroGradient
Right wall	noSlip	fixedFluxPressure	fixedValue 0	zeroGradient
Bottom	noSlip	fixedFluxPressure	fixedValue 0	zeroGradient
Inlet	waveVelocity *	fixedFluxPressure	fixedValue 0	waveAlpha *
Outlet	waveAbsorption2DVelocity *	fixedFluxPressure	fixedValue 0	zeroGradient
Atmosphere	pressureInletOutletVelocity	totalPressure	fixedValue 0	inletOutlet
Buoy–WEC	movingWallVelocity	fixedFluxPressure	calculated	zeroGradient

* `olaDyMFlow`.

For pressure (`P`), all fields were configured with a `fixFluxPressure` value of 0, except for the upper boundary, which was set to the `totalPressure` (`p0`) determined by the model at each time step. In the `pointDisplacement` file, only the bend path was specified as “calculated”. The other boundary condition fields were set to the same fixed values (0,0,0). Table 5 provides a summary of the boundary conditions applied.

3.3.4. Generation and Absorption of Numerical Waves

The IHFOAM toolbox was used for numerical wave generation and absorption, following the procedures outlined in [65,72]. The static boundary method allowed wave generation at the incoming NWT boundary. In contrast, active wave absorption was applied at the outgoing boundary to counteract the incoming wave with an opposite uniform velocity profile [32]. Monochromatic waves were generated using Stokes II wave theory. The IHFOAM toolbox was also used to determine the NWT wave velocity and surface elevation at the entrance.

3.3.5. Model Stability

The initial time step was set to 0.0001 s, and the time step was automatically adjusted based on the Courant–Friedrichs–Lewy (CFL) number, to maintain numerical stability, rather than using a fixed time step. The maximum number of CFL was set to 0.50.

3.3.6. Modelling Scenarios

Two sets of tests were conducted to validate the OpenFOAM numerical model, and the experimental and numerical free surface results from the sensors in the wave tank were

compared. First, tests were performed without the WEC device to validate the OpenFOAM model, Table 6. Subsequently, tests were conducted with the WEC device installed in the wave tank, and the experimental results from the sensors were compared with the numerical free surface results.

Table 6. Cases with regular waves simulated in OpenFOAM, with and without the WEC device for 0° .

Case	Hydrodynamic Parameters		
	Wave Theory	H (m)	T (s)
Cs1	R. Stokes II	0.10	1.8
Cs2	R. Stokes II	0.10	2.0
Cs3	R. Stokes II	0.12	1.8
Cs4	R. Stokes II	0.12	2.0
Cs5	R. Stokes II	0.14	1.8
Cs6	R. Stokes II	0.14	2.0

3.4. Natural Period WEC

The natural period of the system (T_n , Table 6) is a fundamental parameter in designing and analyzing wave energy converters (WECs). The natural period is the time required for the system to complete one full oscillation, when resonating with incident waves. For the WEC prototype, an oscillation period was imposed on the buoy to measure the torque and thus calculate the generated mechanical power. This period was determined experimentally to ensure the device was synchronized with the wave frequencies, to maximize energy absorption.

4. Results and Discussion

4.1. Hydrodynamic Efficiency of the WEC

The relationship between the hydrodynamic efficiency ϵ and the wave period T_{sc} is seen to vary with the different wave heights H_{sc} (Figure 6). The bandwidth of the curves, which represents the range of values on the horizontal axis where the efficiency varies, tends to increase as H_{sc} increases. Also, for medium wave periods, the maximum values of hydrodynamic efficiency are seen, reaching up to 35%, and decreasing towards the extremes of the periods evaluated, with 15% for $H_{sc} = 0.12$ m.

In contrast, for both long and short-wave periods, an increase in hydrodynamic efficiency is seen as H_{sc} increases. These results align with those reported by [13], particularly under the high-damping conditions imposed by the PTO model. The decline in efficiency as resonance approaches can be attributed to nonlinear phenomena, such as increased water flow dispersion, and free surface deformation due to elevated wave heights.

It can thus be inferred that the device achieves maximum efficiency when operated at a wave height of 0.12 m. An increase in wave height enhances the performance of the prototype, particularly for wave periods between 1.6 and 2.6 s. However, the wave height (H_{sc}) does not impact the wave period (T_{sc}), at which resonance occurs.

In addition to the analysis of efficiency versus wave height, a complementary analysis of hydrodynamic efficiency (ϵ) versus wave height (H_{sc}) was conducted. From this analysis, detailed in Appendix B, it is seen how efficiency varies across different wave heights, and identifies trends that reinforce the findings related to the wave period. The results suggest that (1) higher wave heights consistently improve the hydrodynamic performance of the device, particularly for medium wave periods, and (2) efficiency decreases for very short, or very long, wave periods, consistent with the nonlinear phenomena observed in the resonance analysis. For details, see Figure A1 in the Appendix B.

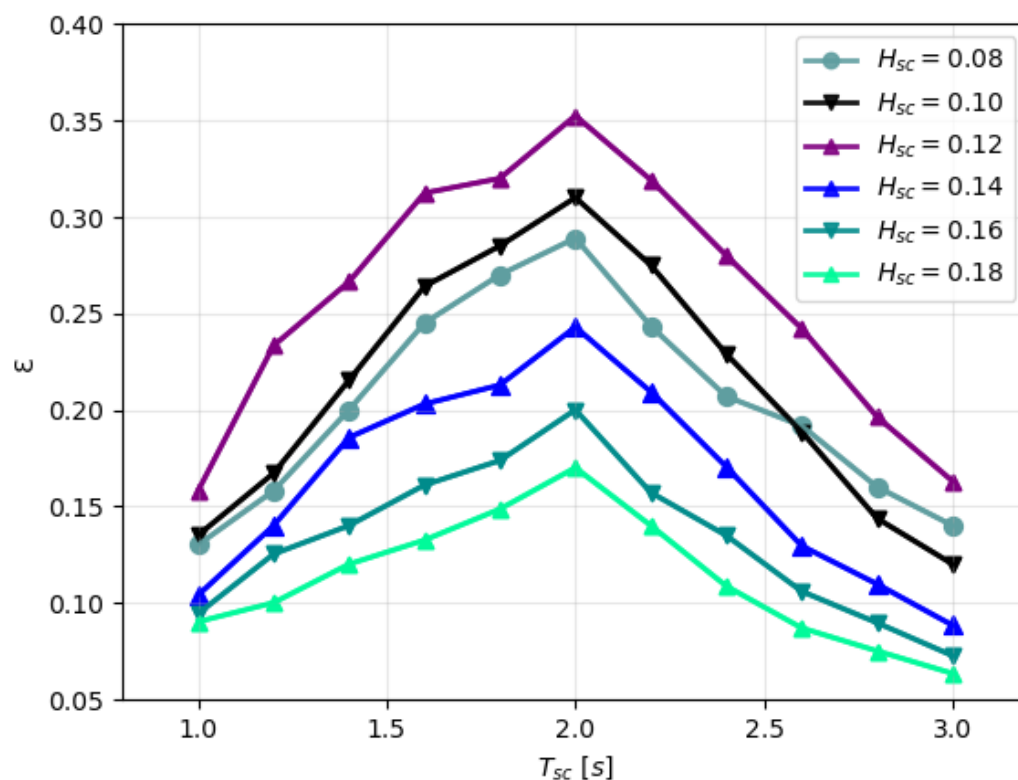


Figure 6. Hydrodynamic efficiency (ϵ) versus wave periods (T_{sc}) for the oscillating buoy model with a wave incidence angle of 0° .

In the After Device series of Figure 7, a notable reduction in spectral energy around the dominant frequencies of the spectrum, around 0.6 Hz, is seen, indicating that the device is efficient in absorbing energy within this frequency band. This is consistent with the resonance frequency identified in previous analyses. For frequencies below 0.4 Hz and above 1.0 Hz, the pre-device and post-device curves show minor differences, suggesting that the device has a limited efficiency outside the resonance band. Overall, the reduction in spectral energy after the device confirms that the WEC is capturing some of the energy available in the waves.

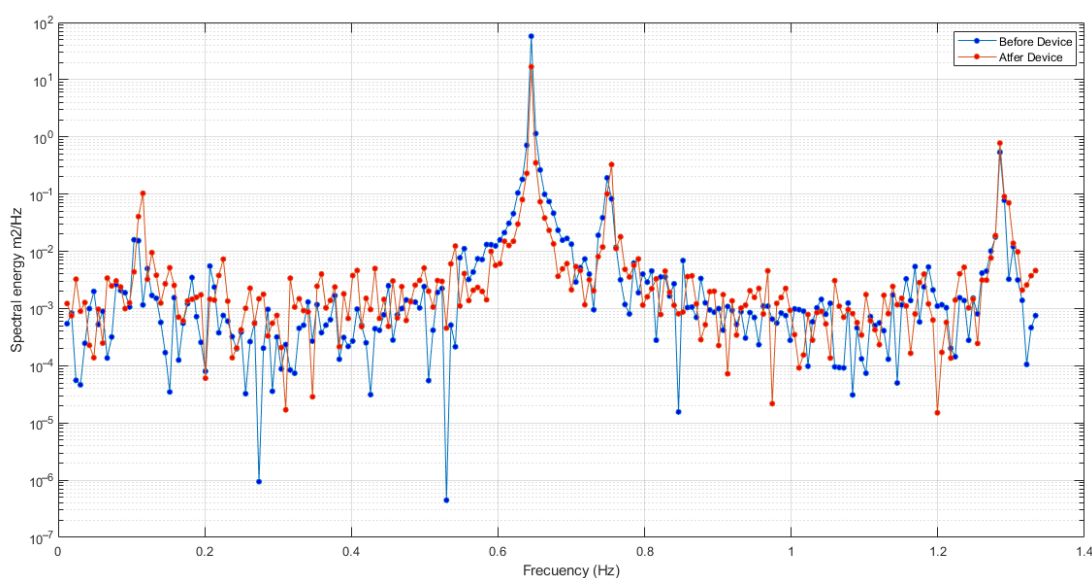


Figure 7. Energy spectrum before and after the WEC device for full-scale values $H_s = 2.0$ m and $T_p = 8.0$ s.

The harmonic decomposition of the wave series before and after the WEC device is presented in Appendix B (see Figure A2). This figure shows the amplitudes of the harmonic components (a and b) and the resulting wave profile ($x(t)$) over time. The analysis highlights the changes in wave dynamics introduced by the device, particularly in the energy distribution across the harmonics. The JONSWAP spectrum is included in Figure A3 to illustrate how wave field conditions affect the device performance. The numerical simulations showed strong agreement with the experimental measurements, effectively capturing the spectral wave variations across all frequencies in the spectrum. This agreement highlights the robustness of the simulation model in accurately reproducing the wave dynamics of the wave tank, including energy distribution and variation trends, which are critical for understanding wave–structure interactions in WEC design. The model’s ability to follow the spectral wave trends ensures reliable predictions of WEC performance under realistic wave conditions.

4.2. OpenFOAM Model Validation

As detailed in the methodology section, the OpenFOAM numerical model was validated against the water free surface recordings using a two-step approach. First, the tests were numerically run without the WEC device, to establish a baseline. Then, the tests with the WEC device installed were compared to the numerical results. Since simulating all the laboratory cases was impractical due to the heavy computational load, a representative selection of cases was chosen for validation.

4.2.1. Comparison of Numerical and Experimental Water Free Surface

The time series of the free water surface obtained from the OpenFOAM simulations were compared to the experimental free surface records. In Figure 8, the data from sensors 1, 2, and 6, for case Cs4 ($H_{sc} = 0.12$ m and $T_{sc} = 2.0$ s), without the device, are plotted along with the numerical results. A good agreement between the experimental and numerical data is seen for all sensors. From these results, it can be stated that the model accurately predicts and reproduces the free surface trend along the tank without the WEC device.

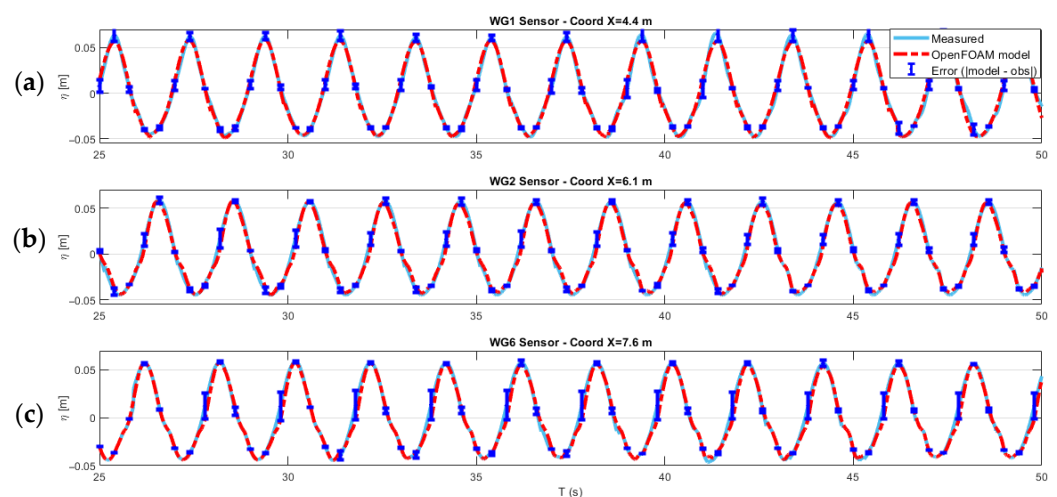


Figure 8. Comparison of free surface results, case Cs4 ($H_{sc} = 0.12$ m, $T_{sc} = 2.0$ s). (a) WG1 sensor $X = 4.4$ m. (b) WG2 sensor $X = 6.1$ m. (c) WG1 sensor $X = 7.6$ m.

In turn, Figure 9 shows the results obtained for wave gauge 6 in the Cs2 case with the WEC in place. An almost exact agreement with the numerical model is seen, and therefore, it can be affirmed that OpenFOAM accurately reproduces the free surface generated in the wave tank with the WEC. Figure 10 shows a linear regression fit between the measured and

modelled data, with confidence bands of 95%, with their respective R^2 . Table 7 summarizes the fit of the statistical parameters.

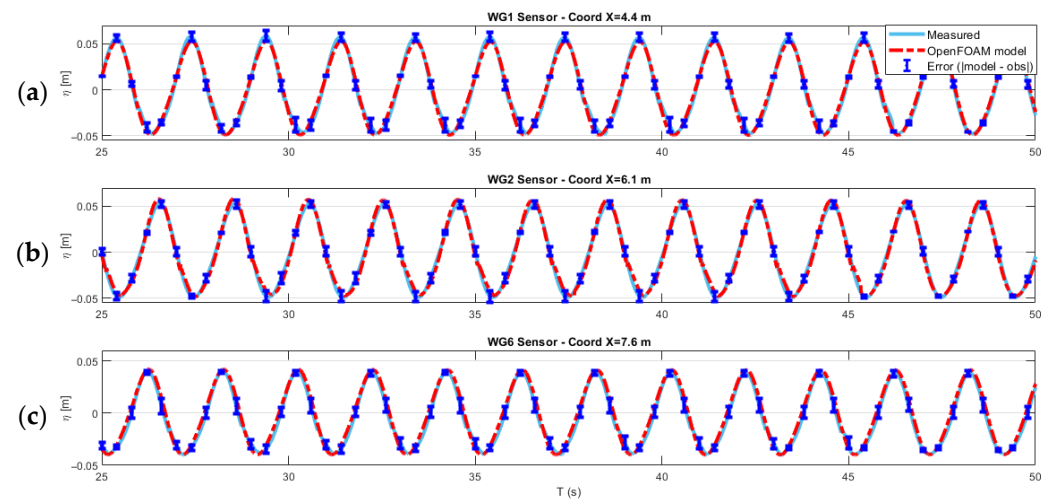


Figure 9. Comparison of free surface results for case Cs2 ($H_{sc} = 0.10$ m, $T_{sc} = 2.0$ s) with the WEC device. (a) WG1 sensor $X = 4.4$ m. (b) WG2 sensor $X = 6.1$ m. (c) WG1 sensor $X = 7.6$ m.

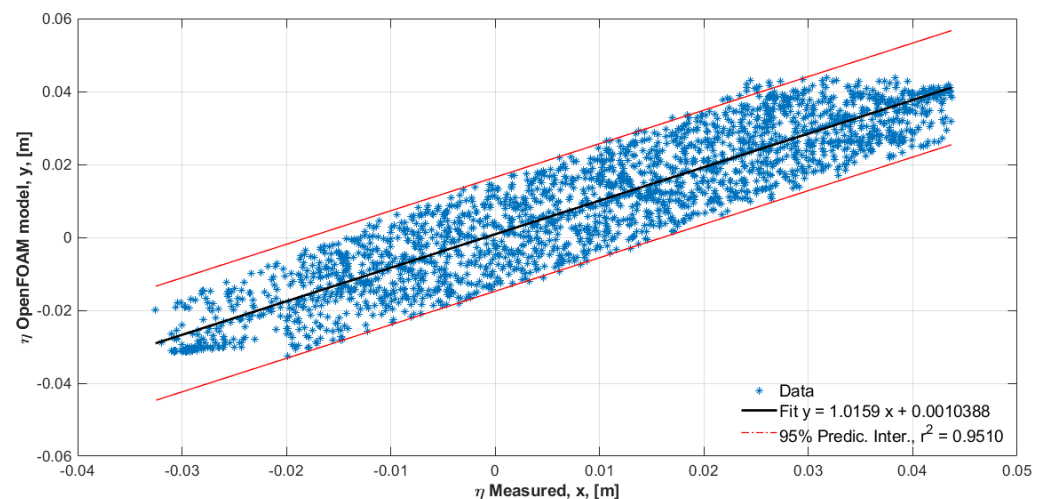


Figure 10. Linear regression analysis with 95% confidence intervals, free surface data simulated in OpenFOAM, and free surface data obtained from measurements in the wave tank.

Table 7. OpenFOAM error parameters.

Parameter	Without WEC	With WEC
Bias	0.010	0.013
Willmott	0.99	0.95
Pearson	0.98	0.96
RMSE	0.0054	0.0078

The model performed remarkably well for the six simulated cases, with and without the device, under different wave conditions. OpenFOAM reproduced the free surface with an error of approximately 1%, according to the Bias parameter.

The Willmott index and Pearson correlation were 0.99 and 0.98, respectively, for the cases without the buoy. As for the fit with the buoy, errors of 1.3%, 0.95, and 0.96, respectively, for Bias, Willmott, and Pearson, were found, implying that the OpenFOAM model recreates the rise and fall of the free surface very well, when compared to the results along the wave tank (Figures 8–10). The error parameters were calculated to demonstrate

a strong fit for both scenarios, with and without the WEC device, yielding coefficient of determination (r^2) values of 0.99 and 0.97, along with root mean square error (RMSE) values of 0.005 and 0.007, respectively.

4.2.2. Comparison of Numerical and Experimental Velocity

Comparing the vertical displacement velocities of the buoy modelled using OpenFOAM and those measured with the PRONOM U750 high-speed camera, good agreement was seen, demonstrating the applicability of the OpenFOAM model for simulating oscillating buoy-type wave energy converters (WEC). The model accurately reproduces the oscillations in buoy velocity in terms of magnitude, frequency, and phase, achieving statistical values of $R^2 = 0.96$ and $RMSE = 0.013$, indicating that the model parameters are appropriately calibrated to represent the experimental conditions.

Figure 11 shows that the sinusoidal oscillations are consistently captured by OpenFOAM, suggesting that the numerical model adequately reproduces the fluid–structure interaction that drives oscillatory motion in a wavy environment.

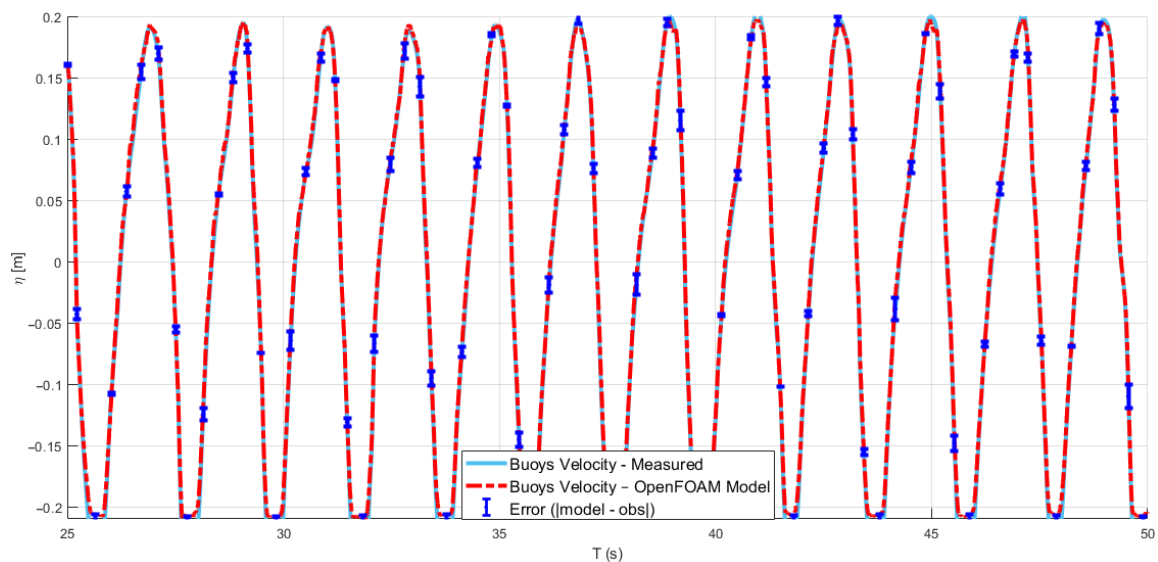


Figure 11. Comparison between measured and calculated velocity of buoy, case Cs4 ($H_{sc} = 0.12$ m, $T_{sc} = 2.0$ s).

4.3. Elevation Movement of the Buoy

Initial studies of the prototype showed that for optimal absorption efficiency, the oscillation frequency of the device must match the frequency of the incident wave. This requires the near-resonance operation of the device, where the object velocity is synchronized with the excitation force [44]. In this study, this correction corresponds to a zero phase difference between the buoy motion and the wave elevation, assuming that the wave excitation power is synchronized with its height.

Figure 12a–c show the time evolution of the free-surface elevation $\eta(t)$ and buoy motion $z(t)$ for various wave heights and periods (see Table 8). These figures also show the instantaneous buoy velocity $u(t)$ derived from OpenFOAM modelling, which was previously validated for wave tank conditions. The time lag between the buoy velocity $u(t)$ and the free-surface elevation $\eta(t)$ is labelled as Δt .

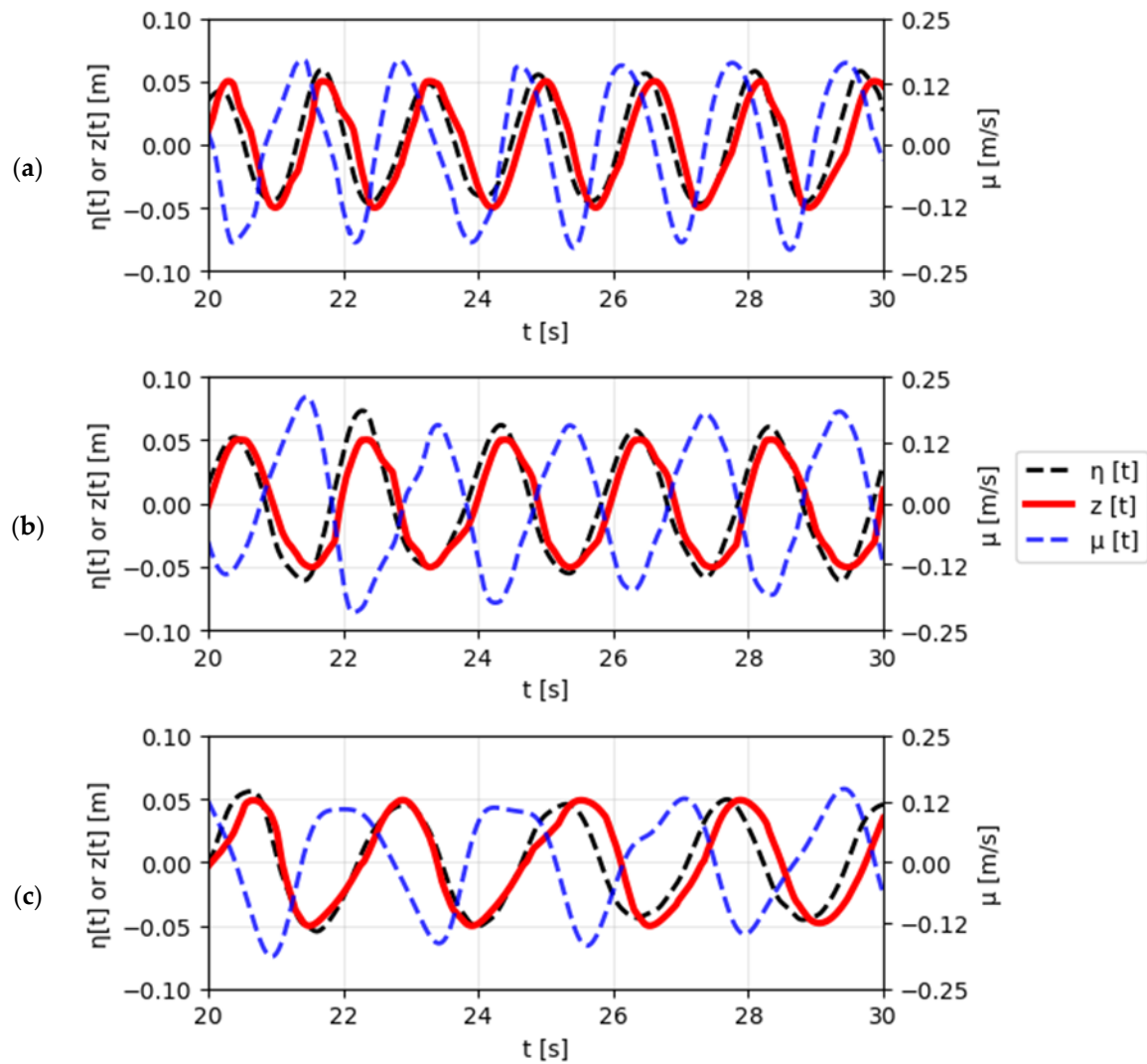


Figure 12. Time series of surface wave elevation $\eta(t)$, buoy displacement $z(t)$, and buoy velocity $\mu(t)$ in regular waves. (a) Case 01. (b) Case 02. (c) Case 03.

Table 8. Scaled wave period and wave height parameters.

Study Case	Wave Height H_{sc} (m)	Period T_{sc} (s)
01	0.10	1.6
02	0.12	2.0
03	0.10	2.4

The cases shown in Table 8 are those in which the highest efficiency of the device was recorded in the wave tank. Analyzing buoy velocity ($\mu(t)$) and displacement ($z(t)$) alongside wave elevation ($\eta(t)$) provides critical insights into the dynamic behaviour of the WEC system under resonant conditions.

Previous studies have shown that when the amplitude of the incident wave (A) is less than the minimum radius of curvature of the wet body surface, the relative motion between the buoy and the surrounding waves is generally acceptable in terms of linearity [18,73,74]. For cases 01 and 03, shown in Figure 12a,c, a phase difference of approximately $\pi/2$ (90 degrees) is seen between the buoy motion and velocity. The height of the wave indicates that the system is far from resonance conditions. However, the amplitude of the wave is the highest in these cases.

In Case 02 the buoy movement is seen to be synchronized with the period of the incident waves, Figure 12b. Furthermore, a phase difference of 90° is seen between the buoy speed and the wave height. This phase difference suggests the possibility of resonance between the buoy and the waves, whereby the buoy achieves peak velocity when the wave height is at its maximum or minimum. The 90° phase difference between buoy and wave motion, shown in Figure 12b, indicates resonance between the buoy and the waves. In this context, resonance implies that, by being in tune with the temporal characteristics of the waves, the buoy can absorb wave energy more efficiently. It is therefore plausible that an amplified response is observed, particularly regarding buoy speed.

These observations highlight the importance of resonance in enhancing the energy absorption capabilities of WECs. They demonstrate the need to consider coincident periods and the particular phase relationships between buoy motion and wave characteristics. Moreover, although $z(t)$ and $\mu(t)$ are indeed kinematic properties of the buoy, their interaction with $\eta(t)$, a wave property, provides valuable information about relationship between the buoy and the wave system. The resonance conditions and phase relationships observed in the previous figures are critical for understanding how buoy motion can be matched with wave dynamics, thereby maximizing energy capture.

4.4. Wave Period Analysis

Tests were conducted under varying wave period conditions to assess the efficacy of the WEC device across diverse regular wave scenarios. The OpenFOAM numerical model was used, known for its precision in replicating the hydrodynamic environment of a wave tank containing a WEC device. It is important to underline that in this part of the work, a wave height of 0.12 m and a natural angular frequency of buoy elevation at 5.76 rad s^{-1} were used, based on the laboratory results previously obtained.

Figure 13a shows the relationship between the mechanical effects (see Equation (1)) and the wave period, when the natural period is set to 1.75, 1.98, and 2.42 s, respectively. Previous research [16,75,76] has shown that when the wave period is close to the natural period, mechanical power increases, and when the wave period is far from the natural period, it decreases significantly. For instance, when the prototype resonates with a wave period of 2.0 s, the mechanical power is 47.6 W, 3.2 times higher than the mechanical power for a non-resonant wave period of 1.2 s.

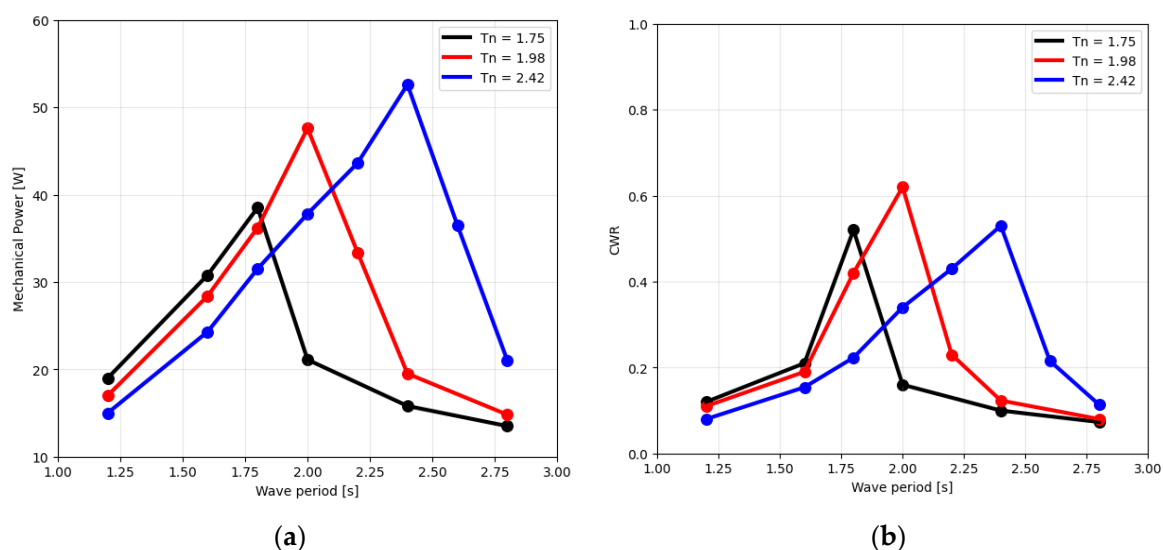


Figure 13. Analysis of the WEC prototype natural periods set at 1.75, 1.98, and 2.42 s: (a) mechanical power; (b) CWR with wave period.

Figure 13b shows the correlation between capture width ratio (CWR) and the wave period. For example, with a natural period of 1.98 s, during resonance at a wave period of 2.0 s, the prototype CWR can attain a value of 0.62, while with a non-resonant wave period of 1.20 s, the CWR is significantly lower, only 0.11. The pattern observed points to a robust connection between the wave period and the efficiency of the prototype in capturing wave energy. During resonant conditions, characterized by the synchronization the natural period of the prototype with the incident wave period, there is a notable surge in CWR, signalling improved efficiency in wave energy capture. Conversely, under non-resonant wave periods, the CWR diminishes, signalling less effective energy capture. These findings highlight the importance of understanding the relationship between the CWR and mechanical power in various operating conditions to optimize performance in various wave scenarios.

4.5. Wave Height Analysis

The effect of constant wave height on the behaviour of the prototype (0.08, 0.1, 0.12, 0.14, and 0.16 m) in resonant mode was explored for wave periods (1.8, 2.0, and 2.4 s), analyzing different metrics and variables. Figure 14a,b illustrate the changes in mechanical power and CWR for wave heights at the specified resonant modes. These periods correspond to the natural frequencies of the device and are critical for understanding its performance in various wave conditions. It was noted that the rise in mechanical power was directly proportional to the increasing wave height, demonstrating an almost linear correlation; the WEC can harness more energy from higher waves. Conversely, the CWR of the prototype falls as wave height increases, highlighting a distinct link between CWR and wave height. This inverse relationship suggests that while more power is captured from higher waves, the efficiency in capture width is reduced. These findings underscore the importance of considering not only the absorbed power, but also the capture width, when designing the oscillating buoy so that it captures wave energy efficiently, particularly in moderate sea conditions.

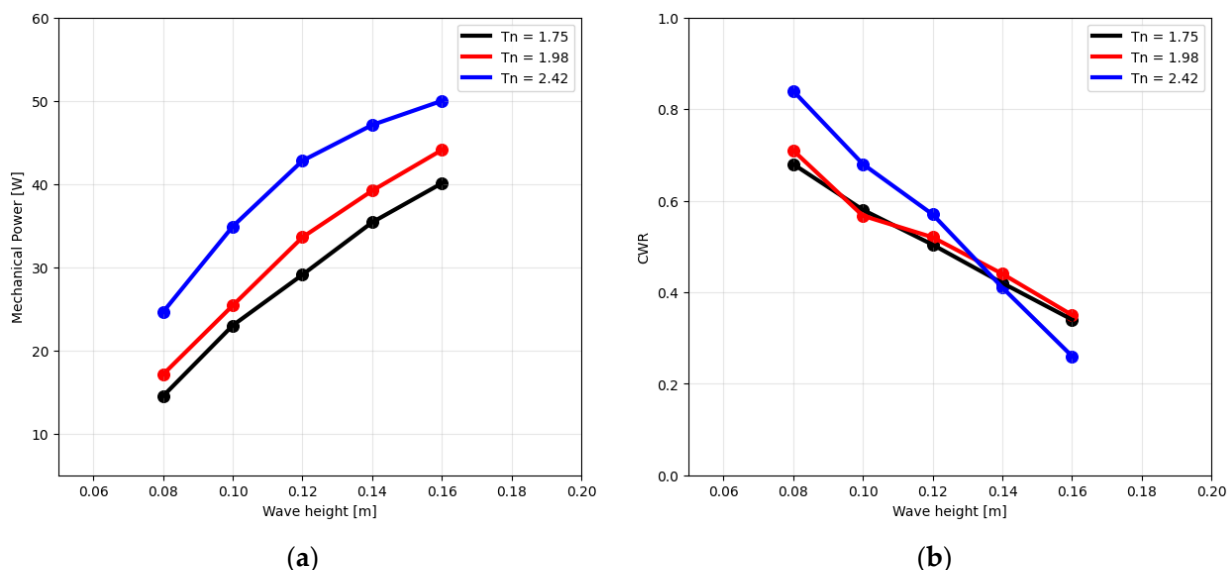


Figure 14. Analysis of the WEC prototype in resonance state: (a) mechanical power and (b) CWR with wave height in regular waves.

Regarding the results in Figure 14b, it is important to note that WEC devices often exhibit nonlinear behaviours, especially under different wave heights. System nonlinearity can significantly affect capture efficiency, leading to a decrease in CWR. Therefore, when theoretically analyzing the behaviour of the prototype under resonant conditions, it is

essential to thoroughly account for the nonlinear effects associated with the WEC's stiffness to ensure an accurate interpretation of the results. This analysis becomes more critical with increasing wave heights, where the nonlinear characteristics of the system may impact capture efficiency differently from those in lower wave heights.

Specific values were selected for wave periods of 1.8, 2.0, and 2.4 s to match the natural frequencies of the device, producing resonance conditions, as observed in other experimental hydrodynamic research on similar systems, such as [77–79]. By addressing both resonant modes and the impact of wave height, it is hoped that this analysis will provide a comprehensive understanding of the WEC performance, to assist in design optimizations in the future for various sea states.

4.6. Effect of the Capture Width Ratio and Buoy Diameter

This section considers the impact of varying buoy diameters on the prototype performance in a resonant state, which is a crucial factor in overall device efficiency. The normalized buoy diameters (R/λ) were assessed at values of 0.05, 0.10, and 0.20, taking into account different wave height variations (0.08, 0.10, 0.12, 0.14, and 0.16 m) and a constant 2.0 s wave period, see Figure 15.

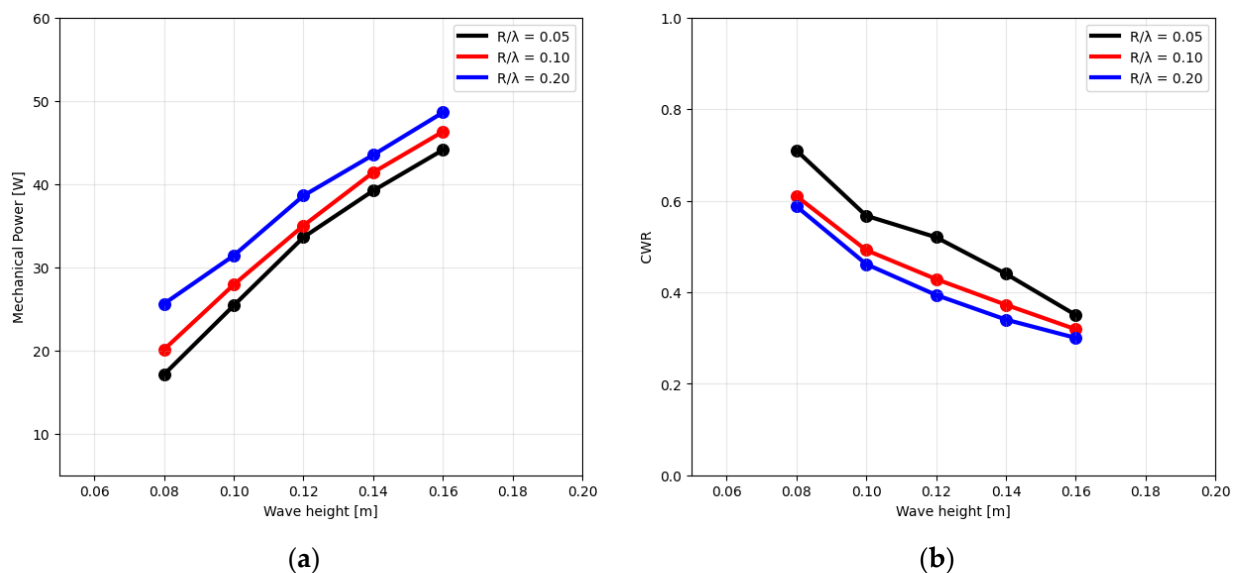


Figure 15. Analysis for different values of the normalized buoy diameter (radius/wavelength) for the natural period $T_n = 2.0$ s: (a) mechanical power; (b) CWR with wave height.

In Figure 15, the effects of the buoy diameter are seen in the power absorption of the prototype for 0.2, 0.4, and 0.8 m diameters. A detailed analysis of Figure 15a shows that the change in diameter produces a relatively modest effect on the absorbed power. Although a larger buoy diameter increases the force of water on the buoy, thus assisting the turning of the mechanism, this increase does not bring a significant change in absorbed power. It is important to highlight that when comparing buoys at the same depth, the absorbed power ratio can vary between 1.8 (under mild sea conditions) and 2.1 (in energetic sea conditions). Thus, a smaller buoy diameter would be better in mild sea states since its capture width would be greater, as shown in Figure 15.

The capture width ratio in Figure 15b is higher for smaller diameters, as illustrated in Figure 14b: a diameter of 0.2 m ($R/\lambda = 0.05$), followed by 0.4 m ($R/\lambda = 0.10$), and lastly 0.8 m ($R/\lambda = 0.20$). This underscores the necessity of considering both the absorbed power and the capture width in optimizing the oscillating buoy design for efficient wave energy capture, particularly in moderate sea conditions. Previous studies, such as [75,80], have

demonstrated the critical role of capture width in evaluating the performance of wave energy converters, aligning with our findings on the effect of buoy diameter on CWR.

The capture width ratio trend arises from the increasing influence of nonlinear energy dissipation mechanisms—particularly viscous drag, internal friction in the PTO system, and hydrodynamic nonlinearities—as wave height increases. While the total wave power scales quadratically with wave height, the rate at which the WEC effectively absorbs energy does not follow this trend due to amplified losses.

The capture width ratio (CWR) is defined in Equation (2). With increasing H , the denominator of Equation (2) increases significantly, while the absorbed power is constrained by nonlinear effects such as enhanced viscous resistance, reduced PTO efficiency, and phase mismatch between buoy motion and wave excitation. These mechanisms limit energy transfer, causing a decline in CWR despite higher incident wave energy.

5. Conclusions

The present study demonstrated the effective coupling of experimental and numerical methods for evaluating the performance of a flywheel-based oscillating buoy-type WEC. Through a combination of regular wave tank testing and advanced CFD modelling in OpenFOAM, the study established a strong agreement between measured and simulated results, with RMSE values below 0.7% and high correlation indices (Willmott > 0.97 , $R^2 > 0.98$). Rigorous mesh sensitivity and phase tracking analyses were used to ensure the quality of the numerical model results. The results show that the prototype can efficiently convert wave energy in various regular wave conditions, confirming its potential for deployment in areas such as La Guajira, Colombia.

It was shown that smaller devices, while capturing less total power, offered superior capture width in moderate sea states, suggesting a design optimization path based on sea climate dynamics. A wide range of wave heights and periods were tested to demonstrate the operation of the device and its efficiency. These results also provided valuable input for developing and refining a Computational Fluid Dynamics (CFD) model, enabling a detailed analysis of WEC behaviour under various wave conditions.

The research also identified the nonlinear behaviour of the capture width ratio (CWR) with respect to wave height, showing a critical commitment between absorbed power and energy capture efficiency. The analysis showed that while mechanical power increases with wave height, almost linearly, CWR decreases under energetic conditions, indicating the onset of hydrodynamics damping and deformation effects. Additionally, the investigation into buoy diameter suggest that smaller devices may offer better performance in moderate seas, due to their enhanced capture width, whereas larger diameters favour mechanical stability in energetic conditions.

The CFD simulations provided insight into the temporal dynamics of wave-buoy interaction, confirming the importance of synchronizing the natural frequency of the WEC with dominant wave periods to maximize energy extraction. The identification of phase resonance as a governing mechanism for energy amplification reinforces the need for sea-state-specific tuning in WEC design. These findings offer a solid foundation for optimizing buoy geometry and PTO systems in future applications.

Future work should focus on irregular wave conditions, integrate real-time PTO feedback, and explore field-scale deployments in Caribbean environments like La Guajira. By addressing both theoretical modelling and practical performance metrics, this study contributes toward the next generation of robust and site-adaptable wave energy converters.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en18164383/s1>, Video S1: WEC_animation.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A Mesh Convergence Analysis

A mesh convergence study was performed to determine the optimal spatial discretization for the computational domain. Different mesh configurations with three discretization levels (coarse, medium, fine) were tested. The numerical uncertainty for the wave crest and trough representation was calculated using the statistical parameters RMSE, R^2 , Bias, and Willmott root mean square error. Configuration C3 was selected for the final simulations as it provided an uncertainty value below 1% for key wave parameters.

Table A1. Discretization level on the x -axis.

Configuration	Discretization Level ΔX			RMSE	R^2	Bias	Willmott
	Coarse	Medium	Fine				
C1 (mm)	350	150	50	0.016	0.890	0.150	0.850
C2 (mm)	200	100	35	0.012	0.940	0.09	0.890
C3 (mm)	150	70	20	0.005	0.990	0.01	0.990
C4 (mm)	100	50	10	0.004	0.992	0.009	0.991

Appendix B Hydrodynamic Efficiency vs. Wave Height

Figure A1 in this Appendix B presents the relationship between hydrodynamic efficiency (ϵ) and wave height (H_{sc}). The results indicate that for lower wave heights 0.08 m, efficiency remains relatively low across all periods. However, as wave height increases, efficiency improves significantly, particularly at wave heights around 0.12 m. This trend demonstrates that higher wave heights provide more favourable conditions for energy capture, especially in the resonance region $T_{sc} = 2.0$ s. Beyond this, efficiency decreases slightly due to nonlinear effects, such as wave breaking and increased energy dissipation. These findings further validate the critical role of wave height in optimizing WEC device performance.

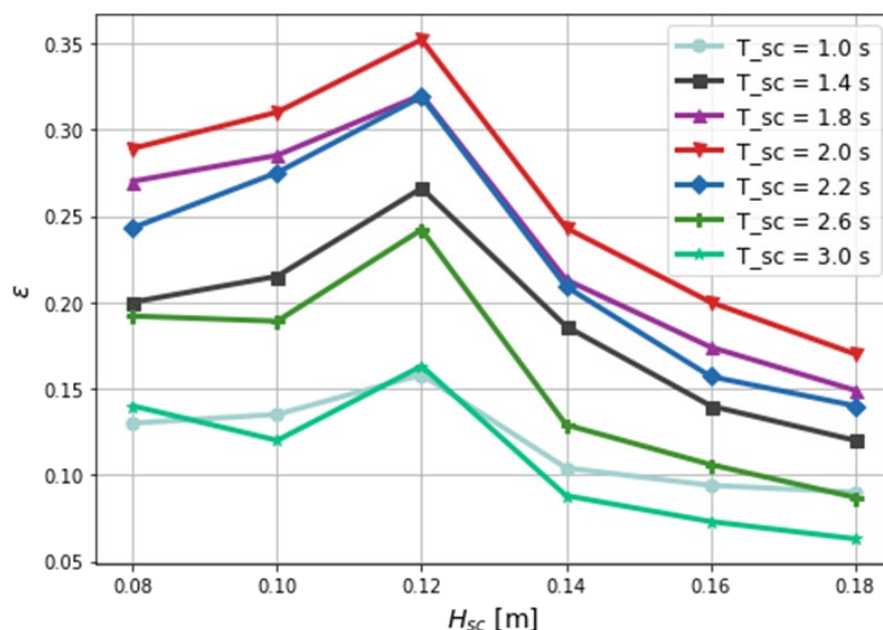


Figure A1. Hydrodynamic efficiency (ϵ) versus wave height (H_{sc}) for the oscillating buoy model for different wave periods.

The harmonic decomposition of the wave series before and after the WEC device, presented in Appendix B (Figure A2), provides critical insights into the interplay between wave harmonics and energy conversion processes. This analysis reveals the amplitudes of the harmonic components (a and b) and their contribution to the resulting wave profile $x(t)$ over time, underlining the significant changes in wave dynamics induced by the WEC. These harmonic shifts are particularly relevant for understanding the redistribution of energy across different frequency bands, which directly impacts the device's energy capture efficiency. The inclusion of the JONSWAP spectrum (Figure A3) further emphasizes the role of spectral characteristics in shaping WEC performance. By characterizing the wave field conditions and their harmonic content, the analysis establishes a direct relationship between the spectral energy distribution and the WEC's design parameters, such as resonance tuning and structural geometry. This connection underscores the importance of harmonics in optimizing WEC configurations, particularly in accounting for the energy concentration and variability inherent in real-world wave climates, as described by the JONSWAP spectrum.

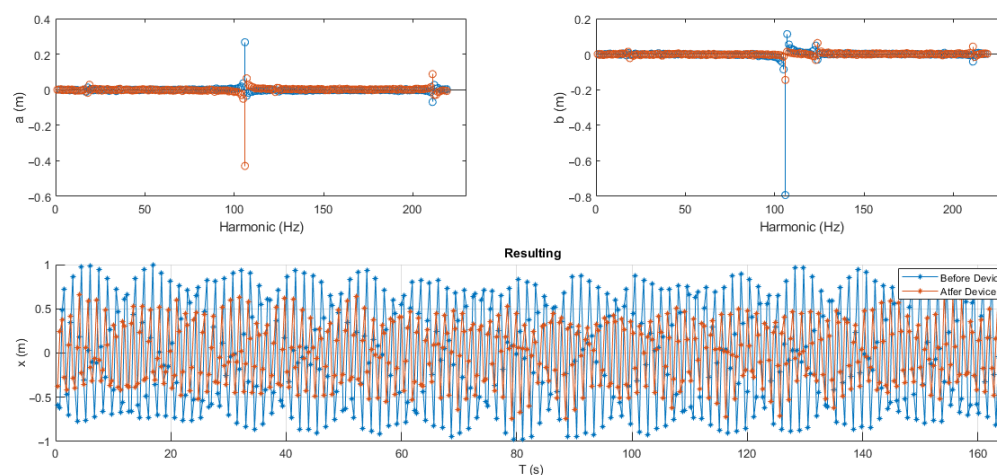


Figure A2. Analysis of variance of wave series before and after the WEC device for full-scale values $H_s = 0.12$ m and $T_p = 2.0$ s. Blue represents the wave signal before the device, and orange represents the wave signal after the device.

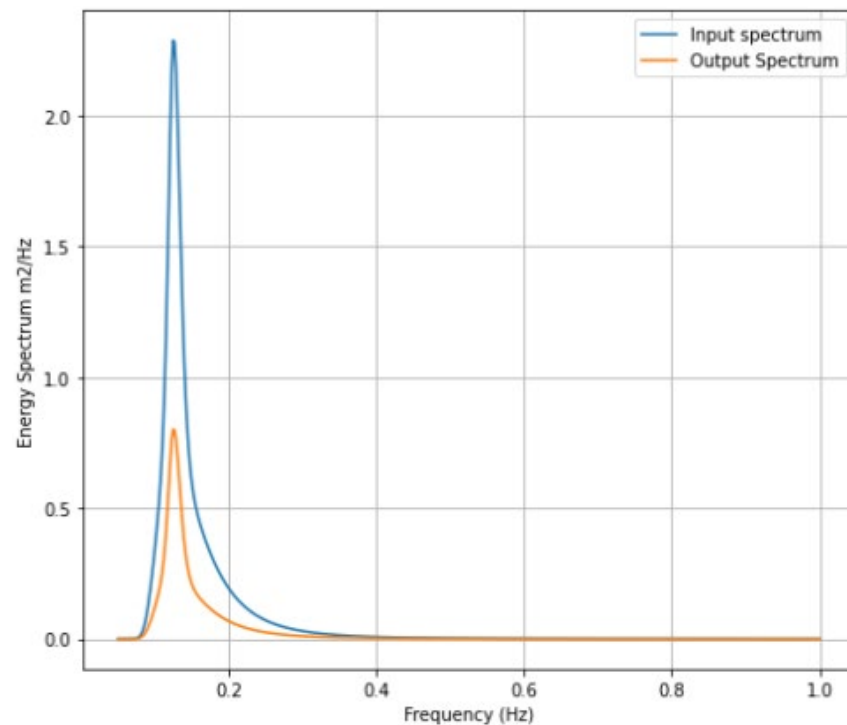


Figure A3. JONSWAP spectrum before and after the WEC device for full-scale values $H_s = 0.12$ m and $T_p = 2.0$ s.

Appendix C Spectral Coherence

The figure below shows the spectral coherence between the wave elevation $\eta(t)$ and the buoy velocity $\mu(t)$, based on high-frequency experimental measurements. A strong coherence peak is observed near 0.5 Hz, with values exceeding 0.9, indicating a high degree of phase locking between the excitation (wave) and the system response (buoy motion) at this frequency. This behaviour is consistent with resonant conditions, where the buoy reaches maximum kinetic energy while synchronized with the wave oscillation. Outside this dominant frequency, the coherence drops, confirming that the system is predominantly tuned to a narrow frequency band

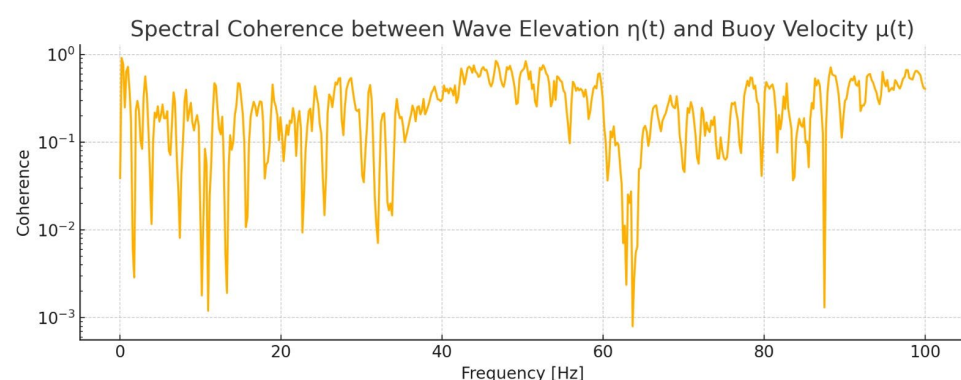


Figure A4. Spectral coherence between measured wave elevation.

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