



A high-efficiency dual-impact horizontal rotor wave energy converter: Design, analysis, and experimental tests

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ABSTRACT

To tackle the challenge of low power generation efficiency of wave energy converters in short-period, low-wave-height sea conditions, this study innovatively proposes a dual-impact horizontal rotor wave energy converter (DHRWEC) system. The system employs a horizontal rotor, designed based on involute principles, as its core component to efficiently capture wave energy through co-rotational motion. The VOF method was employed, and wave types were selected based on wave numerical theory. The Realizable- $k-\epsilon$ turbulence model was selected to establish a numerical wave tank. In the numerical wave tank, the variations in rotor speed and torque for different blade counts were studied, revealing that a blade count of 22 yielded relatively optimal rotor speed and torque, preliminarily determining 22 as the blade count. A physical model was constructed, and wave flume experiments were conducted under short-period, low-wave-height conditions. Experiments show that rotor speed is a critical factor affecting energy conversion efficiency during stable operation, particularly excelling under short wave periods (1.9 s) and low wave heights (0.10 to 0.14 m). An engineering prototype was manufactured, and sea trial experiments were conducted. Sea trial results show that the DHRWEC system achieved a power generation efficiency of 21.33 % under test conditions, significantly outperforming conventional devices. Numerical simulations and experiments collectively validate its superior energy conversion performance.

1. Introduction

In modern society, energy is not only the driving force behind industrial progress but also a key factor in ensuring the stable development of a nation's economy (Nguyen et al., 2020; Østergaard et al., 2020; Segura et al., 2018). With the gradual depletion of traditional energy sources, developing new energy to meet the increasing energy demand has become a common goal for countries around the world (Wang et al., 2018). Promoting the widespread adoption of renewable energy and increasing its share in the energy mix have been proven to be crucial strategies for mitigating energy crises and advancing sustainable development (Østergaard et al., 2020). Thanks to continuous advancements in science and technology, the utilization of renewable energy has achieved significant progress, among which biomass energy and marine renewable energy are considered to have great development potential

(Farrok et al., 2020; McTiernan and Sharman, 2020). Marine energy, a vital component of renewable energy systems, originates from seawater, which covers approximately 71 % of the Earth's surface, offering a clean and sustainable natural resource (Khojasteh et al., 2023; He et al., 2023; Choupin et al., 2022; Teixeira-Duarte et al., 2022; Weiss et al., 2018). It encompasses a diverse range of forms, including offshore wind energy, wave energy, tidal energy, temperature gradient energy, ocean current energy, salinity gradient energy, and marine solar energy, providing vast prospects for global energy development (Melikoglu, 2018; Contestabile et al., 2020; E Zavvar et al., 2025). In coastal regions, the intensity and persistence of sea winds significantly influence wave energy distribution, with areas experiencing higher and more stable wind speeds typically possessing richer wave energy resources, where an increase in wind speed directly correlates with enhanced wave energy (Pablo-Romero et al., 2021; Ivanovski et al., 2021; Lehmann et al.,

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2017). Wave energy converters, designed to capture and convert ocean wave energy, are classified into three main types based on their operating principles and structural characteristics: point absorbers, oscillating water columns (OWC), and overtopping devices, these devices play a crucial role in advancing marine energy utilization (Gubesch et al., 2022; Gallutia et al., 2022; Zheng et al., 2024; Ahamed et al., 2020; Zabihi et al., 2021). However, these devices face significant challenges in practical applications, including low energy conversion efficiency, limited durability in harsh marine environments, high costs, and potential environmental impacts (Faedo et al., 2022). Particularly in short-period, low-wave-height sea regions, which are widely distributed globally and cover vast areas, the low wave energy density poses substantial difficulties for energy capture, resulting in significantly limited efficiency of conventional wave energy converters, failing to meet the demands for efficient energy conversion. Consequently, there is an urgent need to develop a wave energy converter tailored for short-period, low-wave-height conditions (Gong et al., 2022). In this context, this study proposes and designs a novel direct-drive Dual-Impact Horizontal Rotor Wave Energy Converter (DHRWEC) system (Zhang et al., 2023; Jin et al., 2022).

The energy captured by wave energy conversion devices is distributed over a range of frequencies (Ahn et al., 2022). This requires the energy harvesting mechanism of the wave energy generation device to operate within the same frequency range as the primary wave energy frequency band to absorb wave energy for conversion (Dunkle et al., 2022; Cai et al., 2022). Consequently, most wave energy generation devices are designed based on the resonance theory. When resonance occurs between the wave and the device, the natural period of the device matches the motion period of the wave, resulting in the highest wave energy capture efficiency for the device (Shami et al., 2019). However, when the natural period of the wave energy capture device deviates from the dominant motion period of the wave, the energy capture efficiency gradually decreases. Muliawan developed a new energy conversion system (MJ Muliawan et al., 2013; MJ Muliawan et al., 2013). This combined power generation system integrates floating wind turbines and wave energy converters, optimizing marine space utilization and improving energy output efficiency. Zavvar have conducted in-depth research on the structural composition and mooring stability of these offshore power generation floating platforms (E Zavvar et al., 2025; Zavvar et al., 2023). Kim et al. developed a sealed wave energy conversion device that directly drives power generation through the impact of waves on a horizontal rotor within a flow channel. A physical model of the device was constructed, and a six-degree-of-freedom platform experiment was conducted. The device demonstrated very high primary wave energy conversion efficiency and excellent overall sealing performance. If applied to practical prototypes, it is believed that the device would exhibit high reliability (Kim et al., 2015). Currently, most wave energy converters rely on hydraulic components for energy conversion, while experimental studies on horizontal rotor wave energy converters remain relatively limited (Elbatran et al., 2018). To address this challenge, this study proposes and designs a novel direct-drive Dual-Impact Horizontal Rotor Wave Energy Converter (DHRWEC) system (Z Meng et al., 2022). By optimizing the rotor structure and energy capture mechanism, the system aims to enhance wave energy conversion efficiency in short-period, low-wave-height sea conditions, offering a sustainable energy solution for coastal and remote island regions (Z Meng et al., 2022).

2. Working principle of the DHRWEC system

In sea areas with low energy flux density, the wave motion cycle is relatively short, typically ranging from 3 to 6 s. This study draws on the design and operational principles of oscillating water column (OWC) wave energy devices and hydraulic turbines. A dual-impact horizontal rotor wave energy conversion device is employed to achieve efficient wave energy capture. By optimizing the design of the flow channel in the

capture device, the water motion within the channel exhibits periodic changes during wave impact and backflow movements. The working principle is illustrated in Fig. 1. As a result, the operating frequency of the device can adapt to variations in the primary frequency of wave impacts, enabling effective wave energy capture and conversion into electricity (Z Meng et al., 2022).

By optimizing the inlet and outlet flow channels of the horizontal rotor, the device achieves synchronized rotational motion. The device utilizes the impact force of waves to drive the horizontal rotor, while the water level at the outlet gradually rises, converting the wave's kinetic energy into the potential energy of the water body. During the wave's backflow, the water level decreases, and the potential energy of the water body is converted back into kinetic energy, which continues to drive the horizontal rotor. Through one complete cycle of wave impact and backflow, the device efficiently completes the mutual conversion between the kinetic and potential energy of the water body, providing continuous energy to drive the rotor's rotation.

3. Theoretical methodology

The horizontal rotor was designed based on involute theory, leveraging its geometric properties to precisely construct and Optimize the number of blades, significantly enhancing the rotor's interaction efficiency with waves, thereby improving wave energy capture and conversion performance. This design approach not only enhances the rotor's adaptability to short-period, low-wave-height sea conditions but also provides a robust theoretical foundation for the efficient operation of the DHRWEC system in complex marine environments. The horizontal rotor and its blades were preliminarily designed in this study, with detailed research and optimization of the rotor and blade configuration to be conducted in future work.

The rotor diameter was selected as the characteristic dimension for the test model design, with the sea-trial prototype's horizontal rotor initially designed at a diameter of 625 mm. For experimental validation, a physical model was fabricated at a 1:2.5 scale, resulting in a model rotor diameter of 250 mm, ensuring accurate testing in a wave flume. Detailed dimensional parameters of the horizontal rotor are provided in [Table 1](#), offering data support for subsequent simulations and experiments. The specific structure of the involute horizontal rotor, including the involute curves of the blades and the overall rotor layout, is illustrated in [Fig. 2](#). This design establishes a solid foundation for the efficient operation of the DHRWEC system in short-period, low-wave-height sea conditions.

The specific parameters of the selected involute blades are:

$$D_2 = 0.65D_1 \quad (1)$$

In the formula: where D_1 is the inner diameter of the rotor, and D_2 is the outer diameter of the rotor.

The involute equation is:

$$X = r(tsint + cost) \quad (2)$$

$$Y = r(\text{ sint} - t\text{cost}) \quad (3)$$

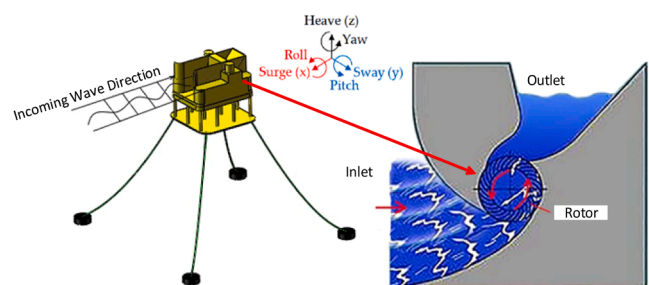
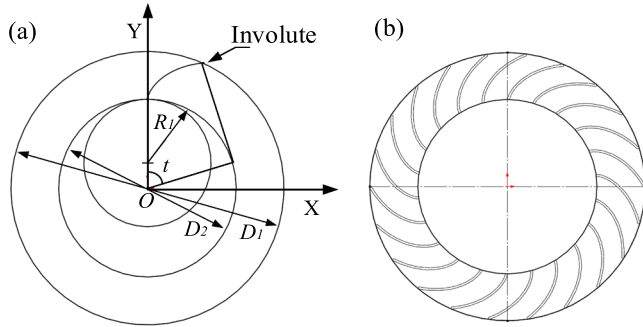


Fig. 1. Principle of power generation.

Table 1

Main design parameters of an involute horizontal rotor.

Parameter	Symbol	Numerical value	Unit
Rotor outer diameter	D_1	250	mm
Rotor inner diameter	D_2	162.5	mm
Involute base circle radius	R_1	$0.233D_1$	mm
Number of blades	Z_z	22	piece

**Fig. 2.** Involute horizontal rotor. (a) parameter relationship. (b) blade shape.

In the formula: where r is the radius of the base circle, and t is the spread angle range of the involute. The parameter t represents the central angle of the tangent point on the base circle. As the string is unwound, the tangent point rotates along the base circle, causing t to gradually increase, and the involute point P moves farther away from the circle's center.

4. Fluent numerical simulation

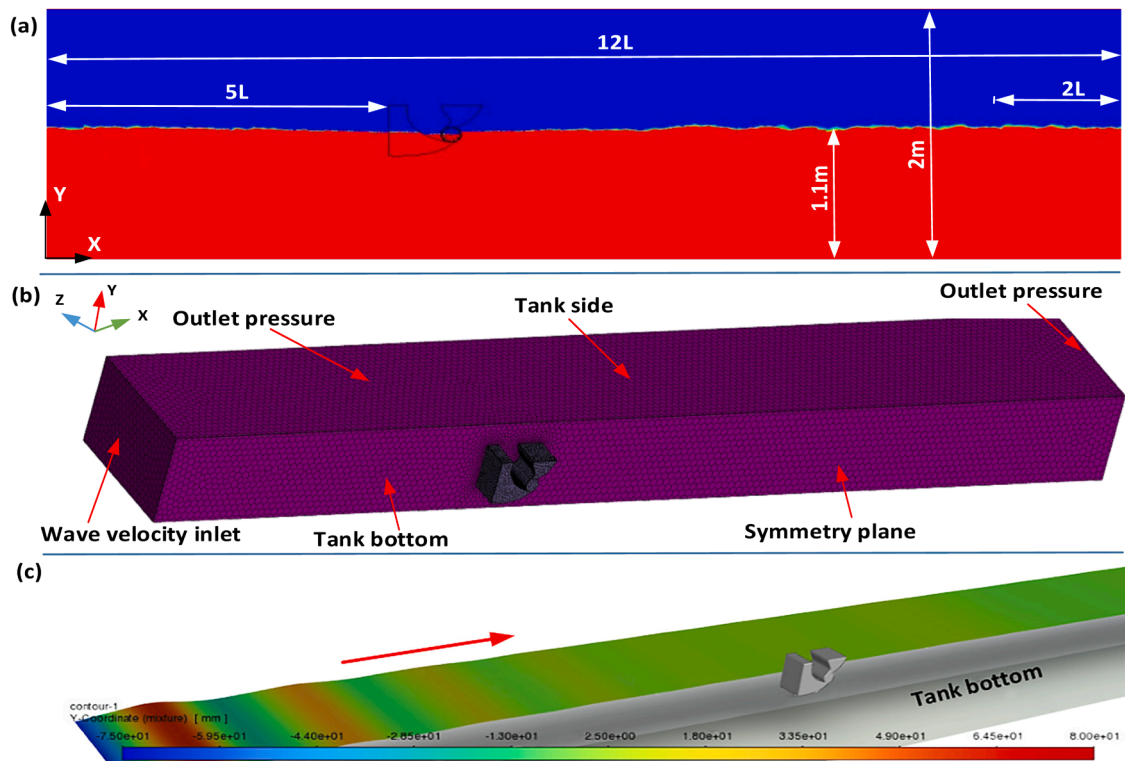
The horizontal rotor and the surrounding flow field were modeled

using SolidWorks, and hydrodynamic simulations were conducted with the Fluent module in ANSYS Workbench (Cui et al., 2019; Zhang et al., 2022). The computational domain and boundary conditions adopted in this study are illustrated in Fig. 3 (A Elhanafi et al., 2017). To ensure accurate numerical results and minimize artificial wave reflections near the DHRWEC model and the outlet boundary, the dimensions of the numerical tank were optimized rather than directly replicating those of the experimental facility. A tank length of 12 L, where L denotes the wavelength of the incident wave, was found sufficient to produce approximately ten complete regular wave cycles during the simulation (Choi and Yoon, 2009). The model was positioned 5 L from the wave-making boundary to allow full wave development prior to interaction with the device, as shown in Fig. 3(a).

The damping zone length is a key factor influencing the attenuation of reflected waves. A Elhanafi et al. (2017) suggested that the damping zone should exceed one wavelength to effectively absorb reflected energy. However, due to the radiation generated by the oscillatory motion of the DHRWEC, a longer region was necessary. Numerical testing indicated that a damping zone length of 2 L effectively dissipated residual waves, which was therefore adopted in this study. The flow was assumed to be incompressible and viscous, and the governing equations were solved using the finite volume method. The free surface motion was modeled with the VOF approach to accurately capture the air–water interface and wave–structure interactions, as shown in Fig. 3(b).

4.1. Fluid domain preprocessing

The geometric model developed in SolidWorks was imported into the preprocessing environment for domain definition and mesh generation (Magkouris et al., 2020). The computational domain was divided into distinct regions representing the rotor and surrounding fluid to ensure accurate flow interaction. The rotor zone was defined separately to avoid numerical interference with the stationary domain. Local mesh refinement and boundary layer grids were introduced near the rotor,

**Fig. 3.** Computational fluid domain (not to scale). (a) overall dimension setup. (b) boundary conditions and mesh generation. (c) schematic diagram of wave generation in the numerical wave tank.

duct wall, and outer boundaries to capture velocity gradients and shear effects with higher precision. Consistent size control was applied to maintain smooth mesh transitions between regions. The resulting unstructured hybrid mesh, composed of triangular and tetrahedral elements, provided sufficient flexibility and accuracy for resolving the complex multiphase flow characteristics within the computational domain.

4.2. VOF method

The VOF multiphase model was employed to resolve the air-water interface and reproduce realistic free-surface wave conditions. An implicit formulation was applied to enhance numerical stability, and gravity was included as a body force in the momentum equations. Air and water were defined as the primary and secondary phases, respectively, with a surface tension coefficient of 0.07 N/m. The Shear Stress Transport (SST) turbulence model was used owing to its ability to accurately predict flow separation and shear effects under oscillatory wave conditions. The detailed numerical parameters and boundary condition settings are summarized in Table 2.

F is a function of spatial points and time. The fluid volume fraction function F_q is defined as the ratio of the volume occupied by the q phase fluid within a cell to the total volume of that cell. That is, if $F_q = 1$, it indicates that the cell is entirely occupied by the q phase fluid; if $F_q = 0$, it means there is no q phase fluid within the cell; if $0 < F_q < 1$, the cell is an interface unit between the two media. For wave problems, since there are only two phases (gas and liquid), $q = 1$ or 2 . F_q satisfies the equation:

$$\frac{\partial F_q}{\partial t} + \frac{\partial(uF_q)}{\partial x} + \frac{\partial(vF_q)}{\partial z} = 0, q = 1, 2 \quad (4)$$

$$\sum_{q=1}^2 F_q = 1 \quad (5)$$

The physical property parameter ϕ within a certain control volume is calculated as follows:

$$\phi = \phi_1 F_1 + \phi_2 F_2 \quad (6)$$

The inlet boundary of the computational domain was defined as a velocity inlet, while the upper surface and outlet were treated as pressure outlets, and the remaining boundaries as solid walls. A free-surface condition was applied at the inlet to generate incident waves represented by second-order Stokes theory, enabling accurate simulation of nonlinear wave propagation. The initial water surface was set at 0 m, corresponding to the rotor center, and the bottom boundary at -1.5 m. The wave parameters included a period of 3 s, wavelength of 3 m, height of 1.5 m, and a heading angle of 120° , corresponding to an average inflow velocity of 1 m/s. The SIMPLE algorithm was used for pressure-velocity coupling, with a time step of 0.01 s and a total of 500 steps (30 iterations per step). The torque on the rotor wall was monitored to evaluate hydrodynamic performance, and the initial conditions are shown in Fig. 3(c).

4.3. CFD-POST processing

Post-processing was conducted in CFD-Post to analyze the transient hydrodynamic behavior of the DHRWEC. Density and pressure contours

on selected cross-sections were examined to visualize the interaction between the incoming waves and the rotor, as well as the corresponding pressure distribution at the duct inlet and outlet. Time-dependent flow fields were analyzed to identify the evolution of wave impact and energy conversion during each simulation cycle, providing a clear understanding of the unsteady flow characteristics and pressure variations within the ducted rotor system.

4.4. Simulation results analysis

4.4.1. Hydrodynamic analysis

Fig. 4 presents the evolution of the fluid density field around water turbine rotors with different blade numbers ($n = 8, 14, 18, 22, 26$, and 30) at representative time steps ($t = 0.6$ s, 1.0 s, 1.6 s, and 2.0 s) during the wave impact and backflow phases. The results reveal that the flow structure and density distribution are strongly influenced by the number of blades. During the initial impact stage ($t \approx 0.65$ s), a primary vortex forms slightly upstream of the rotor, accompanied by a steep density gradient between air and water phases. As n increases, the vortex intensity and density non-uniformity are amplified, indicating enhanced flow disturbance and stronger wavestructure interaction.

At the peak impact stage ($t \approx 1.0$ s), the wave front reaches its maximum momentum exchange with the rotor, and high-density zones become more concentrated near the blade tips, particularly for $n \geq 26$, suggesting increased turbulence and local pressure amplification. During the subsequent backflow stage ($t \approx 1.6$ s), the recirculation region extends downstream, and the flow field gradually stabilizes, though residual vortices persist for larger n . Overall, increasing the blade number intensifies vortex complexity and enhances turbulence within the wake region, leading to stronger energy dissipation but potentially reducing the rotor's hydrodynamic stability.

4.4.2. Impact of rotational speed and torque

The numerical wave model was established based on realistic sea state parameters to simulate actual marine conditions. The hydrodynamic response of the horizontal rotor, including torque and rotational speed, was analyzed under varying operational scenarios to evaluate its performance and dynamic stability in wave-induced flows. Fig. 5 presents the performance parameters of a horizontal rotor with varying blade numbers ($n = 8, 14, 18, 22, 26, 30$) under wave impact and backflow conditions over time. Fig. 5(a) illustrates the rotor's rotational speed (rad/s) as a function of time (s), while Fig. 5(b) depicts the moment (N·m) experienced by the rotor over time (s). Increasing the blade number from 8 to 30 significantly enhances both the rotational speed and moment peak values but also amplifies fluctuations and instability. At $n = 8$, the rotational speed is the lowest (1.5 rad/s) and the moment peak is the smallest (0.5 N·m), yet it exhibits the least fluctuation and the highest operational stability. Conversely, at $n = 30$, the rotational speed reaches the maximum (2.5 rad/s) and the moment peak is the highest (1.75 N·m), but both speed and moment fluctuations are the most severe, indicating the poorest stability. For $n = 14, 18, 22$, and 26 , the rotational speed and moment values increase progressively, with fluctuations intensifying accordingly. Physically, a higher blade number strengthens the rotor-fluid interaction, enhancing driving force and rotational speed, but it also increases flow field complexity, vortex, and turbulence effects, leading to greater fluctuations that may adversely affect the rotor's long-term operational efficiency and structural

Table 2
Numerical simulation analysis conditions.

Numerical wave tank		Numerical model		Number of mesh cells		Wave generation parameters	
Length(m)	30	Length (m)	0.8	External tank domain	809,682	Wave height (m)	0.1
Width (m)	2	Width (m)	0.26	Turbine flow channel domain	549,704	Period (s)	2
Depth(m)	2	Depth (m)	0.6	Rotor rotation domain	6067,236	Wave theory	Second Order Stokes
—	—	Draft depth (m)	1.11	—	—	Inlet flow speed (m/s)	1

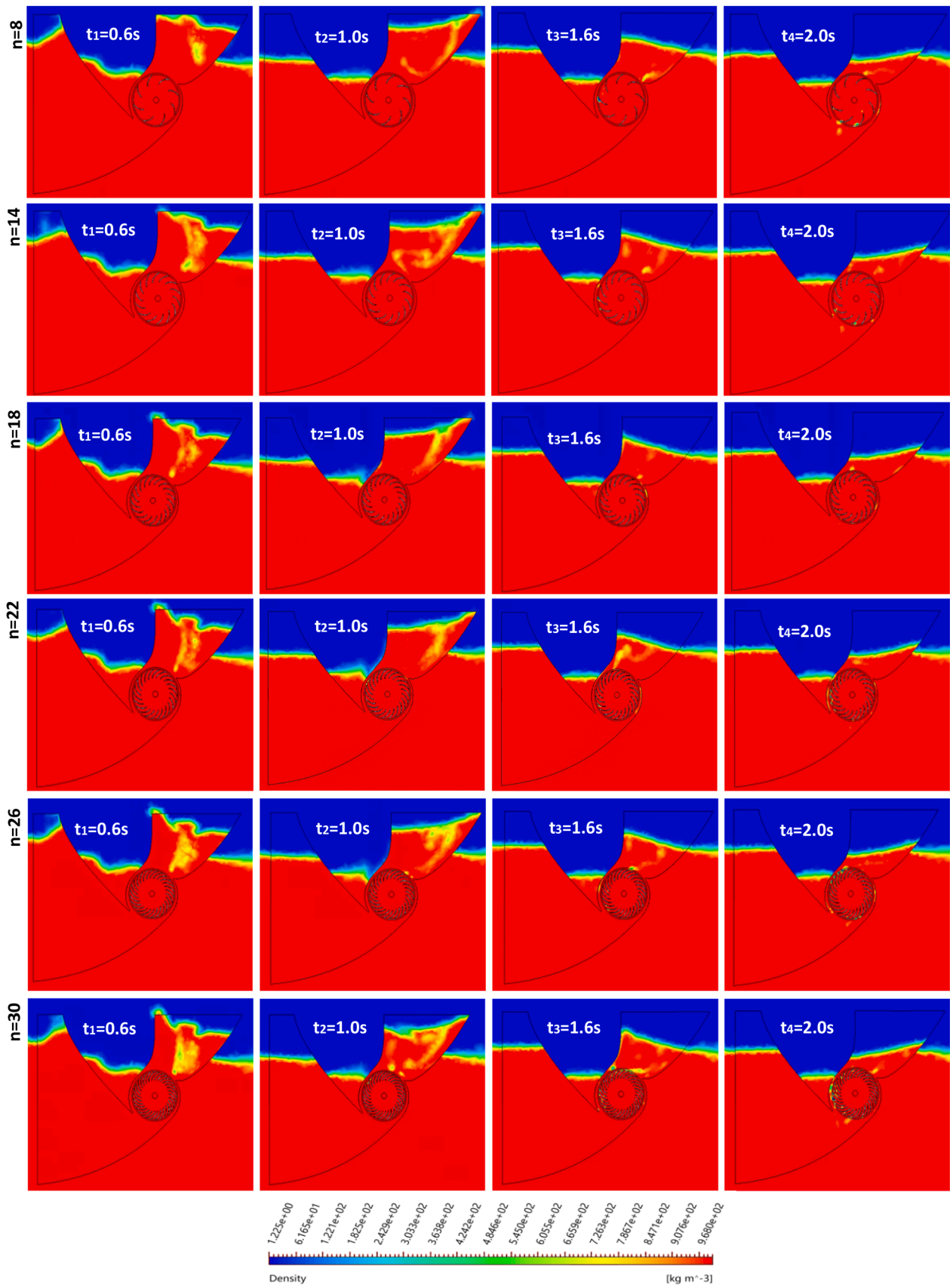


Fig. 4. Fluid density cloud maps of wave impacts on horizontal rotors with different blade numbers.

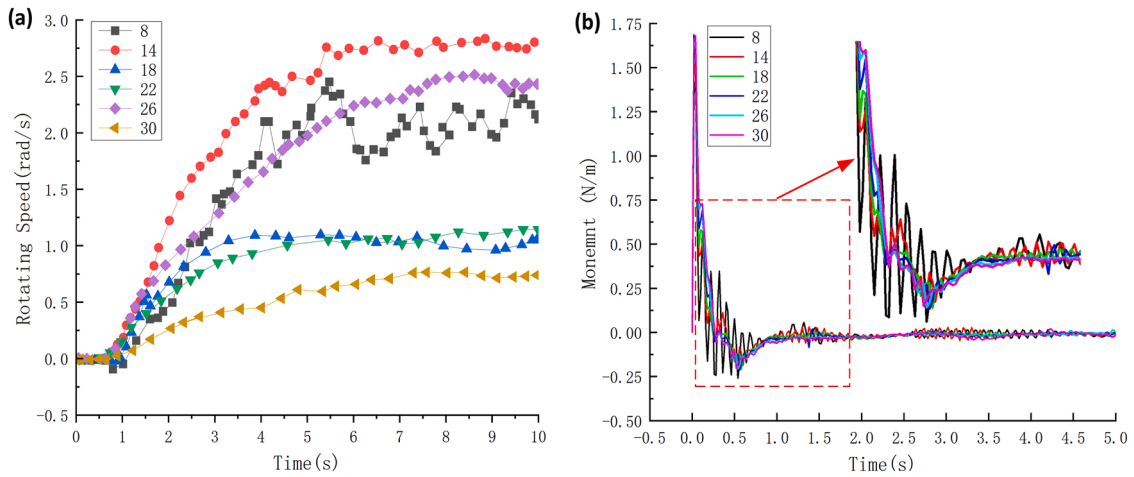


Fig. 5. Rotational speed and torque. (a) rotor speed. (b) rotor torque.

stability. Selecting the optimal blade number requires balancing rotational speed, moment, and stability. While $n = 30$ achieves the highest speed, its excessive fluctuations may cause structural fatigue and efficiency losses. At $n = 8$, the speed is lower, resulting in insufficient power output. Both $n = 22$ (speed of 2.4 rad/s, moment peak of 1.25 N·m) and $n = 26$ (speed of 2.5 rad/s, moment peak of 1.5 N·m) perform well in terms of speed and moment, with relatively manageable fluctuations. Overall, $n = 22$ is likely the optimal choice, offering a near-maximum speed (2.4 rad/s), a moderate moment peak (1.25 N·m), and lower fluctuations compared to $n = 26$ and $n = 30$, thus balancing performance and stability for long-term operation.

5. Model experiment

The model experiments of the DHRWEC system enable the evaluation and optimization of its performance under controlled conditions and serve to validate the accuracy of theoretical models. These experiments provide valuable insights into the dynamic responses of the system under various wave conditions. Moreover, they assist in adapting the system to specific marine environments and provide critical data support for the development of engineering prototypes.

5.1. Physical model

The horizontal rotor model has a diameter of 250 mm, a length of 800 mm, and 22 involute blades. The number of blades directly affects the capture efficiency of the device for wave energy. Here, 22 blades are selected for testing to prove the energy-capturing mechanism of the device. In the future, horizontal rotors with different numbers of blades will be manufactured to study their effect on energy capture efficiency. In order to overcome the deformations and damages on rotor blades when impacted by water flow, transverse partitions are designed for reinforcement. In order to carry out the test as soon as possible, an integrated horizontal rotor is designed. In the future, the structure of the horizontal rotor will be carefully optimized, and the horizontal rotor with detachable blades will be designed.

Compared to conventional wave energy devices, the DHRWEC system optimizes the energy conversion process through an innovative design approach, significantly enhancing the efficiency of wave energy capture and conversion. The system is designed with a rated power of 6 kW, a total weight of approximately 28 tons, and compact dimensions of 6 m in length, 6 m in width, and 5.4 m in height, making it well-suited for deployment in marine environments. For experimental validation, a scaled physical model, geometrically similar to the engineering prototype, was designed and fabricated at a 1:2.5 scale, as depicted in Fig. 6 (a), while the engineering prototype of the DHRWEC system is shown in

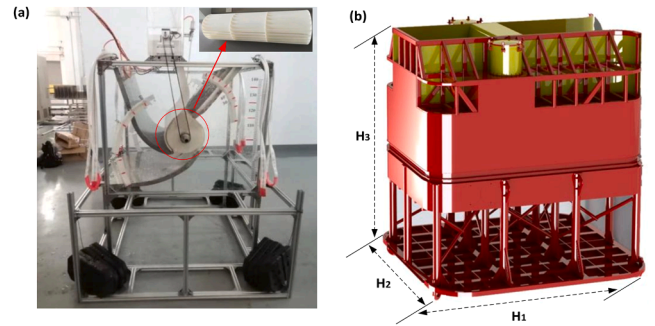


Fig. 6. Model. (a) scaled model. (b) engineering prototype.

Fig. 6(b). During testing, the motion behavior and dynamic response characteristics of the device under wave action were monitored in real time, with model test data used to validate the accuracy of numerical simulations and evaluate the system's power generation performance and stability. To ensure the scientific rigor and reliability of the results, the design parameters between the physical model and the engineering prototype strictly adhered to the principles of fluid mechanics similarity. The tests were conducted based on the Froude similarity law, ensuring similarity in inertial and gravitational forces, while maintaining an equal Strouhal number between the model and the prototype. The DHRWEC system is specifically designed for sea regions with low wave energy density, tailored to short wave periods and low wave heights to achieve efficient wave energy capture and conversion. The sea trial of the engineering prototype was conducted in the sea area near Chengshantou, Weihai, China, located in the Bohai Sea, where wave energy flux density is generally low, making it an ideal site to validate the device's performance under low-energy-density conditions. Detailed dimensional parameters of the DHRWEC engineering prototype and its scaled model are presented in Table 3.

Table 3
Engineering prototype and model prototype dimensions.

Parameter	Engineering Prototype	Model Prototype	Unit
Height(H1)	5.443	1.10	m
Width(H2)	6.000	1.0	m
Height(H3)	5.443	1.80	m
Rotor Diameter	6.250	0.250	m
Rotor Length	2.000	0.800	m

5.2. Model test

The environmental parameters of the wave flume experiment were precisely adjusted based on the principles of fluid mechanics similarity to ensure that the scaled-down parameters accurately reflect the characteristics of real sea conditions. The physical model tests were conducted at the National Key Engineering Laboratory, utilizing a wave flume with dimensions of 30 m in length, 4 m in width, and 3 m in height. The scaled-down model was designed with dimensions of 1.1 m in length, 1 m in width, and 1.8 m in height. The model was hoisted by a crane and precisely positioned 10 m from the wave-making direction, a location selected for its stable wave-making conditions to facilitate smooth experimentation. To ensure the model's stability during testing, the pressure block at its base was secured with counterweights, enhancing its resistance to wave impacts. The primary objective of the regular wave tests was to validate the power generation performance and stability of the model under simulated sea conditions. Under regular wave conditions, the rotational speed and torque driven by the horizontal rotor were measured using a torque sensor, comprehensively documenting the dynamic response characteristics. Additionally, the startup performance of the horizontal rotor from a stationary state to rotation was thoroughly evaluated, and the torque variations of the drive shaft at different rotor speeds were analyzed, providing critical insights for design optimization. The experimental setup consisted of two main components: an external adjustable platform and a core power generation unit, designed to meet diverse testing requirements. To monitor the dynamic wave variations at different locations within the wave flume in real time, five resistive wave gauges (labeled G0-G5) were installed, with their specific arrangement depicted in Fig. 7(a). The

equipment used in the wave flume experiment is shown in Fig. 7(b), providing a clear foundation for subsequent data analysis and result validation.

Wave energy converters are typically deployed in nearshore and coastal regions, where variations in water depth significantly influence their performance. In this study, the experimental water depth was scaled down based on the principles of fluid mechanics similarity, and set at 1.15 m to replicate the water depth conditions of real sea states. During regular wave tests, the research team utilized a data acquisition system to record real-time data on the device's rotational speed and torque. To ensure the stability of the wave generation process in the flume, the ratio of wave height to wavelength was strictly controlled to be $<1/7$, the critical threshold for wave breaking. Exceeding this ratio would result in overly steep waves that break, compromising the reliability of the test results. To systematically evaluate the power generation performance of the device in short-period, low-wave-height sea conditions, the experiments were designed with three combinations of relatively small wave periods and heights, with specific conditions detailed in Table 4. Data analysis was based on regular wave test data spanning more than four complete cycles to ensure result stability. Following the start of the experiment, the wave motion stabilized within approximately 10 s, after which data collection commenced to obtain reliable power generation performance data. Other experimental environment parameter settings are given in Table 5.

5.3. Analysis of experimental results

Fig. 8 illustrates the variations in rotational speed and torque of the horizontal rotor under three distinct operating conditions. In Condition

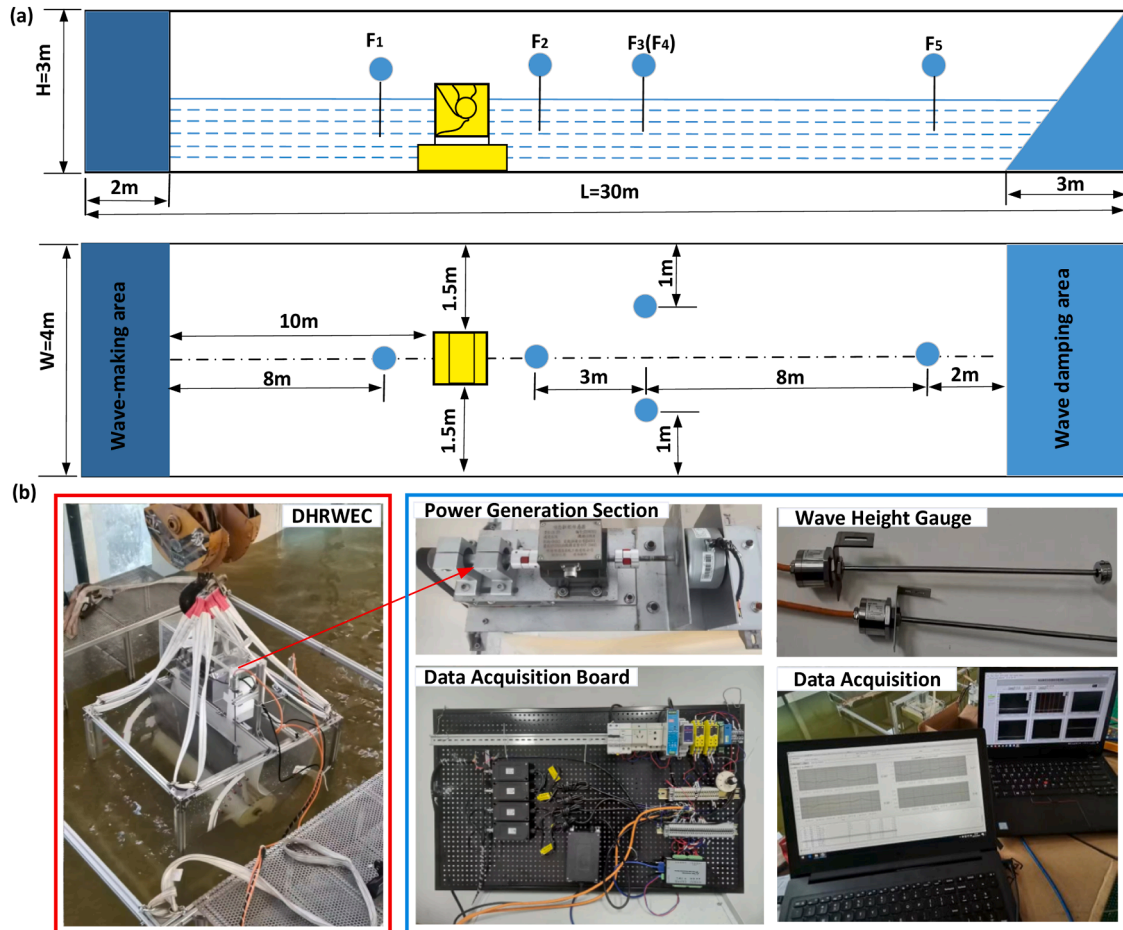


Fig. 7. Experimental setup(non-scale) . (a) deployment of the experimental model. (b) physical model and data acquisition equipment.

Table 4

Regular wave experiment parameters.

Experiment Condition	Prototype Value		Model Value			
	Wave Height H (m)	Cycle T (sec)	Significant wave height H (m)	Cycle T (sec)	Direction (°)	Wave spectrum
Condition 1	0.25	3	0.10	1.9	180	JONSWAP
Condition 2	0.30	3	0.12	1.9	180	
Condition 3	0.35	3	0.14	1.9	180	

Table 5

Other experimental parameters.

Component	Parameter	Value
Wind	Wind speed (m/s)	0.0
	Wind spectrum	NPD
	Direction (°)	0.0
Current	Surface current speed (m/s)	1.0
	Direction (°)	180

1, with a wave period of 1.9 s and a wave height of 0.10 m, the horizontal rotor achieved an average torque of 0.65 N·m and an average rotational speed of 33.48 r/min, demonstrating the device's capability to operate stably and convert energy effectively even at low wave heights. In Condition 2, maintaining the wave period at 1.9 s while increasing the wave height to 0.12 m, the average torque slightly increased to 0.66 N·m, with a modest increment, whereas the average rotational speed significantly rose to 48.14 r/min, indicating a pronounced effect of wave height on rotational speed. Compared to Condition 1, the torque variation was limited, but the increase in rotational speed was substantial, underscoring the device's sensitivity to wave height changes. In Condition 3, with the wave period unchanged at 1.9 s and the wave height further increased to 0.14 m, the average torque

continued to rise modestly to 0.68 N·m, while the average rotational speed further improved to 56.98 r/min, reflecting the sustained enhancement of rotational speed with increasing wave height. Across all three conditions, the generator maintained reliable operation, validating the DHRWEC system's reliability and efficiency in short-period, low-wave-height conditions. These results provide critical data support for the optimization design of subsequent engineering prototypes and further confirm the device's superior performance in low-energy-density sea regions. The average rotational speeds and torques of the horizontal rotor under the three conditions are detailed in Table 6.

The experimental results indicate that the physical model of the

Table 6

The average rotational speed and average torque of the horizontal rotor under different working conditions.

Simulation Condition Parameter	Model Value		Measurement Parameters	
	Wave Height H (m)	Cycle T (sec)	Average Speed (r/min)	Average Torque (N·m)
Condition 1	0.10	1.9	33.48	0.65
Condition 2	0.12	1.9	48.14	0.66
Condition 3	0.14	1.9	56.98	0.68

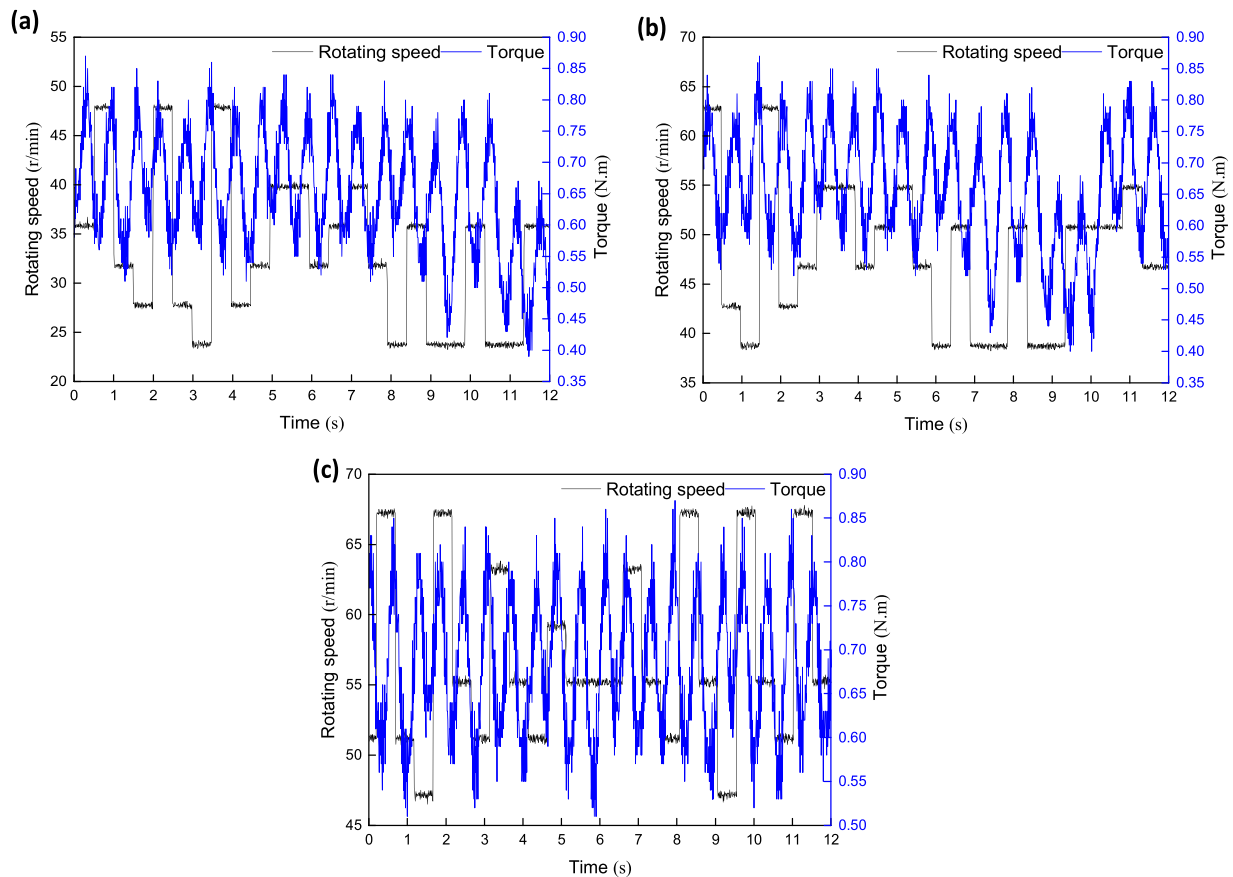


Fig. 8. Torque and rotational speed of the horizontal rotor under different experimental conditions. (a) Condition 1. (b) Condition 2. (c) Condition 3.

horizontal rotor, designed based on the involute equation, can reliably start and operate under regular wave conditions, particularly demonstrating exceptional startup performance and power generation capability in sea conditions characterized by short wave periods and low wave heights. Under test conditions with a short wave period (e.g., 1.9 s) and low wave heights (e.g., 0.10 m to 0.14 m), the horizontal rotor achieves rapid startup even at low wave energy density, showcasing excellent adaptability to short-period, low-wave-height sea regions. Further analysis reveals that, with a constant test period, as the wave height increases from 0.10 m to 0.14 m, both the average torque and average rotational speed of the horizontal rotor exhibit an upward trend. The average torque rises from 0.65 N·m to 0.68 N·m with a modest increase, while the average rotational speed significantly improves from 33.48 r/min to 56.98 r/min, underscoring the substantial impact of wave height on rotational speed.

5.4. Discussion of experimental results

The experimental results indicate that the horizontal rotor wave energy device demonstrates excellent operational stability and power generation performance under different wave height conditions. As the wave height increases from 0.1 m to 0.14 m, the average torque of the horizontal rotor slightly increases from 0.65 N·m to 0.68 N·m, showing minimal variation. This suggests that the effect of wave height on torque is limited, primarily constrained by wave impact forces. However, the rotational speed increases significantly with wave height, rising from 33.48 r/min to 56.98 r/min, indicating that the increase in wave height directly enhances the input wave energy, significantly accelerating the rotor's rotational speed, which is a critical factor affecting device performance. Under all experimental conditions, the generator operates normally, demonstrating that the transmission system is well-designed, and the device exhibits strong adaptability and reliability. The periodic variations in the rotor's torque and speed align with the periodic changes in wave motion, highlighting the device's ability to effectively capture wave energy. Overall, the increase in wave height enhances the device's energy capture efficiency, with the rotational speed showing a much greater improvement than the torque, further confirming that rotational speed is a key indicator of power generation performance. The device maintains stable energy capture efficiency under different wave heights, and higher wave heights further improve energy utilization efficiency. Future studies could focus on optimizing the structure of the rotor and flow channel to further enhance power generation performance under low wave height conditions. These findings not only validate the device's power generation potential in low-wave-height, short-period conditions but also provide critical insights for the optimization design of subsequent physical model tests and engineering prototypes, particularly in enhancing rotational speed stability and energy conversion efficiency.

6. Offshore testing and analysis

The sea trial of the DHRWEC system's engineering prototype was conducted in the coastal waters of Shandong Province, China, through a collaborative effort between Shandong University and the China Institute of Water Resources and Hydropower Research. The single-unit installed capacity is 6 kW (with an effective wave height of 1.5 m and an effective period of 5.77 s), and the weight is 29.5 tons (excluding the weight of the anchor chain). The test site was located near Chengshantou in Weihai City, Shandong Province, a region within the Bohai Sea characterized by generally low wave energy flux density and short wave periods (typically ranging from 3 to 5 s), making it an ideal location to validate the power generation performance and adaptability of the DHRWEC system under short-period, low-wave-height conditions. The collaboration ensured the scientific rigor of the testing process and the reliability of the collected data, laying a solid foundation for the engineering application and further optimization of the DHRWEC

system.

6.1. Offshore test results

Due to the complexity of the marine environment and the constraints of experimental conditions, the average amplitude data of the power generation device could not be directly obtained during testing. Instead, the research team measured the power generation efficiency per unit time to evaluate the actual performance of the DHRWEC system. The sea trial area provided an ideal experimental environment for system performance validation. The power generation data collected during the sea trials closely reflected real-world application scenarios, and through systematic data analysis, the research team derived the following key conclusions, offering a scientific foundation for subsequent optimization design and commercial applications:

The test results indicate that the DHRWEC device achieves a power generation efficiency of 21.33 %. During the engineering prototype test, the average wave height was 0.35 m, slightly lower than the prototype value of 0.4 m in the model test after conversion, thus validating the reliability of the model test data. Comparative analysis reveals that the DHRWEC system significantly outperforms similar devices in wave energy capture efficiency, particularly under short wave periods and low wave heights, where the device enhances energy utilization through co-rotational motion of the horizontal rotor and a secondary capture mechanism. Furthermore, by employing time-series wave energy inputs representative of real sea conditions, statistical biases associated with calculating wave energy power using wave parameters for real sea states were avoided, yielding results closer to actual values and reflecting the scientific rigor of the research methodology.

Both model tests and sea trials demonstrate the considerable flexibility of the DHRWEC system in design parameter selection, with notable adaptability to short-period, low-wave-height conditions. Although key parameters such as the flow channel and outlet inclination are still in the preliminary optimization stage, the system already exhibits significant performance advantages, with substantial potential for further improvement in energy capture efficiency, providing a clear direction for future research. The marine test of the DHRWEC engineering prototype, as shown in Fig. 9, further confirms its engineering application potential, laying a solid foundation for the commercial development of wave energy.

6.2. Discussion of test results

The model test provided an initial evaluation of the system's performance under controlled conditions, with experimental data indicating that the system operated effectively and maintained stable power generation efficiency at an average wave height of 0.4 m. The sea trial, conducted under real marine conditions, further validated the results of the model test. During the sea trial, the average wave height was 0.35 m, slightly lower than the prototype value obtained in the model test.

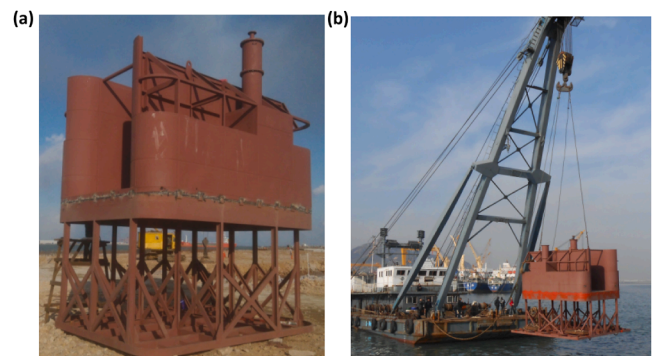


Fig. 9. Sea trial experiment. (a) engineering prototype. (b) sea test.

Nevertheless, in sea conditions with low wave height and short wave period, the device achieved a power generation efficiency of 21.33 %. In contrast, other types of wave energy converters typically have power generation efficiencies below 20 %, or even below 15 %, in normal sea conditions (Aderinto and Li, 2019). This demonstrates the device's strong adaptability and ability to maintain high energy capture efficiency in complex and variable marine environments.

7. Conclusions

This study innovatively proposes a Dual-Impact Horizontal Rotor Wave Energy Converter (DHRWEC) system, utilizing a horizontal rotor designed based on involute theory to efficiently capture wave energy through co-rotational motion, offering a novel solution for wave energy exploitation in short-period, low-wave-height sea regions. The research team developed and fabricated a physical model, conducting systematic numerical simulations and wave flume experiments to analyze the hydrodynamic characteristics and power generation performance of the horizontal rotor under regular wave conditions, with a focus on the influence of rotational speed and torque on power efficiency. Additionally, a sea-trial prototype was successfully manufactured and tested, validating the device's potential in short-period, low-wave-height conditions. Key findings include:

Numerical simulations reveal that rotational speed is a critical factor affecting the energy capture efficiency of horizontal rotors with varying blade numbers, providing a scientific basis for optimization.

Wave flume tests demonstrate excellent startup performance across three conditions, particularly under short wave periods (1.9 s) and low wave heights (0.10 to 0.14 m), where the rotor achieves rapid startup at low energy density and sustains rotation during backflow, enabling secondary wave energy capture and significantly enhancing energy utilization.

Sea trials indicate a power generation efficiency of 21.33 % under real sea conditions, confirming engineering feasibility.

Further efficiency improvements are attainable through optimization of the energy capture system. The theoretical and experimental approaches of this study offer a practical energy complement solution for coastal and remote island regions, with the successful sea-trial prototype laying a solid foundation for far-ocean array deployment and commercial applications. Future research will focus on optimizing the flow channel structure, adjusting blade shape and number, and enhancing secondary wave energy utilization to comprehensively improve the device's energy capture efficiency and engineering applicability, supporting the large-scale development of wave energy.

CRedit authorship contribution statement

Zhongliang Meng: Writing – original draft, Validation, Methodology, Funding acquisition, Conceptualization. **Yi Ding:** Project administration, Funding acquisition, Conceptualization. **Yanjun Liu:** Supervision, Project administration. **Wahyu Rahmiani:** Project administration. **Zijian Li:** Software. **Ammar Ahmed:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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