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Hydrodynamic Response and Power Efficiency Analysis of Heaving Wave Energy Converter Integrated with Breakwater

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Abstract

The hydrodynamic and power capture performance of an asymmetric floating device called “Dolphin” wave energy converter (WEC) integrated with a fixed breakwater has been proposed. The operation of the floating WEC device is restricted to the vertical direction called heaving motion. In this research, the theories of heaving motion, wave energy conversion, and computational fluid dynamics (CFD) were studied. A numerical simulation of the CFD with the laminar model was conducted; namely, the effects of four different model shapes were investigated, distance effect between the WEC device and breakwater, WEC integrated with/without breakwater, and vorticity effect analysis using STAR-CCM+ software based on the viscous flow theory in the time domain. The optimal power take-off (PTO) system was considered during the numerical calculation, including the parameters of the WEC model, which were optimized to exploit a higher efficiency by analyzing the motion response in order to obtain the response amplitude operator (RAO) and capture width ratio (CWR) values. From the RAO and vortex field analysis, the RAO value of the Dolphin WEC was exhibited better than that of the other models. A vortex method was applied to verify the CFD simulation results. From the vortex simulation, it can be clearly seen that the integration of breakwater also affected the hydrodynamic performance of the WEC. The Dolphin WEC model with breakwater integration at experimental scale was built and tested in wave tank at Harbin Engineering University under various wave conditions. The breakwater was welded with the steel plate to restrict movement. The displacement sensor and linear generator were installed on top of the WEC device during the experiment. To modify the damping in the system, the heaving motion and power generation characteristics were analyzed and electrical resistance was assumed. The displacement and power in the time domain, RAO, and CWR for different wave periods and wave heights were investigated in the experiment, where the maximum motion response and power efficiency of the WEC model were 1.57 and 0.376, respectively.

Keywords:

Wave energy converter, Breakwater, Wave-structure interaction, Heaving motion, Capture width ratio, CFD simulation.

1. Introduction

The rapid growth of the economy and industry has improved the quality of life; however, such growth has also aggravated environmental pollution. The main cause of such pollution is the combustion engine's ignition of fossil fuels; in the process, sulfuric acid and carbon dioxide are generated [1, 2]. In this regard, the relationship between an industrial manufacturing structure and pollutant emissions in a tropical industrial city has been investigated [3]. Reference [4] reports the 1960-2014 CO_2 emission statistics. Research related to carbon emissions and policy to reduce environmental pollutants in China is presented in [5]; the study predicts that carbon emissions would increase by 15-20% from 2013 to 2030. For this reason, China has been actively developing renewable energy technologies and has made rapid progress during the last two decades. The objective is to achieve 60% of generated energy from renewable energy sources (10 GW from ocean power) for the entire country by the 2050s [6].

Wave energy power is enormous and more reliable than wind and solar energy resources. Wave energy resources are abundant in the Southern Hemisphere; the largest amounts can be found in the South Indian Ocean with values of approximately 120 kW/m of wavefront [7]. Moreover, the South Pacific areas were found to have values greater than 90 kW/m. In this regard, China is located in an area with a vast coastline of 18,000 km, has a significant potential. It can be the site for the development of a wave energy converter that can achieve an estimated wave power of approximately 128.5 GW through the application of wave energy technologies along the nearshore [8]. We intended to install the prototype developed in this research at the South China Sea. The concept of wave energy is introduced, and the investigation of its potential use in electricity generation through wave energy technologies as well as the suitable locations for its application are presented by [9–12]. Wave energy converter (WEC) technologies have been studied and developed for more than three decades. The WECs classified in [13,14] show that various types of these devices can be described based on location, device size, device direction, and operation principle. According to the size and direction of the device, the WECs can be classified as attenuator, point absorber, and terminator. The point absorber type, which oscillates in the vertical direction, comprises the majority (over 81%) of WECs.

Heaving wave energy converters have been studied and developed to optimize vertical motion performance under wave conditions. Point absorber WECs are optimized geometrically based on a frequency domain analysis by satisfying the primary requirements: natural buoy heave frequency and maximum mechanical power. The geometry of the WEC model can also influence the power capture performances of the WEC device; the geometry optimization result indicates that a cylindrical shape WEC model with a large diameter and draft can generate maximum mechanical power [15]. An asymmetric heaving WEC (called The Berkley wedge (TBW)) with a special smooth line curve formula is designed to reduce the effects of viscosity during operation. The device can be concurrently operated using a breakwater function; accordingly, the experimental results demonstrate a significant hydrodynamic performance [16]. Furthermore, TBW model design uses pressure channels on the device to investigate survivability based on the wave-exciting force conditions reported in [17].

Recently, several studies on the integration of WEC devices with other marine installation functions have been conducted. The WEC device integrated with different types of breakwater devices is reviewed in [11]. The comparison of hydrodynamic performance between single-pontoon and two-pontoon systems is presented in [18]; the results indicate that the CWR of the two-pontoon system is greater than that of the single-pontoon system with the same total volume. A hydrodynamic analysis of a two-pontoon WEC-type breakwater is conducted; it is found that the transmission, reflection, and CWR coefficients of the system depend on the natural frequency in the heave mode and the spacing between the two structures [19,20]. The wave interaction and loading analysis of the submerged semi-circular shape of a breakwater are reported in [21,22]. Therefore, our breakwater model is designed as a fixed circular cylinder with a semi-submerged draft; it is installed behind the oscillating WEC device with a single degree of freedom.

The hydrodynamic and power capture performances of the integrated system, consisting of the WEC device and a fixed breakwater, are investigated in this study. The power take-off (PTO) or power conversion system can be implemented to convert wave power into electrical energy [23]. For the testing scale, the permanent magnet linear generator (PMLG) system is installed on top of the WEC device [24]. The linear generator type is commonly applied with the point absorber WEC device [25].

The objectives of this study are to investigate the hydrodynamic and power capture performances of the WEC integrated with a fixed breakwater. Base on CFD calculation and experiment; the equation of motion, energy conversion, theories of CFD, and design optimization are presented in this paper. Moreover, the heaving motion and power performance of specific WEC models are analyzed. The primary variables, such as the wave period, wave height, and electrical damping, are considered. The characteristics of WEC devices can be indicated based on the RAO and CWR values. This paper is organized as follows: Section 1 discusses the general research background and status of wave energy globally, including the WEC with the integration of breakwater technology. Hydrodynamic analyses of heaving motion, energy conversion, and CFD theories are described in Section 2. Section 3 presents the principal dimensions and positions of the structures. Based on a numerical calculation, the CFD simulation model, floating-body shape effects, hydrodynamic effect of breakwater, distance between two floating structures, and vortex field analysis are elaborated in Section 4. The motion and power efficiency of the WEC device as indicated by the experimental results and the validation method applied between the CFD calculations and experiment are presented in Section 5. Finally, concluding remarks are presented in Section 6.

2. Mathematical theories

2.1. Heaving motion equation

The equation of motion applied to a wave energy converter device is derived from the ship motion theory. To compute the response of a vessel under wave conditions, the equation of motion under six degrees of freedom is as follows [26]:

$$\sum_{j=1}^{6}\left[\left(M_{ij}+A_{ij}\right)\ddot{\eta}_j+B_{ij}\dot{\eta}_j+C_{ij}\eta_j\right]=\sum F_i \quad \text{for } i = 1, 2, \ldots, 6 \tag{2.1}$$

where η is the amplitude of motion, M_{ij} are the elements of the generalization mass matrix, A_{ij} are the elements of the hydrodynamic mass or added mass matrix, B_{ij} are hydrodynamic damping or radiation damping coefficients, C_{ij}

are the hydrostatic stiffness or restoring coefficients, and $\sum F_i$ represents the result of all other forces in the i direction.

In this study, the WEC model was calculated in the vertical direction, and based on the CFD was considered through a time-domain analysis. The equation of motion in the time domain can be established based on Newton's second law of motion as follows [26]:

$$(M)\ddot{z} = \sum F \tag{2.2}$$

where M is mass of the WEC model, $\ddot{z}$ is an acceleration in the vertical direction, and $\sum F$ is a summation of all forces applied.

In Eq. (2.2), $\sum F = F_e + F_r + F_h$, where F_e is the excitation force, F_r is the radiation force, and F_h is the hydrostatic buoyancy. Thus, the governing equation of motion can be written as follows [27]:

$$(M)\ddot{z} = \int_0^t h_e(t-\tau)\eta(\tau)d\tau - \left(\int_0^t k_r(t-\tau)\dot{z}(\tau)d\tau + A_{r\infty}\ddot{z} + k_h z\right) \tag{2.3}$$

On the right side of Eq. (2.3), the terms of the applied forces are the integration on the product of the Dirac impulse h_e, and the wave elevation surface $\eta(t)$. The second and third terms constitute the radiation force owing to the waves generated through the oscillation $z(t)$, in which $k_r(t)$ is the function of the radiation impulse and $A_{r\infty}$ is the added mass of $A(\omega)$ from inertia. The last term represents the Archimedes buoyancy force F_h.

2.2. Energy conversion

The mechanical power from the WEC device in the vertical direction is related to the PTO damping force F_z and the velocity in heaving motion u_z, as shown in Eqs. (2.4) and (2.5) [28].

$$F_z = B_g \cdot u_z(t) \tag{2.4}$$

$$u_z = \frac{dz}{dt} = -\omega Z_0 \sin\left(\omega t + \gamma - \sigma_z\right) \tag{2.5}$$

where B_g is the PTO damping coefficient, Z_0 is the motion amplitude, ω is the circular wave frequency, *t* is time in seconds, γ is a phase angle that depends on the wave force component, and σ_z is a phase angle that depends primarily on the damping factor of a dimensionless system.

The power of pure heaving in a resonance wave can be calculated using Eq. (2.6), and the average power over a single wave period is as shown in Eq. (2.7).

$$P_z = F_z \frac{dz}{dt} \tag{2.6}$$

$$\overline{P} = \frac{1}{T}\int_0^T P_z dt \tag{2.7}$$

Thus, when substituting Eq. (2.6) into Eq. (2.7), the equation of the average power is as follows:

$$\overline{P} = \frac{1}{T}\int_0^T F_z(t) u_z(t) dt \tag{2.8}$$

The power conversion efficiency of a WEC device can be written in the form of CWR in Eq. (2.9) [29],

$$CWR = \frac{\overline{P}}{P_{wave} \times D} \tag{2.9}$$

$$P_{wave} = \frac{\rho g^2 H^2 T}{32\pi} \tag{2.10}$$

where T is the period of the wave, u_z is the vertical velocity of the WEC device, P_{wave} is the wave power per unit wavelength, D is the width of the WEC device, ρ is the water density, g is the acceleration of gravity, and H is the water depth.

2.3. CFD theories

Based on the theory of viscous hydrodynamics, the CFD method is used to calculate the numerical change within a finite volume. In this study, simulations are conducted using a commercial CFD software, STAR-CCM+. The volume of fluid method is used to simulate a wave surface accurately. The overlapping mesh technique, which is highly accurate for large amplitude motion, is applied to calculate the heave motion. The governing equations, basic CFD method, laminar model, and overlapping mesh, which are utilized as the basis of simulation and precise estimation, are introduced in this section.

2.3.1. Mass conservation equation

In the time unit, the mass increase in a fluid microelement is equal to the net mass of the fluid flowing into the element. The continuity equation is determined according to the law of conservation of mass.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{2.11}$$

Eq. (2.11) is an unsteady continuity equation of an incompressible fluid, where the density is a constant, which can be expressed as follows:

$$\nabla \cdot \vec{u} = 0 \tag{2.12}$$

where ρ is the fluid density, $\vec{u}$ is a velocity vector, and t is time.

2.3.2. Momentum conservation equation

The momentum conservation equation is Newton’s second law in momentum form, and the time derivative of the momentum in a fluid microelement is equal to the net force. The expansion equation in the x, y, and z directions are as follows:

$$
\begin{aligned}
&\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho u\vec{u})=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+F_x\\
&\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho v\vec{u})=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+F_y\\
&\frac{\partial(\rho w)}{\partial t}+\nabla\cdot(\rho w\vec{u})=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+F_z
\end{aligned}
\tag{2.13}
$$

where *p* is the pressure of the fluid microelement. τ_{xx}, τ_{xy}, and τ_{xz} represent the component of the viscous stresses and on the element. F_x, F_y, and F_z are the body force of the element, which in general is only the force of gravity, $F_z=-\rho g$, which is negative along the z-axis.

2.3.3. Laminar model

In this study, the numerical wave tank is designed using STAR-CCM+ software, and the laminar flow condition has been considered to generate wave elevation. Consider the two fluid conditions in the numerical wave tank (air and water). The fluids are separated by a free surface; thus, based on the governing equation, Eq. (2.11), the incompressible laminar fluid flow condition can be defined as follows [30]:

$$
\frac{\partial\rho\vec{u}}{\partial t}+\nabla\cdot\left(\rho\vec{u}\vec{u}\right)-\nabla\cdot\left(\mu\left(\nabla\vec{u}+\left(\nabla\vec{u}\right)^T\right)\right)=\rho g-\nabla p
\tag{2.14}
$$

To evaluate the laminar flow assumption, the dimensionless variable, “Reynolds number (Re),” is used to express the ratio between inertial and viscous forces, as follows:

$$
\mathrm{Re}=\frac{u\cdot L}{\nu}
\tag{2.15}
$$

where *u* is the characteristic free stream velocity, *L* is the characteristic length, and *v* is the kinematic viscosity. The heaving WEC is studied in the latching control; $\mathrm{Re}\approx 2x10^4$, which assumes laminar flow [31]. Moreover, for the CFD simulation, the flow around cylindrical and spherical shapes is indicated in [32]; with $\mathrm{Re}<2x10^5$, this flow can be considered in the laminar regime.

2.3.4. Overlapping mesh

In an overlapping mesh, also known as overset mesh, are used to investigate a computational domain with several different meshes that overlap each other. The cells are categorized into three groups: active, inactive, and acceptor cells. Within an active cell, discretized governing equations are solved. However, inactive cells, no equation is solved, although these cells can become active if the overset region is moving. Acceptor cells separate active and inactive cells in the background region and attach to the overset boundary within the overset region. Acceptor cells are used to couple the solution to two overlapping mesh. Variable values at the donor cells of one mesh express variables for the acceptor cells in another mesh through an interpolation. The donor cells are the active cells from another mesh; that is nearest the acceptor cell. Between the wall and overlap boundary of an overlap region, there must be at least four cells in both the overlap and background meshes.

3. Geometry model

A wave energy converter device is a type of ocean structure that differs from traditional floating vessels and offshore platforms; it has a resonance frequency designed to avoid external wave frequencies. However, the resonance frequency of a WEC device is designed to be approximate or equal to the external wave frequency for generating large motion and maximizing power production. This research examines an integrated WEC device, which includes two parts WEC and breakwater. The vertical oscillation of the WEC with interacting waves is used to drive the generator and convert the potential energy into electricity. The breakwater is fixed to eliminate the wave force from the WEC device during operation. The WEC device is installed in front of the breakwater to encounter external waves.

The principal dimensions of the WEC and breakwater at the experimental scale are listed in Table 1. In Fig. 1, the breakwater is designed with a circular shape with D as diameter; the draft is $0.5D$. The WEC captures the wave potential energy. The floating WEC is considered as an asymmetric model with a smooth line shape called “Dolphin.” The beam overall and height of the structure are denoted by a and b, respectively; L is the distance between two structures, and the water depth is h. The motion of the Dolphin WEC model is limited to a single degree of freedom, the heaving motion (ζ_3) is defined at the center of gravity. The masses of the two bodies are assumed to have uniform distribution, where the center of gravity is also the centroid.

Table 1

Principal dimensions of Dolphin WEC and breakwater at experimental scale.

Parameter	Dolphin WEC	Breakwater
Height, mm	300	-
Beam overall, mm	125	-
Width, mm	750	750
Draft, mm	150	400
Fillet (radius), mm	40	-
Bottom arc (radius), mm	6	-
Weight, kg	9.74	188.5
Diameter, mm	-	800

Fig. 1. Scheme of Dolphin WEC device and breakwater used in experiment.

4. Numerical calculations

The factors that influence the hydrodynamic performance and power generation presented in this section are as follows: the CFD simulation model, floating-body shape of the WEC, WEC device with/without a breakwater, distance between the WEC and breakwater, and vorticity effect.

4.1. CFD simulation model

As reported in [33–35], the comparison of wave generation between the laminar and $k-\varepsilon$ turbulence model is studied to investigate the effects of viscosity; the turbulence model includes the history effects, such as turbulent kinematic energy and turbulent dissipation. The results reveal that there is no difference in wave elevation between the two models. Thus, in our present work, the laminar flow model is applied. The Reynolds number of the Dolphin WEC model, when the wave period of 1.2 s, is approximately 5×10^4.

The meshes with different sizes and settings have a critical impact on accuracy and computing speed. In general, a low-volume mesh does not necessarily result in solution runtime problems; however, it reduces the accuracy and efficiency of the solution obtained. Thus, the mesh size should be considered to optimize the calculation time and the accuracy of computational results. In this study, three types of volume meshes are arranged in a numerical wave tank without any structure; a wave height recorder is located at the same position of the WEC model. Table 2 summarizes the mesh settings of the three models: model 1 coarse mesh; model 2 fine mesh; model 3 finer mesh. In the table, Δt represents the time step, Δx is the mesh size in the wave propagation direction, and Δz is the mesh size in the wave height direction.

Table 2

Parameters of three mesh models.

Mesh model	Model 1 Coarse mesh	Model 2 Fine mesh	Model 3 Finer mesh
Time step	$\Delta t = T/1000$	$\Delta t = T/1000$	$\Delta t = T/1000$
Mesh size	$\Delta x = L/13$	$\Delta x = L/27$	$\Delta x = L/54$
	$\Delta z = H/4$	$\Delta z = H/8$	$\Delta z = H/16$

The comparison results of the wave evaluation of the three models are illustrated in Fig. 2. The wave height is defined as 0.08 m in the simulation condition because the WEC prototype is intended to be installed in South China Sea, where the average wave height of the specific area is 0.8 m. Moreover, because the experimental model scale is 1:10, the condition of the wave height in this calculation should be 0.08 m. In comparing the three models, the wave height curve of model 1 is found to be rough because the mesh is not sufficiently fine in this case. On the other hand, the curves of models 2 and 3 are smooth, the wave elevations are stable, and the wave height deviation between these models is less than 1%. Although the mesh quality of model 3 is better than that of model 2, the results of both models are accurate and in agreement; however, the calculation time of model 2 is faster than that of model 3. Therefore, the time step and mesh size settings of the CFD model follow those of model 2.

Fig. 2. Comparison of wave height between the different meshes models at the WEC location without a structure.

The boundary condition and dimensions of the CFD simulation model are illustrated in Fig. 3. The WEC device is located in front of the fixed breakwater. The models are designed in two dimensions; the length, height, and thickness of the computational domain are 14 m, 5.5 m, and 10 mm, respectively. The thickness is represented as a single layer of mesh in the simulation domain. The typical mesh of the two-dimensional wave tank domain is presented in [36–38]. The air and water phases are separated; the water depth is 3.5 m. The right and left sides are defined as the velocity inlet and pressure outlet, respectively. The top and bottom of the computational domain are considered as walls. The lengths of the CFD simulation domain and wave damping region are more than 7 and 1.5 times that of the wavelength, respectively. The WEC model is located at the center of the computation domain.

As illustrated in Fig. 4, the mesh around the WEC is the overlapped mesh presented in subsection 2.3.4, and the mesh near the wave surface is a fine mesh. The trimmed cell mesher and prism layer mesher function with a 0.32 m base size is utilized for mesh generation. The volume growth rate is defined with a maximum cell size of 100%. The volumetric control, designed as a fine mesh, cover the vertical movement of the WEC model and wave surface. The WEC device integrated with a breakwater is designed using a fine mesh; the mesh quantities are set at approximately 26,000 elements for all models (following model 2 listed in Table 2).

Fig. 3. CFD model boundary condition.

Fig. 4. Mesh diagram of Dolphin WEC with a breakwater.

4.2. Numerical calculation results

4.2.1. Model shape effect analysis

The shape of a floating WEC is important for hydrodynamic efficiency and power generation. From a theoretical perspective, the slenderness and sharpness of a floating WEC may significantly influence its hydrodynamic performance. An example in this regard is “TBW” model, which is designed as an asymmetric WEC with a specific smooth-line curve function. TBW is slender and sharp at the bottom and can reach a wave-capturing efficiency of 96.34% when the floating structure is operating at a resonance frequency [16]. Although slenderness and sharpness may function in theoretical and laboratory model tests, it is necessary for the WEC design process to consider the structural strength and construction process, in which a specific geometry may be difficult and complicated.

In view of the foregoing reason, the Dolphin WEC model is designed as an asymmetric type with a stocky and smooth line shape, as illustrated in Fig. 5(a); this simplifies the construction process while still maintaining the hydrodynamic performance under acceptable conditions. The principal dimensions of the experimental scale Dolphin WEC with a breakwater model are listed in Table 1. In this study, the different shapes of WEC models are compared and investigated to determine a suitable geometry for the WEC; four specific shapes of the WEC models are illustrated in Fig. 5.

Fig. 5. Two-dimensional diagrams of four WEC models with different geometric shapes.

To investigate the hydrodynamic performance during a heaving motion under regular wave conditions, a two-dimensional numerical CFD model integrated with a breakwater is designed and analyzed based on the viscous flow theory using STAR-CCM+ software. In the simulation process, the four particularly shaped models are set to have the same basic dimensions, including the height, width, mass, and displacement. As illustrated in Fig. 6, the comparison results of hydrodynamic and power performances that are considered for the two variations are the RAO and CWR with a PTO damping of 35 N·s/m. The RAO is the ratio between the floating device motion response and the incident wave height. In the case of a WEC operation, during heaving motion, it is necessary to calculate the RAO value because of its influence on electricity production. The RAO equation is as follows:

$$RAO = \frac{Heave\ translation}{Wave\ height} \tag{3.1}$$

(a) (b)

Fig. 6. Comparison results of RAO and CWR for the four different geometrically shaped models.

In Fig. 6(a), for the WEC models with a breakwater, the RAO curves tend to continuously increase when the wave periods are from 1.0 to 1.3 s. When the period is 1.0 s, the lowest RAO value is 1.39 for the rectangle model. In contrast, the maximum value of RAO is 1.65, when the period is 1.0 s for the Dolphin model; this demonstrates a difference of approximately 18.84% between the two models. The triangle and trapezoid models exhibit similar RAO values when the period is 1.0 s; the RAO of the trapezoid model is greater than that of the triangle model by 1.47% but is still lower than that of the Dolphin model by 4.1%. For the period of 1.2-1.4 s, the RAOs of the Dolphin, triangle, and trapezoid models are all similar; the RAO of the rectangle model also approach those of the others. When the wave period is 1.3 s, the RAO of the WEC models with four different shapes reach the maximum value.

The CWR is also an important variable to consider in terms of the capture power performance of the WEC device. The CWR values of the four models with different shapes are calculated and compared, as illustrated in Fig. 6(b). When the period is 1.0 s, the tendency of CWR values are similar to those of the RAO comparison; the greatest CWR is that of the Dolphin model at 0.637, which differs from those of the other models by practically 31.3%. When the period is 1.1-1.4 s, the Dolphin, triangle, and trapezoid models exhibit similar CWR values; the CWR values of the rectangle model approach those of the other models when the period is 1.3-1.4 s.

Figure 6 clearly depicts that the breakwater device influences the hydrodynamic performance of the WEC device. The RAO and CWR values of the Dolphin WEC integrated with breakwater are greater than those of the Dolphin WEC without breakwater. When the period is 1.0 s, the RAO value of the former is more than that of the latter by 27.98%. Moreover, the curves show that for the entire range of wave periods, the RAO and CWR values of the Dolphin WEC without breakwater are less than those of the rectangle model with breakwater. When the WEC device is integrated with breakwater, the wave energy becomes concentrated because of refraction; the wave height around the fore of the breakwater is amplified and becomes higher than the incident wave.

In Fig. 6, the RAO and CWR comparisons clearly demonstrate that the shape of a floating structure affects the hydrodynamic performance. In particular, in the low-wave period, a smooth line contour more significantly affects the hydrodynamic performance than the chamfer shape does. Moreover, the breakwater significantly affects the hydrodynamic performance of the WEC device. Accordingly, the Dolphin WEC model integrated with breakwater is deemed suitable for a wave energy converter device oscillating under a heaving motion.

4.2.2. Distance between Dolphin WEC and breakwater

As mentioned in Section 3, the Dolphin WEC model is integrated with breakwater to reduce the external wave impact force after the WEC device is operated; the Dolphin WEC is installed in front of the fixed cylindrical breakwater. Clearly, the distance between the two structures, denoted by *L* in Fig. 1, can influence the hydrodynamic performance of the Dolphin WEC. For a wave period of 1.2 s, the effects of distance on selected hydrodynamic variables are illustrated in Fig. 7; the distance between the two structures is 30-150 mm at 10 mm intervals.

In Fig. 7, the curves decrease as the distance between the two structures increases. At a distance of 30 mm, the RAO and CWR reach the maximum values of 1.738 and 0.428, respectively; at 150 mm, the minimum RAO and CWR values are 1.573 and 0.349, respectively. Therefore, between 30 and 150 mm, the RAO and CWR values differ by approximately 9.5% and 18.46%, respectively. Moreover, the maximum results of the RAO and CWR obtained at a distance of 30 mm are considered to be extremely close between the two experimental structures. In naval architecture and marine engineering, it is not ideal to design a distance that is extremely close between two marine structures because these could be influenced by aquatic plants or marine life. Thus, the appropriate distance between the Dolphin WEC and breakwater for this experimental model could be 50-70 mm.

Fig. 7. RAO and CWR results corresponding to different distances between Dolphin WEC and breakwater.

4.2.3. Vortex field analysis

When the device is moving in a viscous fluid, the boundary layer separation will produce a vortex and low-pressure area; the core of the vortex phenomena represents the lower pressure. Hence, with the vortex distribution, the device will oscillate with a considerable drag force when the vortex strength is large; consequently, this can resist the motion of the device. The vortices are computed with the CFD simulation software STAR-CCM+. In this study, the vorticity field can be observed for four different moments during a single period. When the wave period is 1.0 s, a vortex shade for the WEC model oscillatory heave motion is mainly generated as the body moves near the lowest point, as illustrated in Fig. 8(a)-8(d). The vortex phenomena in a rectangle WEC model is selected because the vorticity shade has clearly occurred during the simulation.

For the heaving WEC device, water along the path of the WEC structure is forced around the edges of the structure forming vortices and turbulence that dissipate energy; this effect is called form drag [39]. By comparing the vorticity fields, it is found that the lowest point of the four different shapes of the WEC device clearly occurs when the period is 1.0 s. The boundary layer separation is suppressed by the smooth line shape of the Dolphin WEC; this explains why the RAO and CWR values of the Dolphin WEC are higher and the hydrodynamic performance is better than those of the other shapes, as illustrated in Fig. 9(a)-9(d).

(a) Lowest position (b) Moving upward at a normal position

(c) Highest position (d) Moving downward at a normal position

Fig. 8. CFD simulation of vortex phenomena for rectangle WEC model.

(a) Dolphin model (b) Triangle model

(c) Trapezoid model (d) Rectangle model

Fig. 9. CFD simulation of vortex phenomena for different shapes of WEC device.

The breakwater effect described in subsection 4.2.1 indicates that the Dolphin WEC integrated with breakwater can improve the hydrodynamic performance of the WEC device. The hypothesis is that a single WEC model without a breakwater can produce higher magnitudes of vorticity than a WEC integrated with a breakwater. When the two conditions of the Dolphin WEC in Figs. 9(a) and 10 are compared, it is evident that the Dolphin WEC without breakwater has vortices that occur around the model. Accordingly, this also explains why the performance of the device can be significantly improved with the integration of breakwater.

Fig. 10. CFD simulation of vortex phenomena for single Dolphin WEC without breakwater.

5. Model experiment in wave tank

5.1. Experimental setup and model

Fig. 11. Schematic of wave and electrical data collection in the experiment.

Figure 11 illustrates the schematic of the experiment in which heave motion and power generation are required. The heave motion can be measured with a linear displacement sensor installed on top of the Dolphin WEC device. The linear displacement sensor, which measures the displacement of the WEC device integrated with breakwater, is implemented as a rod type. The measuring range of this sensor is 550 mm with a maximum error of 0.01 mm. The PTO system applied in this research is the permanent magnet linear generator (PMLG) type with a peak force of 1200 N. The two primary components of the PMLG are stator (primary coils) and rotor (rotating magnets). The wave height recorder is an instrument that obtains the incident wave height result. In the experiment, the distances of the wave height recorder from the wavemaker and the Dolphin WEC model are 10 and 6 m, respectively; the recorder is installed in the midst of the wave tank, as illustrated in Fig. 12.

Fig. 12. Experimental setup for the Dolphin WEC integrated with breakwater.

The electrical power produced by the linear generator can be obtained from the electrical system with an adjustable resistor. For the electrical system, the generator is the power source; the voltage of the adjustable resistor is equal to the electrodynamic potential of the power source. The power can be calculated using the total resistance and voltage; a light bulb with specific resistance value is connected to the circuit to demonstrate the generation effect. All experimental data are transferred to the data collection system and recorded. The data collection system has 12 channels, which can collect the wave height, electrical voltage, and displacement of the Dolphin WEC device from the measuring instruments (Fig. 12).

Fig. 13. Experimental model and testing device in wave tank.

The hydrodynamic performance of the Dolphin WEC integrated with a breakwater model is tested in the wave tank of Harbin Engineering University (HEU) to demonstrate the potential of the WEC device. The tank length, width, and depth are 108, 7, and 3.5 m, respectively. The tested wave conditions in the experiment are summarized in Table 3. In Fig. 13, the Dolphin WEC device is installed in front of the fixed breakwater to encounter the incident wave from the wavemaker. The distance between the two structures is 50 mm. The breakwater is welded with a steel plate so that it can cling onto the crane. The rollers are installed behind the Dolphin WEC model to restrict movement in the vertical direction. Moreover, the linear displacement sensor and PTO system are installed on top of the Dolphin WEC device to measure the displacement and electricity output when the device operates.

Table 3
Experimental wave conditions.

Wave Period (s)	1.0	1.1	1.2	1.3	1.4	1.6
Wave Height (m)		0.12	0.12	0.12		
		1.0	1.0	1.0		
	0.08	0.08	0.08	0.08	0.08	0.08
		0.05	0.05	0.05		

The RAO and CWR can be calculated using Eqs. (3.1) and (2.9), respectively. In the experiment, the RAO value can be calculated by means of the WEC displacement and wave height, which can be obtained from the linear displacement sensor and wave height recorder, respectively. Apart from the CWR calculation, the electrical power obtained by the linear generator and wave power depends on the wave condition.

5.2. Experimental results

5.2.1. Analysis of WEC motion

The experimental calculation results are presented in this section. The stable range of displacement results of the experiment when the wave period is 1.0-1.6 s is extracted and illustrated in Fig. 14. The results clearly show that the highest displacement values occur when the wave period is 1.2 s.

Fig. 14. Experiment results of displacement in time domain.

As illustrated in Fig. 15, the RAO experimental results increase when the wave period is 1.0-1.2 s and thereafter decrease after a 1.2 s wave period. Therefore, the natural period of the experimental WEC is approximately 1.2 s, and the device resonates when the wave period is equal to the natural period. During the resonance period, the maximum RAO value is 1.57 at a wave height of 0.08 m, and the corresponding motion amplitude is 125.7 mm. The STAR-CCM+ simulation results show that the RAO values increase at different PTO damping values. During low wave periods, the RAO values are extremely small. As illustrated in Fig. 16, the RAO results for wave periods of 1.1, 1.2, and 1.3 s are related to the wave height; basically, the RAO directly varies with wave height. In Fig. 16, when the wave period is 1.2 s, the RAO results are the largest; the RAO is 2.16 at a wave height of 0.12 m, which is considered extreme under ocean conditions.

Fig. 15. RAO results of experiment and STAR-CCM+ calculation at different PTO damping values.

Fig. 16. RAO corresponding to different wave heights at wave periods of 1.1, 1.2, and 1.3 s.

During the natural period, at a wave height of 0.08 m, the maximum RAO value is 1.57 at an electrical resistance of 120 Ω, as illustrated in Fig. 17. In the comparison between the experimental and CFD simulation results when the wave period is 1.2 s (curve with black stars in Fig. 15), the RAO can predict the tendency when the PTO damping is 65 N·s/m in the numerical simulation.

Fig. 17. RAO at different electrical resistances when wave period is 1.2 s.

5.2.2. Power efficiency analysis

The electrical power versus time when the wave period is 1.0-1.6 s is illustrated in Fig. 18. It is outstanding that when the wave period is 1.2 s (the natural period), the maximum power is approximately 2.0 W.

Fig. 18. Experimental results of power in time domain when wave height is 0.08 m.

In Fig. 19, the CWR curves of the experiment and simulation increase when the wave period is from 1.0 to 1.2 s; thereafter, the values decrease. The comparison results in Fig. 19 show that the CWR values of the experiment are less than those of the CFD simulation because mechanical friction influences power generation. By comparing the CWR values of the experiment and those of the CFD simulation at a PTO of 35 N·s/m when the period is 1.2 s (the natural period), it can be observed that the mechanical friction in the experiment increased by 69.39%. The CWR results of the CFD simulation are greater than those of the experiment because the CFD simulation model is designed without any installation equipment.

Fig. 19. CWR results of experiment and STAR-CCM+ calculation at different PTO damping values.

The relationship between the CWR and wave height in the experiment at each of the three wave periods (1.1, 1.2, and 1.3 s) is illustrated in Fig. 20. The CWR curve when the wave period is 1.2 s is considerably higher than the curves when the wave periods are 1.1 and 1.3 s; this tendency is the same as that in the RAO results illustrated in Fig. 16. When the wave periods are 1.1 and 1.3 s, the CWRs are similar (for wave height of 0.05-0.10 m); thereafter, they diverge. When the period is 1.2 s, which is the resonance period, the maximum CWR result is 0.376 at a wave height of 0.08 m; the CWR is 0.603 at a wave height of 0.12 m. Figure 21 depicts the CWR results versus the electrical resistance when the wave period is 1.2 s at a wave height of 0.08 m. When the electrical resistance is approximately 120 Ω, the maximum CWR is 0.376.

Fig. 20. CWR results with wave height at wave periods of 1.1, 1.2, and 1.3 s.

Fig. 21. CWR at different resistances of generation circuit in experiment.

Hence, the hydrodynamic and power performances from the experiment on the Dolphin WEC integrated with breakwater can oscillate regularly in the heaving direction. The maximum RAO result is 1.57 (Fig. 17) during the natural period, and the energy conversion efficiency can reach 0.376 (Fig. 21) at a wave height of 0.08 m.

5.2.3. Numerical calculation and experimental validation

Fig. 22. Comparison of displacements between CFD calculation and experiment.

To verify that the settings and definitions are correct and the results are accurate, the numerical calculations and experimental results are validated. In this study, apart from the verification of the mesh size and arrangement mentioned in Section 4.1, the comparison of displacements between those of the CFD simulation and experiment is necessary to confirm their accuracy. Figure 22 illustrates the aforementioned displacement comparison when the wave period is 1.4 s, and the PTO damping is optimal in the time domain; the comparison proves that the displacement results between the CFD simulation and experiment are shown in agreement.

6. Conclusion

The hydrodynamic and power performances of an asymmetric WEC device integrated with a fixed breakwater were investigated based on CFD calculations and results yielded by experiment in the wave tank. It was observed that the operation of the WEC device intended to oscillate in a heaving motion. The heaving motion equation, energy conversion, and CFD theories were examined, and the hydrodynamic performances were investigated through a numerical CFD simulation using the viscous flow theory software, STAR-CCM+. The CFD simulation process defined the regular wave characteristics as the range of wave period and wave height based on the laminar flow model. Four different shapes of the WEC device were designed to calculate the RAO and CWR values. The Dolphin WEC with a smooth line curve exhibited the best performance; when the wave period was 1.0 s, the values of RAO and CWR were greater than those of the rectangle model by 18.84% and 45.57%, respectively. The integration of the breakwater also affected the hydrodynamic performance of the WEC. As illustrated in Fig. 6, the RAO value of the

Dolphin WEC with breakwater was greater than that without breakwater by 27.98%. The effects of distance between these two structures were also studied. At a distance of 30 mm, the RAO and CWR values were 1.738 and 0.428, respectively; these were the largest values yielded by the distance analysis. However, based on the ideal marine structure design, the optimal distance was found to be in the range 50-70 mm. The vortex field analysis verified the oscillating performance of the WEC device; it clearly showed a slight vorticity around the smooth line of the Dolphin WEC model. Accordingly, the numerical CFD simulation results indicated the suitability of the WEC model; these results also showed that the smooth line shape and integration of breakwater influenced the performance of the model.

The Dolphin WEC and cylinder breakwater models were built based on the parameters listed in Table 1. A linear displacement sensor and linear generator were also installed on top of the WEC model for the experiment in the HEU wave tank. The heaving motion of the Dolphin WEC was analyzed within the wave period range of 1.0-1.6 s; it was found that the highest displacement values occurred when the wave period was 1.2 s (natural period). With a wave height of 0.08 m during the natural period, the maximum RAO value was 1.57 at an electrical resistance of 120 Ω. In the power efficiency analysis, the maximum power during the natural period was approximately 2.0 W. Moreover, the maximum CWR result was 0.376 under a wave height of 0.08 m, and the CWR was 0.603 under a wave height of 0.12 m, as illustrated in Fig 20. The experimental CWR values were less than those of the CFD simulation because mechanical friction influenced power generation. In the comparison of displacements between the CFD simulation and experiment, it was observed that the results are in agreement over time, as illustrated in Fig. 22. In future studies, the Dolphin WEC model can be scaled up to suit ocean wave conditions. The results of this project demonstrated that several model devices can be utilized to absorb wave energy.

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