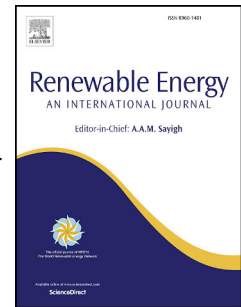


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Hydrodynamic performance of a three-unit heave wave energy converter array under different arrangement

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Abstract

A pile-restrained floating wave energy converter (WEC) array is proposed as an alternative to a single floater of the size of the array for use as a floating breakwater. The hydrodynamics of the WEC are modelled based on the Navier-Stokes equations and the model is verified by comparing its results with existing experimental data. The model then is used to characterize the array composed by a line of three WECs in terms of floater heaving, wave energy conversion, wave reflection, transmission and dissipation, for different layouts.

In the examined array configuration, the aligned arrays exhibit superior performance compared to the staggered arrays, comprehensively considering both wave energy conversion and wave transmission. Specifically, when $kh_i > 1.73$, the wave energy conversion efficiency of the aligned array with a spacing of 0.1 times the WEC width ranges from 0.141 to 0.330, while the wave transmission coefficient ranges from 0.187 to 0.472, indicating the effectiveness of the arrays in simultaneously reducing wave transmission and converting wave energy under shorter-wavelength conditions. Compared to a single WEC of the same dimensions, the array exhibits a remarkable increase in wave energy conversion efficiency and effectively reduce wave reflection.

Keywords: Wave energy converter (WEC); Array; Wave energy conversion; Wave transmission; Wave dissipation; Pile-restrained.

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1. Introduction

Floating breakwaters (FBWs) are increasingly being used as wave dissipation structures due to their low disturbance to water circulation, flexible movement, and wide range of applications (McCartney, 1985). FBWs can be broadly classified into two types based on their installation forms: mooring-type and pile-restrained-type (Dai et al., 2018; He et al., 2012; Ren et al., 2017). The pile-restrained FBW, which is limited to heave motion, has a simple structure and is easy to install, making it a popular focus for researchers studying its hydrodynamic behaviour.

Isaacson et al. (1998) developed a numerical model of a pile-restrained FBW with a rectangular section under the action of normally incident waves and studied the influence of the gap between the pile and the FBW. Their findings suggest that when the gap width is comparable to the incident wave height, the FBW behaves similarly to a free-floating breakwater. Traditionally, the FBWs reduce wave transmission through two primary mechanisms: wave reflection and turbulent dissipation. (Dong et al., 2008; Koutandos et al., 2010). With the advancement of wave energy harvesting technology, the integration of FBWs with wave energy converters (WECs) has been proposed and gained significant attention. This approach involves integrating the power take-off (PTO) system of the WEC with the FBW to enhance wave dissipation while capturing wave energy. Furthermore, the shared use of the floating platform between the WEC and the FBW can reduce the offshore equipment costs.

Ning et al. (2016) conducted an experimental investigations of a pile-restrained FBW system with an integrated PTO system. Their results indicate that when the transmission coefficient is kept below 0.50, the capture width ratio (CWR) can reach around 24%, indicating effective performance of the integrated system. The FBW is tested in a wave tank, with the dimensions along the wave direction and wave crest direction being equal, and nearly matching the width of the wave tank. However, to effectively reduce wave transmission, FBWs are typically designed with larger dimensions along the wave crest direction compared to the dimensions along the wave direction, as illustrated in the left diagram of Fig. 1. In contrast, heave WECs are generally designed with the same size along both directions and are specifically intended to capture the vertical motion of waves and convert it into usable energy. The heave float drives the gear to move up and down on the rack, thereby driving the generator

shaft to rotate and converting mechanical energy into electrical energy. Consequently, directly combining WECs with FBWs can be challenging due to the differences in their sizes and functionalities. To address this, a pile-restrained floating WEC array composed by a line of WECs is proposed as an alternative to a single large WEC for use as an FBW, as shown in Fig. 1. This configuration offers a potential solution for wave energy harvesting while providing the wave attenuation capabilities of an FBW.

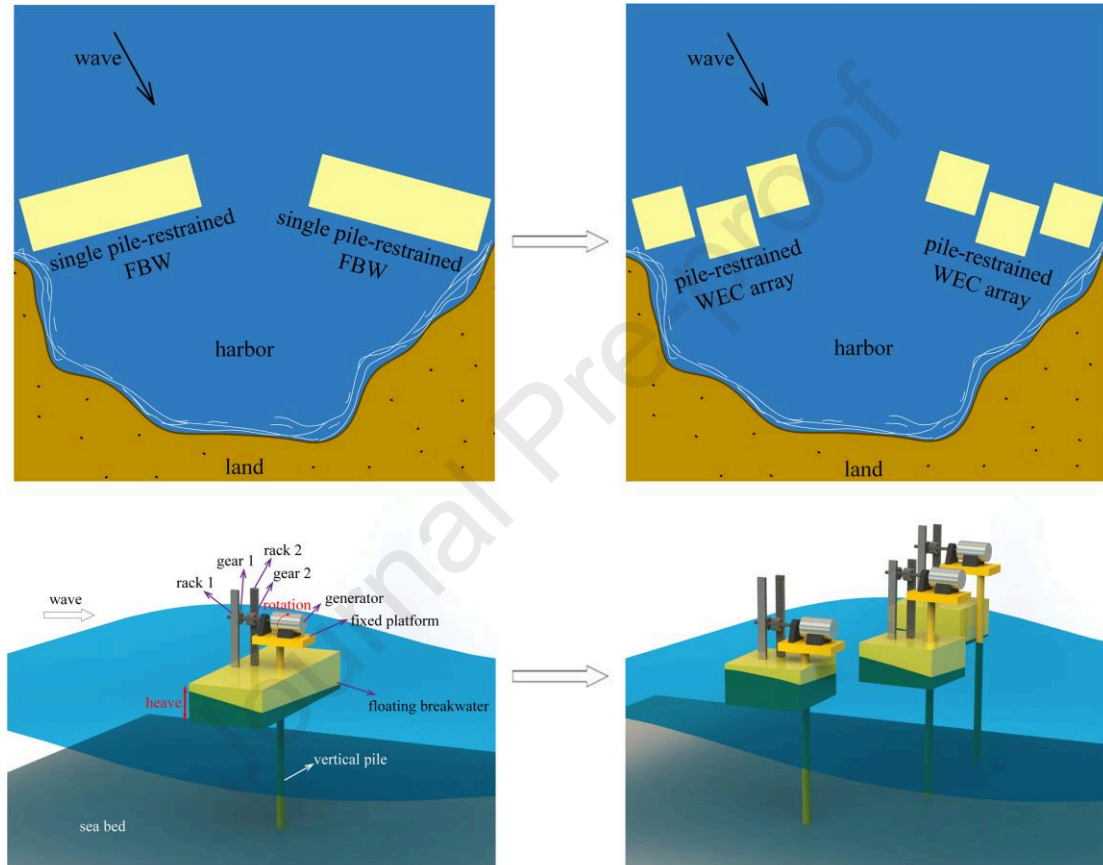


Fig. 1. Schematic of a single FBW and an array of WEC, constrained by vertical piles.

The hydrodynamic characteristics of point-absorbing WEC arrays have been extensively investigated (Bailey et al., 2018; López-Ruiz et al., 2018; Murai et al., 2021; Neshat et al., 2022; Shi et al., 2016; Sun et al., 2021; Teixeira-Duarte et al., 2022). These studies have shown that the arrangement scheme of the WEC array can have a significant impact on energy harvesting performance. Siddorn and Eatock Taylor (2008) observed a significant increase in wave height around an array of floaters in close proximity, while Kara (2016) found that the interaction factor due to diffracted and radiated waves between floaters decrease exponentially as the

transverse and longitudinal spacing of the floaters increases. Erselcan and Kükner (2017) discovered that the average energy generated by each WEC in an array is less than that generated by a single isolated WEC, and the amplitude of the reduction increases with the size of the array. Wu et al. (2017) analysed the hydrodynamic characteristics of a single-row array consisting of three solo Duck floaters and found that the CWR of the middle floater differed most from that of the individual WEC due to wave radiation from the floaters on either side. Bailey et al. (2018) used the normalised standard deviation and the frequency content relationships between the power of an individual WEC and an array of WECs to determine that the WECs are independent when the separation distance is greater than a specific value, and the WEC architecture and movement degrees of freedom were shown not to affect the independence. Murai et al. (2021) found that optimizing array arrangement increase power generation efficiencies by 15%. Sun et al. (2021) studied a cylindrical oscillating buoy array and found that the overall CWR could be effectively improved by arranging the lengths of buoy actuating arms staggered. Ghafari et al. (2022) discovered that hydrodynamic interactions between multiple WECs reduce the average power generated, while Zhong and Yeung (2022) found that multi-body wave-interactions have a destructive effect on array power production. Overall, these studies have shed light on the influence of the arrangement scheme of point-absorbing WEC arrays on their energy harvesting performance. However, less work has been dedicated to investigating the mechanism of the variation of the wave dissipation performance with the arrangement scheme of the array.

To date, most studies have mainly focused on analysing the dynamics of single FBWs without accounting for multi-body interactions, or on the energy harvesting of WEC arrays without fully considered wave reflection, transmission, and dissipation within the array. This paper proposes a pile-restrained floating WEC array consisting of multiple WECs aligned in a line as an alternative to a single large WEC for FBW applications (Fig. 1). This study primarily focuses on the hydrodynamic analysis of a three-unit WEC array under regular wave conditions. The PTO system of the WEC can be implemented using various technologies, such as hydraulic cylinders (Chen et al., 2016), direct-drive linear generators (Chen et al., 2017), or mechanical components (Ai et al., 2014). In this paper, Coulomb damping force is applied to represent the PTO force (Babarit et al., 2012). A numerical model is set up using the Reynolds-average Navier-Stokes (RANS) equation to simulate the nonlinear interaction of the wave and the

WECs. The reliability of the numerical model is assessed by comparing the obtained results with existing experimental data. Subsequently, the numerical model is employed to investigate the influence of different array arrangements on the motion of WECs, as well as the phenomena of wave reflection, transmission, energy absorption, and energy dissipation within the array. Finally, the hydrodynamic characteristics of the investigated WEC arrays are compared with those of a single WEC with identical dimensions to the array. This comprehensive analysis aims to provide insights into the performance and potential benefits of utilizing WEC arrays as FBWs compared to single WEC configurations.

The paper is organised as follows. In Section 2, the numerical model is presented. In Section 3, a validation is performed using the available published data. The numerical results are discussed in Section 4. The conclusions are given in Section 5.

2. CFD-Setup

A 3D numerical wave tank (NWT) is created based on the Reynolds time-averaged Navier-Stokes (RANS) equation, as depicted in Fig. 2. The WEC array is arranged within the NWT, and the hydrodynamic problem is solved using the Cartesian coordinate system (O - x , y , z). The origin of the coordinate system (O) is located at the still water surface. The x and y axes correspond to the directions of wave propagation and the wave crest line respectively, while the z axis denotes the vertical direction. The length of the NWT along the x -axis is 12 times the wavelength λ , and its height along the z -axis is twice the still water depth H .

Fig. 2 illustrates the six boundaries of the NWT: the left boundary is a velocity inlet boundary, the right and top boundaries are pressure outlet boundaries, and both the side and bottom boundaries are no-slip walls. The distance from the velocity inlet boundary to the leading edge of WEC array is 5λ . The dimensions of a single WEC are denoted by L (length), D (height), B (width), and d (draft). The spacing between adjacent WECs along the x -axis and y -axis are l_x and l_y , respectively, while the distance between the side walls of the WECs and those of the NWT is δy .

In this study, we adopt a staggered arrangement that has been commonly employed in various investigations concerning heave WEC arrays to optimize power extraction (Child and Venugopal, 2010; Mercadé Ruiz et al., 2017; Stratigaki et al., 2014). This article's scope is

restricted to a configuration involving three WECs arranged in a row, wherein the middle WEC alternates backward in relation to the two neighboring WECs. It should be noted that the application of the WECs shown in Fig. 2 is within a closed water environment, which has been investigated in previous studies (Chen et al., 2016). However, it is important to clarify that the present study does not specifically address open water applications, where the domain width would need to be sufficiently large to eliminate side boundary effects.

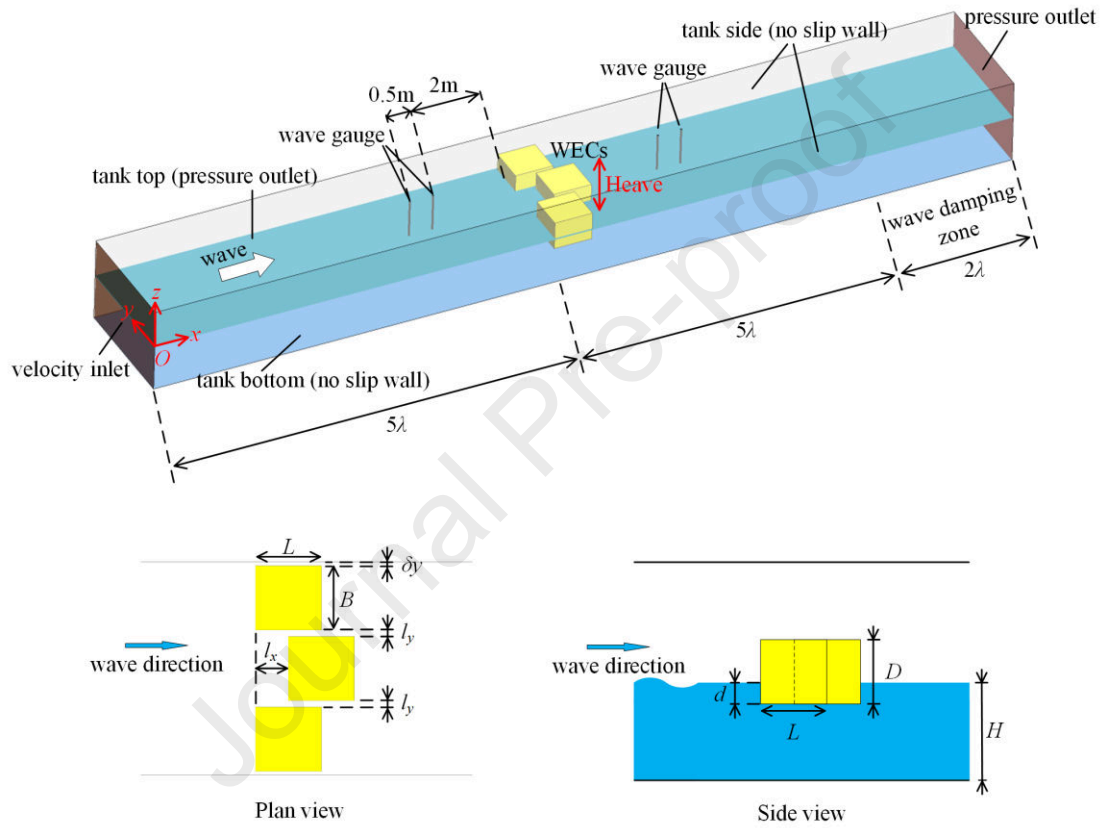


Fig. 2. Schematic of the NWT and the WEC array within it.

2.1. Mathematical model

2.1.1. Fluid motion

It is assumed that the fluid is incompressible. The mass continuity equation is expressed as

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

where $\mathbf{v}$ is the fluid velocity vector. The momentum conservation is described by Navier-Stokes equations as

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot \mathbf{T} + \mathbf{S} \quad (2)$$

where t is time; ρ is the fluid density; p is the pressure; $\mathbf{T}$ is the viscous part of the stress tensor; $\mathbf{S}$ is the body force (such as gravity). For incompressible Newtonian fluids considered here, $\mathbf{T}$ is defined as

$$\mathbf{T} = \mu(\nabla \mathbf{v} + (\nabla \mathbf{v})^T) \quad (3)$$

where μ is the dynamic viscosity of the fluid.

2.1.2. Structural movement

The motions of the floaters are written as

$$m_i \dot{\mathbf{v}}_i = m_i \mathbf{g} + \mathbf{F}_{h,i} + \mathbf{F}_{d,i} \quad (4)$$

where m_i , $\dot{\mathbf{v}}_i$ are the mass and the acceleration of the i -th floater, respectively; $\mathbf{g}$ is the gravitational acceleration; $\mathbf{F}_{h,i}$ is the hydrodynamic force acting on the i -th floater; $\mathbf{F}_{d,i}$ is the PTO force acting on the i -th floater. The hydrodynamic force $\mathbf{F}_{h,i}$ is obtained by integrating the pressure and shear stress over the i -th floater surface S_i as

$$\mathbf{F}_{h,i} = \int_{S_i} (\mathbf{T} - p\mathbf{I}) \cdot \mathbf{n} ds \quad (5)$$

where $\mathbf{n}$ is the unit normal vector of the floater surface element. The PTO force $\mathbf{F}_{d,i}$ adopts friction damping, specifically Coulomb damping (Babarit et al., 2012), and is represented by the following equation:

$$\mathbf{F}_{d,i} = \begin{cases} -\mathbf{v}_i / |\mathbf{v}_i| f_d, & |\mathbf{v}_i| > 0 \\ 0, & \mathbf{v}_i = 0 \end{cases} \quad (6)$$

where f_d is the value of friction damping.

2.1.3. Boundary condition

The motion of the floaters and fluid are fully coupled by velocities and forces at the fluid-structure interface as (Chen et al., 2021)

$$\mathbf{v}_s = \mathbf{v} \quad \text{on } S \quad (7)$$

$$\mathbf{F}_s + \mathbf{F}_f = 0 \quad \text{on } S \quad (8)$$

where $\mathbf{v}_s$ is the velocity vector of the floater on the fluid-structure interface; $\mathbf{F}_s$ is the vector of traction acting on the floater on the fluid-structure interface; $\mathbf{F}_f$ is the vector of stresses exerted on the fluid on the fluid-structure interface.

The water particle velocities are specified at the inlet boundary based on the characteristics of the fifth-order Stokes wave (Fenton, 1985). The static pressure at the pressure outlet boundary of the NWT is $p_{\text{out}} = \rho g z$. To mitigate the numerical reflection caused by the outlet boundary, a numerical beach is applied by adding a momentum damping term S_d in the z -direction momentum equation (Eq. (2)) within a distance of $0-2\lambda$ from the pressure outlet boundary. The S_d is given by Park and Kim (1998) as

$$S_d = -\zeta \left(\frac{x - x_s}{x_e - x_s} \right)^2 \frac{z_b - z}{z_b - z_{fs}} \mathbf{v}_z \quad (9)$$

where ζ is a parameter to be controlled, which is set as 10 initially and should be larger if the wave is not dissipated enough in the numerical beach zone; x_s and x_e are the start and end positions of the dissipation zone in the x -direction, respectively; z_b and z_{fs} are the bottom and free-surface positions of the dissipation zone in the z -direction. Consider, for instance, a wave with a period of 1.37 s and a wave height of 0.20 m. In this scenario, the maximum spectral density of the incident wave is estimated to be approximately 1000 times greater than that of the reflected wave. The reflection coefficient is approximately 0.02. Consequently, the wave reflection is deemed negligibly small within the damping zone.

2.1.4. Wave separation and data analysis

Fig. 2 illustrates the deployment of four wave gauges for the measurement of surface elevation. Two gauges are positioned in front of the WECs, while the remaining two gauges are placed behind the WECs. The wave data collected by the front gauges enables the separation of incident and reflected waves by applying the GODA two-point method (Goda and Suzuki, 1977). Similarly, the wave data recorded by the gauges positioned behind the WECs is utilized to separate the transmitted wave and the wave that undergoes slight reflection by the numerical beach. Then, the reflection coefficient K_r and transmission coefficient K_t are calculated as

$$K_r = h_r / h_i \quad (10)$$

$$K_t = h_r / h_i \quad (11)$$

where h_r is the average reflected wave height across the transverse direction; h_i is the incident wave height. h_t is the average transmitted wave height across the transverse direction.

The total wave dissipation coefficient K_d is defined as He and Huang (2014):

$$K_d = 1 - K_r^2 - K_t^2 \quad (12)$$

The turbulence specific dissipation rate ξ is given by Wilcox (1998):

$$\xi = \frac{\varepsilon}{C_\mu I} \quad (13)$$

where ε is the value of turbulence dissipation rate, which is estimated by Eq. (14); C_μ is the model constant of 0.09; I is the kinetic turbulent energy, which is calculated by Eq. (15).

$$\varepsilon = C_\mu^{1/2} I \frac{dU}{dz} \quad (14)$$

$$I = \frac{1}{2} (\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \quad (15)$$

where U is the profile of vertical velocity in the AIJ power-law method; σ_u , σ_v , and σ_w are the standard deviation of U , V and W , which are turbulent velocity at x -, y - and z -direction, respectively.

Wave dissipation within the WEC array consists of two components. The first component corresponds to the turbulent dissipation around the WEC array, while the second component represents the energy captured by the PTO system of the WECs. The WECs' PTO system converts wave energy into mechanical energy, subsequently transforming it into electrical energy. However, the analysis within this study does not encompass the mechanical efficiency and generator efficiency. The focus is solely on the efficiency of the PTO system regarding the conversion of wave energy into mechanical energy, denoted by η , and can be expressed as follows

$$\eta = \frac{P_d}{B_a P_{in}} \quad (16)$$

where P_d is the average power that the WEC array captures through the PTO system; B_a is the width of the WEC array; P_{in} is the incoming wave power per unit width of the wave front. The P_d is calculated as

$$P_d = \frac{1}{T} \sum_i \int_T \mathbf{F}_{d,i} \cdot \mathbf{v}_i dt \quad (17)$$

And P_{in} is given as

$$P_{in} = \frac{\rho g h_i^2 \omega}{16k} \left[1 + \frac{2kH}{\sinh(2kH)} \right] \quad (18)$$

where ω and k are the wave angular frequency, and wave number, respectively.

2.2. Numerical method

ANSYS Fluent is employed to solve the fluid motion equations using the finite volume method. The motion equations of the wave energy converters (WECs) are solved using a self-developed program that utilizes the 4th-order Runge-Kutta method. This WEC motion program is integrated into the Fluent solver through user-defined functions (UDFs). The computation flowchart is depicted in Fig. 3.

At the beginning of each time step, the UDF provides Fluent with the motion parameters of the WECs (i.e. $\dot{\mathbf{v}}_i$, and $\mathbf{v}_i$). Then the moving structure surface S_i is updated using the dynamic mesh with diffusion-based smoothing (Fluent user's guide, Chapter 10) [31]. By applying the updated structure surface boundaries, the fluid motion is solved by pressure-based segregated solver. The PISO method is applied to couple the pressure and velocity fields, while a second-order implicit time discrete format, least squares cell based gradient discretization method, PRESTO! pressure discretization method, and second-order upwind convection discrete format are used. The Geo-Reconstruct method is utilized to capture the free surface. During the iterations in Fluent, the UDF retrieves p , $\mathbf{T}$, $\mathbf{n}$ once per iteration from the Fluent solver. These values are then used to calculate $\mathbf{F}_{h,i}$ and $\mathbf{F}_{d,i}$ as determined by Eq. (5) and Eq. (6) respectively. Additionally, the UDF solves the motion of the WECs once per time step by employing Eq. (4). If the termination criterion is not satisfied, the solution is transferred to the next time step by the UDF.

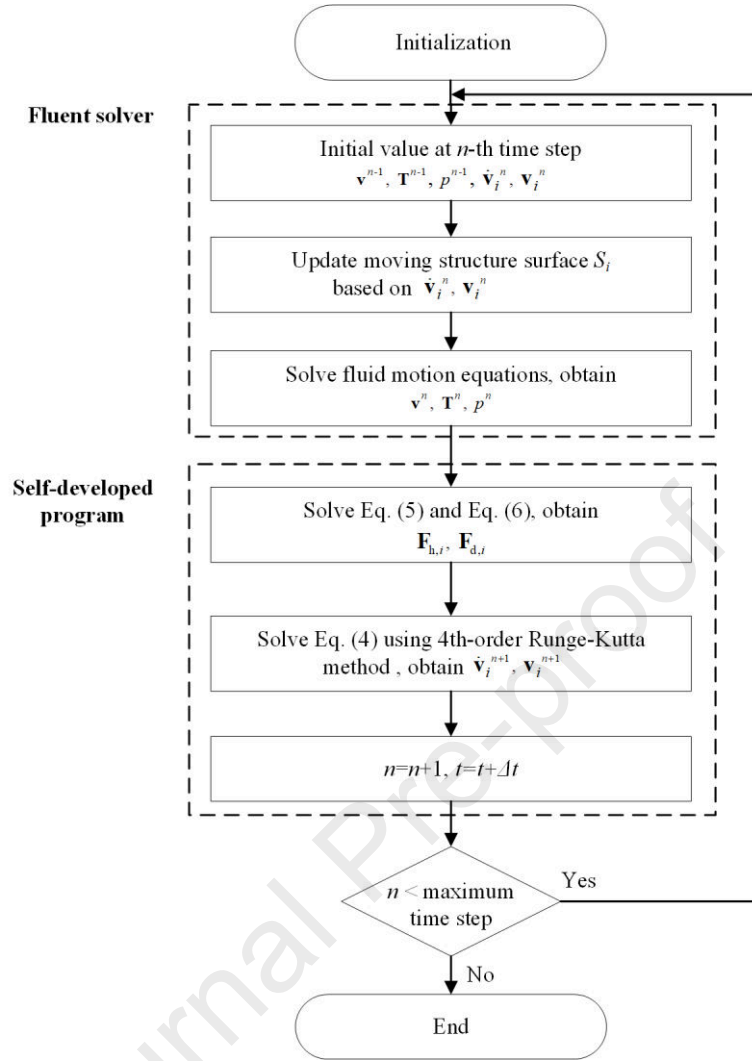


Fig. 3. Computation flowchart.

The calculation domain is discretised using hexahedral grid cells. The calculation domain can be divided into six regions based on grid partitioning characteristics: the air area, water area, wave surface refinement area, floater refinement area, transition area, and wave dissipation area, as depicted in Fig. 4. The cell sizes refer to the research of Finnegan and Goggins (2012), Chen et al. (2017) and Marques Machado et al. (2018), as summarized in Table 1. Along the wave propagation direction, the cell size Δx ranges from $1/143\lambda$ to $1/8\lambda$. In the wave surface refinement area, the cell size is approximately $1/40\lambda$. In the transition area, Δx decreases from $1/40\lambda$ to $1/143\lambda$ with a growth rate of 1.08. The floater refinement area has a uniform Δx of $1/143\lambda$. In the wave dissipation area, Δx gradually increases from $1/40\lambda$ to $1/8\lambda$ with a growth rate of 1.11. The cell size Δy along the crest line is approximately $0.4\Delta x$. Along the vertical direction, the cell size Δz varies from $1/20 h_i$ to $4/7 h_i$, with a Δz of $1/20 h_i$ in the wave surface

refinement. In the air area, Δz increases gradually from $1/20 h_i$ to $4/7 h_i$ as the z -coordinate increases, with a grid growth rate of 1.15. In the water area, Δz increases gradually from $1/20 h_i$ to $2/9 h_i$ as the z -coordinate decreases, with a grid growth rate of 1.05.

Table 1. Grid settings.

Area	Cell size	Growth rate
Δx		
Wave surface refinement area	$1/40\lambda$	1
Floater refinement area	$1/143\lambda$	1
Transition area	$1/143\lambda - 1/40\lambda$	1.08
Wave dissipation area	$1/40\lambda - 1/8\lambda$	1.11
Δy		
All areas	$0.4\Delta x$	1
Δz		
Wave surface refinement area	$1/20 h_i$	1
Air area	$1/20 h_i - 4/7 h_i$	1.15
Water area	$1/20 h_i - 2/9 h_i$	1.05

In this study, a fixed time step is employed to solve the problem. While Finnegan and Goggins (2012) recommend a time step of $\Delta t = T/50$, this study uses a smaller time step of $\Delta t = T/270$ to more accurately capture the water surface. The CFL number ranges from 0.03 to 0.46 in this study.

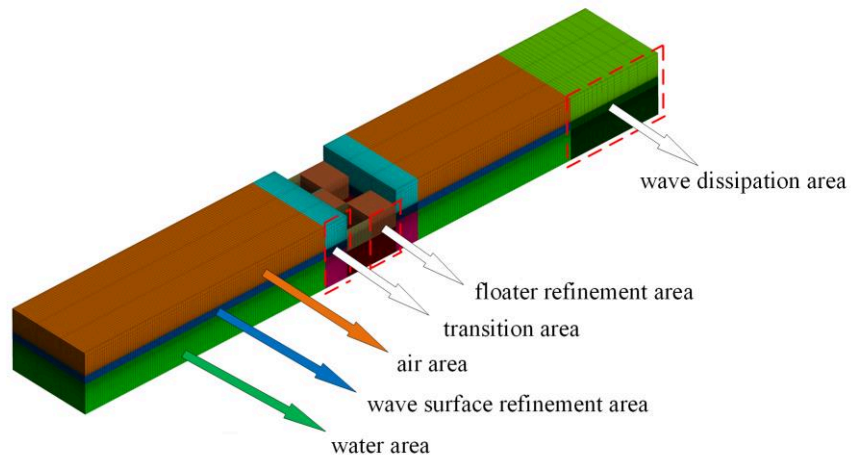


Fig. 4. Grid of the NWT with the air area above the floater refinement area removed.

3. Convergence analysis and model validation

To validate the accuracy of the numerical model, a comparison is conducted between the numerical results and the experimental results of Ning et al. (2016) for the hydrodynamic characteristics of a WEC. The geometric and physical parameters used in the experimental model are replicated in our numerical model, and Table 2 summarizes these parameters.

Mesh convergence tests are conducted to demonstrate the effectiveness of the adopted grid accuracy. Apart from the medium mesh created according to Table 1, two additional grid resolutions, namely the coarse grid and the fine grid, were also designed. Fig. 5 illustrates the vertical sections of the coarse, medium, and fine grids surrounding the WEC. The respective element numbers for these three grids are 0.146 million, 0.785 million, and 3.044 million. Fig. 5 also indicates that the relative deviation of results obtained from the medium and fine grids is approximately 3.0%, suggesting a reasonable level of agreement between the two grids. Considering the need to save computational costs and ensure numerical accuracy, subsequent examinations deem the medium grid to be sufficient.

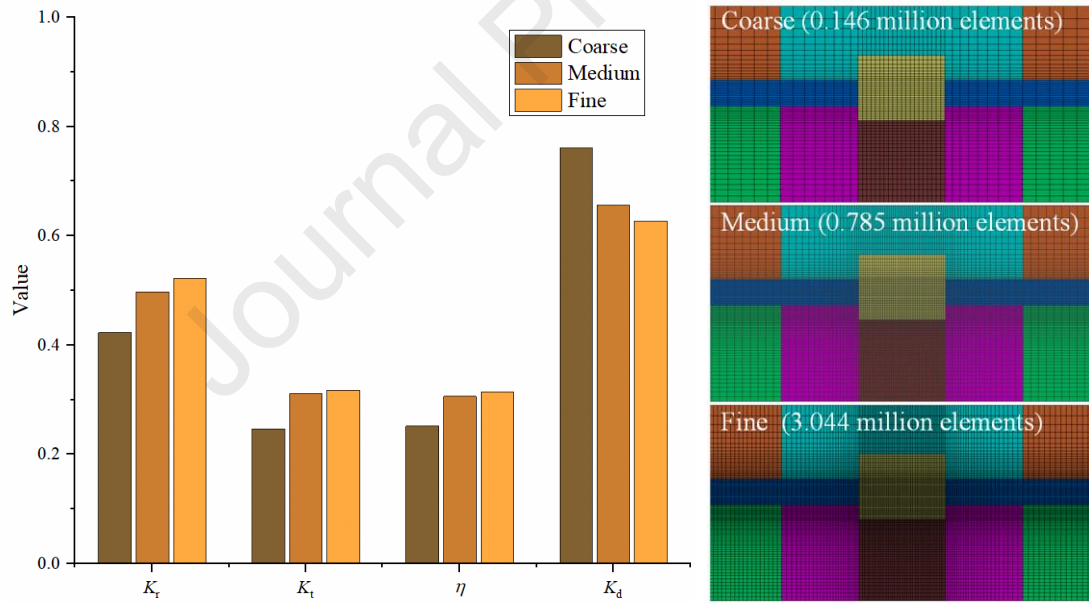
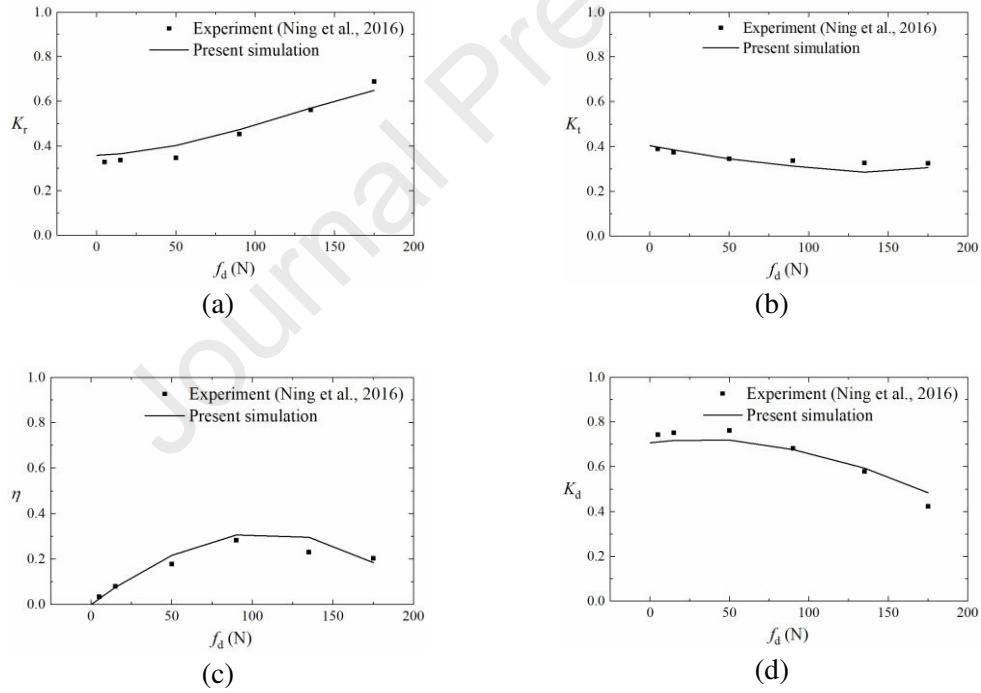


Fig. 5. Mesh convergence results in terms of K_r , K_t , η and K_d for $T = 1.37$ s and $h_i = 0.2$ m.

289 Table 2. Geometric and physical parameters of the single WEC.

Parameter	Value
L (m)	0.80
B (m)	0.78
D (m)	0.60
d (m)	0.25
δy (m)	0.05
f_d (N)	0–175
H (m)	1.0
h_i (m)	0.2
T (s)	1.37
λ (m)	2.858

290 Fig. 6 illustrates the experimental and numerical results for the hydrodynamic coefficients
 291 of the WEC, including K_r , K_t , η and K_d , under regular waves with $T = 1.37$ s and $h_i =$
 292 0.2 m. The results exhibit a consistent curve trend between the experimental and numerical data,
 293 indicating the reliability of the numerical model.



294 Fig. 6. Comparison between the experimental and numerical results for the hydrodynamic
 295 coefficients of the WEC: (a) K_r ; (b) K_t ; (c) η ; (d) K_d .

296 To further evaluate the accuracy of the numerical model, the difference between the
 297 experimental and numerical results is quantitatively analysed using the Mean Absolute
 298 Percentage Error (MAPE). The MAPE is defined as:

$$\text{MAPE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{\hat{y}_i - y_i}{y_i} \right| \times 100\% \quad (19)$$

where $\hat{y}_i$ and y_i represent the calculated and measured values, respectively, and n is the number of data points. The MAPE values for K_r , K_t , η and K_d are 7.6%, 5.3%, 14.4% and 5.4%, respectively, suggesting an acceptable level of agreement between the numerical results and the experimental results. It is worth noting that the MAPE value for η is relatively larger compared to the other variables. This can be attributed to the unavoidable difference in PTO damping force between the experimental and numerical models, as shown in Fig. 7. In the experimental setup, a current controller-magnetic powder brake system is utilized to simulate Coulomb damping, but it is acknowledged that this system may not perfectly represent ideal Coulomb damping. On the other hand, in the numerical simulation, ideal Coulomb damping is assumed. Consequently, there exists a slight deviation between the damping force curves obtained from the experimental and numerical results. The impact of the damping force is more pronounced on η , which explains the higher MAPE value. Nevertheless, despite this discrepancy, the overall agreement between the experimental and numerical results remains acceptable.

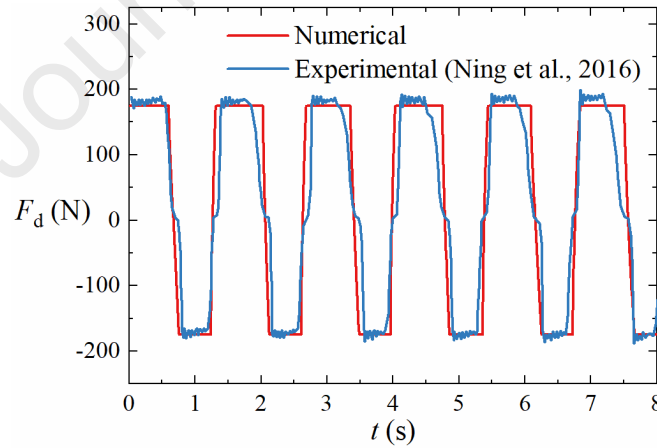


Fig. 7. Difference in PTO damping force between the experimental and numerical models.

The numerical model is then used to predict the interaction of multiple heave floats, which has been studied experimentally by Zhao et al. (2019). Fig. 8 compares the simulated heave time series curves of the heaving floats under a regular wave of $T = 1.17$ s and $h_i = 0.12$ m with the published experimental results, demonstrating a good agreement between the numerical and experimental results.

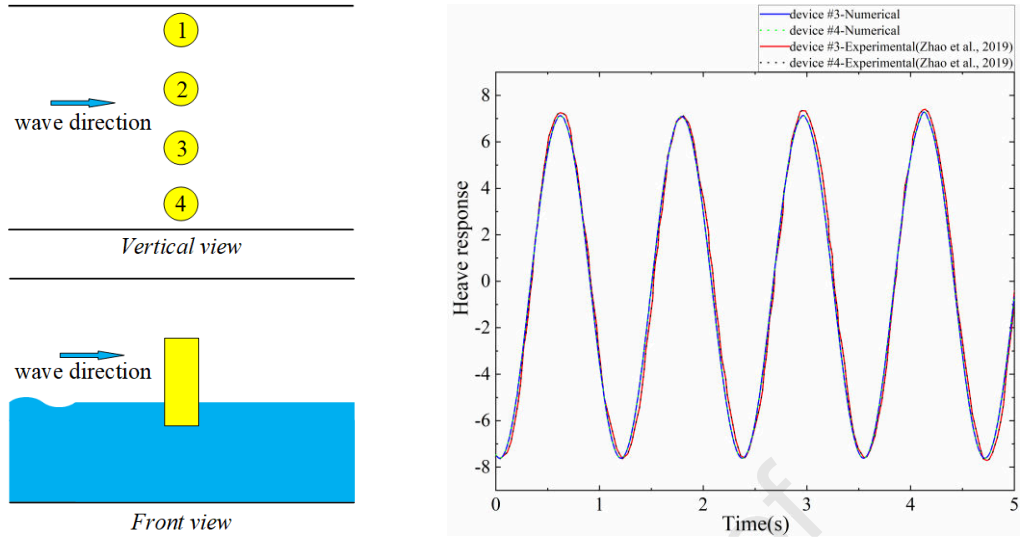


Fig. 8. Comparison of the heave response between the numerical and experimental results.

All the above demonstrates the effectiveness and reliability of the model as a tool for predicting the hydrodynamic performance of heave WECs operating under regular wave conditions.

Results and discussion

The numerical model is utilized to investigate the hydrodynamic characteristics of a WEC array consisting of three box-shaped heave WECs. The individual WECs within the array possess the same geometric and physical parameters as the single WEC (summarized in Table 2). The configuration of the array is depicted in Fig. 2 and determined by $\bar{l}_x$ and $\bar{l}_y$, which are non-dimensionalized as

$$\bar{l}_x = l_x / L \quad (20)$$

$$\bar{l}_y = l_y / B \quad (21)$$

In this study, $\bar{l}_x$ varies from 0 to 1, while $\bar{l}_y$ varies from 0.05 to 0.15. The geometric and physical parameters specific to the WEC array are presented in Table 3. This study examines the effects of array arrangement on the heave amplitude of the WECs, as well as K_r , K_t , η , and K_d . Additionally, it compares the hydrodynamic characteristics of the WEC array with those of a single WEC of the same dimensions.

Table 3. Geometric and physical parameters of the WEC array.

Parameter	Value
$\bar{l}_x$	0.05, 0.10, 0.15
$\bar{l}_y$	0, 0.5, 1.0
f_d (N)	90
H (m)	1.0
h_i (m)	0.2
T (s)	1.37
Number of grid elements N_c	2.67×10^6
Time step Δt (s)	$T/270$
λ (m)	2.858

4.1. Effect of array arrangement on heave amplitude

The dimensionless heave amplitude σ is defined as the ratio of the WEC heave amplitude A_z to incident wave height h_i . Due to symmetry, the σ values of the side WECs are identical and represented by σ_s , while the σ value of the middle WEC is represented by σ_m . Fig. 8 illustrates the variations of σ_m , σ_s and σ_m/σ_s with $\bar{l}_x$ and $\bar{l}_y$ for $f_d = 90$ N, $T = 1.37$ s and $h_i = 0.2$ m.

In Fig. 8 (a), it can be seen that for a given $\bar{l}_y$, as $\bar{l}_x$ increase, σ_m initially increases and then decreases, reaching its maximum value when $\bar{l}_x = 0.5$. To explore the underlying reasons for this variation in σ_m with respect to $\bar{l}_x$, Fig. 9 and Fig. 10 display the changes in instantaneous wave surface elevation and instantaneous specific dissipation rate around the array for different $\bar{l}_x$ and $\bar{l}_y$, respectively. Fig. 9 shows that when $\bar{l}_x = 0.5$, waves converge in front of the middle WEC, resulting in an increase in the heave amplitude of the middle WEC. Conversely, when $\bar{l}_x = 0.0$, more waves are reflected by the WEC array, and when $\bar{l}_x = 1.0$, more waves are transmitted to the rear through the gap between WECs. This leads to a smaller value of σ_m at $\bar{l}_x = 0.0$ and 1.0 than at $\bar{l}_x = 0.5$. Furthermore, Fig. 10 reveals that when $\bar{l}_x = 1.0$, more energy is dissipated around the WEC array, resulting in a lower value of σ_m compared to when $\bar{l}_x = 0.0$ and 0.5 .

It can also be seen from Fig. 8 (a) that, for a determined $\bar{l}_x$, σ_m increases with the increase of $\bar{l}_y$. This phenomenon can be attributed to the fact that an increase in $\bar{l}_y$ leads to a

greater diffraction of waves from the side WECs, which drives the heaving motion of the middle WEC (Wu et al., 2017).

Fig. 8 (b) illustrates that σ_s decreases as both $\bar{l}_x$ and $\bar{l}_y$ increase. This is due to that an increase in $\bar{l}_x$ and $\bar{l}_y$ results in more waves bypassing the side WECs to drive the middle WEC to heave or transmit to the downstream, thereby reducing in less waves driving the side WECs to heave.

Additionally, Fig. 8 (c) demonstrates that σ_m/σ_s varies significantly between 0.551 and 2.367. This indicates that the variation in $\bar{l}_x$ and $\bar{l}_y$ significantly impacts the hydrodynamic interaction among the WECs, ultimately affecting the heave amplitude of each WEC in the array.

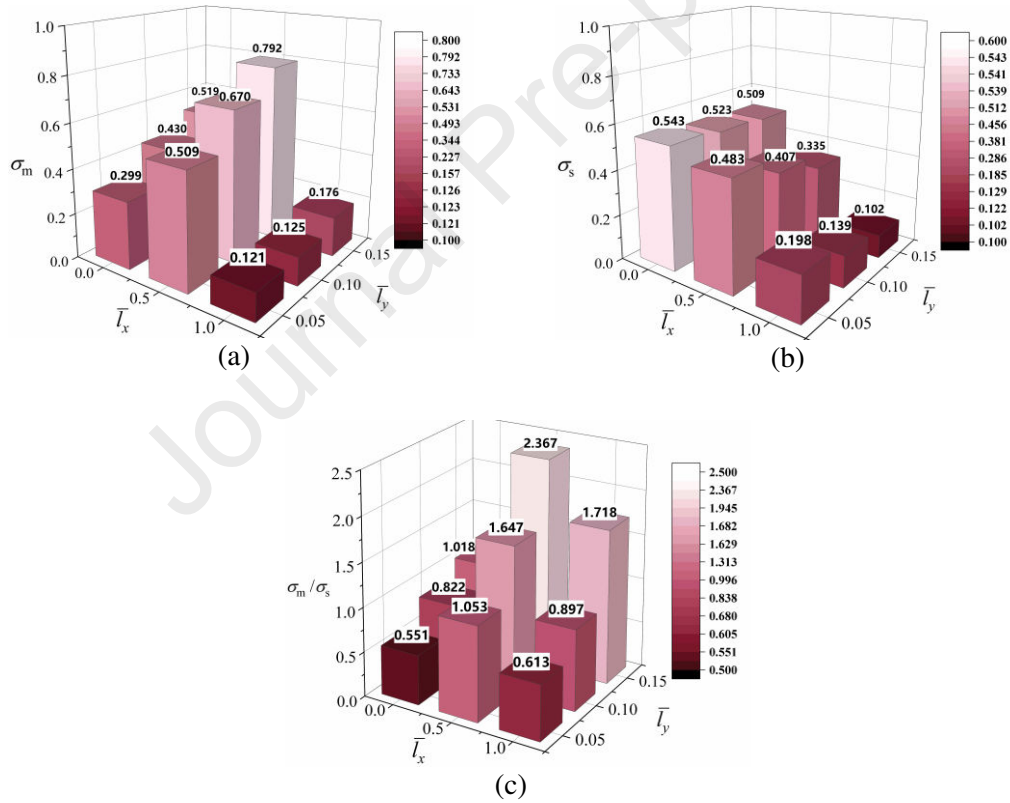


Fig. 8. Variations of σ_m , σ_s , and σ_m/σ_s with $\bar{l}_x$ and $\bar{l}_y$ for $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m: (a) σ_m ; (b) σ_s ; (c) σ_m/σ_s .

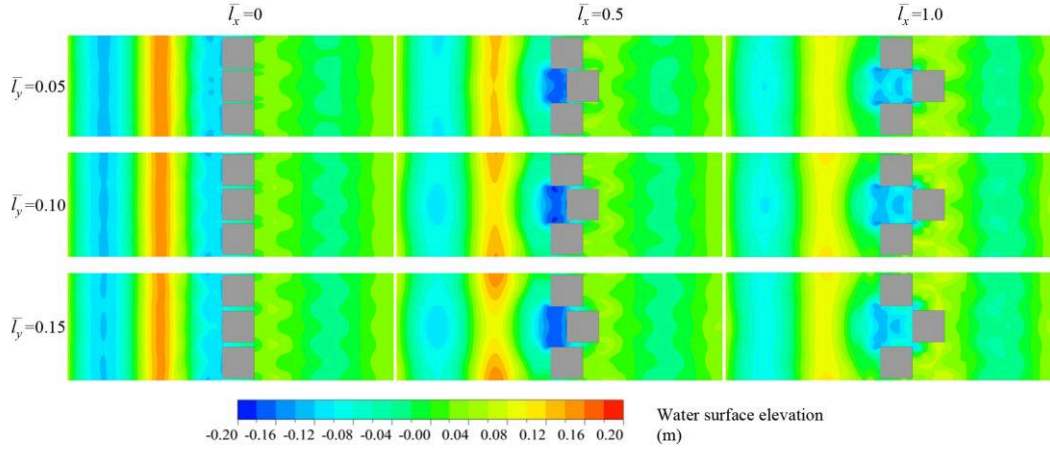


Fig. 9. Variation of instantaneous wave surface elevation around the WEC array with $\bar{l}_x$ and $\bar{l}_y$ for $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m.

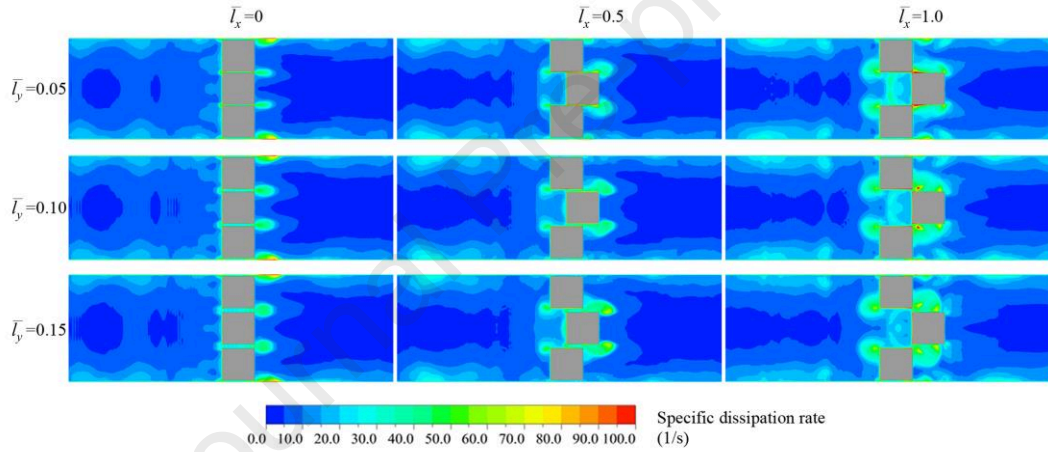


Fig. 10. Variation of instantaneous specific dissipation rate of wave surface around the WEC array with $\bar{l}_x$ and $\bar{l}_y$ for $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m.

4.2. Effect of array arrangement on K_r , K_t , η , and K_d

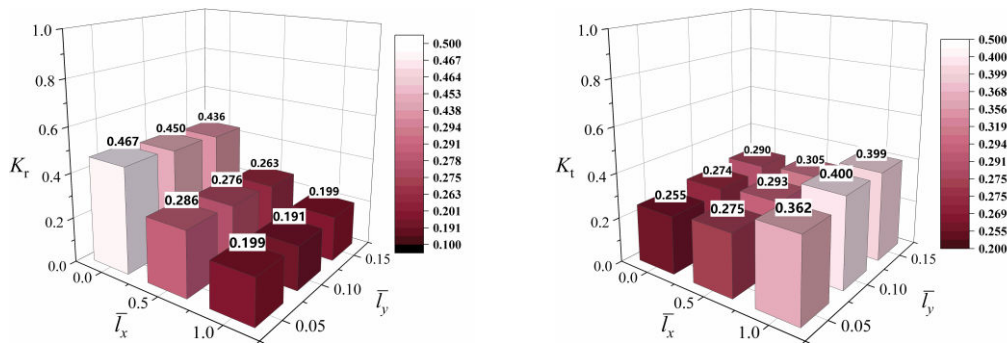
Fig. 11 illustrates the variations of K_r , K_t , η , and K_d with $\bar{l}_x$ and $\bar{l}_y$ under the conditions of $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m. The figure reveals that within the considered range of $\bar{l}_x$ and $\bar{l}_y$, the impact of $\bar{l}_y$ on K_r , K_t , η , and K_d is minor. It is worth noting that the impact of $\bar{l}_y$ on these hydrodynamic characteristics may vary when $\bar{l}_y$ exceeds 0.15. However, this possibility is beyond the scope of this paper.

Fig. 11 (a) shows that the value of K_r decreases as $\bar{l}_x$ increases for a given $\bar{l}_y$.

Particularly, when $\bar{l}_x$ falls between 0.0 and 0.5, K_r exhibits significant changes. Fig. 9 suggests that, when $\bar{l}_x = 0.0$, the water surface elevation in front of the WEC array reaches a conspicuous maximum, indicating that more incident waves are reflected by the array.

As shown in Fig. 11 (b), when $\bar{l}_x$ increases from 0.0 to 0.5, and $\bar{l}_y$ increases from 0.05 to 0.15, K_t varies slightly, ranging from 0.255 to 0.305. However, as $\bar{l}_x$ approaches 1.0, K_t increases significantly by approximately 40% to 0.362–0.400. Similarly, Fig. 11 (c) indicates that η remains relatively stable as $\bar{l}_x$ increases from 0.0 to 0.5 and $\bar{l}_y$ increases from 0.05 to 0.15, ranging from 0.274 to 0.304. However, when $\bar{l}_x$ reaches 1.0, η decreases by about 70% to 0.074–0.100.

Fig. 11 (d) demonstrates that as $\bar{l}_x$ increases from 0.0 to 0.5, K_d increases by approximately 16%. However, for $\bar{l}_x$ values between 0.5 and 1.0, the change in K_d is less than 5%. The parameter K_d comprises two components, namely, the turbulent dissipation energy coefficient around the WEC array and η of the damping system to harvest wave energy. Fig. 11 (c) shows that η remains almost unchanged as $\bar{l}_x$ varies from 0.0 to 0.5. However, Fig. 10 reveals that when $\bar{l}_x = 0.5$, there is greater turbulence dissipation around the WEC array than when $\bar{l}_x = 0.0$, which causes an increase in K_d . As $\bar{l}_x$ increases from 0.5 to 1.0, η decreases significantly. Nevertheless, the turbulent dissipation around the WEC array increases considerably, as shown in Fig. 10, resulting in a negligible difference in K_d between $\bar{l}_x = 0.5$ and $\bar{l}_x = 1.0$.



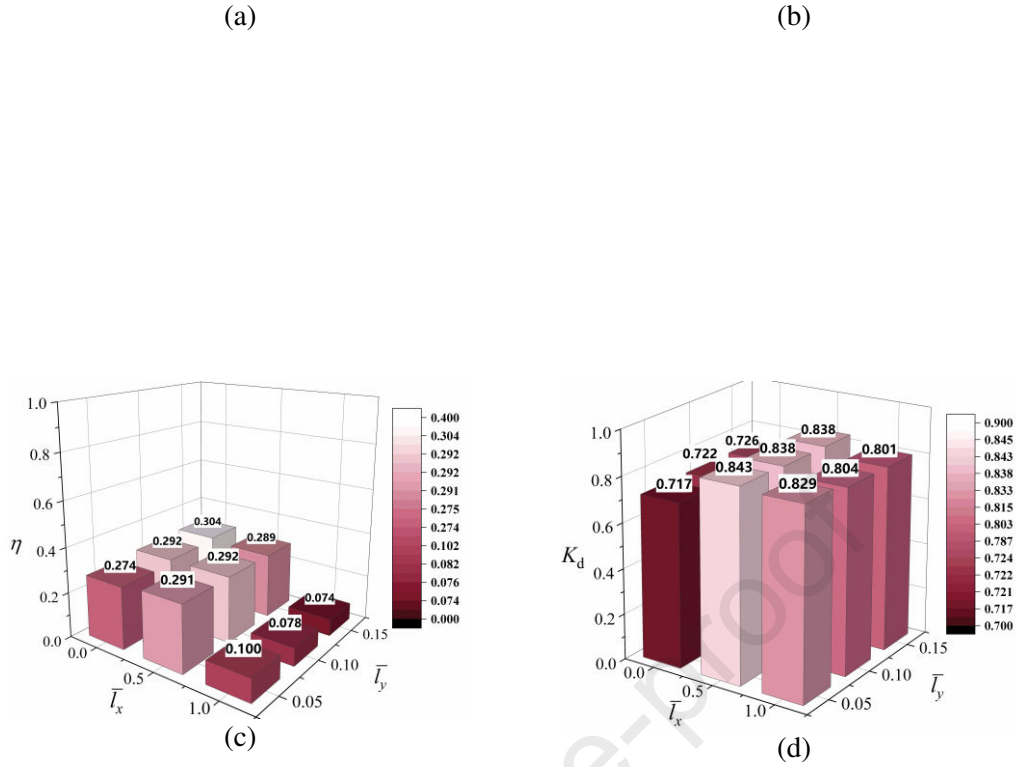


Fig. 11. Variations of K_r , K_t , η and K_d with $\bar{l}_x$ and $\bar{l}_y$ for $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m: (a) K_r ; (b) K_t ; (c) η (d) K_d .

Fig. 12 shows the variation of K_t with η under the conditions of $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m. It can be seen that there is a negative correlation (correlation coefficient of 0.9448) between K_t and η ($K_t = -0.5047\eta + 0.4288$). This suggests that as the wave energy conversion efficiency of the WEC array improves, there is generally a decrease in wave transmission coefficient. In other words, when the array becomes more effective at converting wave energy, it tends to allow less wave energy to pass through. This relationship highlights the importance of maximizing wave energy conversion efficiency to minimize wave transmission through the array.

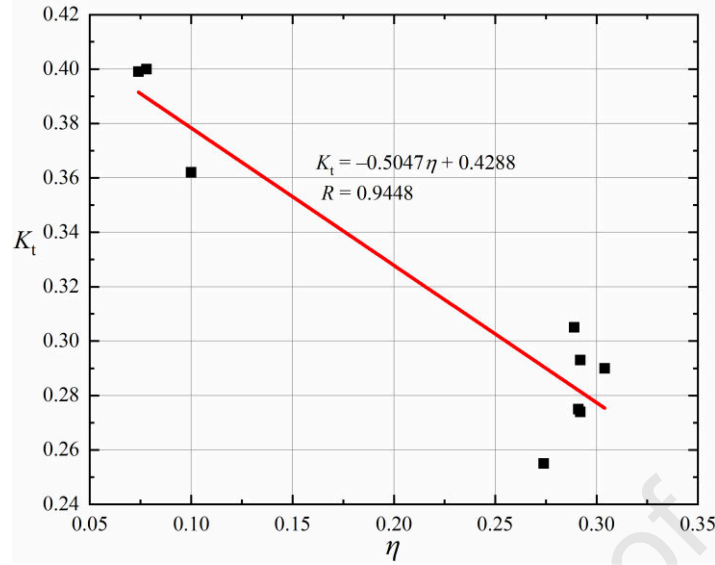


Fig. 12. Variation of K_t with η for $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m.

The wave energy conversion efficiency of the middle WEC and both side WECs are denoted as η_m and η_s , respectively. Fig. 13 (a) shows that as $\bar{l}_x$ increases from 0.0 to 0.5 and $\bar{l}_y$ increases from 0.05 to 0.15, the ratio η_m/η_s varies significantly between 0.550 and 2.380, despite the small overall change in η (as shown in Fig. 11c). When $\bar{l}_x = 0$ and $\bar{l}_y = 0.05$, $\eta_m/\eta_s = 0.550$, which suggests that wave energy conversion is dominated by the side WECs. Conversely, when $\bar{l}_x = 0.5$ and $\bar{l}_y = 0.15$, $\eta_m/\eta_s = 2.380$, indicating that wave energy conversion is dominated by the middle WEC. Fig. 13 (b) further reveals a strong positive correlation (correlation coefficient of 0.9994) between η_m/η_s and σ_m/σ_s . This correlation further emphasizes the significance of the heave amplitude ratio in determining the efficiency of wave energy conversion. A higher heave amplitude ratio indicates a higher efficiency ratio, implying that optimizing the heave amplitude ratio is crucial for achieving optimal wave energy conversion efficiency in individual WECs. This highlights the decisive role played by the heave amplitude ratio in determining the wave energy conversion efficiency of each WEC within the array arrangement.

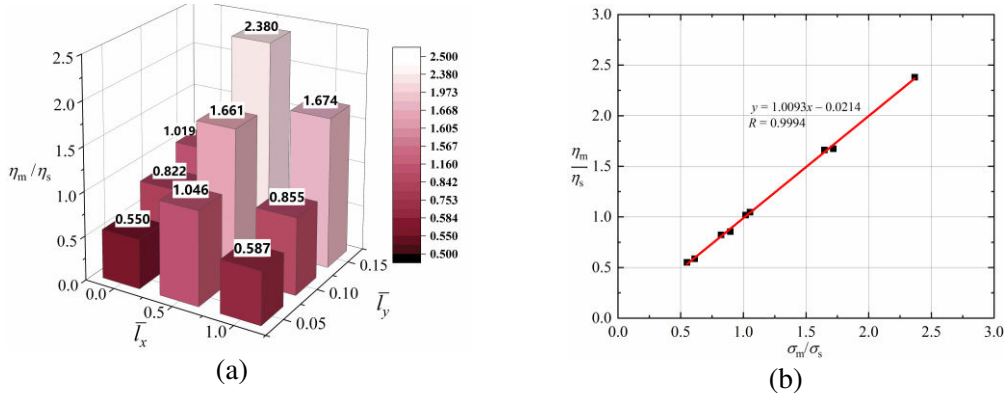


Fig. 13. Variations of η_m/η_s with $\bar{l}_x$, $\bar{l}_y$, and σ_m/σ_s for $f_d = 90$ N, $T = 1.37$ s, and $h_i = 0.2$ m: (a) η_m/η_s varies with $\bar{l}_x$ and $\bar{l}_y$; (b) η_m/η_s varies with σ_m/σ_s .

4.3. Comparison of hydrodynamic characteristics between WEC arrays and a single WEC

Taking into account the significance of both η and K_t as essential parameters for evaluating the performance of the WECs, we introduce the benefit coefficient, denoted as $Y = k_1\eta - k_2K_t$, to comprehensively incorporate the effects of both parameters. Here, k_1 and k_2 represent the respective weights assigned to η and K_t . It is worth noting that the sum of k_1 and k_2 is constrained to be equal to 1, ensuring a balanced evaluation that adequately considers both parameters.

According to Fig. 11 (b) and (c), when $\bar{l}_x = 1.0$, η is smaller and K_t is larger, respectively, than those for $\bar{l}_x = 0.0$ and $\bar{l}_x = 0.5$. This implies that Y for $\bar{l}_x = 1.0$ must be smaller than those for $\bar{l}_x = 0.0$ and $\bar{l}_x = 0.5$. Additionally, comparing to the arrays for $\bar{l}_x = 0.5$, the array of $\bar{l}_x = 0.0$ and $\bar{l}_y = 0.10$ has larger or equal η , and smaller K_t , and therefore larger Y .

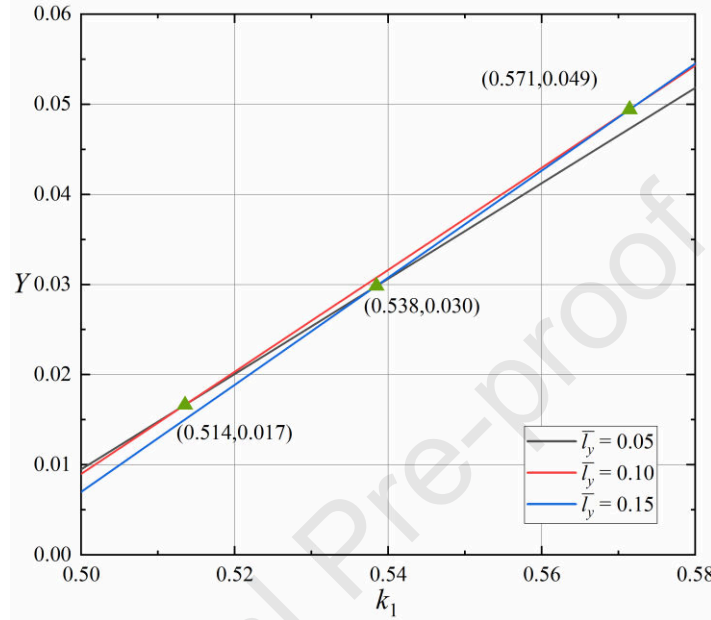
The above analysis indicates that Y is greater for $\bar{l}_x = 0.0$ than for $\bar{l}_x = 0.5$ and 1.0 . This suggests that the performance of aligned arrays ($\bar{l}_x = 0.0$) is superior to that of staggered arrays ($\bar{l}_x = 0.5$ and 1.0). Fig. 14 shows the variation of Y with respect to k_1 for different $\bar{l}_y$, with $\bar{l}_x = 0.0$. It is evident from the figure that for $k_1 < 0.514$, the Y with $\bar{l}_x = 0.0$ and $\bar{l}_y = 0.05$ is the largest, while for $k_1 > 0.571$, the Y with $\bar{l}_x = 0.0$ and $\bar{l}_y = 0.15$ is the largest. When

448 $0.514 < k_1 < 0.571$, the Y with $\bar{l}_x = 0.0$ and $\bar{l}_y = 0.10$ is the largest. It is evident from Fig.

449 11 that K_t and η of the three arrays with $\bar{l}_x = 0.0$ are within the range of 0.255–0.290 and

450 0.274–0.304, respectively. This indicates the effectiveness of the arrays in simultaneously

451 reducing wave transmission and converting wave energy.



452 Fig. 14. Variations of Y with k_1 for $\bar{l}_x = 0.0$, and $\bar{l}_y = 0.05$ –0.15.

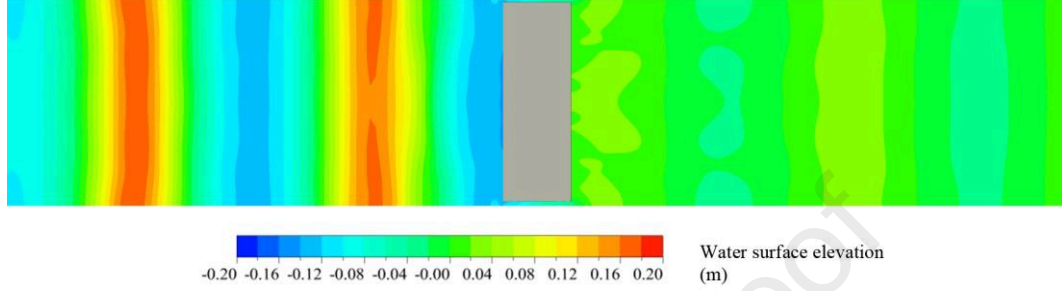
454 The hydrodynamic characteristics of the aligned arrays are further compared to those of a
 455 single WEC, where the single WEC has the same dimensions as the array, specifically with a
 456 length (L) of 0.80 m and a width (B) of 2.34 m. Fig. 15 and Fig. 16 illustrate the instantaneous
 457 wave surface elevation and instantaneous specific dissipation rate around the WEC,
 458 respectively. Comparing these figures with Fig. 9 and Fig. 10, it can be observed that the wave
 459 height is greater for the single WEC configuration, indicating a higher level of wave reflection.
 460 Additionally, less energy is dissipated around the WEC in the single WEC case.

461 To quantify the differences, the relative increments (R) of K_r , K_t , η , and K_d for the
 462 WEC arrays compared to the single WEC is calculated as

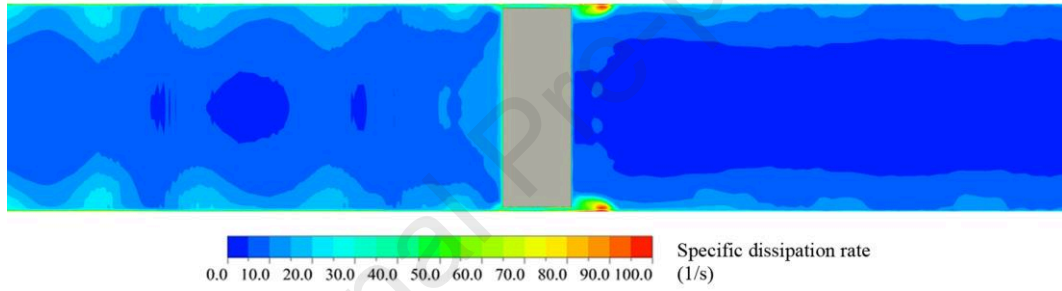
$$463 \quad R = \frac{x_2 - x_1}{x_1} \quad (22)$$

464 where x_1 and x_2 denote the hydrodynamic characteristics of the single WEC and the WEC
 465 array, respectively. R_r , R_t , R_η , and R_d represent the relative increments of K_r , K_t , η ,

466 and K_d , respectively. Table 4 displays the R_r , R_t , R_η , and R_d of the three aligned arrays.
 467 It can be seen that comparing to a single WEC, the aligned WEC arrays increases K_d by
 468 4.78%–6.09%, K_t by 7.46%–22.21%, and η by 14.62%–27.16%, while reducing K_r by
 469 8.30%–14.39%.



470 Fig. 15. Instantaneous wave surface elevation around the single WEC.
 471



472 Fig. 16. Instantaneous specific dissipation rate of wave surface around the single WEC.
 473

474 Table 4. Relative increments of K_r , K_t , η , and K_d for the three aligned arrays compared
 475 to the single WEC.

Array parameters	R_r	R_t	R_η	R_d
$\bar{l}_x = 0.0$, $\bar{l}_y = 0.15$	-14.39%	22.21%	27.16%	6.09%
$\bar{l}_x = 0.0$, $\bar{l}_y = 0.10$	-11.64%	15.46%	22.15%	5.51%
$\bar{l}_x = 0.0$, $\bar{l}_y = 0.05$	-8.30%	7.46%	14.62%	4.78%

476 The performance of both the aligned array arrangement with $\bar{l}_y = 0.10$ and the single
 477 WEC are further tested under different regular wave conditions. T varies from 1.16 s to 2.42 s
 478 and, correspondingly, the kh_i varies from 2.98 to 0.94. Detailed wave conditions are provided
 479 in Table 5.

480 Table 5. Wave condition parameters.

T (s)	h_i (m)	kh_i
1.16, 1.37, 1.58, 1.79, 2.00, 2.42	0.2	2.98, 2.20, 1.73, 1.41, 1.18, 0.94

Fig. 17 illustrates the variations of K_r , K_t , η , and K_d of the aligned array and single WEC for different kh_i . Fig. 18 shows the relative increments of K_r , K_t , η , and K_d for the aligned array compared to those of the single WEC.

Fig. 17 (a) and Fig. 18 (a) show that K_r of the aligned array consistently remains smaller than that of the single WEC across different kh_i values, with R_r ranging from -2.6% to -21%. Fig. 17 (b) and Fig. 18 (b) reveal that K_t of the aligned array exceeds that of the single WEC for most kh_i , with R_t ranging from -1.2% to 15.5%. This discrepancy is likely attributed to wave diffraction from the gap between the WECs towards the rear. Examining Fig. 17 (c) and Fig. 18 (c), it is evident that η of the aligned array consistently surpasses that of the single WEC for different kh_i values, with R_η ranging from 0.8% to 29%. This improvement may due to the enhanced wave energy capture resulting from the interaction effects between different WECs within the array (Zheng et al., 2019). Furthermore, Fig. 17 (b) and (c) indicate a lack of significant distinction in both the K_t and K_d curves between the aligned array and the single WEC when $kh_i < 1.18$. This behavior primarily arises from that the aligned WEC array effectively resembles a single WEC under long-wavelength conditions (Nader et al., 2012). Specifically, when $kh_i = 0.94$, the ratio of the corresponding wavelength to the WEC gap is 85.5, thus causing the aligned array to behave as a single WEC. Fig. 17 (d) and Fig. 18 (d) show that when $kh_i > 1.73$, K_d of the aligned array is greater than that of the single WEC, with R_d ranging from 5.5% to 12.2%. Overall, the aligned WEC array exhibit a significant increase in wave energy conversion efficiency, as well as a considerable increase in wave transmission. It is worth noting that generally the aligned array effectively enhances wave energy dissipation and reduce wave reflection. This indicates that the arrays are more suitable to reducing wave in enclosed water compared to a single WEC, as less wave would be reflected back at the boundary (Chen et al., 2016).

Fig. 19 illustrates the variations of Y of both the aligned array and the single WEC with kh_i for $k_1 = 0.54$. When $kh_i < 1.73$, the Y value of the aligned array is almost the same with that of the single WEC, while when $kh_i > 1.73$, the Y value of the aligned array exceeds that of the single WEC. In addition, Y gradually increases with increasing kh_i and subsequently decreases

after reaching its peak value at $kh_i = 2.20$ for both the aligned array and the single WEC. This trend suggests that both the aligned array and the single WEC perform more effectively under shorter-wavelength conditions. Notably, when $kh_i > 1.73$, as evident in Fig. 17 (b) and (c) for K_t and η respectively, the aligned array demonstrates a K_t range from 0.187 to 0.472 and an η range from 0.141 to 0.330. This observation indicates the aligned array's effectiveness in both reducing wave transmission and converting wave energy under shorter-wavelength conditions.

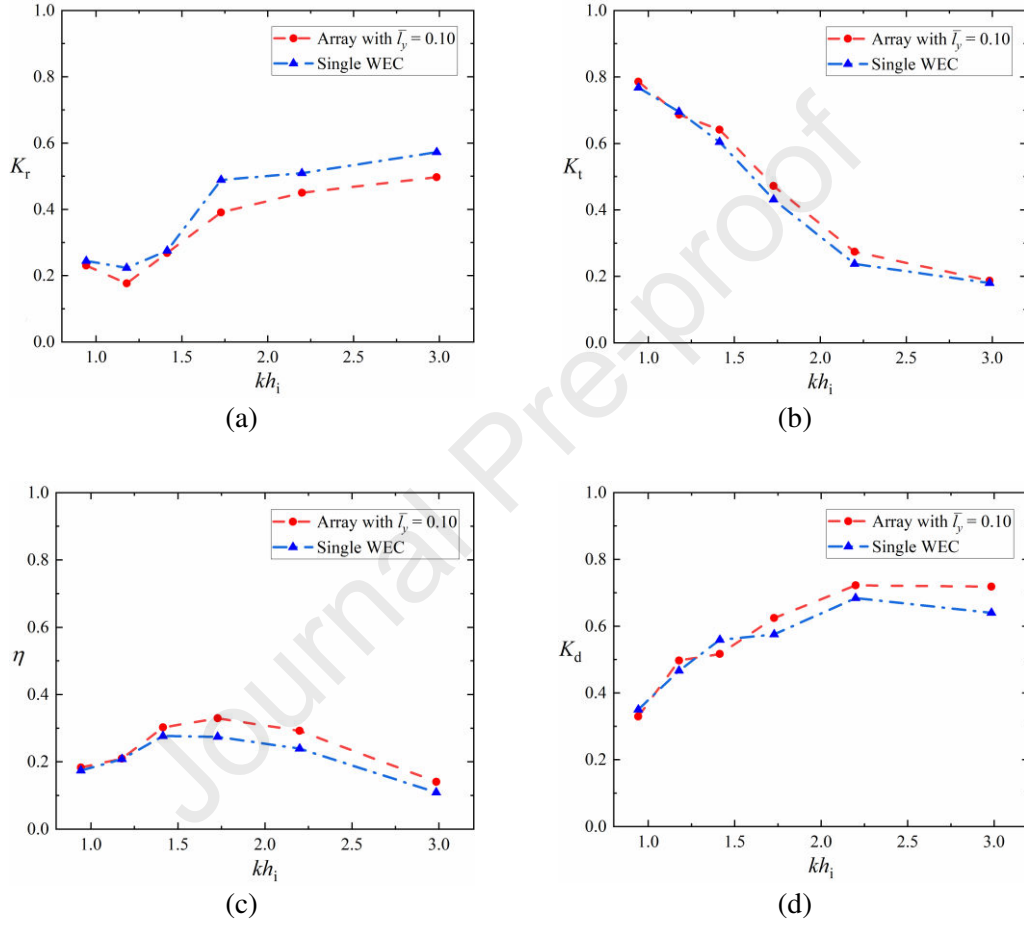


Fig. 17. K_r , K_t , η and K_d of the aligned array with $\bar{l}_y = 0.10$ and the single WEC for different kh_i .

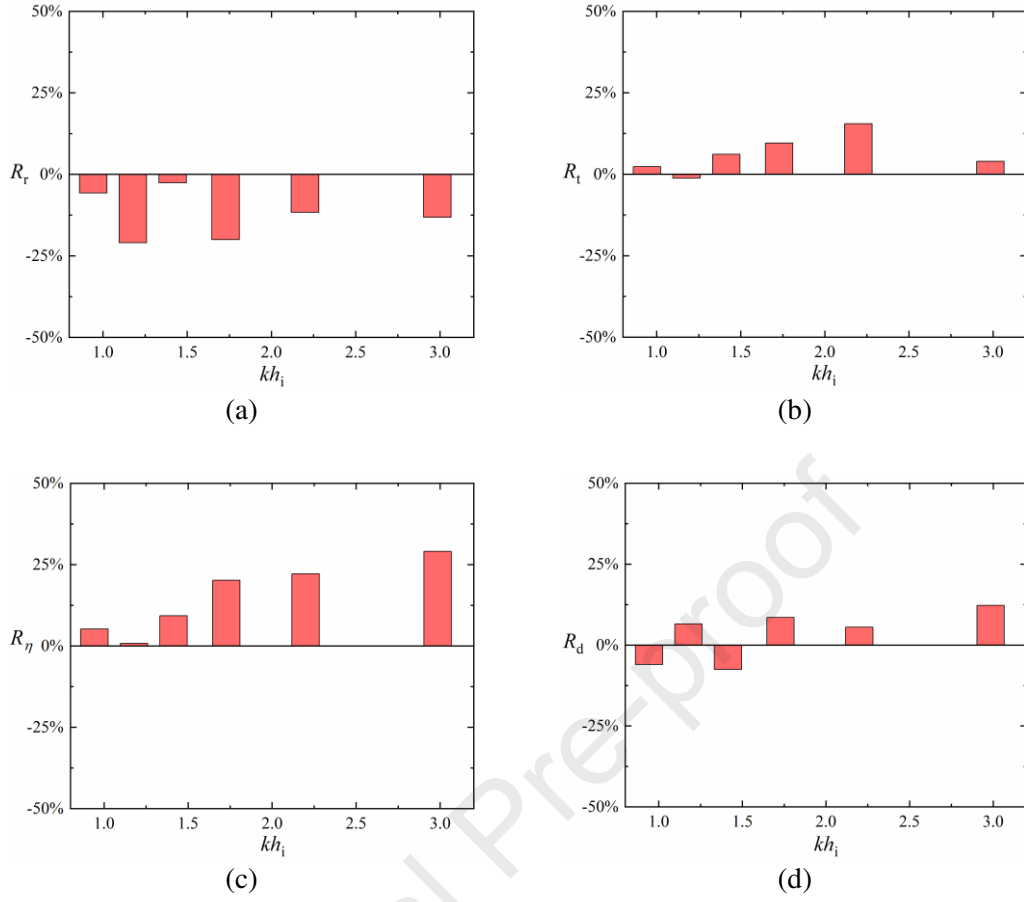


Fig. 18. Relative increments of K_r , K_t , η and K_d for the aligned array with $\bar{l}_y = 0.10$ compared to those of the single WEC.

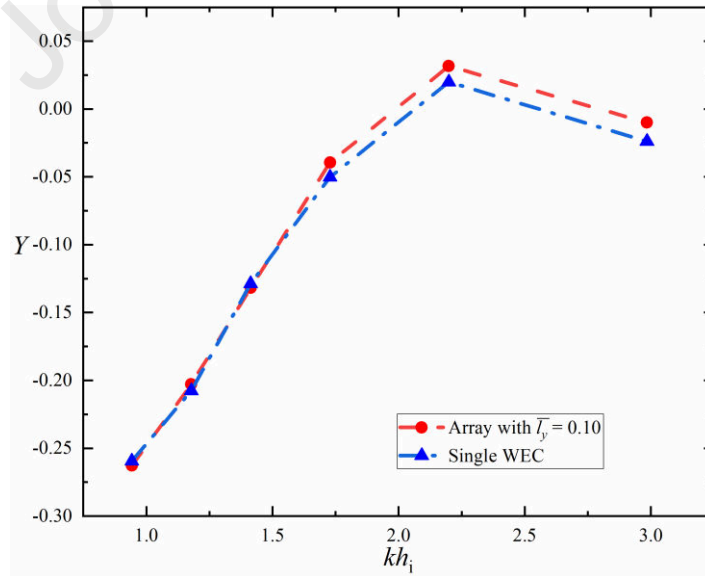


Fig. 19. Variations of Y of both the aligned array and the single WEC with kh_i for $k_1 = 0.54$.

Conclusions

Based on the Navier-Stokes equation, the hydrodynamics of pile-restrained WECs are modelled. The model is verified by comparing the numerical results with existing results, and then applied to examine the impact of different array arrangements on the motion of WECs, as well as the phenomena of wave reflection, transmission, energy absorption, and energy dissipation within the array. Based on the research findings, the following conclusions can be drawn:

1) The aligned arrays ($\bar{l}_x = 0.0$) exhibit superior performance compared to the staggered arrays ($\bar{l}_x = 0.5$ and 1.0), comprehensively considering both wave energy conversion and wave transmission. Specifically, when $kh_i > 1.73$, the wave energy conversion efficiency of the aligned array with $\bar{l}_y = 0.10$ ranges from 0.141 to 0.330, while the wave transmission coefficient ranges from 0.187 to 0.472, indicating the effectiveness of the arrays in simultaneously reducing wave transmission and converting wave energy.

2) In comparison to a single WEC of the same dimensions as the array, the aligned WEC array with $\bar{l}_y = 0.10$ demonstrate a substantial increase in wave energy conversion efficiency up to 29.0% across the examined range of kh_i . Furthermore, it shows a notable increase in the wave transmission coefficient for most kh_i values, up to 15.5%. Specifically, the benefit coefficient Y of the aligned array significantly exceeds that of the single WEC under shorter-wavelength conditions. In addition, the aligned WEC array generally enhance wave energy dissipation and reduce wave reflection.

3) In the examined array configuration, a higher efficiency ratio of wave energy conversion between the middle WEC and the side WEC is indicated by a higher heave amplitude ratio between them. Moreover, there is a general tendency for a higher wave energy conversion efficiency of the array to be associated with a smaller wave transmission coefficient.

This article exclusively focuses on the Coulomb damping model, restricting the WECs to a box shape and comprising only three units. However, further investigation into the variations of both the shape and the quantity of WECs within the array is warranted.

Acknowledgements

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Nomenclature

A_z	WEC heave amplitude
B	WEC width
B_a	Width of the WEC array
C_μ	Model constant of 0.09
D	WEC height
d	WEC draft
$\mathbf{F}_{h,i}$	Hydrodynamic force acting on the i -th floater
$\mathbf{F}_{d,i}$	Damping force acting on the i -th floater
$\mathbf{F}_s$	Vector of traction acting on the floater on the fluid–structure interface
$\mathbf{F}_f$	Vector of stresses exerted on the fluid on the fluid–structure interface
f_d	Friction damping value
$\mathbf{g}$	Gravitational acceleration
H	Still water depth
h_i	Incident wave height
I	Kinetic turbulent energy

572	K_r	Reflection coefficient
573	K_t	Transmission coefficient
574	K_d	Wave dissipation coefficient
575	k	Wave number
576	k_1	Weight assigned to η for calculating benefit coefficient Y
577	k_2	Weight assigned to K_t for calculating benefit coefficient Y
578	L	WEC length
579	l_x	Spacing between adjacent WECs along the x -axis
580	l_y	Spacing between adjacent WECs along the y -axis
581	m_i	Mass of the i -th floater
582	N_c	Grid cell number
583	$\mathbf{n}$	Unit normal vector of the floater surface element
584	P_d	Power of WECs PTO system to convert wave energy
585	P_{in}	Incoming wave power per unit width of the wave front
586	p_{out}	Static pressure at the pressure outlet boundary of the NWT
587	p	Water pressure
588	R_r	Relative increments of K_r for the WEC arrays compared to the single WEC
589	R_t	Relative increments of K_t for the WEC arrays compared to the single WEC
590	R_η	Relative increments of η for the WEC arrays compared to the single WEC
591	R_d	Relative increments of K_d for the WEC arrays compared to the single WEC
592	$\mathbf{S}$	Body force
593	S_d	Momentum damping term

594	$\mathbf{T}$	Viscous part of the stress tensor
595	T	Incident wave period
596	t	Time
597	U	Profile of vertical velocity in the AIJ power-law method
598	$\mathbf{v}$	Fluid velocity vector
599	$\dot{\mathbf{v}}_i$	Acceleration of the i -th floater
600	$\mathbf{v}_s$	Velocity vector of the floater on the fluid-structure interface
601	x_s	Start positions of the dissipation zone in the x -direction
602	x_e	End positions of the dissipation zone in the x -direction
603	x_1	Hydrodynamic characteristic of single WEC
604	x_2	Hydrodynamic characteristic of WEC array
605	Y	Benefit coefficient
606	$\hat{y}_i$	Calculated value
607	y_i	Measured value
608	z_b	Bottom positions of the dissipation zone in the z -direction
609	z_{fs}	Free-surface positions of the dissipation zone in the z -direction
610	σ	Dimensionless heave amplitude of the WEC
611	σ_m	Dimensionless heave amplitude of the middle WEC
612	σ_s	Dimensionless heave amplitude of the side WEC
613	σ_u	Standard deviation of U , which are turbulent velocity at x -direction
614	σ_v	Standard deviation of V , which are turbulent velocity at y -direction
615	σ_w	Standard deviation of W , which are turbulent velocity at z -direction

616	η	Efficiency of the WEC PTO system to convert wave energy
617	η_m	Wave energy conversion efficiency of the middle WEC
618	η_s	Wave energy conversion efficiency of the side WEC
619	μ	Dynamic viscosity of the fluid
620	δy	Distance between the side walls of the WECs and those of the NWT
621	λ	Wave length
622	ω	Wave angular frequency
623	ς	Control parameter of the damping term
624	ξ	Turbulence specific dissipation rate
625	ε	Turbulence dissipation rate
626	Δt	Time step
627	Δx	Cell size in x-direction
628	Δy	Cell size in y-direction
629	Δz	Cell size in z-direction

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



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