

Hydroelastic modelling of a deformable wave energy converter including power take-off

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ABSTRACT

Given the advantages of flexible wave energy converters (FlexWECs), such as deformation-led energy harnessing and structural loading compliance, there has been a significant interest in FlexWECs in both academia and industries. To simulate the FlexWEC interaction with ocean surface waves, a 3D computational fluid-structure interaction approach is developed in this study. The fluid and solid governing equations are discretized using finite difference and finite element methods, respectively. An immersed boundary method is used to couple the two independent grid systems. A novel numerical technique is introduced to model the dielectric elastomer generator (DEG) as the power take-off (PTO). The wave energy capture performance is analysed for different PTO configurations and at various wave conditions. Based on the obtained results, the PTO damping coefficient and the relative wavelength range that maximizes the capture width ratio (CWR) are determined. The wavefield results also reveal the presence of wave-height enhancement and attenuation points around a single FlexWEC, providing potential site selection references when deploying multiple FlexWECs in an array.

1. Introduction

Over the past four decades, there have been numerous global initiatives aimed at harnessing the power of ocean waves through the use of wave energy converters (WECs). Unlike other renewable energy sources such as solar and wind, which are dependent on weather conditions, waves are a more predictable and reliable source of energy owing the ability to generate electricity consistently. Such reliability makes WECs a promising option for providing a stable and sustainable power supply.

There are a great number of review papers emerging in academia that have been instrumental in exploring and unlocking the potential of WECs to generate clean, renewable, and sustainable energy, aligning with the urgent global goal of transitioning to a low-carbon future [1]. Drew et al. [2] provided valuable insights into WEC concept designs, Falcão [3] further explored the advancements in WEC technology and its potential applications, Day et al. [4] and Ahamed et al. [5] reviewed the operational principles and challenges associated with WECs, Moretti et al. [6] critically examined the recent progress made in the field and highlighted the prospects of WECs.

Typically, WECs come in various concepts and sizes, ranging from floating buoys [7,8] and submerged structures [9,10] to

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oscillating water columns [8,11,12] or elastic devices [13,14]. Each type of WEC operates based on different principles and technologies, but they all share the common goal of extracting energy from ocean waves. For instance, the mechanical type of WECs mainly relies on one or multiple interconnected rigid bodies, directly interacting with incoming waves and converting wave energy into electricity. However, in most cases these rigid bodies experience significant forces and stress concentrations when exposed to extreme sea conditions [15]. This poses a challenge to the economic feasibility of such WEC technology, as the costs associated with the structures and mooring systems of these devices are quite high [16].

Recent trends have prompted the re-evaluation of WEC design by focusing on flexible bodies, known as FlexWECs. These FlexWECs aim to address the reliability and survivability issues faced by conventional designs while providing greater conversion efficiency [16]. They offer several advantages, including broadband ocean wave energy absorption [17], a highly redundant multiplexed power take-off (PTO) system [18], and low cost and ease of material fabrication. As a result, they have emerged as a solution to drive breakthroughs in the wave energy market [19]. Review studies by Renzi et al. [20], Moretti et al. [21] and Collins et al. [16], provided a broad overview of such devices, elucidating the findings and goals achieved in the context of recent research on modelling and designing concepts.

Several leading projects on FlexWECs, i.e., the PolyWEC project [22] joint between the universities of Trento, Bologna, SSSUP (Pisa), and Edinburgh. Subsequent research funds in exploring the numerical and physical modelling, and possible routes towards upscaling and market development of WECs with dielectric elastomer generators (DEGs) by WETFEET and Wave Energy Scotland WES-PTO [23]. Another branch of research aimed at the development of specific devices and DEG-WEC architectures is currently being investigated in the ELASTO project led by Edinburgh University and the National Renewable Energy Laboratory (NREL) [24]. This project takes a structured approach and aims to promote field testing, ultimately leading to a prototype for commercial use.

The power take-off (PTO) system in FlexWEC differs significantly from the mechanical type of WECs. Such a system relies heavily on embedding DEGs into PTO units. The working membrane surface can be generated using dielectric elastomer material and the embedded DEG systems operate as elastic capacitors with specific charging-discharging schemes. The electro-active polymers within these systems undergo structural deformations so as to generate electricity. The DEG-PTO systems offer several advantages, including 1) light-weightiness, 2) high energy conversion efficiency that is relatively independent of operation frequency, 3) Easy manufacturing and assembly, 4) Strong resistance to shock and corrosion and 5) low cost. DEGs have shown promise in various applications related to wave energy harvesting, while the majority are still in an early research and development stage, i.e., (Peline et al. [25]; Bar-Cohen et al. [26]; Babarit et al. [15]; Moretti et al. [27]; Moretti et al. [6]; Collins et al. [16,20]).

There have been a number of researchers who have studied FlexWEC using a reduced-order model. Babarit et al. [15] proposed a linear model for analysing the hydroelastic response and energy performance of a flexible tube-type WEC. Nové-Josserand [17] presented a 1D interference model on the evaluation of various parameters (configuration, flexibility, wave frequency) on the energy distribution of the FlexWECs. Their further studies extended the applications to explore many possible array configurations to determine the optimal spatial distributions of FlexWECs regarding both attenuation and energy conversions [28].

Compared to the simplified model, the coupled Computational Fluid Dynamics (CFD) and Computational Solid Mechanics (CSM) simulation provide more reliable results for structural loading because all unsteady flow effects are taken into account. Numerous research studies have been conducted on the CFD-CSM simulation of flexible WECs, implemented using various approaches. For example, King et al. [29] utilized a CFD-CSM coupling model to investigate the Bombora WEC. In their model, OpenFOAM was chosen to solve the incompressible flow, and the finite element model (FEM) without considering inertial terms was employed to obtain membrane deformations. Additionally, Zou and Abdelkhalik [30] simulated the dynamic response of VSB WEC using ANSYS. Huang et al. [31] applied a simulation platform for flexible WECs based on OpenFOAM, CalculiX, and preCICE, studying the Poly-A-OWC and Anaconda flexible WECs. Liu et al. [32] first conducted numerical simulations of hydro-viscoelasticity problems using the Smoothed Particle Hydrodynamics (SPH) method. In their model, the viscoelastic floating cover was discretized into elementary rigid sections with damping rotational hinges. Chen et al. [33] coupled the δ -SPH and Total Lagrangian Smoothed Particle Hydrodynamics (TL-SPH) models to separately solve the fluid and structural phases. They proposed a multi-resolution algorithm to handle the thin elastic components of the structure, accurately simulating the interaction between waves and elastic plates. The above-mentioned studies have rarely addressed bottom-mounted FlexWEC. Recently, Wei et al. [34] conducted numerical simulations of a two-dimensional bottom-mounted FlexWEC array using Finite Difference Method (FDM) and FEM, determining the optimal lateral separation

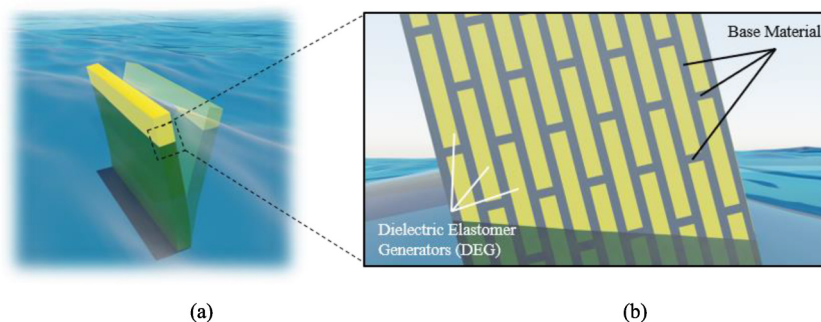


Fig. 1. Schematic of the seawall-type deformable WEC, (a) overview observations of the whole structure, (b) inner DEG-PTO systems.

distance. However, in Wei et al. [34], only the two-dimensional interaction between FlexWEC and waves was considered, while the damping effect of the PTO was neglected. This could lead to inaccurate predictions of the motion and energy conversion efficiency of bottom-mounted FlexWEC.

In this paper, a comprehensive analysis is conducted on the hydroelastic behavior, and energy conversion of FlexWEC under the three-dimensional interaction with waves, as shown in Fig. 1(a). A fully-coupled fluid-structure interaction (FSI) framework was employed, which coupled a fluid solver solving the incompressible Navier-Stokes equations, with a solid solver that calculates the large-deformation Euler-Bernoulli beam equations. Compared to state of the art (e.g. Refs. [34–37]), they are all in 2D and have not considered the effect of PTO. This work for the first time extended the model to 3D and added the damping effect of distributed PTO on the structure, as shown in Fig. 1(b). Subsequently, the dynamic characteristics, energy extraction efficiency, and spatial distribution of wave heights of FlexWEC under different PTO damping and relative incident wavelengths were explored. According to the disturbed wave field by a deforming WEC, promising locations for deploying neighbor WEC devices are suggested.

This paper is organized as follows: Section 2 describes the numerical methodology applied in the FSI approach. Section 3 presents a series of verification and validation procedures. Section 4 elaborates on the simulation results concerning various parametrical studies, including the effects of structural damping, and the determination of optimal damping coefficients under various wave conditions. Then, the spatial distribution of wave fields is also evaluated to provide valuable insights for the layout and arrangement of FlexWEC arrays. Finally, concluding remarks are drawn in Section 5.

2. Computational approach

In this study, finite difference and finite element methods were employed to solve the fluid and structural motion problems, respectively, with an immersed boundary method used for their coupling. Referring to prior work provides additional details on these methods [38,39].

2.1. Discretization methods

In space, the fluid sub-domain is divided by an orthogonal grid and the solid sub-domain is divided into a line grid over the FlexWEC length. As shown in Fig. 2, within the region where the free surface and the FlexWEC are expected to move, the grid was locally refined. The structural grid is uniform. In the temporal domain, the time dimension is discretized into a finite number of time steps. The computational grid and time step size were chosen based on a parameter dependence check, as represented in Section 3.

2.2. Fluid governing equations

This study utilizes an incompressible, viscous Newtonian model to describe the fluid mechanics, which is governed by the Navier-Stokes equations as follows:

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T)) + \rho \mathbf{g} + \mathbf{f} \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

where ρ is the fluid density; μ is the fluid dynamic viscosity; $\mathbf{u}$ is the fluid velocity; t is time; p is the pressure; $\mathbf{g}$ is the gravity; and $\mathbf{f}$ is the external force acting on the fluid excluding the gravitational force. Interface capturing is done by the Volume of Fluid (VoF) method [40]. α is defined as the liquid volume fraction in each computational cell (if $\alpha = 1$, the cell is completely occupied by liquid, while if $\alpha = 0$, the cell is completely occupied by gas). Therefore, the free surface is located at $0 < \alpha < 1$. The evolution of the free surface with time is solved by the advection equation for α , as expressed by Eq. (3). The density and viscosity are obtained as Eq. (4).

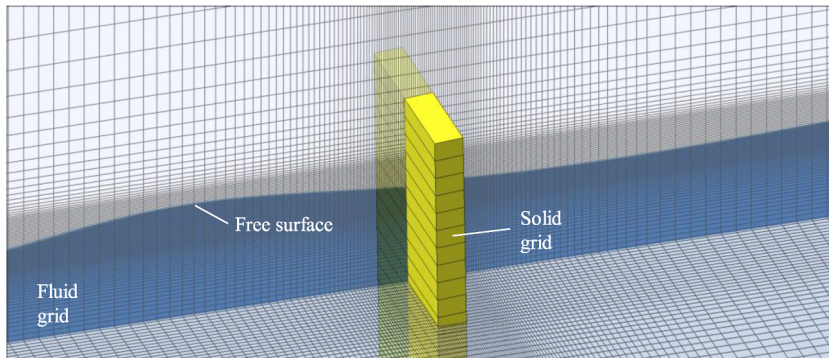


Fig. 2. Fluid mesh and structural mesh setup.

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\mathbf{u}\alpha) = 0 \quad (3)$$

$$\rho = \rho_w \alpha + \rho_a (1 - \alpha), \mu = \mu_w \alpha + \mu_a (1 - \alpha) \quad (4)$$

In the following content, $\rho_w = 1000 \text{ kg}\cdot\text{m}^{-3}$, $\rho_a = 1.29 \text{ kg}\cdot\text{m}^{-3}$, $\mu_w = 0.89 \times 10^{-3} \text{ kg(m}\cdot\text{s)}^{-1}$, $\mu_a = 1.86 \times 10^{-5} \text{ kg(m}\cdot\text{s)}^{-1}$ are generally taken.

Eqs. (1) and (2) are solved with a fractional-step method described in Choi and Moin [41]. In this process, the resulting parabolic “advection-diffusion equations” are solved using the alternating direction implicit (ADI) method, and the elliptic “pressure-equation” is solved with the Biconjugate gradient stabilized method (Bi-CGSTAB) method. An explicit, second-order Adams-Bashforth method is used for the time-discretization of the advection terms, and the implicit Crank-Nicolson method is used for the viscous terms. The spatial discretization utilizes a third-order Quadratic upwind (QUICK) scheme for the advection terms and a second-order central difference scheme for the viscous terms.

2.3. Solid solver with PTO

The conservation of momentum of FlexWEC can be represented by:

$$\rho_s \frac{\partial^2 d_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j} + \frac{\partial \sigma_{ij}^{pto}}{\partial x_j} + \rho_s g_i, \quad (5)$$

where d_i is the displacement in i th direction (where $i = 1, 2, 3$ for x, y , and z directions), ρ_s is the density of the solid, g_i is the body force. σ represents the elastic mechanical stress and σ^{pto} represents the additional stress caused by DEG.

The principle of energy generation in DEG can be characterized by the following four stages, as illustrated in Fig. 3. P1–P2: the DEG is stretched, the corresponding capacitance also transitions from its minimum to maximum, with no charge on the electrodes. P2–P3: Charging the electrodes. P3–P4: External loads bring the DEG back to its minimum capacitance configuration. During this stage, external forces do work against the electrostatic forces, demonstrating the damping effect of structural motion, and increasing the electrostatic energy within the DEG. P4–P1: The DEG is completely discharged, and the stored electrostatic energy is reclaimed.

This study adopts a linear PTO model to approximate the energy harvesting process described above. The σ^{pto} is assumed proportional to the strain rate and ν_{pto} is the so-called PTO (Power Take-Off) damping coefficient [15]. Eq. (6) further elaborates on σ^{pto} .

$$\sigma_{ij}^{pto} = \begin{cases} -\nu_{pto} \frac{\partial^2 d_i}{\partial x_j \partial t}, & i = j \\ 0, & \text{else} \end{cases} \quad (6)$$

This study is based on the Euler-Bernoulli assumption and neglects the deformation of FlexWEC in the cross-section, which could introduce errors when simulating wide structures. In Appendix A, the error of the beam model was evaluated, which is $<10\%$. Based on the Euler-Bernoulli hypothesis, the FlexWEC is discretized by several beam elements. Each beam element has two nodes and 12 degrees of freedom. The equilibrium equation of all degrees $\{\delta\}$ can be written as Eq. (7). The hydrodynamic force f_h is obtained by solving Eq. (8).

$$[m]\{\ddot{\delta}\} + ([k_e] + [k_g] + [\Delta k_g])\{\delta\} + [C_{pto}]\{\dot{\delta}\} = \{f_h\} - \{F\}, \quad (7)$$

$$\{f_h\} = f_{hl} = \int_{S^n} \left[-pn_j + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) n_i \right] N_{ji} dS. \quad (8)$$

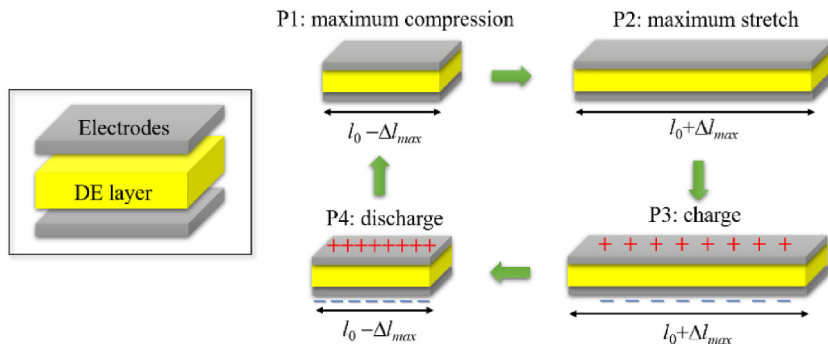


Fig. 3. Illustration for the operating cycle of a DEG.

where $[m]$ is the mass matrix, $[k_e]$ denotes the linear stiffness matrix, $[k_g]$ is the geometrical stiffness matrix, $[\Delta k_g]$ is the high-order stiffness matrix, $\{f_h\}$ is the hydrodynamic force vector and $\{F\}$ is the body-stress vector (see more information in Chang [42]). $[C_{pto}]$ denotes the effects of damping forces due to the PTO system. S^n is the surface of the structure. $[N]$ is the shape function. The matrices in Eq. (7) can be written as:

$$[m] = \int_{V^n} \rho_s [N]^T [N] dV, \quad (9)$$

$$[k_e] = \int_{V^n} [B_L]^T \begin{bmatrix} E & 0 & 0 \\ 0 & G & 0 \\ 0 & 0 & G \end{bmatrix} [B_L] dV, \quad (10)$$

$$[k_g] \{\delta\} = 2 \int_{V^n} [B_N]^T \{\sigma\} dV, \quad (11)$$

$$[\Delta k_g] = 2 \int_{V^n} [B_N]^T \left[\frac{\partial \sigma}{\partial \epsilon} \right] [B_L] dV, \quad (12)$$

$$\{F\} = \int_{V^n} [B_L]^T \{\sigma\} dV, \quad (13)$$

$$[C_{pto}] = \int_{V^n} [B_L]^T \begin{bmatrix} \nu_{pto} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} [B_L] dV, \quad (14)$$

where V^n is the space occupied by the structure. $[B_L]$ and $[B_N]$ are the linear and non-linear parts of the strain-displacement transformation matrix, respectively. E and G denote Young's modulus and shear modulus. The formula of $[k_e]$, $[k_g]$ and $[\Delta k_g]$ are explicitly shown in Chang [42]. The $[C_{pto}]$ can be further written as:

$$[C_{pto}] = \begin{bmatrix} [C_1] & [C_2] \\ [C_2]^T & [C_3] \end{bmatrix}. \quad (15)$$

Where the submatrices are

$$[C_1] = \begin{bmatrix} \frac{\nu_{pto} A}{L} & 0 & 0 & 0 & 0 & 0 \\ \frac{12\nu_{pto} I_z}{L^3} & 0 & 0 & 0 & \frac{6\nu_{pto} I_z}{L^2} & \\ \frac{12\nu_{pto} I_y}{L^3} & 0 & -\frac{6\nu_{pto} I_y}{L^2} & 0 & & \\ & 0 & 0 & 0 & & \\ & & \frac{4\nu_{pto} I_y}{L} & 0 & & \\ \text{Symm.} & & & & \frac{4\nu_{pto} I_z}{L} & \end{bmatrix} \quad (16)$$

$$[C_2] = \begin{bmatrix} -\frac{\nu_{pto} A}{L} & 0 & 0 & 0 & 0 & 0 \\ -\frac{12\nu_{pto} I_z}{L^3} & 0 & 0 & 0 & \frac{6\nu_{pto} I_z}{L^2} & \\ -\frac{12\nu_{pto} I_y}{L^3} & 0 & -\frac{6\nu_{pto} I_y}{L^2} & 0 & & \\ & 0 & 0 & 0 & & \\ \frac{6\nu_{pto} I_y}{L^2} & & \frac{2\nu_{pto} I_y}{L} & 0 & & \\ -\frac{6\nu_{pto} I_z}{L^2} & & & \frac{2\nu_{pto} I_z}{L} & & \end{bmatrix} \quad (17)$$

$$[C_3] = \begin{bmatrix} \frac{\nu_{pto} A}{L} & 0 & 0 & 0 & 0 & 0 \\ & \frac{12\nu_{pto} I_z}{L^3} & 0 & 0 & 0 & -\frac{6\nu_{pto} I_z}{L^2} \\ & & \frac{12\nu_{pto} I_y}{L^3} & 0 & \frac{6\nu_{pto} I_y}{L^2} & 0 \\ & & & 0 & 0 & 0 \\ & & & & \frac{4\nu_{pto} I_y}{L} & 0 \\ Symm. & & & & & \frac{4\nu_{pto} I_z}{L} \end{bmatrix} \quad (18)$$

Upon determining the response of the FlexWEC, the absorbed power, P_a , from the deformable structure is calculated by the integration of stress tensor and strain rate, as shown in Eq. (19). The time-averaged absorbed power in one wave period is given by Eq. (20).

$$P_a = \int_V \sigma_i^{plo} \dot{\epsilon}_i dV = \{\dot{\delta}^e\}^T [C_{pto}] \{\dot{\delta}^e\}, \quad (19)$$

$$P_{a,avg} = \frac{1}{T} \int_T P_a dt = \frac{1}{T} \int_T \{\dot{\delta}^e\}^T [C_{pto}] \{\dot{\delta}^e\} dt, \quad (20)$$

where T denotes the wave period. In this study, the capture width ratio (CWR) is utilized to quantify the efficiency of the PTO system in converting wave energy, which is the ratio of the absorbed power to the incident wave energy:

$$CWR = \frac{P_{a,avg}}{P_w D}, \quad (21)$$

where $P_w = \rho g c_g H^2 / 8$ is the wave energy flux per unit width, c_g is the wave group velocity, H is the wave height. D denotes the width of the FlexWEC.

2.4. Fluid-structure interaction

The non-boundary-conforming FSI scheme developed by Ref. [38] is used to couple the fluid and solid components. This involves solving the fluid and structural equations separately and coupling them at the fluid-solid interface. The coupling is established by the application of no-slip, no-penetration, and traction conditions. The no-slip and no-penetration conditions at the interface are realized by a discrete-forcing immersed boundary method [39]. Meanwhile, the traction conditions are achieved by pressure and viscous force reconstruction. Fig. 4 illustrates the procedure within one timestep as follows.

- At the start of a new timestep t^{n+1} , the pressure and viscous force are initially interpolated to the fluid-solid interface based on the flow field at t^n .
- The structure solver then calculates the displacement of the solid according to Eq. (7).
- A preliminary explicit step is performed to obtain the structural far-field velocity.
- The immersed boundary method is implemented in the following order: firstly, the surface reconstruction is executed to determine the relative position of the fluid nodes to the structure. Following this, the velocity reconstruction is performed at the fluid node

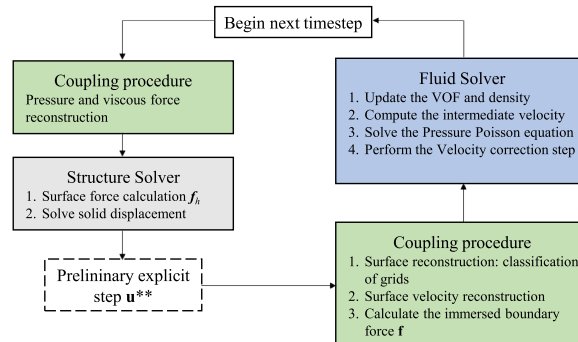


Fig. 4. The flow chart for the present fluid-structure procedure.

closest to the surface of the structure based on the structural surface velocity and the far-field velocity. Finally, the corresponding immersed boundary force $\mathbf{f}$ is applied based on the reconstructed velocity, as follows:

$$\mathbf{f} = \frac{\rho^{n+1} \mathbf{U} - \rho^n \mathbf{u}^n}{\Delta t} + L_{conv}(\mathbf{u}^n) - L_{diff}(\mathbf{u}^n) + \nabla p^n - \rho^{n+1} \mathbf{g}, \quad (22)$$

where L_{conv} and L_{diff} denote spatial operators for the convective and diffusion terms, respectively.

- The intermediate velocity $\mathbf{u}^*$ can be obtained by solving the momentum equation (Eq. (23)). Then the pressure at t^{n+1} is determined by solving the pressure Poisson equation. A velocity correction step is executed to derive the velocity at t^{n+1} . Finally, the solver completes the computation for t^{n+1} and proceeds to the next timestep.

$$\rho^{n+1} \mathbf{u}^* = \rho^n \mathbf{u}^n + \Delta t [-L_{conv}(C^n, \mathbf{u}^n) + L_{diff}(C^n, \mathbf{u}^n) + \mathbf{f}], \quad (23)$$

2.5. Computational domain and boundary condition

Fig. 5 shows the schematic diagram of the three-dimensional computational domain. The origin is set at the midpoint of the wetted area of the WEC, with x-axis parallel to the incoming wave, y-axis in the direction of the width of the WEC, and z-axis positive upwards. The computational domain size ranges from $[-2L, 4L] \times [-2L, 2L] \times [-1.0h_s, 0.6h_s]$ in the x, y, and z-axis directions, where L represents the wavelength and h_s represents the water depth. The fluid sub-domain is occupied by initially quiescent water of depth h_s . Air occupies the remainder of the domain from $y = 0$ to $y = 0.6h_s$. The solid sub-domain represents the initial stationary position of the WEC and the root of the WEC is fixed at the bottom boundary of the domain. The dimensions of the WEC in x, y, and z-axis directions, specifically the thickness, width, and length, are denoted as b , D , and h , respectively.

The boundary conditions are set as follows. At the upper boundary, pressure and the gradients of fluid velocity are set to zero. The velocity is given as zero at the bottom boundary. On the two side boundaries perpendicular to the y-axis, the free-slip boundary condition is applied. The left and right sides of the domain are set as wave inlet and outlet boundaries, respectively. Periodic regular waves are generated by giving the corresponding water level variation and fluid velocity at the inlet boundary based on second-order Stokes wave theory. Sommerfeld radiation condition is applied for the outlet boundary. To effectively absorb the radiated waves generated by the oscillation of the FlexWEC, a wave absorption zone is placed at the right end of the domain. For the solid sub-domain, the base of the FlexWEC is fixed, and the remaining boundaries are allowed to move freely.

3. Verification and validation

To the best of the authors' knowledge, there are limited experimental results available concerning a bending plate inclusive of a PTO system. In this section, the investigation focuses on the interaction between a regular wave and a flexible plate without a PTO system. This wave-structure interaction (WSI) problem was initially explored through experiments conducted by Nové-Josserand [17]. The associated parameters are summarized in Table 1.

To quantify the dependency of the numerical results on the grid spacing, three numerical simulations with different grids are conducted. Non-uniform grids are used, with local refinement in the fluid region where the plate is expected to move. Table 2 shows the grid spacing for the three grids with different densities. To ensure that at least one layer of fluid cells covers the thickness of the structure, Δx of the coarsest grid is limited to $b/2$. The plate is discretized into 30 beam elements in length to accurately capture the first modes of deformation [34].

The simulation results for the three different grids are compared to the experiments of Nové-Josserand [17] and are detailed in Table 3. The relative errors of the mean maximum displacement of the free end and the mean maximum shear force at the fixed end were presented. When using a medium grid, the maximum displacement difference is within 5 %, and the maximum force difference is within 10 %. Furthermore, both the displacement and shear force values for the medium grid are less than 3 % different from their corresponding values for the fine grid. Consequently, the medium grid was chosen for this study.

Using the medium grid, the convergence of time-step is further analysed. The simulations are performed with three different timesteps: $\Delta t = T/500$, $T/1000$, and $T/2000$, corresponding to Courant number $C_r \leq 0.6$, 0.3, and 0.15, respectively. The relative errors

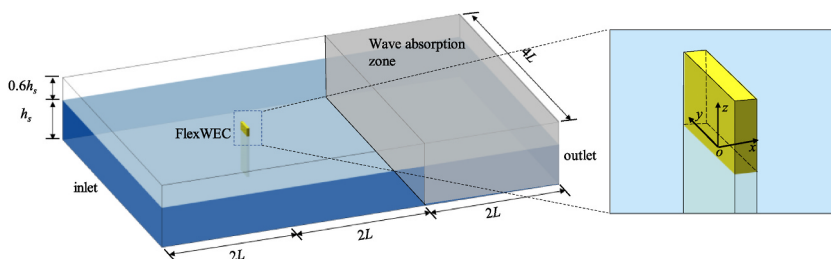


Fig. 5. Schematic of the computational domain and partial enlargement of the flexible plate.

of the displacement and shear force from the different time-steps are compared in Table 4. The results demonstrate that $\Delta t = T/1000$ is adequate for predicting accurate results.

The time series of the response displacement of the free end, based on the medium grid, is compared with the experimental results in Fig. 6. The plate displacements obtained from the simulation and experiment exhibit oscillations at almost the same frequency and amplitude.

A detailed verification of the current computational approach is conducted against Hu et al. [13], where the authors investigated a single deforming seawall under various wave conditions in two dimensions. The computational setup is consistent with Hu et al. [13], and comparisons are made regarding both structural deformation and the surrounding wave field. The corresponding parameter sets for this verification study are summarized in Table 5. The computational grid in the x and z directions is identical to the medium grid setup in Table 2, while in the y direction, a single layer grid is employed with $\Delta t = 1/1000T$.

Fig. 7 illustrates the analysis of the maximum displacement $D_{x, \max}/A_w$, reflection coefficient k_r , and transmission coefficient k_t against the relative incident wave frequency f_w/f_n . We obtained good agreement with the results reported in Hu et al. [13]. As the wave frequency increases, the displacement of the beam initially increases and then decreases, while the reflection coefficient gradually decreases and the transmission coefficient increases.

To further assess the accuracy of the computational model, the Mean Absolute Percentage Error (MAPE) is employed to analyze the difference between the two sets of results:

$$\text{MAPE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{\hat{y}_i - y_i}{y_i} \right| \quad (24)$$

where $\hat{y}_i$ and y_i represent the results from Hu et al. [13] and our numerical results, respectively, and n is the number of data points. The MAPE values for displacement, k_r , and k_t are 5.54 %, 2.52 %, and 6.52 %, respectively. These results indicate that the numerical model reliably predicts the hydrodynamic performance of a flexible plate under regular wave conditions.

4. Results and discussion

The present study delves into the examination of a full-scale FlexWEC constructed from a rubber-like material. Through methodical simulations, we explore the variations in the damping coefficient (ν_{pto}) and the wave period (T), aiming to analyze their collective influence on both hydroelastic interaction and wave energy conversion performance.

The parameters used in this section are listed in Table 6. In order to make the results more general, the following dimensionless physical quantities are defined:

$$\bar{L} = \frac{L}{D}, \bar{\nu}_{pto} = \frac{\nu_{pto}}{1000E} \sqrt{\frac{g}{h_s}}. \quad (25)$$

The natural frequency of the FlexWEC is measured by the free oscillation test in still water. By applying an initial displacement of the free end of the FlexWEC and then releasing it, the structure oscillates freely in the water. As shown in Fig. 8(a), the free end of the FlexWEC swings in a periodic pattern. According to the spectral analysis of Fig. 8(b), the natural frequency f_1 is 0.1452hz and the corresponding period is 6.87s. When the wave frequency is equal to the natural frequency of the FlexWEC, the corresponding relative wavelength $\bar{L}$ is 5.58.

4.1. Wave energy conversion performance

In this section, the effect of PTO damping coefficients on the wave energy conversion performance of the FlexWEC is investigated under various wave states. The optimal $\bar{\nu}_{pto}$ corresponding to the maximum CWR is determined, providing insights into the recommended operational modes for each sea state.

Fig. 9 shows the variation of CWR with $\bar{L}$ and $\bar{\nu}_{pto}$, where blue color indicates low CWR (CWR < 30 %), while red color represents high CWR (CWR > 40 %). It can be seen that the CWR for the FlexWEC reaches the peak value at CWR = 61 % when $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$ and $\bar{L} = 3.33$. The right vertical profile line shows the variation of CWR with $\bar{\nu}_{pto}$ for $\bar{L} = 3.33$. The CWR increases with increasing $\bar{\nu}_{pto}$

Table 1
Parameters setting for the WSI involving a flexible plate.

Parameter	Value
Wave height, H (m)	4.0×10^{-3}
Wave period, T (s)	0.2
Wave length, L (m)	6.24×10^{-2}
Water depth, h_s (m)	8.0×10^{-2}
Plate length, h (m)	12.0×10^{-2}
Plate widths, D (m)	1.4×10^{-3}
Plate thickness, b (m)	350×10^{-6}
Solid density, ρ_s (kg/m ³)	1380
Young modulus, E (Gpa)	5.0

Table 2
CFD mesh details of three grids.

Mesh grid	Coarse	Medium	Fine
x axis	$\Delta x = b/2$	$\Delta x = b/4$	$\Delta x = b/8$
y axis	$\Delta y = b/14$	$\Delta y = b/28$	$\Delta y = b/56$
z axis	$\Delta z = H/10$	$\Delta z = H/20$	$\Delta z = H/40$
Number of grid cells	2,472,800	4,030,000	9,044,000

Table 3
Grid convergence results in terms of the mean maximum displacement and mean maximum shear force.

Mesh grid	Coarse	Medium	Fine	Nové-Josserand [17]
Mean maximum displacement (mm)	2.187 (−8.38 %)	2.298 (−3.73 %)	2.319 (−2.85 %)	2.387
Mean maximum shear force (mN)	4.012 (−14.4 %)	4.239 (−9.58 %)	4.372 (−6.74 %)	4.688

Table 4
Time step convergence results in terms of the mean maximum displacement and mean maximum shear force.

Time step	$T/500$	$T/1000$	$T/2000$	Nové-Josserand [17]
Mean maximum displacement (mm)	2.254 (−5.57 %)	2.298 (−3.73 %)	2.331 (−2.39 %)	2.387
Mean maximum shear force (mN)	4.198 (−10.5 %)	4.239 (−9.58 %)	4.287 (−8.55 %)	4.688

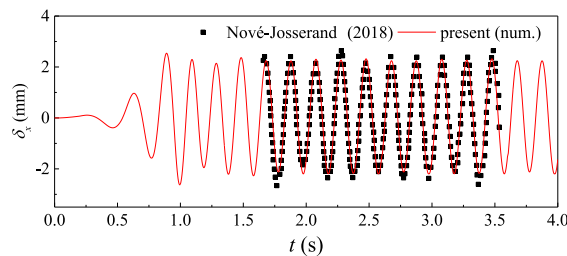


Fig. 6. Experimental and computational comparison for time series of horizontal displacement of the free end of the plate.

Table 5
Parameters setting for the WSI involving a flexible plate.

Parameter	Value
Wave height, H (m)	4.0×10^{-2}
Wave period, T (s)	0.8, 1.0, 1.2, 1.4, 1.6
Water depth, h_s (m)	0.3
Plate length, h (m)	0.35
Plate thickness, b (m)	2.0×10^{-2}
Solid density, ρ_s (kg/m ³)	1200
Young modulus, E (Gpa)	0.018

and then decreases after reaching its maximum value. This behaviour is due to the bi-directional effect of increased damping on energy absorption: while it enhances the structure's energy absorption capability, it concurrently reduces the structure's dynamic response. The upper transverse profile line shows how the CWR changes with $\bar{L}$ at $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$. For $1 < \bar{L} < 2$, the corresponding CWR remains 46%–43 %. Notably, the CWR at $\bar{L} = 1$ surpasses the theoretical limit of $1/\pi$ for a rigid WEC with a single surge or pitch degree of freedom [19]. This observation underscores the FlexWEC's ability to harness wave energy from multiple motion modes compared to the conventional rigid WEC. Over a relatively broad range of wavelengths ($2 < \bar{L} < 5$), the FlexWEC consistently delivers commendable CWR values ranging between 52 % and 61 %. For $\bar{L} > 5$, where the structure is relatively small compared to the wavelength, waves can easily transit through the FlexWEC, resulting in a smaller CWR. Appendix B provides a comparison to show that the energy efficiency of the FlexWEC is generally higher than its rigid counterpart.

Fig. 10(a) provides the ratio between the maximum and average power captured by the FlexWEC. Maintaining low power fluctuations is crucial for enhancing system efficiency [43]. In the present study, the power fluctuations are mainly determined by $\bar{L}$, while the effect of damping is limited. As $\bar{L}$ increases, the max-to-mean ratio of power $P_{a,max}/P_{a,avg}$ sharply increases from 2 to 5. For the range

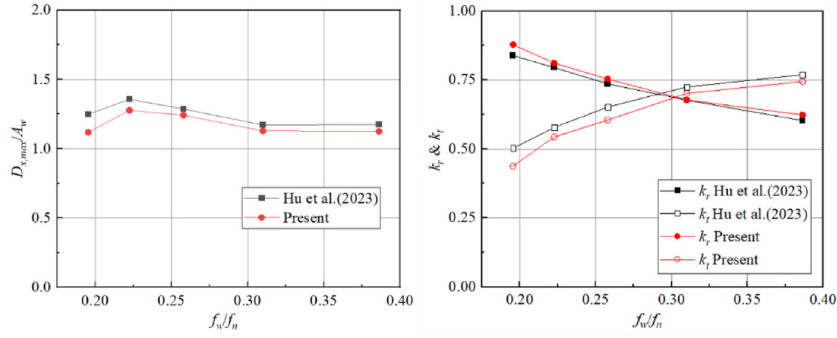


Fig. 7. Comparison of the present model with Hu et al. [13]. (a) Maximum deflection at the free end of beam, (b) Wave reflection and transmission for different wave frequencies.

Table 6

Parameters setting for the WSI involving FlexWEC.

Parameter	Value
Wave steepness, kH	0.05
Water depth, h_s (m)	5.0
Wave period, T (s)	2.27–14.52
WEC length, h (m)	6.0
WEC widths, D (m)	8.0
WEC thickness, b (m)	0.6
Solid density, ρ_s (kg/m ³)	1200
Young modulus, E (Mpa)	12.0
PTO damping coefficient, ν_{pto} (MPa•s)	0, 5, 10, 20, 50, 100, 200, 500, 1000
Relative wave length, $\bar{L}$	1.0–12.5
Dimensionless damping coefficient, $\bar{\nu}_{pto}$	0–0.117

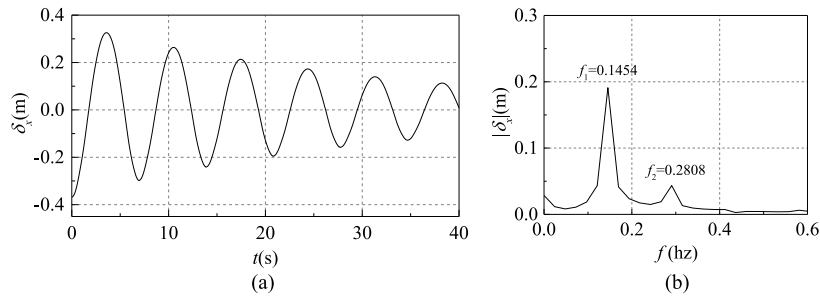


Fig. 8. (a) Time series of the horizontal displacement of the free end of the free decay oscillation in the still water. (b) The amplitude spectrum of the displacement.

with high CWR ($2 < \bar{L} < 5$), $P_{a,max}/P_{a,avg}$ remains less than 2.5. Fig. 10(b) shows the time series of the dimensionless power captured $P_a/P_{a,max}$ at $\bar{L} = 3.33$ and 10, respectively. Generally, two power peaks can be observed within one wave period. A primary and secondary power peak arises during a wave period at $\bar{L} = 3.33$. The difference between the primary and secondary peaks is more apparent at $\bar{L} = 10$. This behaviour results in high fluctuations in the power delivered by the FlexWEC. This is related to the motion characteristics of the FlexWEC and will be thoroughly described in section 4.2. By comparing the time series of the absorbed power for different damping in Fig. 10(b), it can be found that the damping changes the morphology of the secondary peaks while exerting a lesser effect on the primary peak. In summary, the effective operational range for the examined WEC, characterized by high CWR values and low power fluctuations, are within the range of $2 < \bar{L} < 5$ and $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$. As analysed in Appendix C, the damping coefficient corresponding to $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$ is also below the feasibility upper limit.

4.2. Fluid-structural interactions

Fig. 11 shows a superposition of the FlexWEC positions at successive times over a wave period for $\bar{L} = 3.33$ and $\bar{\nu}_{pto} = 2.33 \times 10^{-3}$.

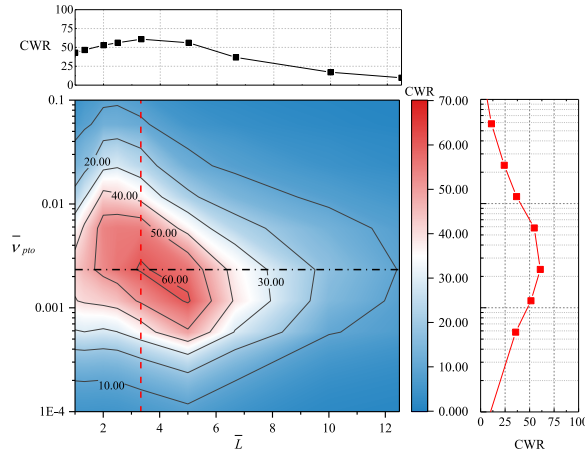


Fig. 9. Variation of capture width ratio CWR with relative wavelength $\bar{L}$ and dimensionless damping coefficient $\bar{v}_{pto}$.

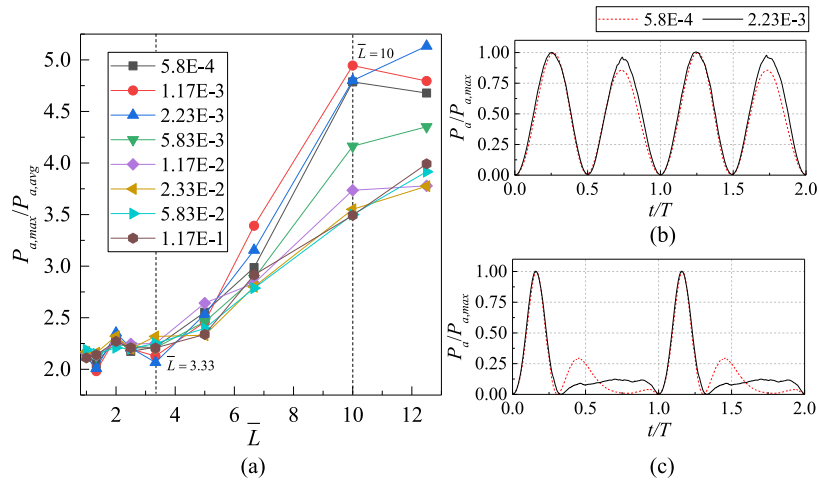


Fig. 10. (a) Max-to-mean ratio, (b) Power curves for $\bar{L} = 3.33$ and $\bar{v}_{pto} = 5.8 \times 10^{-4}$ and 2.23×10^{-3} , (c) Power curves for $\bar{L} = 10$ and $\bar{v}_{pto} = 5.8E-4$ and 2.23×10^{-3} .

The results show that FlexWEC vibrates on its first mode of deformation. The amplitude of motion to the seaward side is smaller than the amplitude of motion to the shoreside. Fig. 12(a) shows the maximum displacement of the free end of the FlexWEC for various $\bar{L}$ and $\bar{v}_{pto}$. As $\bar{L}$ increases, the motion increases and then decreases after reaching a maximum value of $2.84H$ at $\bar{L} = 5$, where the wave

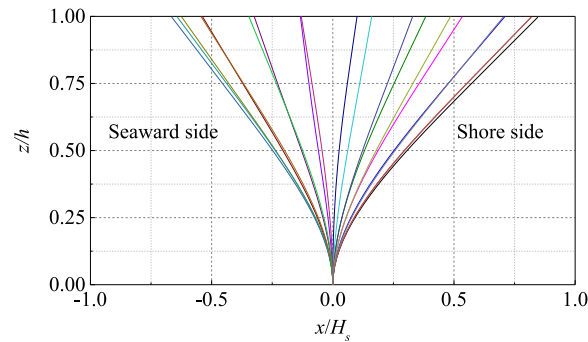


Fig. 11. Superposition of the WEC positions at successive times when $\bar{L} = 3.33$, $\bar{v}_{pto} = 2.33 \times 10^{-3}$. The time step is $0.05T$ and the time duration is T .

frequency is close to the FlexWEC first natural frequency ($\bar{L} = 5.58$). Moreover, an increase in damping reduces the motion of the structure. Fig. 12(b) shows the variation of horizontal peak wave force with $\bar{\nu}_{pto}$ and $\bar{L}$. The results show that when wave frequencies are greater than the resonant frequency, corresponding to $\bar{L} < 5.58$, the horizontal wave force increases with increasing damping. Conversely, when the wave frequency is below the resonance frequency, corresponding to $\bar{L} > 5.58$, the trend is opposite. In this study, the FlexWEC is subjected to small hydrodynamic loadings when $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$, which is conducive to its more stable long-term operation.

Fig. 13(a)–(c), and (e) show the comparisons between the time series of wave elevation at coordinates ($x = 0, y = 4L$), dimensionless horizontal wave force F_x , and dimensionless horizontal displacement at the free end δ_x . The phase difference between δ_x and F_x are $-0.1T$, $-0.21T$ and $-0.3T$ for $\bar{L} = 12.5$, $\bar{L} = 10$ and $\bar{L} = 2$, respectively. This is because in elastic systems when the excitation frequency is lower than the natural frequency, the phase difference between the motion and force is 0, and conversely, it is $-0.5T$ [44]. There is also a phase difference between the FlexWEC motion and the wave elevation, with the motion phase being close to that of the wave elevation when $\bar{L} = 12.5$ and $0.25T$ behind when $\bar{L} = 2$. A portion of the wave forces acting on a FlexWEC comes from the obstructive effect of the FlexWEC on wave propagation, while another part is induced by the motion of the FlexWEC itself. When $\bar{L} = 12.5$, these two force components combine, whereas when $\bar{L} = 2$, they tend to counterbalance each other. This also explains the opposite effects of the damping coefficient on the wave force amplitude for different $\bar{L}$ value in Fig. 12(b). Note that the curve of δ_x at $\bar{L} = 12.5$ is not a standard sinusoid one, which is due to the superposition of higher-order nonlinear wave components. In the right column of Fig. 13, the time varies are decomposed into the components of the fundamental frequency and higher harmonics using fast Fourier transform. The frequencies are normalized by the incident frequency, denoted as f_w . In general, the forces and motions are dominated by fundamental frequency, while the 2nd and 3rd harmonic components play a minor role. At $\bar{L} = 12.5$, the 2nd harmonic component becomes notably more pronounced. When combined with the fundamental frequency motion, this results in a slower motion of the FlexWEC towards the shoreside and a faster motion towards the seaside. This explains the observation in Fig. 10(a) that there are higher power fluctuations at $\bar{L} = 12.5$.

Fig. 14 shows the wave elevations and 3D vortex structures represented by the z -vorticity ($4\pi w_z D / TgkH$) around the FlexWEC for four specific moments within one wave period. Fig. 14(a)–(d) depict four specific moments: when the wave crest is $L/4$ from the FlexWEC, when the wave crest reaches the WEC, when the wave trough is $L/4$ from the WEC, and when the wave trough reaches the FlexWEC for $\bar{L} = 5$, respectively. Similarly, Fig. 14(e)–(h) display the same four moments for $\bar{L} = 10$, respectively. The phase difference between the FlexWEC motion and the wave elevation is different for the two different $\bar{L}$ values, which is consistent with the observations in Fig. 13. Radiation waves with FlexWEC as the source can be observed in the wave elevation distribution. The radiated wave is more significant at $\bar{L} = 5$ than at $\bar{L} = 10$, which are determined by the motion amplitude and the relative width of FlexWEC. At $\bar{L} = 10$, the velocity changes more gradually, which makes the vortex easier to form and shed and thus significant vortex shedding can be observed at the straight corner on both sides of the FlexWEC. In Fig. 14(h), the water level distribution reveals the presence of lower water regions on both sides of the FlexWEC, and this is induced by the shedding of vortices. Vortices are primarily generated on the leeward side in the direction of FlexWEC motion. The negative pressure generated by these vortices impedes the motion of the FlexWEC and further reduces the CWR. To achieve more wave energy extraction of the FlexWEC under long wave conditions, a rounded design could be applied for the left and right edges of the FlexWEC to reduce vortex shedding.

4.3. Spatial distribution of wave heights

The study of the spatial distribution of wave heights around FlexWECs is crucial because it can provide valuable insights into the layout and arrangement of FlexWEC arrays. In the subsequent discussion, it is assumed that the FlexWEC operates at optimal damping, i.e., $\bar{\nu}_{pto} = 2.33 \times 10^{-3}$. Fig. 15 includes the contour of wave height in an area of $4L \times 8L$ around the FlexWEC for different $\bar{L}$. The wave height is obtained by calculating the average wave height over five wave periods using the zero-crossing method. In Fig. 15, the

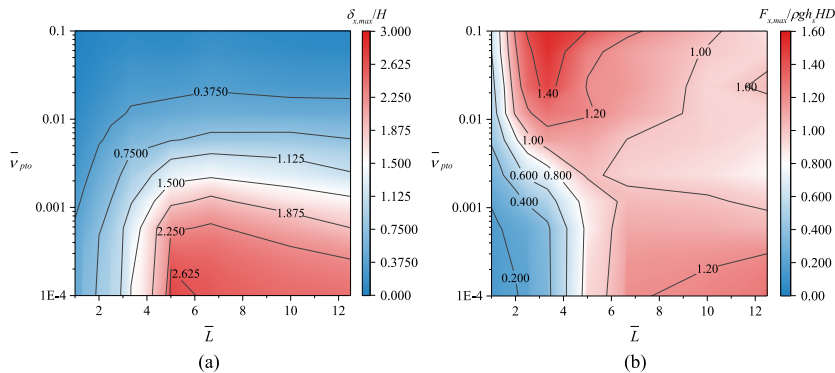


Fig. 12. Variation of (a) maximum displacement and (b) horizontal peak wave force for different $\bar{L}$ and $\bar{\nu}_{pto}$.

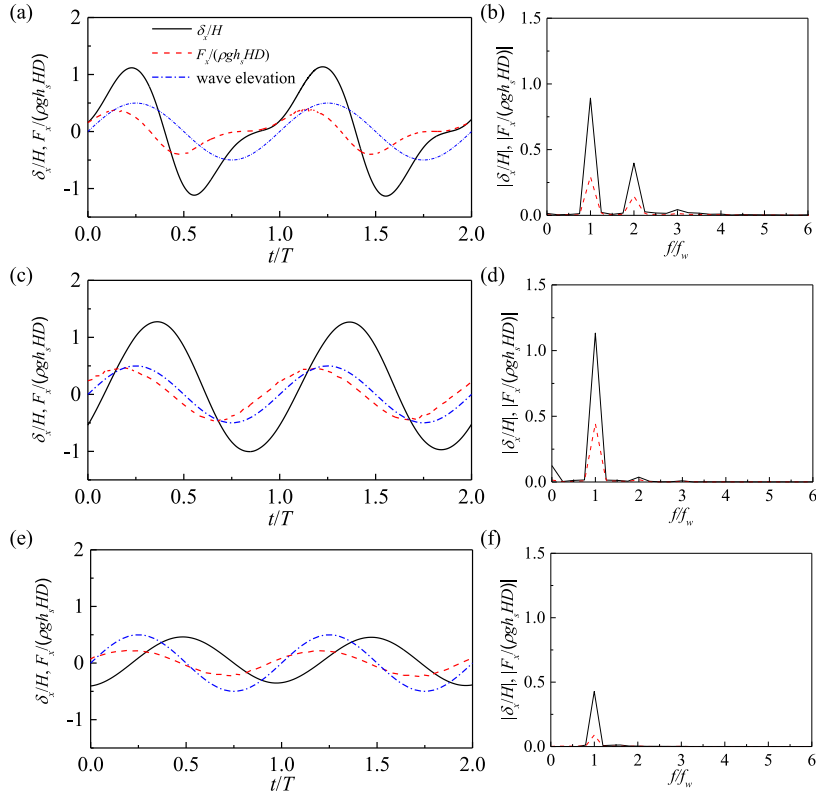


Fig. 13. Time series of wave elevation, horizontal wave force, and horizontal displacement of the free end and the corresponding amplitude spectrum of the horizontal wave force, and horizontal displacement for (a–b) $\bar{L} = 12.5$, (c–d) $\bar{L} = 5$ and (e–f) $\bar{L} = 2$ with $\bar{v}_{pto} = 2.33 \times 10^{-3}$.

interaction between FlexWEC and wave generates a partial standing wave on the seaward side and lower wave height region downstream of the FlexWEC. Additionally, there are checkerboard-like patterns of wave height enhancement and reduction areas on both sides of the FlexWEC. From Fig. 15(a)–(c), as the relative wavelength increases, the variations in wave height around the WEC become smaller. The dashed line in Fig. 15 represents the contour of the wave height equal to H . It can be noted that FlexWEC has a blocking effect on waves. With an increase in $\bar{L}$, the blocking range of FlexWEC is larger, but the blocking effect is weaker, resulting in higher wave heights.

The spatial variations in the wave height at $y = 0$ are plotted in Fig. 16. It should be noted that the wave height reaches its maximum value at antinodes and decreases to its minimum value at nodes, separated by $L/4$. This is consistent with the results shown in Fig. 15. As x decreases, the wave height at the antinodes gradually decreases, indicating the attenuation of the wave spokes during the propagation of a three-dimensional radiating wave. Behind the FlexWEC, there is a region of lower wave height, which gradually increases as x increases, consistent with the results in Fig. 15.

In order to quantitatively study the covering effect of FlexWEC, the positions x' of wave heights equal to $0.25H$, $0.5H$, $0.75H$, and $0.95H$ when $y = 0$ were recorded in Fig. 17(a), respectively. The results show that as $\bar{L}$ increases, the corresponding x'/L is smaller, indicating faster wave height recovery. When the FlexWEC is in the optimal operating range of $2 < \bar{L} < 5$, a minimum of $0.21L$, $0.68L$, and $1.56L$ distance is required to restore the wave height to 50 %, 75 %, and 95 % of the incident wave height, respectively.

Fig. 18 shows the spatial variations in the wave height at $x = 0$. Considering the wave height distribution on both sides of the FlexWEC is symmetrical, this figure demonstrates the wave height distribution along the positive y -axis direction. It can be noticed that there are specific locations where the wave heights are strengthened, which indicates the superposition of the radiated and diffracted waves. They were defined as the first, second, third, and fourth reinforcement points, respectively, according to their distance from the FlexWEC. The interval between the enhancement points is L . When $\bar{L} = 6.66$, high harmonics are present at the first reinforcement point, which may be related to the radiated waves generated by the high harmonic motion of the FlexWEC. In addition, there was no significant third enhancement point at $\bar{L} = 6.66$.

For further illustration, the positions y' of the first four wave height enhancement points under different wave conditions are recorded and plotted in Fig. 19(a). The first and third wave height enhancement points were not recorded as they were not evident when $\bar{L} > 3.33$. When the FlexWEC is in the optimal operating range of $2 < \bar{L} < 5$, y' of the four enhancement points equal to $0.46L$, $1.43L$, $2.38L$, and $3.40L$, respectively. These results provide a valuable reference for the optimization of FlexWEC arrays. As shown in Fig. 19(b), it is argumentatively expected that for an in-line array of WECs, if the WECs are positioned at the wave height enhancement

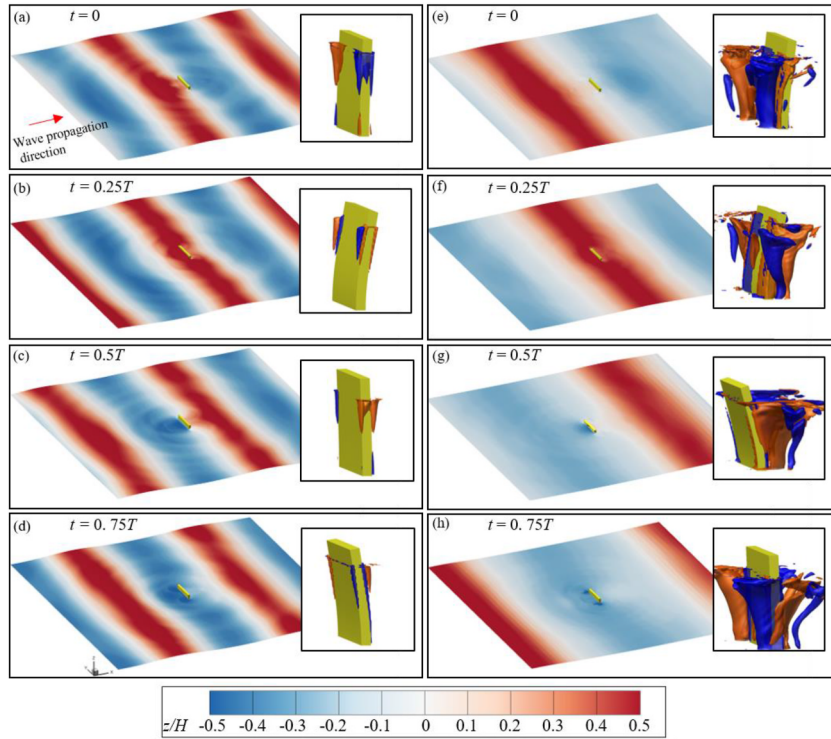


Fig. 14. The spatial distribution of wave elevations and iso-surfaces of z -vorticity ($4\pi w_z D / TgkH = \pm 0.05$) around the FlexWEC for (a–d) $\bar{L} = 5$, (e–h) $\bar{L} = 10$ with $\bar{v}_{pto} = 2.33 \times 10^{-3}$. The red iso-surfaces of z -vorticity represent positive values, while the blue ones represent negative values.

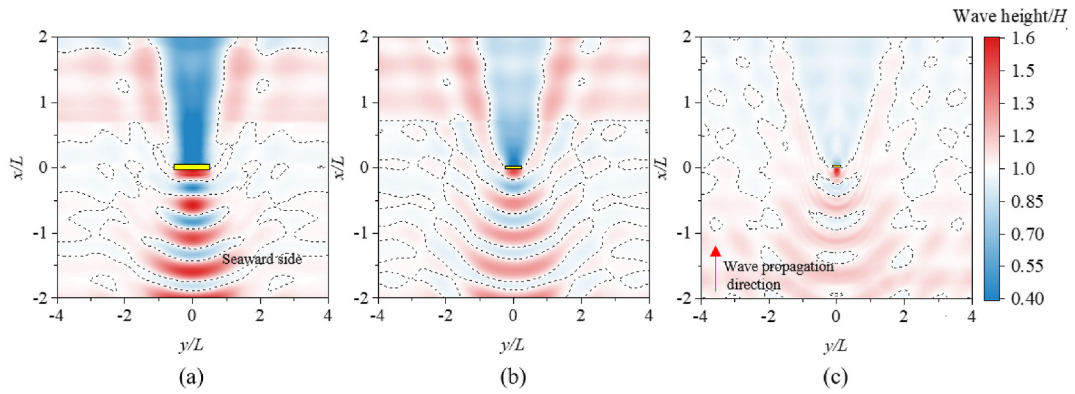


Fig. 15. Spatial distribution of wave amplitudes around FlexWEC with (a) $\bar{L} = 1$, (b) $\bar{L} = 2$, (c) $\bar{L} = 6.67$. Contours represent wave height/ $H = 1$.

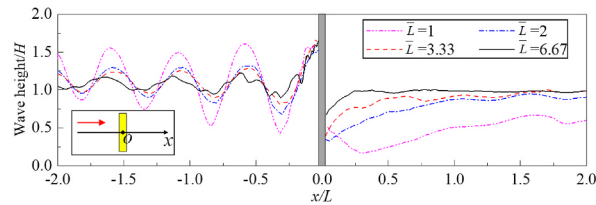


Fig. 16. Variations in wave height at $y = 0$. The position of $y = 0$ is shown in the small figure, with the red arrow representing the direction of the incoming wave. The grey area represents the region occupied by the FlexWEC.

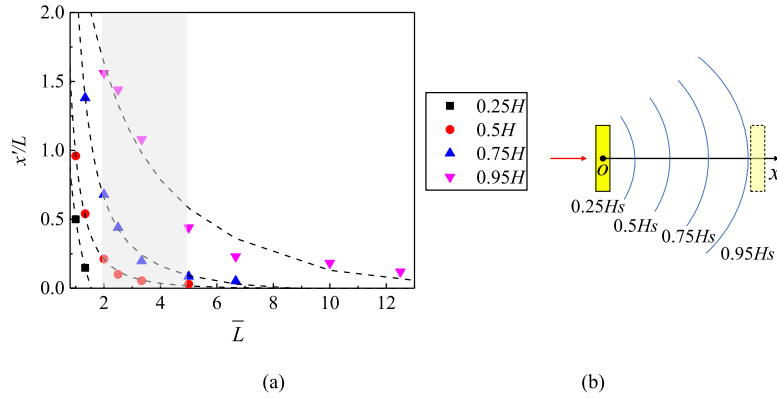


Fig. 17. (a) The positions x' of wave heights equal to $0.25H$, $0.5H$, $0.75H$, and $0.95H$. The grey area represents the optimal operating range of $2 < \bar{L} < 5$. (b) Sketch of the shading effect of upstream FlexWEC on downstream FlexWEC. The red arrow representing the direction of the incoming wave.

points, the captured energy of the array could potentially exceed that of an equal number of independent WECs. This phenomenon indicates a constructive interaction between the FlexWECs within an array, which will be further investigated in our future work.

5. Conclusions

In this study, a coupled computational model was developed to simulate the interaction between FlexWEC and regular ocean waves. The Navier-Stokes equations coupled with the VOF method is used to describe the fluid phase. FlexWEC is simulated using the nonlinear beam finite element method. In order to represent the effects of the DEG PTO system, the deformations influenced by energy extraction are considered and integrated into the beam finite element method. Based on the validated model, the combined effect of damping coefficient $\bar{\nu}_{pto}$ and relative width $\bar{L}$ on both hydroelastic interaction and wave energy conversion performance of a full-scale seawall-type FlexWEC was carried out. The following conclusions can be made:

- The optimal operating interval of the FlexWEC is $2 < \bar{L} < 5$ and $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$, which corresponds to a CWR of 53%–61 % and max-to-mean ratio of power of 2.06–2.53. Therefore, the FlexWEC should be designed according to the actual sea state to ensure that the FlexWEC works in the optimal operation interval for efficient energy harvesting.
- Damping reduces the amplitude of FlexWEC motion, but the effect on hydrodynamic loads is bi-directional. In this study, when $\bar{\nu}_{pto} = 2.3 \times 10^{-3}$, it ensures that the FlexWEC is subjected to small hydrodynamic loads throughout the wave range.
- In the optimal operation interval, the downstream FlexWEC needs to be spaced $1.56L$ from the leading FlexWEC to avoid its sheltering effect. In the direction of the wave crest line, periodic wave height enhancement points exist on both sides of the WEC at locations of $0.46L$, $1.43L$, $2.38L$, and $3.40L$ away. These provide valuable references for the design of WEC arrays.

In future research, the interaction of the FlexWEC with oblique and irregular waves, as well as the performance of the FlexWEC array will be investigated to support the development of wave farms.

Chao Wang: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. Yujia Wei: Writing – original draft, Investigation. Wenchuang Chen: Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. Luofeng Huang: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

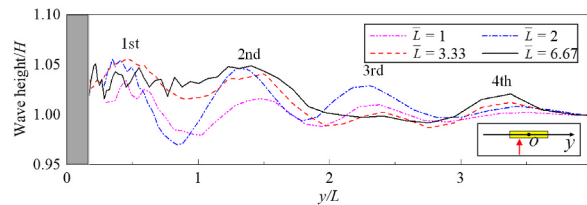


Fig. 18. Variations in wave height at $x = 0$. The position of the $x = 0$ is shown in the small figure, with the red arrow representing the direction of the incoming wave. The grey area represents the region occupied by the FlexWEC.

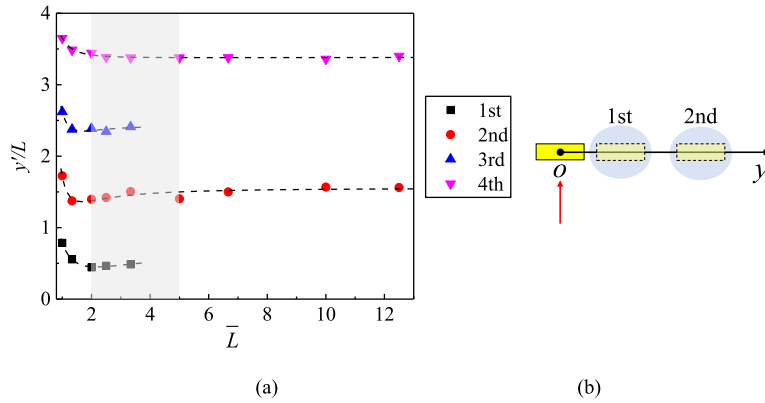


Fig. 19. (a) Distance of the first four wave height enhancement points from the side of the FlexWEC. The grey area represents the optimal operating range of $2 < \bar{L} < 5$. (b) Schematic of arranging the FlexWEC at the wave height enhancement point. The red arrow represents the direction of the incident wave.

influence the work reported in this paper.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

Acknowledgements

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Appendix A

To verify the impact of beam modelling on the accuracy, the deformation of the FlexWEC was compared between beam elements utilized in the present study and shell elements in ANSYS Mechanical. A pressure of 2500 Pa was applied to one side of the FlexWEC (as shown in Fig. A1(a)) to approximate the load it might encounter in water. The parameters of FlexWEC are shown in Table 6. The FlexWEC undergoes oscillation under this pressure, and Fig. A1(b) presents the predictions of maximum free-end motion for both models.

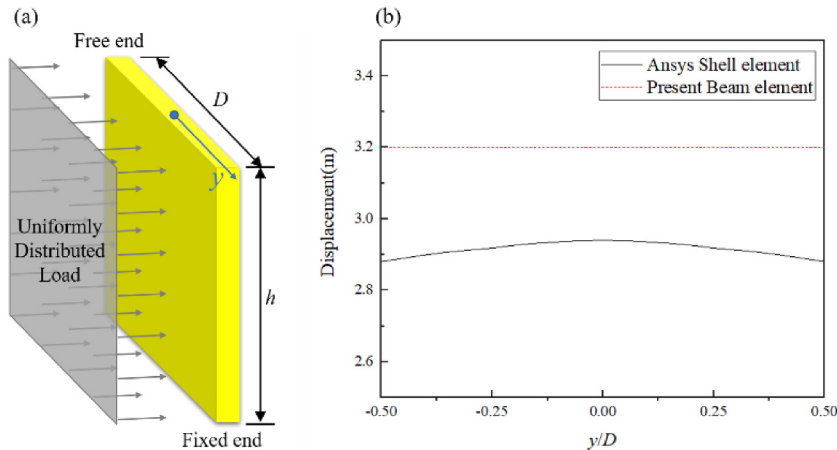


Fig. A1. Plate structure test: (a) Computational setup, (b) Comparison between ANSYS shell elements and beam elements.

Due to the in-plane deformation of the plate, there is a discrepancy in the displacements predicted by ANSYS at the mid-point and

edge points of the plate. The beam method predicts structural displacements with an average difference of 9.7 % compared to the ANSYS. This indicates that the beam model tends to overestimate the motion of the FlexWEC. To test the applicability boundary of the beam model, the difference in results between the two models at different relative heights (h/D) was also studied, as shown in Fig. A2. It can be seen that the errors are generally $<10\%$. When the relative height is less than 0.5, the error of the beam element exceeds 10% but this is near the fixed bottom - within an area of very small deformation.

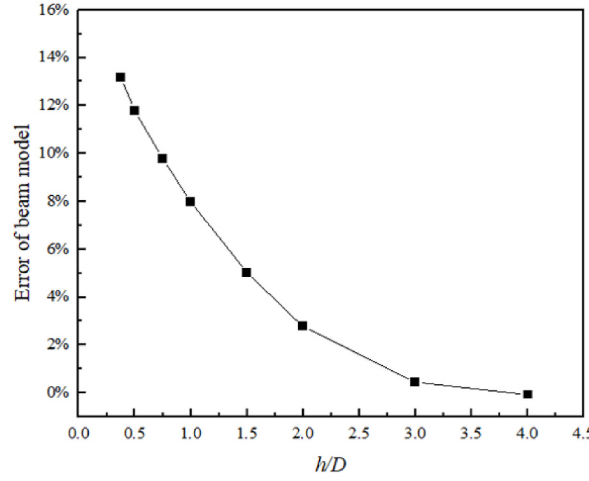


Fig. A2. Error in structural motion prediction by beam model at different relative heights.

Appendix B

Referring to Babarit [45], the conversion efficiency of WECs at scales similar to the present FlexWEC is compared (as shown in Table B1), demonstrating the FlexWEC generally has higher conversion efficiency than rigid WECs.

Table B1
Summary table of energy performance of wave energy converters

Technology	$\eta(\%)$	Width	Category
Pico	20	12	Oscillating Water Column
KNSWING	18	7.5	Oscillating Water Column
SSG	23	10	Overtopping devices
AquaEnergy/AquaBuOY	20	6	Heaving devices
OWSC	35	6	Fixed OWSC
Inspired by Oyster	22	6	Fixed OWSC
Surface piercing flap	36	10	Fixed OWSC
WEPTOS	32	8.3	Fixed OWSC
Present FlexWEC	61	8	Flexible WEC

Appendix C

The following derivation aims to establish the range of equivalent linear damping coefficients corresponding to the DEG power generation process shown in Fig. 3, ensuring the practical significance of the linear PTO model in energy harvesting. According to Eitzen et al. [46], the absorbed energy per unit volume of DEG per cycle can be approximated by the following equation:

$$U_0 = \frac{1}{2} \bullet \epsilon_0 \bullet \epsilon_r \bullet E_{\max}^2 \quad (C1)$$

Where $E_{\max}$ represents the maximum voltage during the cycle, which should be less than the dielectric breakdown strength. ϵ_0 is the permittivity of free space, and ϵ_r is the permittivity of the DE material.

Based on the linear damping approach, the absorbed energy per unit volume of DEG can also be expressed as:

$$U_0 = \int_0^T \sigma^{pto} \dot{\epsilon} dt = \int_0^T \nu^{pto} \dot{\epsilon}^2 dt \quad (C2)$$

σ^{pto} represents the additional stress of the PTO system, $\dot{\epsilon}$ represents the strain rate. Assuming FlexWEC undergoes standard sinusoidal oscillation, with $\dot{\epsilon} = \frac{2\pi}{T} e_{\max} \sin\left(\frac{2\pi}{T} t\right)$, where $e_{\max}$ represents the maximum structural strain, and T is the cycle period.

Substituting this into Eq. (C2) yields:

$$U_0 = \frac{2\pi^2 e_{\max}^2}{T} \nu^{\text{pto}} \quad (\text{C3})$$

Combining Eqs. (C1) and (C3), it can be obtained:

$$\nu^{\text{pto}} = \frac{T \epsilon_0 \epsilon_r E_{\max}^2}{4\pi^2 e_{\max}^2} \quad (\text{C4})$$

where $\epsilon_0 = 8.854 \times 10^{-12}$ (F/m), $\epsilon_r = 5$ for silicone, and $E_{\max} < 3 \times 10^7$ (V/m) for silicone. We select the wave period range of $T = 4.23\text{--}6.25$ s, corresponding to the most efficient performance of FlexWEC. The maximum structural strain $e_{\max}$ can be estimated based on the amplitude of free-end motion and the curvature of the first mode shape. In this study, the maximum strain of FlexWEC is approximately $e_{\max} \sim O(10^{-2})$. According to Eq. (C4), the corresponding upper limit of ν^{pto} is 42.7–63.1 MPa s.

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