

Article

Hydrodynamic Numerical Study of Regular Wave and Mooring Hinged Multi-Module Offshore Floating Photovoltaic Platforms

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Abstract

The floating photovoltaic (FPV) power generation technology in water has made up for some of the shortcomings of traditional inland photovoltaics and has developed rapidly in the past decade, enabling truly sustainable solar energy exploitation. Multi-module hinged offshore floating photovoltaics (OFPV) are widely used in the sea. However, how to ensure the survival of OFPVs in extreme natural environments is the biggest challenge for the implementation of the project in the future. The focus of this paper is the hydrodynamic problems that multi-module OFPV structures may encounter under regular waves. The effects of column spacing and heave plates were analyzed for a single FPV platform in order to obtain the ideal single module. Furthermore, the motion responses and inter-module forces of each module are calculated within the overall OFPV system under regular waves to investigate the overall hydrodynamic characteristics. Qualitative and quantitative comparisons between single and multi-modules are made for a deep understanding of this structure to ensure its sustainability. The corresponding conclusions can provide scientific references for multi-module OFPVs and the sustainable utilization of energy.

Keywords: offshore floating photovoltaic; multi-module; motion response; inter-module forces



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1. Introduction

Solar energy, the most sustainable resource on Earth, has long challenged scientists seeking its efficient utilization. Since the successful implementation of the world's first commercial water-based photovoltaic project in 2008, FPV system [1], as an innovative photovoltaic power generation technology, has gradually demonstrated its enormous potential for application. FPV does not only overcome some limitations of land-based PV systems but also promotes the rapid development of the water-based photovoltaic industry. Scholars have proposed multiple floating body design schemes to support the development of this technology, including floater-truss type, multi-floater type and flexible film type [2–4]. Each design has its unique advantages and application prospects. Recently, people have begun to turn their attention to the ocean and explore the potential of OFPV power generation with an increase in maturity of IFPV system technology. By leveraging the vast, untapped surface area of offshore environments, FPV technology not only circumvents terrestrial limitations but also enhances energy yield through the cooling effects of water bodies, thereby establishing a new paradigm for sustainable solar energy utilization at gigawatt scales. Dutch company Ocean of Energy has collaborated on the development

of the Zon op Zee project in the North Sea near the Netherlands [5,6] which is the first offshore floating solar power generation system installed on the open sea. In addition, since April 2021, Dutch developer SolarDuck [7] has been operating a 65 kW PV array called King Eider in the Dutch Inland Bay. The FPV structure adopts a modular triangular column stable platform design, which flexibly combines rigid modules through flexible connections to form a stable platform. This design optimizes the layout effect of the mooring system. Although research on OFPVs has made some progress in recent years, it faces problems such as wind and wave damage, damage to the connection between floats, and chemical and biological pollution during actual implementation [8,9]. The existence of these problems does not only affect the stability and power generation efficiency of OFPV systems but also limits their application in deep-sea environments.

In order to gain a deeper understanding of the hydrodynamic characteristics of OFPV platforms, researchers have conducted extensive research on their hydrodynamic characteristics, which involves the hydrodynamic force and response, as well as the influencing factors on OFPV in waves. Ikhennichen et al. [10] proposed the calculated methods of wave, current and wind loads on OFPV, and found that the wave load is the most important load in near offshore environment. Zhang et al. [11] have consolidated three numerical methods commonly utilized in evaluating the hydrodynamic performance of offshore articulated floating structures. Al-Yacoubi et al. [12] investigated the dynamic response of floating solar power plants intended for maritime applications in Malaysia, examining the impact of various parameters on the dynamic response of FPV platforms. Moreover, Zeng et al. [13] and Pan et al. [14] conducted a dynamic stability analysis of single-module FPV structures under different wave loads, revealing that the connection points at the four corners of the floaters are prone to stress concentration, necessitating reinforcement in the design phase. They found that the structural integrity of the float array was particularly weak at the wave-facing corners and the ear plates connecting the floats.

The hydrodynamic analysis of novel floating structures constitutes a fundamental aspect of ensuring structural design safety, particularly given the distinct hydrodynamic challenges faced by various OFPV structures. For OFPV platforms comprising multiple interconnected floaters, it is crucial to consider the intricate interplay between waves and the multi-floater system. Unlike single-floater configurations, the interaction between waves and multiple floaters involves not only the coupling between waves and individual floaters but also the hydrodynamic coupling among the floaters themselves. This inter-floater hydrodynamic coupling significantly impacts the hydrodynamic coefficients, wave-induced excitation forces, and motion responses of the floaters. Diamantoulaki and Angelides [15,16] have explored the influence of wave frequency and the number of floaters on the motion response of articulated multi-floater systems. Gou et al. [17] employed the total modal method to investigate the motion response of two articulated floaters under wave action, identifying resonant phenomena in the box-like structure's motion response. They derived the system's motion response by directly supplementing the motion constraint equations based on the displacement matching conditions between the articulated dual-floater system. Subsequently, Wang [18] established the interaction between waves and rigidly connected or articulated multi-floater systems, examining the impact of wave parameters and structural parameters on motion responses. In recent years, multi-floater structures have undergone rapid development in the research of WECs. Luan et al. [19,20] and He et al. [21] conducted analyses based on viscous flow theory to investigate oscillating-buoy WECs, identifying the optimal wave frequency and buoy distribution patterns that maximize power generation efficiency. They found that the damping factor can affect the motion response and the wave force it receives. Following this, they performed relevant calculations tailored to the conditions in the South China Sea. Similarly, Jin et al. [22] utilized potential flow theory

to evaluate multi-floaters WECs, comparing the power generation efficiency of platforms with varying numbers of buoys in both cross-wave and along-wave configurations, and provided recommended buoy arrangements for optimal performance. Furthermore, more and more scholars are adopting numerical simulation to investigate the hydrodynamic characteristics of the OFPV platform. Xu et al. [23,24] employed the ANSYS-AQWA (Version 19.0) to investigate the effects of different mooring setups and the impact of different arrangements of OFPV system on hydrodynamic performance. Ji et al. [25] also used ANSYS-AQWA (Version 19.0) to analyses the hydrodynamics of a novel OFPV with multi-module connection. Fu et al. [26] used the potential flow theory to analyses the hydrodynamic performance of FPV systems in coupled wave-wind co-directional conditions. Lee et al. [27] applied the CFD model and focused on the motion response and tried to understand the relative motion that may occur in a unit platform. Xiong et al. [28] employed the SESAM software to study the hydrodynamic response of a novel OFPV with the membrane structure.

In summary, the design and construction of OFPV power plants in deep offshore environments will be a key technological challenge for future advancements. This paper investigates the overall motion response of OFPV platforms, the forces acting on the mooring system and connection points, and their influencing factors. This study also explores the qualitative and quantitative differences in hydrodynamic characteristics of OFPV platform between multi module and single module, which provides valuable references for the subsequent design and optimization of OFPV platforms. Chapter 2 was the basic theory for the calculation, containing the hydrodynamic part and mooring part, as well as the model validation. Chapters 3 and 4 introduced the hydrodynamic characteristics of single- and multi-module OFPV platform. Finally, Chapter 5 was the conclusions.

2. Basic Theory

2.1. Governing Equation and Boundary Conditions

Assume that there are N rigid bodies in the waves, undergoing small-amplitude harmonic oscillations, labeled as 1, 2, ..., as illustrated in Figure 1. The global coordinate system $Oxyz$ is established for the entire spatial domain, with the Oxy plane located at the still water surface. Additionally, local coordinate systems $O_1x_1y_1z_1$, $O_2x_2y_2z_2$, ..., are defined for each individual floating body. In Figure 1, S_f denotes the free water surface, S_b represents the surface of the floating bodies, which can be expressed as $S_b = S_{b1} + S_{b2} + \dots$, and S_d signifies the underwater bottom surface.

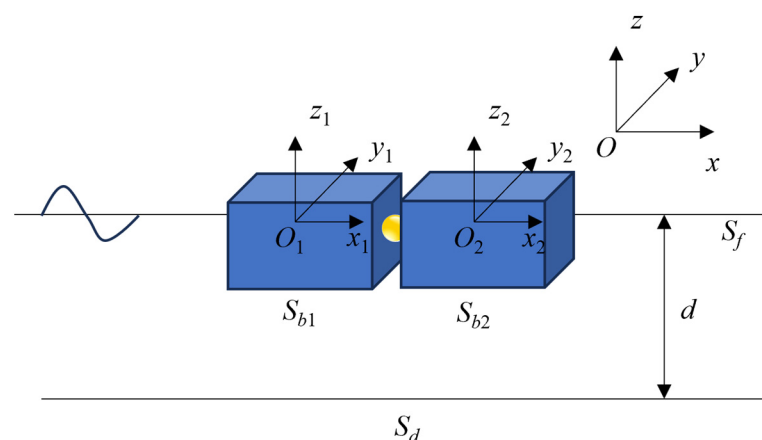


Figure 1. Definition of coordinate systems.

The fluid is assumed as incompressible and ideal fluid; the velocity potential satisfies the Laplace equation.

$$\nabla^2 \phi = 0 \quad (1)$$

When considering the interaction between a simple harmonic wave of frequency ω propagating in a water of constant depth and a structure, it is noteworthy that under the linear approximation, the velocity potential Φ and motion responses Ξ , Λ are both harmonic functions with the same frequency ω . Consequently, it is feasible to extract the time factor $e^{-i\omega t}$ from these physical quantities.

$$\begin{aligned} \Phi(x, t) &= \text{Re}[\phi e^{-i\omega t}] \\ \Xi(x, t) &= \text{Re}[\xi e^{-i\omega t}] \\ \Lambda(x, t) &= \text{Re}[\alpha e^{-i\omega t}] \end{aligned} \quad (2)$$

The velocity potential can be divided into incident potential ϕ_I , diffraction potential ϕ_D , and radiation potential ϕ_R , as follows:

$$\phi = \phi_I + \phi_D + \phi_R \quad (3)$$

The diffraction and radiation potentials satisfy the boundary conditions at the still water surface and seabed, as follows:

$$\frac{\partial \phi_D}{\partial z} = \frac{\omega^2}{g} \phi_D, \quad \frac{\partial \phi_R}{\partial z} = \frac{\omega^2}{g} \phi_R, \quad z = 0 \quad (4)$$

$$\frac{\partial \phi_D}{\partial z} = 0, \quad \frac{\partial \phi_R}{\partial z} = 0, \quad z = -d \quad (5)$$

where g is the gravity acceleration, d is the water depth. The body boundary condition is shown as follows:

$$\frac{\partial \phi}{\partial n} = -i\omega \{ \xi \cdot n + \alpha \cdot [(x - x_0) \times n] \} \quad (6)$$

The generalized directions are defined as $(n_4, n_5, n_6) = (x - x_0) \times n$, and the rotational vector $(\alpha_1, \alpha_2, \alpha_3)$ are defined as (ξ_4, ξ_5, ξ_6) , $\mathbf{n}$ is the normal vector of the body, then Equation (6) can be written as:

$$\frac{\partial \phi}{\partial n} = -i\omega \xi \cdot \mathbf{n} \quad (7)$$

For the convenience of the study, the radiation potential (7) is further decomposed according to the six components of the object motion as:

$$\phi_R = \sum_{j=1}^6 -i\omega \xi_j \phi_j \quad (8)$$

2.2. Hydrodynamic Coefficient and Wave Force

The wave force can be obtained by integrating the fluid pressure on the instantaneous wet surface of any floating body J .

$$f_{ex} = i\rho\omega \iint_{S_{BJ}} (\phi_I + \phi_D) n ds \quad (9)$$

where ρ is the fluid density. The wave force induced by radiation potential can be written as:

$$f_r = i\rho\omega \iint_{S_{BJ}} \phi_R n ds = \rho\omega^2 \sum_{j=1}^{6N} \xi_j \iint_{S_{BJ}} \phi_j n ds \quad (10)$$

The hydrodynamic coefficients containing added mass and radiation damping. If the discussion is carried out for a multi-floater system, the hydrodynamic coefficients due to the interaction between the floaters are additionally taken into account:

$$a_{ij}^J = \text{Re}(\rho \int_{S_{BJ}} \phi_j n_i ds), b_{ij}^J = \frac{1}{\omega} \text{Re}(\rho \iint_{S_{BJ}} \phi_j n_i ds) \quad (11)$$

When $i = 6(J - 1) + 1, \dots, 6J, j = 6(J - 1) + 1, \dots, 6J$, a_{ij} and b_{ij} represent the added mass and radiation damping caused by the motion of the floating body J . When $i \neq 6(J - 1) + 1, \dots, 6J, j \neq 6(J - 1) + 1, \dots, 6J$, a_{ij} and b_{ij} indicates the added mass and radiation damping generated by other floating body movements on floating body J .

2.3. Motion Response of Multi-Floater System

When the frequency of the incident wave is ω , the structural motion response behaves as a simple harmonic function with the same frequency ω . Based on the derivation of wave force mentioned above, by separating out the time term from each component, the motion equation response for the I th floater can be obtained as follows:

$$\left(-\omega^2([M_I] + [a_{II}]) - i\omega([B_I] + [b_{II}]) + ([k_{II}] + [C_I]) \right) \{\varepsilon_I\} + \sum_{J=1, J \neq I}^n \left(-\omega^2 a_{IJ} - i\omega b_{IJ} \right) \varepsilon_J = f_{exJ} \quad (12)$$

where $[M]$, $[a]$, $[B]$, $[b]$, $[C]$, $\{f_{ex}\}$ and $[k]$ are the mass matrix, added mass matrix, damping matrix, radiation damping matrix, restoring matrix, wave exciting force matrix and stiffness matrix, respectively. The notation “ II ” represents physical quantities resulting from the motion of the floating body I itself, whereas “ IJ ” signifies the physical quantities induced on floating body I by the motion of floating body J .

For rigid or hinged multi-floater systems, Equation (14) can be expressed as:

$$\left(-\omega^2([M_I] + [a_{II}]) - i\omega([B_I] + [b_{II}]) + ([k_{II}] + [C_I]) \right) \{\varepsilon_I\} + \sum_{J=1, J \neq I}^n \left(-\omega^2 a_{IJ} - i\omega b_{IJ} \right) \{\varepsilon_J\} = \{f_{exJ}\} + \{f_L\} \quad (13)$$

where $\{f_L\}$ is the connecting force and moment. Equation (13) can be simplified as:

$$[K]\{\varepsilon\} = \{F\} \quad (14)$$

where $[K]$, $\{\varepsilon\}$ and $\{F\}$ are the system stiffness matrix, displacement vector and external force vector; therefore, the potential energy within the system can be expressed as:

$$\Pi = \frac{1}{2} \{\varepsilon\}^T [K] \{\varepsilon\} - \{\varepsilon\}^T \{F\} \quad (15)$$

For the connection points of multi-floater structure, the displacement continuity condition should be met, that is $[D]\{\varepsilon\} = \{0\}$. Therefore, according to the Lagrange multiplier method:

$$\Pi = \frac{1}{2} \{\mathcal{E}\}^T [K] \{\mathcal{E}\} - \{\mathcal{E}\}^T \{F\} + \{\lambda\}^T [D] \{\mathcal{E}\} \quad (16)$$

Let m represent the total number of constraints at all constraint connection points in the system, the amount of matrix $\{F\}$, $\{\varepsilon\}$, $[K]$, $[D]$, $[\lambda]$ are $(6n \times 1)$, $(6n \times l)$, $(6n \times 6n)$, $(m \times 6n)$, $(m \times l)$. The simultaneous variation on both sides of Equation (16) yields,

$$\delta \Pi = \{\delta \varepsilon\}^T [K] \{\varepsilon\} - \{F\} + [D]^T \{\lambda\} + \{\delta \lambda\}^T [D] \{\varepsilon\} = 0 \quad (17)$$

$$\begin{cases} [D] \{\varepsilon\} = \{0\} \\ [K] \{\varepsilon\} + [D]^T \{\lambda\} = \{F\} \end{cases} \quad (18)$$

The vector $\{\lambda\}$ in the above equations is the connecting force; we use f_L to represent λ . The equation can be transformed into the system motion equation.

$$\begin{bmatrix} [K]_{6n \times 6n} & [D]_{6n \times 6n}^T \\ [D]_{m \times 6n} & [0]_{m \times 6n} \end{bmatrix}_{(6n+m) \times (6n+m)} \begin{Bmatrix} \{\varepsilon\}_{6n \times 1} \\ \{f_L\}_{m \times 1} \end{Bmatrix}_{(6n+m) \times 1} = \begin{Bmatrix} \{F\}_{6n \times 1} \\ \{0\}_{m \times 1} \end{Bmatrix}_{(6n+m) \times 1} \quad (19)$$

For the constraint matrix of structure $[D]$, if the structure can only rotate around the Y-axis, then the displacement continuity condition is satisfied at the hinge point, as follows:

$$\chi_{I1} = \sigma_{J1}, \chi_{I2} = \sigma_{J2}, \chi_{I3} = \sigma_{J3}, \chi_{I4} = \sigma_{J4}, \chi_{I6} = \sigma_{J6} \quad (20)$$

where χ_I and σ_J are the translational displacement and rotation angle of floating body I and J at the hinge point, respectively.

$$\chi_{I1} = \varepsilon_{I1} + Z_0 \times \varepsilon_{I5} - Y_0 \times \varepsilon_{I6} \quad (21)$$

$$\sigma_{J1} = \varepsilon_{I1} + Z_0 \times \varepsilon_{I5} - Y_0 \times \varepsilon_{I6} \quad (22)$$

where (X_0, Y_0, Z_0) is the coordinate of hinge point, $\varepsilon_{I1}, \dots, \varepsilon_{I6}$ are the translational and rotational motion of floating body I , $\varepsilon_{J1}, \dots, \varepsilon_{J6}$ are the translational and rotational motion of floating body J . The expressions of $\zeta_{I2}, \zeta_{I3}, \zeta_{I4}, \zeta_{I6}$ and $\zeta_{J2}, \zeta_{J3}, \zeta_{J4}, \zeta_{J6}$ can be obtained by the same method.

Due to the potential flow theory is employed to calculate the hydrodynamic characteristics of OFPV here, the calculation results may be overestimated at specific frequencies.

2.4. Catenary Theory in Mooring System

The catenary equation is often employed in the initial design of mooring systems due to its computational efficiency. During these calculations, it is assumed that the mooring line has a uniform mass distribution and is incapable of transmitting bending moments. Additionally, viscous drag, inertial resistance, and elastic deformations of the mooring line are neglected. Figure 2 illustrates the static force diagram for an infinitesimal element of the catenary, where WL represents the weight per unit length, dl denotes the differential length, dT signifies the incremental tension in the mooring line per unit length, θ is the angle between the tension direction and the seabed, and $d\theta$ represents the incremental change in θ per unit length. The equilibrium equations in the horizontal and vertical directions can be expressed as follows:

$$\begin{cases} dx = dl \cos \theta \\ dy = dl \sin \theta \end{cases} \quad (23)$$

$$\begin{cases} (T + dT) \cos(\theta + d\theta) - T \cos \theta = 0 \\ (T + dT) \sin(\theta + d\theta) - T \sin \theta - WL dl = 0 \end{cases} \quad (24)$$

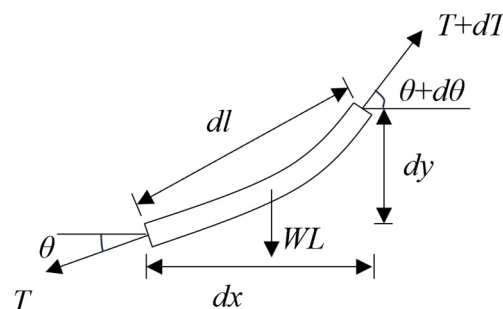


Figure 2. Static diagram of catenary element segment.

Further analysis yields the relationship between the overall structural load and the final positions of the mooring points, as depicted in Figure 3. Specifically, T_a and θ_a , as well as T_b and θ_b , represent the tensions and inclination angles at the two ends of the catenary, respectively, while T_0 denotes the horizontal load acting on the floating structure. The horizontal distance between the two ends of the catenary is denoted as x , and the vertical distance is denoted as y . The relationship between T_0 and T_a , T_b can be expressed as follows:

$$T_0 = T_a \cos \theta_a = T_b \cos \theta_b \quad (25)$$

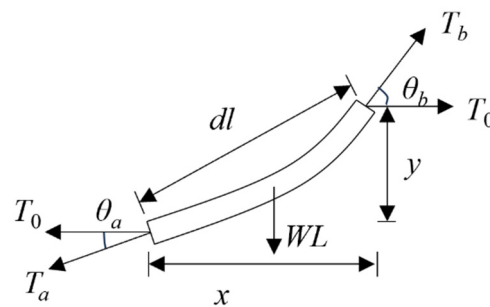


Figure 3. Static diagram of catenary section.

Based on Equations (23)–(25), the relationship between the horizontal component of the tension at the end of the catenary, T_0 , and its coordinates as well as the length of the mooring line can be derived.

$$\begin{cases} x = \frac{T_0}{WL} [\sinh^{-1} + (\tan \theta_b) - \sinh^{-1}(\tan \theta_a)] \\ y = \frac{T_0}{WL} (\sqrt{1 + \tan^2 \theta_b} - \sqrt{1 + \tan^2 \theta_a}) \end{cases} \quad (26)$$

$$l = \frac{T_0}{WL} (\tan \theta_b - \tan \theta_a) \quad (27)$$

In the model construction, commercial software ANSYS AQWA (Version 19.0) is employed. It can simulate the motion and response of ocean structures under various environmental conditions. The ANSYS AQWA (Version 19.0) is based on the FEM, which enables precise simulation of the dynamic behavior of marine structures in different environments, referencing theories such as the 3D potential flow radiation-diffraction theory and Morison equation.

2.5. Model Validation

The study of waves and OFPV is actually a multi-floating body interaction problem. To validate the numerical model, the linear wave interaction of a twin-box structure is modeled, as shown in Figure 4. L , B , T and W are the length, width, draft and spacing of the twin-boxes, respectively. The detailed dimensions and calculation parameters of the square box are shown in Table 1. The mass center of the square box is located 2.56 m directly above the center of the box bottom. All the parameters are the same as in the work of Choi and Hong [29]; the hydrodynamic coefficient and motion response are calculated in the regular waves at a depth (d) of 15 m.

In order to compute the hydrodynamic coefficients and motion responses of two free rectangular boxes under the condition of incident waves along the x -axis. Figure 5 presents the relationship between the wave-excitation forces and the incident wave frequency for the boxes facing the wavefront and those positioned on the opposite side, respectively. These figures provide a comprehensive understanding of how the excitation forces vary with changes in wave frequency for both configurations. Figure 6 presents the motion responses

at various wave frequencies. To standardize and generalize the findings, the hydrodynamic calculations obtained for various directions must be nondimensionalized. F_x is the wave force in surge direction and ζ_5 is the pitch motion response. The variables m , g , A , and ω represent the mass of the rectangular box, the gravitational acceleration, the amplitude of the incident wave, and the frequency of the incident wave, respectively. This notation is essential for clarifying and maintaining consistency in the subsequent calculations and analysis presented in this paper.

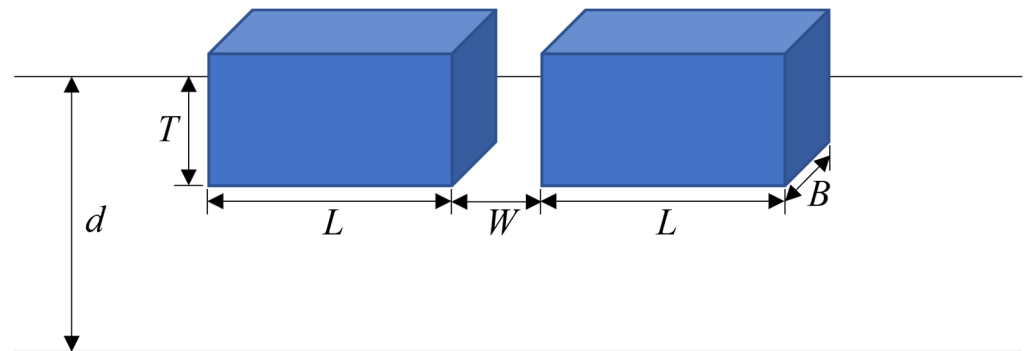


Figure 4. Schematic diagram of double-box model ($d = 15$ m).

Table 1. Parameters of double-box model.

Symbol	Meaning	Value
L	Length (m)	30
B	Width (m)	22
T	Draft (m)	1.5
d	Water depth (m)	15
W	Distance of twin-boxes (m)	8
R_x	Rotation radius around x-axis (m)	9.0
R_y	Rotation radius around y-axis (m)	6.6
R_z	Rotation radius around z-axis (m)	10.8

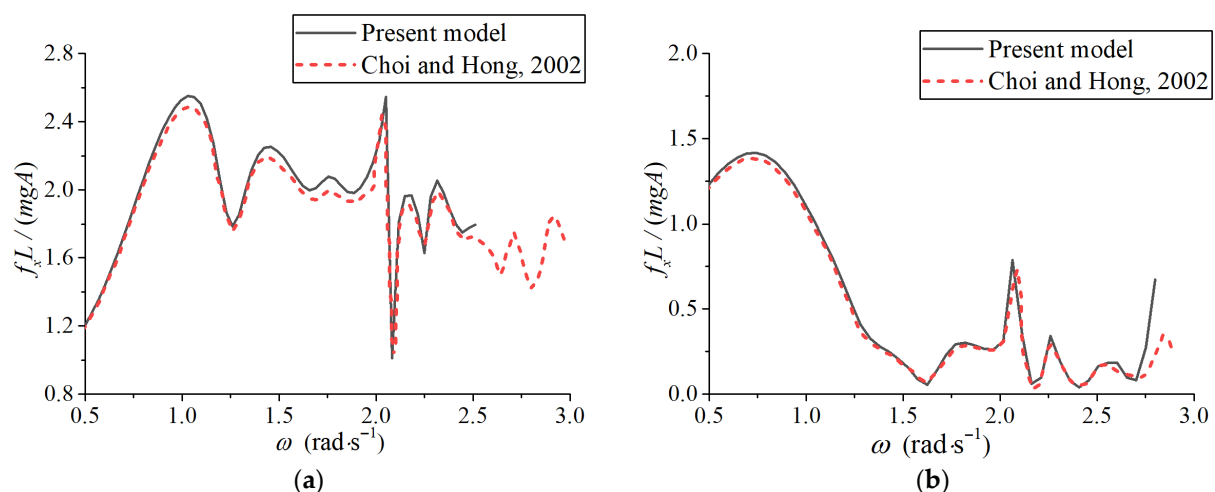


Figure 5. Wave forces of barges in the surge direction: (a) up-wave barge; (b) back-wave barge.

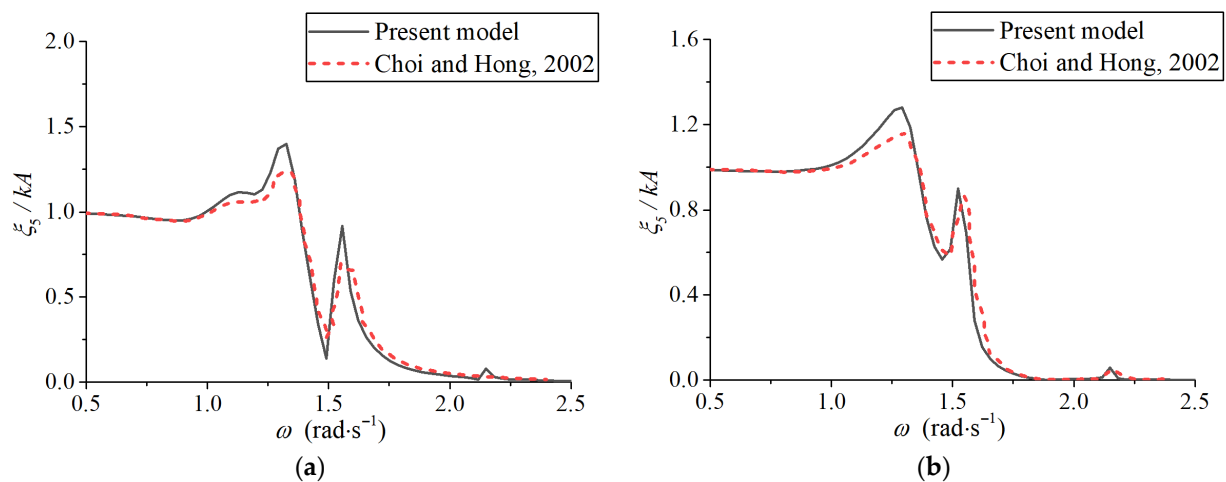


Figure 6. Displacement of barges in the pitch direction: (a) up-wave barge; (b) back-wave barge.

Based on the comparison presented in Figures 5 and 6, the numerical results obtained in this numerical model align closely with those calculated by Choi and Hong [29], albeit with minor discrepancies. This comparison validates the accuracy of the approach used in this paper for considering the interaction between waves and multi-floater bodies.

3. Analysis of Single OFPV Platform

In this paper, the 3D model was inspired by the King Eider PV array developed by Solar Duck. The fundamental structure comprises three evenly distributed supporting columns, topped with a rigidly connected triangular deck. Each column measures 2.5 m in diameter and 8 m in depth, with a hollow interior and a ballast tank at the base. These columns are positioned at equal distances of 5 m from the centroid of the triangle, forming the corners of the triangular deck. A visual representation of this configuration is presented in Figure 7 (left). The parameters of the initial OFPV are listed in Table 2.

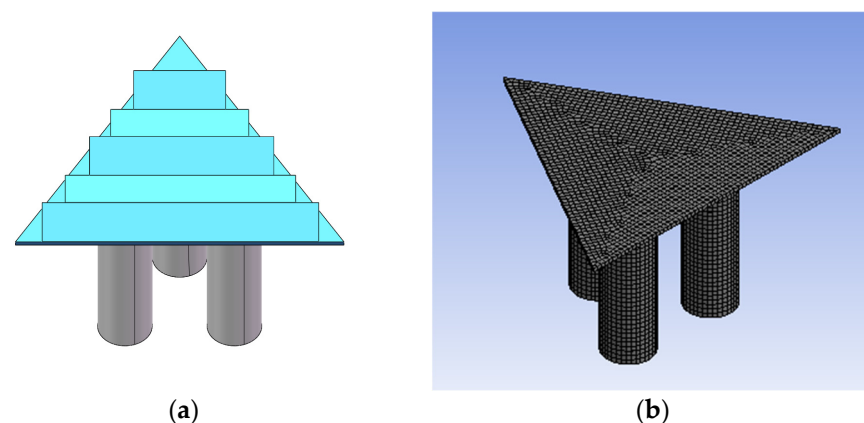


Figure 7. Structural model and grid division diagram: (a) Model design; (b) Mesh grid.

Table 2. Initial design parameters of single module model.

Component	Parameter	Value
Column	Diameter (m)	2.5
	Depth (m)	8
	Column spacing (m)	5
	Mass m_1 (kg)	20,142

Table 2. Cont.

Component	Parameter	Value
Deck	Side Length L (m)	16
	Mass m_2 (kg)	7500
	Draft H' (m)	4.5
Hull model	Coordinate of floating center(m)	(0, 0, −2.25)
	Coordinate of gravity center(m)	(0, 0, −2.55)
	Roll moment of inertia I_{xx} (kg·m ²)	9.856×10^5
	Pitch moment of inertia I_{yy} (kg·m ²)	9.856×10^5
	Yaw moment of inertia I_{zz} (kg·m ²)	6.914×10^5

3.1. The Influence of Column Space on the Motion Response

The impact of the spacing between the three columns of an OFPV platform on its structural motion response is investigated in the frequency domain. As illustrated in Figure 8, the floating body comprises three columns, with the centroid of the upper triangular deck located at the center. The columns are equally spaced by a distance D , with the bisectors of the angles of the triangle passing through the centers of each column. Three different spacing configurations are considered: D1, which is set to 1.5 times the diameter of the cylinder, resulting in a value of 3.75 m; D2, which equals twice the cylinder diameter, yielding 5 m; and D3, equivalent to 2.5 times the diameter, resulting in 6.25 m.

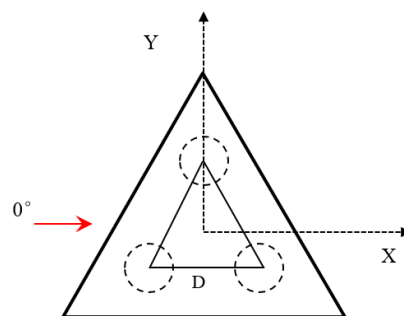


Figure 8. Schematic plan of column spacing.

As depicted in Figure 9, the impact of column spacing on the heave and sway motion responses is minimal due to the unchanged structural weight of the platform, exhibiting a slight decreasing trend with increasing spacing only in the high-frequency range. Meanwhile, the natural frequency of pitch motion increases with the enlargement of column spacing. The primary factor influencing the motion amplitude seems to be the variation in the waterplane moment of inertia caused by changes in column spacing, which subsequently alters the static stability of the platform. Table 3 presents the calculations of platform static stability parameters under different column spacings. By integrating the information from the table and the figure, it can be concluded that while reducing column spacing effectively controls the pitch motion and enhances the natural period of the platform, a smaller spacing also leads to a lower metacenter height and reduced righting moment when the floating body continuously generates tilting moments under wind and wave loads. Therefore, to ensure the floating body's ability to resist tilting moments and maintain a favorable metacenter height, the column spacing should not be excessively small, and a balanced consideration of stability and motion performance is crucial.

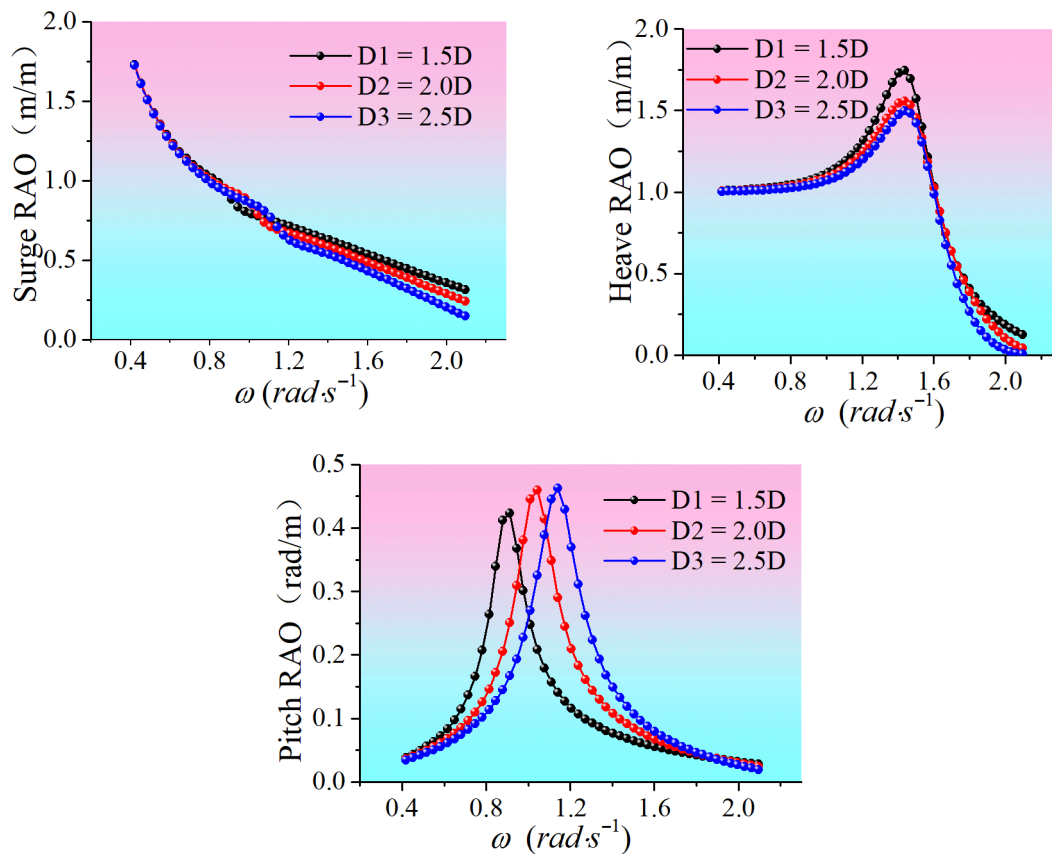


Figure 9. Motion response of single FPV platform under different column spacings.

Table 3. Static stability parameters of FPV platform under different column spacings.

Spacing	Metacentric Height $\overline{GM}$	Restoring Moment M_R
D1	0.907 m	10,493 N·m/°
D2	1.312 m	15,179 N·m/°
D3	1.833 m	21,203 N·m/°

3.2. The Influence of Heave Plates on the Motion Response

As a passive hydrodynamic damper, the heave plate offers added mass and viscous damping in the heave direction of the platform. This reduces the response amplitude of heave motion while simultaneously increasing the natural period. This section delves into the impact of heave plates on the motion response of OFPV platforms. While maintaining the structural parameters of the original model, a prototype heave plate with an outer diameter of 4 m and a spacing of 2 m was selected, as shown in Figure 10.

Figure 11 compares the motion response of the platform without heave plates and with different layers of heave plates under 90° incident waves. The addition of heave plate at the base of the column buoy significantly reduces the RAO, resulting in a shift in the platform's natural frequency towards lower values. As the number of heave plate layers increases, the heave response and the nature frequency of the platform decreases. However, the rate of decrease diminishes, indicating that the efficiency of using heave plates diminishes with an increasing number of layers.

Due to the coupled motion among various degrees of freedom, the heave motion has an impact on the pitch motion. The heave plates exhibit a certain frequency-reducing effect on pitch motion, albeit less significant than on heave motion. This effect becomes more apparent as the number of heave plate layers increases. Conversely, the heave plates have

no significant impact on the surge motion response of the platform, as evidenced by the minimal changes in the RAO curves under various conditions.

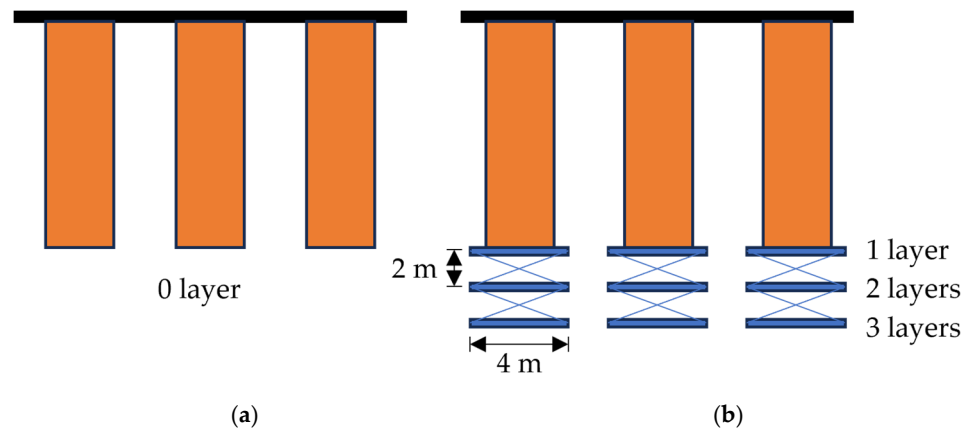


Figure 10. Front view of model heave plate layout: (a) 0 layer schematic diagram; (b) 1/2/3 layers schematic diagram.

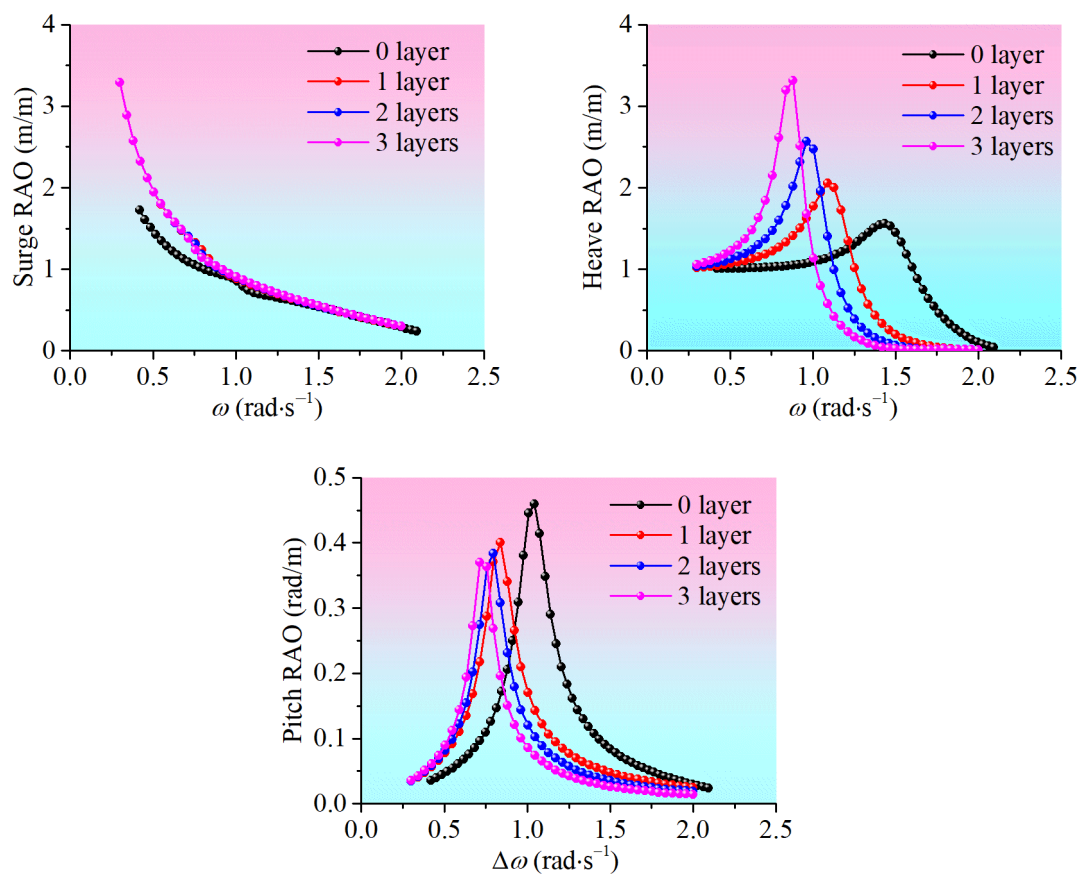


Figure 11. Influence of heave plate structure on motion response of FPV platform.

4. Analysis of Mooring Hinged Multi-Module Model in Regular Waves

4.1. Design of Mooring Hinged Multi-Module Model

In this section, the fundamental structural parameters of the multi-module integrated model are established based on the initial model described in the previous section, augmented by the addition of three heave plates. The model considers the combination of four single-module platforms, as illustrated in Figure 12 (left). At the same time, the sketch of motion response is also in Figure 12. Here, the platforms of S1–S4 are reconfigured into

a new large triangular platform by connecting them pairwise. The connecting structure employs a linking mechanism as depicted in Figure 12 (right). Table 4 presents the positions of various hinge points and the coordinates of module centroids in the global coordinate system. Here, G1 represents the centroid of structure S1, J1 denotes hinge structure 1, and so on, following this pattern.

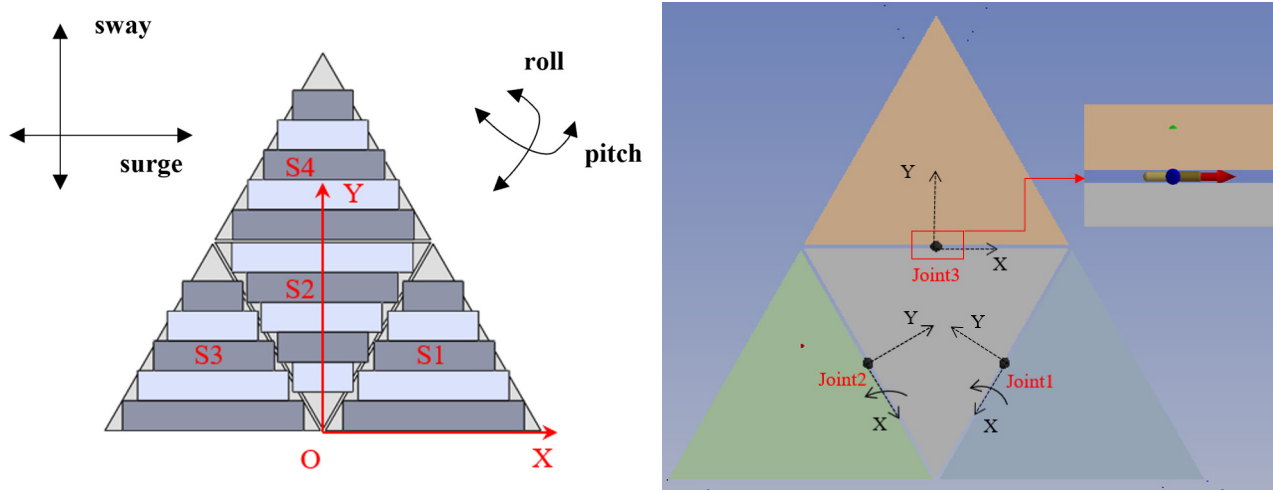


Figure 12. Layout of overall model (left) and hinge structure (right).

Table 4. Position coordinates of center of gravity of each hinge and structure.

Item	Coordinate
G1	(7.67, 4.43, −2.55)
G2	(0, 8.86, −2.55)
G3	(−7.67, 4.43, −2.55)
G4	(0, 17.72, −2.55)
J1	(3.85, 6.67, 3.6)
J2	(−3.85, 6.67, 3.6)
J3	(0, 13.29, 3.6)

A single catenary mooring line, with a length of 160 m is selected as the anchor chain. The fairleads for nine mooring lines are arranged in three groups in a symmetrical pattern at the height of the center of gravity on the side of the floating structure, as illustrated in Figure 13. Each group of fairleads secures three anchor chains distributed at a 30° angle. This decentralized configuration allows for a more balanced resistance against external wind and wave loads, providing restoration forces to the floating platform from various directions. The parameters of the mooring material properties are detailed in Table 5.

Table 5. Mooring line properties.

Mooring Line Type	76 mm Steel Core Steel Cable
Equivalent diameter	0.076 m
Equivalent section area	0.003 m ²
Wet weight per meter	20 kg/m
Axial Stiffness	2.33×10^8 N/m
Drag coefficient	1.2
Axial drag coefficient	0.4
Added mass coefficient	1
Breaking force	3.66×10^6 N
Pretension force	5.45×10^4 N

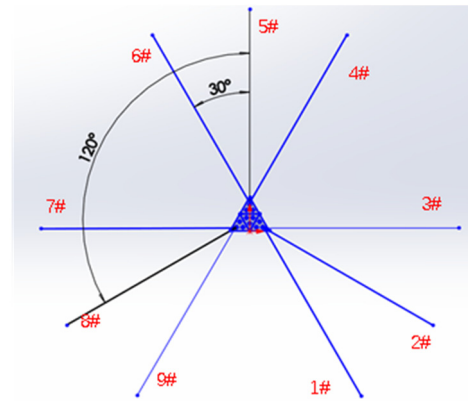


Figure 13. Arrangement of mooring system.

4.2. Motion Response Analysis of Hinged Multi-Module OFPV

The time-history curves of the displacement of the centroid positions of each module platform under the action of unit wave height waves incident at -90° with periods of 4 s and 9 s are depicted in Figures 14 and 15, respectively. The results indicate that when the incident wave period is short, the sway motion of the platform's various structures along the wave propagation is greater than the surge motion perpendicular to the wave propagation. Moreover, the motion of the lateral platforms (S1, S3) is more significant than that of the central platforms (S2, S4). However, with regard to platform S4, its transverse motion is exceptionally high due to the wave incidence being perpendicular to the hinge structure, thus resulting in less constrained movement. In contrast, the sway and roll motions of the remaining structures (S1, S2, S3) in short-period waves are nearly identical.

In the case of longer incident wave periods action, the motion amplitudes of the lateral structures (S1 and S3) continue to exhibit a trend of being greater than those of the central structures (S2 and S4). Compared to the results of shorter wave periods, the platform's motions along and perpendicular to the wave propagation direction become more comparable. The hydrodynamic performance of multi-module hinged OFPV platforms exhibits significant differences from large-scale single-module configurations and cannot be calculated using equivalent single-module parameters. Analysis reveals distinct motion responses across all six degrees of freedom. Under combined axial and shear forces at inter-module connections, the integrated system demonstrates pronounced motion characteristics perpendicular to wave propagation direction.

The displacement time history curves of various platform structures under an incident wave angle of -90° were processed, and the RAO of each platform in different degrees of freedom in the local coordinate system is presented in Figure 16. The motion response of each module was compared and analyzed with the calculation results of a single module. Statistical analysis reveals that when the incident wave period exceeds 7 s, the motion amplitudes in the surge and pitch directions of the lateral structures are significantly higher than those of the central structures. Conversely, when the wave period is 7 s or less, the longitudinal displacements of all structures are relatively small. Overall, the motion responses in various directions predominantly demonstrate a pattern where the lateral structures (S1 and S3) exhibit larger motion responses, while the central structures (S2 and S4) exhibit smaller motion responses. The motion amplitudes in all degrees of freedom of the platform tend to increase with an increase in the wave period. According to the comparisons in Figure 16, for surge and pitch motions, the motion amplitudes of the lateral structures (S1 and S3) in the multi-module system are greater than those of the single module. This is because the multi-module system is influenced by the hinge forces between

every two adjacent modules. In contrast, for sway, heave, and roll motions, the connections among the modules restrict their motions. As a result, the motion response amplitudes of the multi-module system are smaller than those of the single module, especially for heave and roll motions.

Detailed comparison with single-module results shows substantial reductions in key motion parameters: sway motion decreased by 15.4%, heave motion showed an average reduction of 51.8% and reached 68% in specific wave periods, while roll motion demonstrated an average decrease of 39.6% with peak reduction of 65.6% in certain cycles. These findings indicate significant inter-module interaction effects that must be considered in multi-body system design. A pronounced reduction in both the overall dynamic response and the relative motion between adjacent modules effectively precludes excessive shear forces at their connections, thereby safeguarding structural integrity and long-term sustainability. Consequently, rigorous mechanical analysis of these joints becomes pivotal to the structure's endurance over its design life.

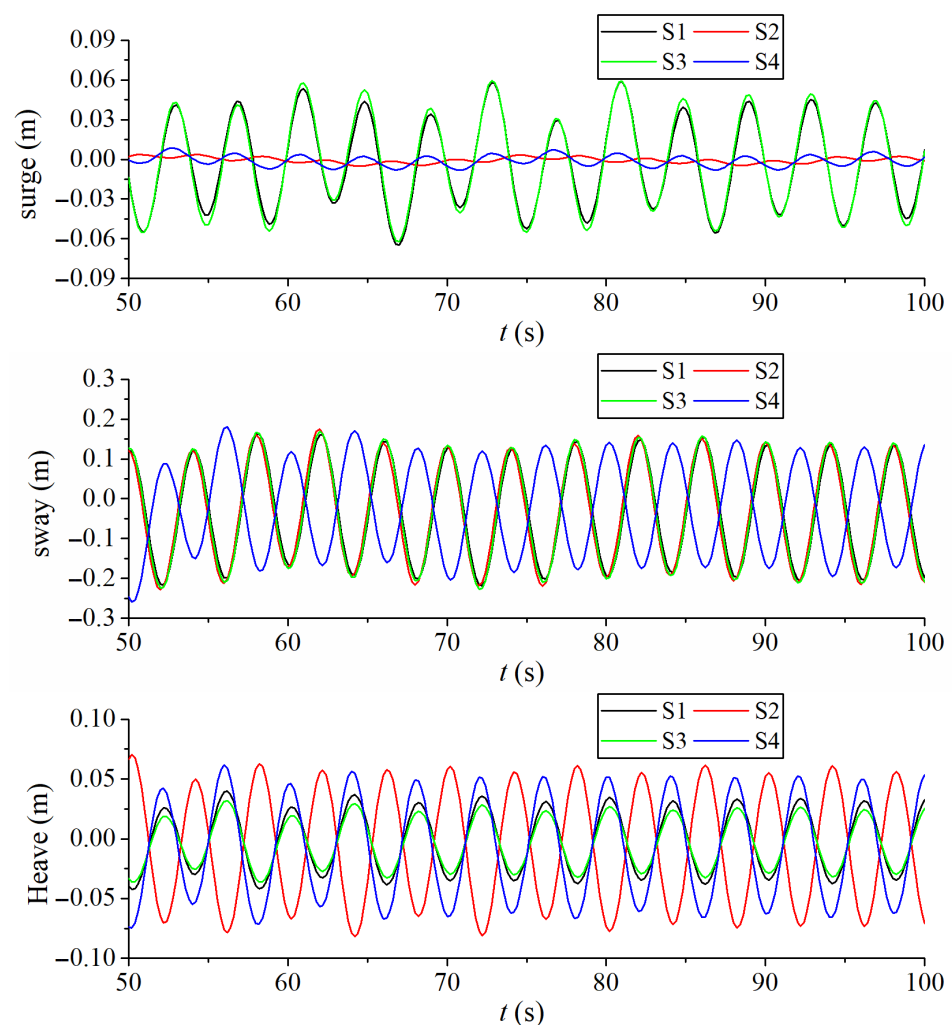


Figure 14. Cont.

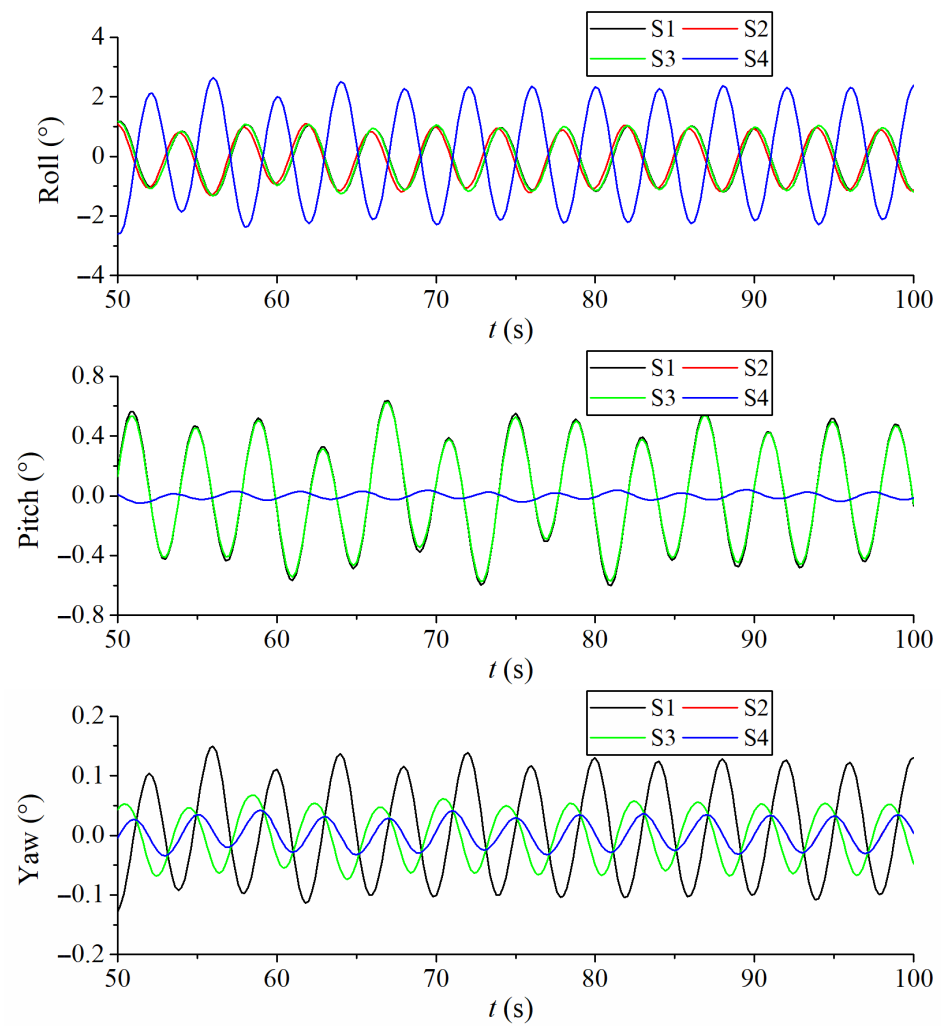


Figure 14. Displacement time histories of structure 1–4 ($T = 4$ s, $\beta = -90^\circ$).

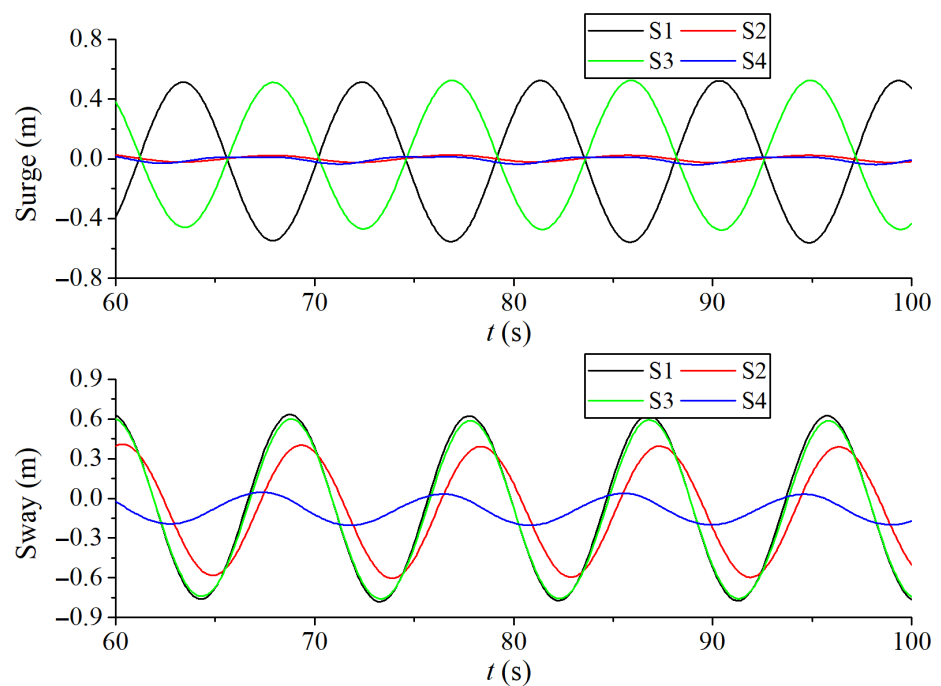


Figure 15. Cont.

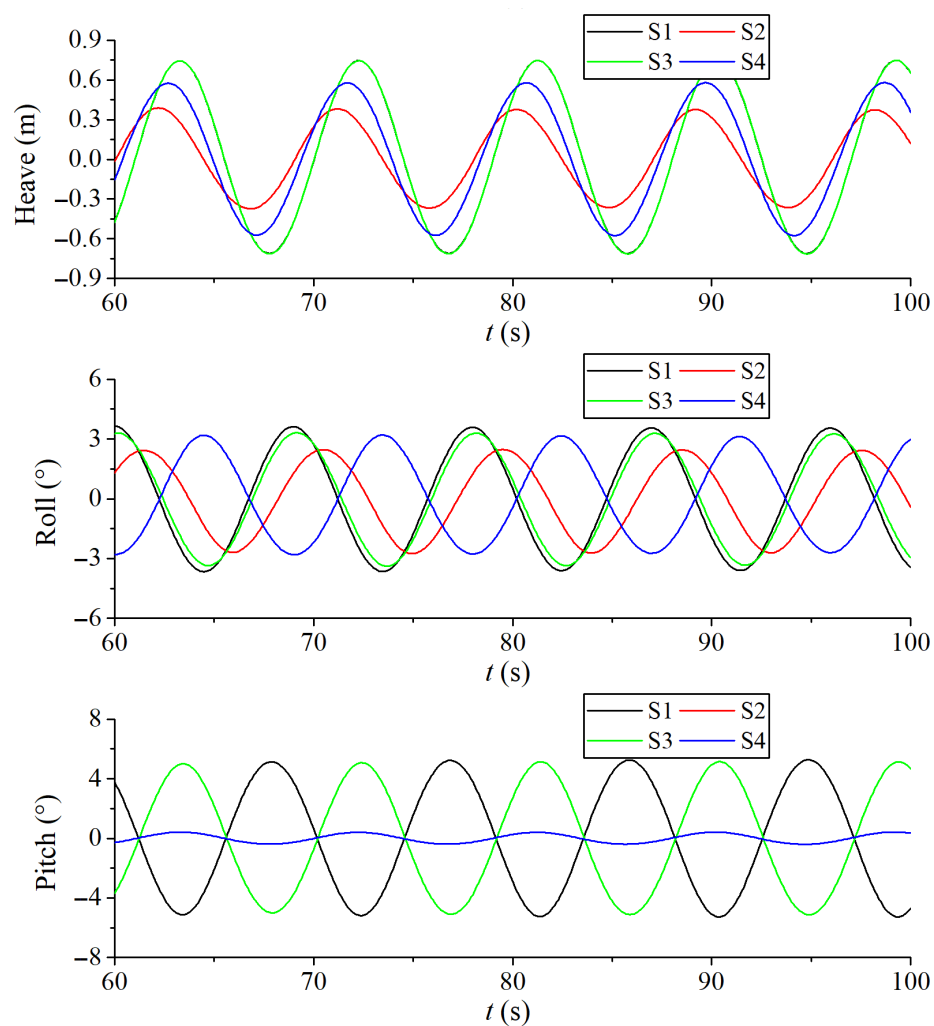


Figure 15. Displacement time histories of structure 1–4 ($T = 9$ s, $\beta = -90^\circ$).

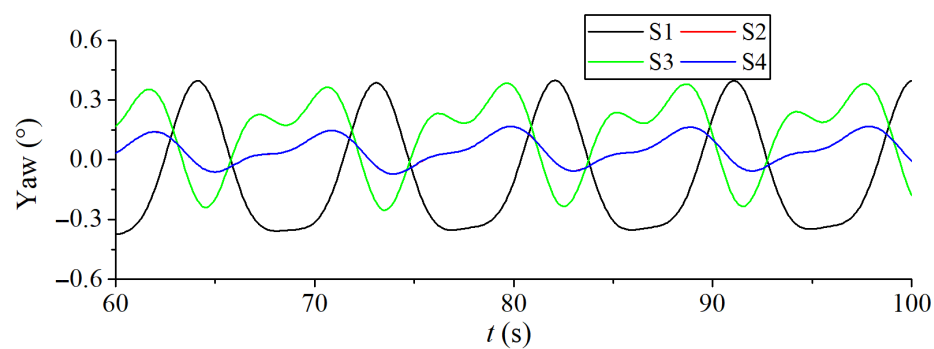


Figure 15. Displacement time histories of structure 1–4 ($T = 9$ s, $\beta = -90^\circ$).

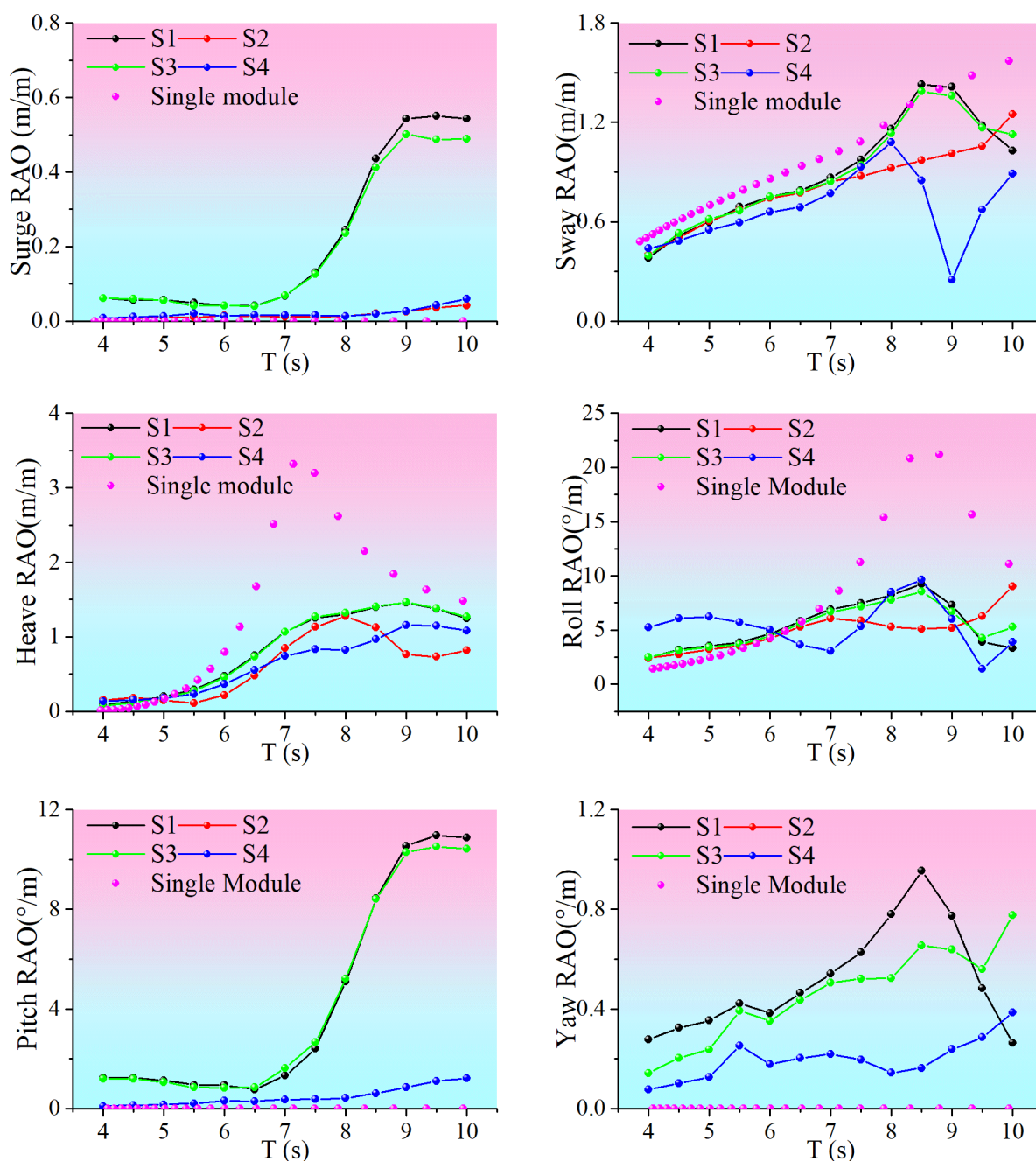


Figure 16. Comparisons of RAOs of structure1–4 in -90° incident wave.

4.3. Force Analysis of Hinged Multi-Module OFPV

Utilizing a local coordinate system based on the hinged structure, six degrees of freedom force directions are defined, as illustrated in Figure 17. In the figure, F_x represents the horizontal shear force, F_y denotes the horizontal axial force, and F_z signifies the vertical shear force.

Figure 17 presents the time history curves of the hinged forces acting on Joint 1–3 when a regular wave with a unit wave height and a wave period of 4 s at a -90° incident angle. Due to the symmetry of wave incidence along the overall platform's axis, the force time histories in all directions for Joint 1 and Joint 2 are nearly identical.

The time-history curves of the forces acting on various hinge locations were processed, and the amplitude values of forces in various directions under wave periods ranging from 4 s to 10 s were summarized, resulting in Figures 18 and 19. A statistical analysis revealed

that the lateral shear forces exerted on the structural connections (J1 and J2) on both sides were significant, while those at the central structural connection (J3) were minimal. The axial forces primarily originate from the prestressing of the mooring system, and when considering dynamic effects alone, the axial forces are comparable to the lateral shear forces, albeit greater at the central connection (J3) compared to the lateral ones (J1 and J2). Vertical shear forces exhibit a similar trend to axial forces, but their magnitudes are relatively smaller by an order of magnitude.

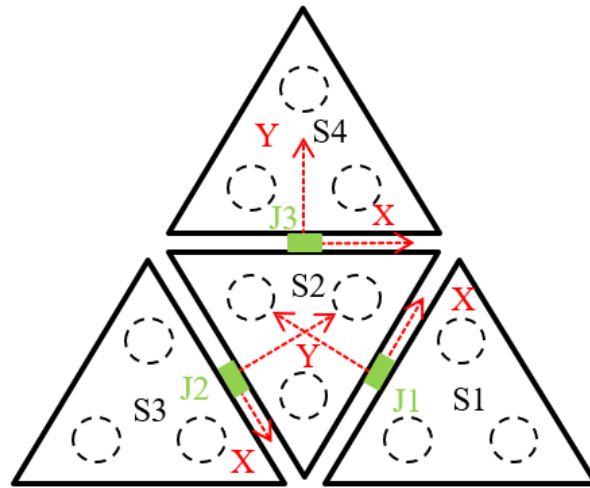


Figure 17. The local coordinates of the articulated structure.

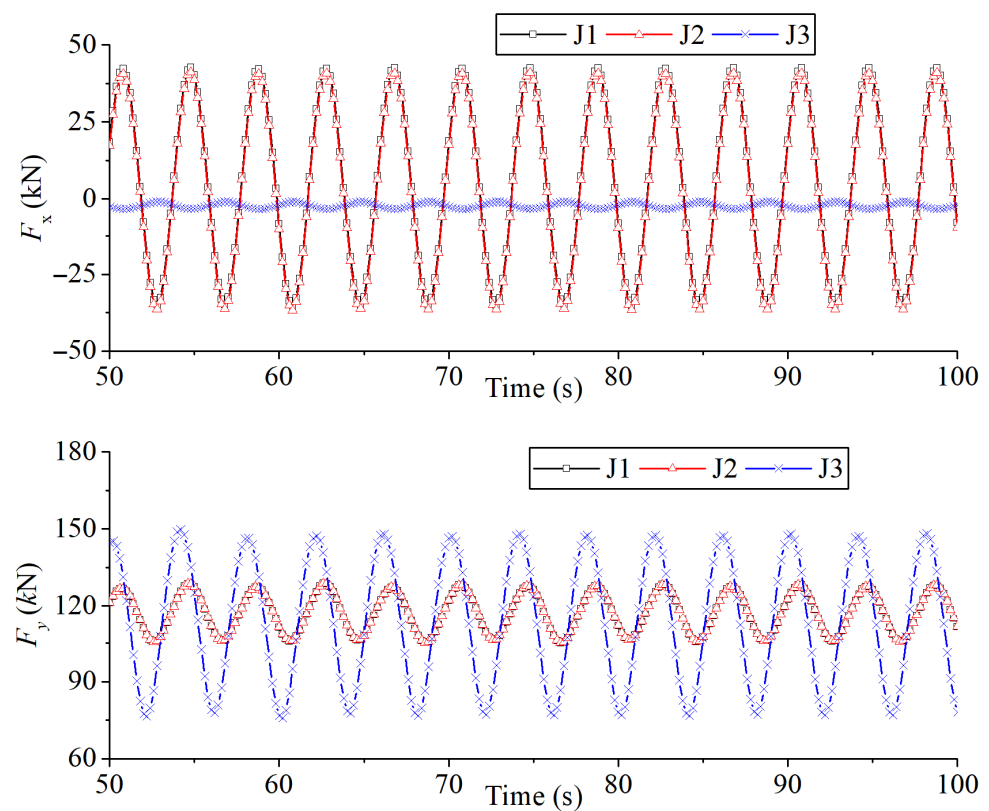


Figure 18. Cont.

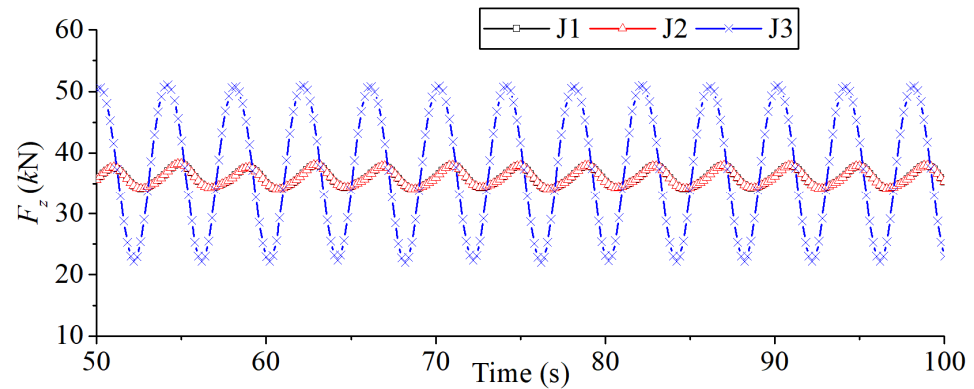


Figure 18. Force time histories of Joint1–3 ($T = 4$ s, $\beta = -90^\circ$).

Overall, with the exception of axial force F_x , which peaks at $T = 5.5$ s (when the geometric size of a single module structure is approximately equal to $1/4$ of the wavelength), and vertical shear force F_z , which peaks at $T = 9$ s (when the overall platform geometric size is approximately $1/4$ of the wavelength), the forces in other directions generally decrease gradually as the wave period increases. This is due to the closer alignment of wave phases among the various components of the platform as the wave period elongates, resulting in a significant reduction in mutual forces.

Force analysis at the connection can provide support for structural strength and fatigue analysis and provide important data basis for the sustainability of the OFPV platform.

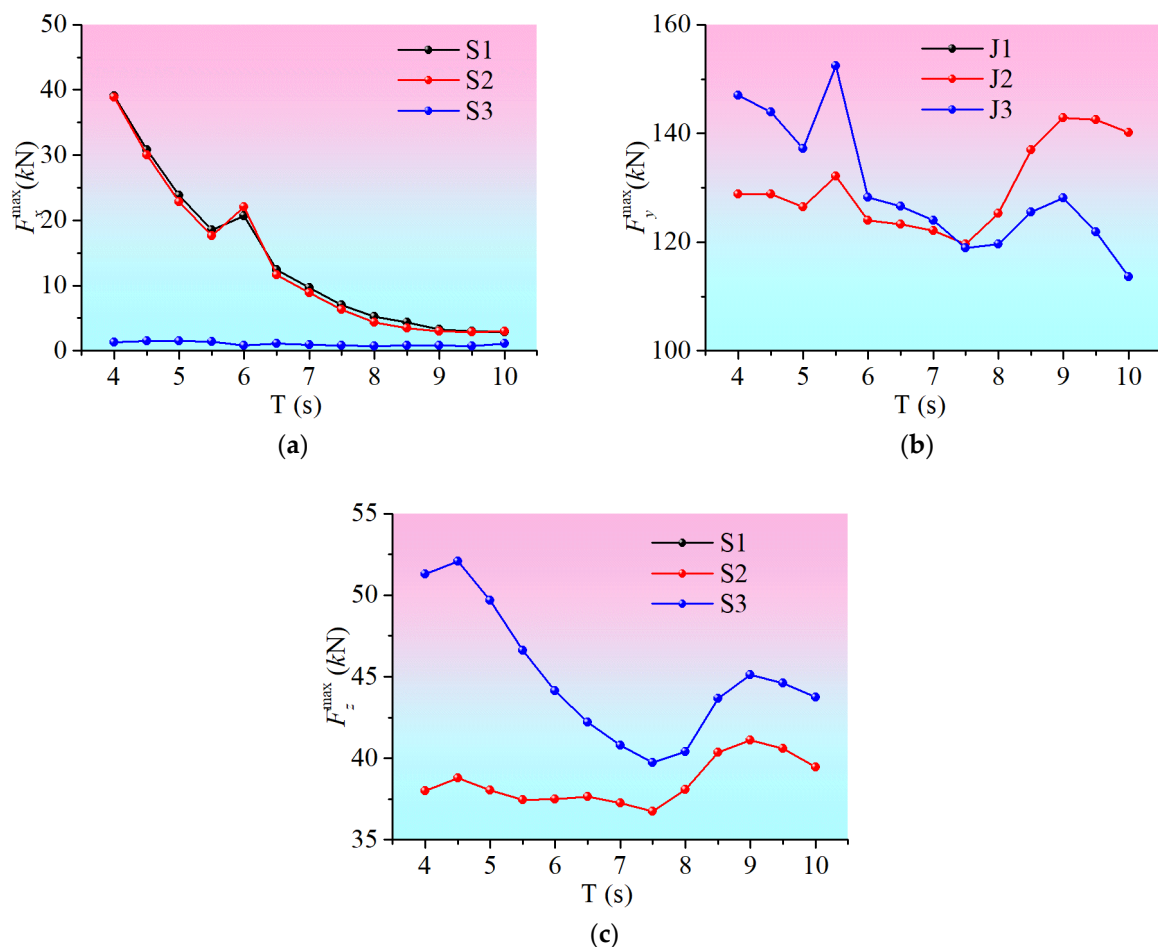


Figure 19. Force amplitude of joint1–3 in -90° incident wave: (a) horizontal shear force; (b) horizontal axial force; (c) vertical shear force.

5. Conclusions

This paper explores one of the future development directions for the effective utilization of sustainable solar energy, namely the hydrodynamic issues of OFPV. ANSYS-AQWA (Version 19.0) is used for the interaction between waves and a mooring multi-module OFPV platform, considering the articulated connections between individual FPV modules. The differences in hydrodynamic characteristics of the OFPV platform between multi module and single module are compared and analyzed in detail. The key conclusions are summarized as follows:

- (1) The spacing between columns in a single FPV platform has minimal impact on surge and heave motions. The heave plate exerts a considerable influence on the heave and pitch motions of a single platform, notably reducing them in specific motion ranges. Additionally, as the number of heave plates increases, the maximum value of the RAO shifts towards lower frequencies.
- (2) For an integrated system comprising four platforms, the motion responses of all modules are much different from single modules. The RAOs on both sides tend to be greater than those in the middle, primarily due to the reduced hinge constraints on the peripheral structures. Except for heave and roll motions, where each structure exhibits a peak near its natural period but much less than the single-module platform. A reduction in the relative motion between adjacent modules effectively ensures structural integrity and long-term sustainability.
- (3) Within the overall OFPV platform in regular waves, the lateral connections experience significant horizontal shear forces and moments of rotation, while the intermediate connections are subjected to lesser forces. Except for peak values in axial and vertical shear forces at specific periods, the forces in all directions decrease as the wave period increases, attributable to the convergence of wave phases among platform structures under long-period waves, leading to a reduction in mutual forces.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Abbreviations

PV	Photovoltaic
FPV	Floating Photovoltaic
IFPV	Inland floating photovoltaic
OFPV	Offshore floating photovoltaic
3D	Three Dimensional
RAO	Response Amplitude Operator
CFD	Computational Fluid Dynamics
WEC	Wave Energy Converter
FEM	Finite Element Method

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