Dynamics Simulation Analysis of Multi-body Coupled System Consisting of Multi-float Wave Energy Converter and Semi-submersible Floating Wind Turbine Platform

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Abstract. Compared with the distribution of onshore and near-shore wind resources, the deep and remote seas exhibit significantly higher wind speeds and richer wind resources, rendering the development of floating wind power in these regions immensely promising. The semi-submersible platform serves as a vital component in the structure of deep-sea floating wind power. However, the motion response generated by traditional semi-submersible platforms under irregular wave loads can lead to an increase in structural fatigue loads on components such as blades and towers, ultimately affecting the wind turbine's power generation efficiency and system durability. In order to tackle the previously mentioned concerns and challenges, this paper develops a novel multi-body coupled system consisting of moorings, floaters, and a semi-submersible floating platform. This design is based on the traditional DTU 10MW semi-submersible floating platform, with the integration of an array of heave cylinder floater-type wave energy converters. Next, the AQWA software is utilized to model the multi-body coupled system. Based on the hydrodynamic wave theory and the coupled theory of the mooring system, numerical simulation methods are employed to analyze the six degrees of freedom directional motion responses of the multi-body coupled system under realistic irregular wave loads. The numerical simulation result indicates that the array arrangement of heave cylinder buoy-type wave energy converters can effectively reduce the sway, roll, heave, pitch, and yaw displacements of the semi-submersible floating platform. Notably, the suppression rates for sway, roll, and pitch displacements all exceed 50%.

Keywords: Semi-submersible platform, WEC, Multi-body coupled system, Dynamics simulation analysis.

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1 Introduction

Compared to fixed offshore wind turbines in nearshore areas, deep-sea floating wind turbines can capture more stable and abundant wind resources. However, traditional semi-submersible floating platforms (SSFP) float on the sea surface, and their motion performance is susceptible to the randomness of wave and current loads, which complicates the safety issues of floating wind turbine platforms. Thus, emphasizing research into the dynamic response of semi-submersible platforms subjected to random wave and current forces, while comprehensively taking into account the safety implications of wind, wave, and current unpredictability on semi-submersible wind turbine platforms, is of paramount importance. Based on this, designing wind turbine platforms with strong adaptability and durability under complex sea conditions is of great significance for ensuring their safe and economic operation.

In the structural design of semi-submersible platforms, Yu, M. et al. proposed three conceptual designs for floating foundations, and carried out a comprehensive study on triangular platforms, circular platforms and quadrilateral platforms, and found that the triangular platforms have better stability.[1] Roddier et al. proposed a three-float WindFloat eccentric platform, and proved that it has good hydrodynamic properties and meets the strength requirements of the design criteria through model tests.[2] Cheng, Y. et al. based on the Braceless concept developed by the Norwegian University of Science and Technology, each side column is connected to the centre column at the bottom by floats, which increases the effect of the static tilt angle on the turbine bending moment at the rated rotational speed, and at the same time improves the strength of the floats. [3] Sismani, G. et al. also used the Braceless semi-submersible platform to carry out a study on the impact of wave nonlinear effects on different water depths and mooring systems, and finally proposed a feasible design concept for shallow water semi-submersible turbine moorings. [4]

In terms of the design and dynamics analysis of multi-body coupling system (MCS) of Wave Energy Converter (WEC) and SSFP, there are relatively mature WECs in the world, such as oscillating water column, push-pendulum, point-absorption, and oscillating float, etc.[5] Rony, J.S. et al. established two multi-body WECs platform systems and investigated the effect of different wedge angles between the floating body and the platform on the hydrodynamic performance of the multi-body WECs system, and the results showed that the different wedge angles would have a greater effect on the platform motion.[6] Chandrasekaran, S. et al. investigated the hydrodynamic interactions between floating platforms and multiple WECs in the frequency domain based on the potential flow theory, and simulated the dynamically coupled response of the floating platforms and the WECs, and the analysis results showed that the WECs dynamic response had a significant difference.[7]

Based on the aforementioned research, this paper aims to reduce both the structural design cost and the motion response amplitude of a semi-submersible floating platform under irregular wave loads. To achieve this, a multi-body coupling system consisting of a multi-buoy wave energy converter, catenary mooring lines, and a semi-submersible floating platform is designed. The AQWA software is utilized to model and conduct numerical analysis of the motion responses of this multi-body coupling system. The results demonstrate that the system effectively suppresses the displacement amplitudes of sway, roll, pitch, and yaw under real irregular wave loads, thereby enhancing the overall stability of the system.

2 Basic Theory

2.1 Potential Flow Theory (PFT)

In marine engineering structures, the wave load calculation method is usually determined based on the scale of the structure. Large-scale structures (D/λ>0.2, D is the characteristic scale of the member cross-section and λ is the wavelength of the incident wave) cause significant bypassing and reflections of the incident wave, so the potential flow theory based on the theory of bypassing and radiation needs to be used to calculate the wave force and hydrodynamic force of large-scale structures.[8] When an incident wave acts on a large-scale structure, the wave velocity potential is decomposed into an incident wave velocity potential Φ_I, a radiated wave velocity potential Φ_R, and an orbiting wave velocity potential Φ_D. Where Φ_I is the wave velocity potential when there is no interference from any object on the free surface, Φ_R is the velocity potential generated by the forced vibration of the floating body structure, and Φ_D is the velocity potential of the wave that has a disturbing effect on the floating body structure. PFT takes into account the influence of free surface effects and scattering effects of the incident wave, and the wave mainly produces additional mass effects and wrap-around effects on the structure. The velocity potential Φ after wave incidence can be calculated by Eq. (1), where the wave incidence potential Φ_I can be calculated from linear wave theory by Eq. (2). Φ_R and Φ_D are obtained by solving the Laplace equation according to the initial and boundary conditions, and are often solved by the Green's function method. The Green's function method, also known as the boundary element method, determines the surface source strength by finding a function G such that the velocity potential Φ in the watershed can be expressed as an integral of the function G over the physical boundary surface and discretising the boundary into a finite number of grids, then distributing the source points within the grids and distributing the control points that satisfy the boundary conditions in each grid. [9]

$$\Phi = \Phi_I + \Phi_R + \Phi_D = Re\{[\Phi_I(x,y,z) + \Phi_R(x,y,z) + \Phi_D(x,y,z)]e^{i\omega t}\} \tag{1}$$

$$\Phi_I = Re\left[\frac{-igA}{\omega}\frac{\cosh k\,(z+d)}{\cosh k\,d}e^{i(kx-\omega t+g)}\right] \tag{2}$$

2.2 Equations of Motion for SSFP

The floating platform can be regarded as a rigid body under wave action, simultaneously subjected to fluid dynamic moments and static moments. The motion equation of the floating platform in the time domain is expressed as Eq. (3). Where $X(t)$ is the generalised displacement of the floating platform in the time domain, $\dot{X}(t)$

and $\ddot{X}(t)$ represent the generalised velocity and acceleration, respectively; M is the mass matrix; A and C are the additional mass matrix and damping coefficient matrix, which are induced by wave radiation; and K stands for the hydrostatic restoring force matrix. $F^{waves}(\mathrm{t})$ is the incident wave excitation force; $F^{\mathrm{mooring}}(t)$ represents the mooring tension.

$$(M + A)X(t) + CX(t) + KX(t) = F^{waves}(t) + F^{mooring}(t) \tag{3}$$

The motion response of the rigid platform consists of six degrees of freedom, as shown in Fig. 1.

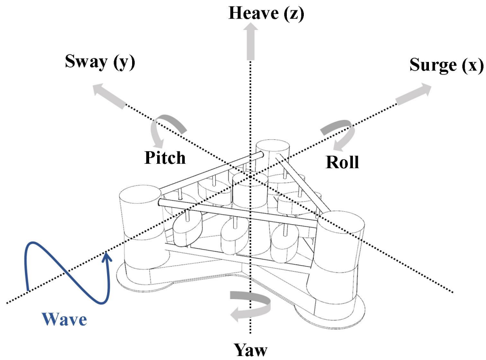

Fig. 1. Schematic illustration of the six-degree-of-freedom motion of a SSFP on the sea.

2.3 Computational Theory for Mooring Systems

Offshore floating foundations, deployed for prolonged periods in specific maritime environments, rely on mooring systems to constrain their movement amidst complex wind and wave conditions, thereby ensuring the smooth operation of wind turbine systems. This paper initially delves into the suspension chain mooring system, renowned for its remarkable flexibility and the general assumption that the mooring cables do not endure shear forces or bending moments. When subjected to external loads, the floating platform attains a static equilibrium position, prompting the static analysis of the mooring system to focus on the equilibrium state of the suspension chain line and the magnitude of tensions therein. This analysis aims to quantify the reactive force provided by the mooring system. Traditionally, the concentrated mass method is employed to formulate equations describing the suspension chain line, while quasi-static theory is utilized to determine the shape and tension of the chain, facilitating static analysis. The suspension chain line can be categorized into two types based on the absence or presence of a slack length, each with distinct governing equations. The force diagram for a single suspension chain linem, depicted in Fig.2., illustrates the forces at play.

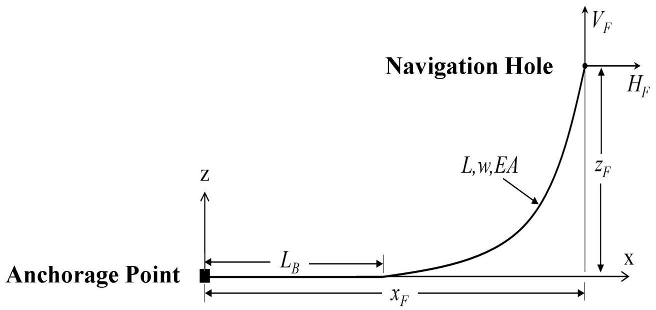

Fig. 2. Schematic diagram of the model of the mooring forces on a single suspension line

When an overhanging chain mooring is slack and a section of cable is slack on the seabed, the position versus tension equation is shown in Eq. (4) and Eq. (5).

$$x_F(H_F, V_F) = L_B + \frac{H_F}{w} ln\left[\frac{V_F}{H_F} + \sqrt{1 + \left(\frac{V_F}{H_F}\right)^2}\right] + \frac{H_F L}{EA} + \frac{C_B w}{EA} \tag{4}$$

$$z_F(H_F, V_F) = \frac{H_F}{w}\left[\sqrt{1 + \left(\frac{V_F}{H_F}\right)^2} - \sqrt{1 + \left(\frac{V_F - wL}{H_F}\right)^2}\right] + \frac{1}{EA}\left(V_F L - \frac{wL^2}{2}\right) \tag{5}$$

Where x_F and z_F are the horizontal and vertical coordinates of the cable guide hole relative to the position of the anchor point, H_F and V_F are the horizontal and vertical components of the effective tension in the suspension chain line on the cable guide hole, w denotes the mass per unit length of the suspension chain line, L is the total length of the unstretched suspension chain line, EA denotes the tensile and compressive stiffness of the suspension chain line, C_B is the static friction coefficient of the suspension chain line and the seabed, and $L_B = L - \frac{V_F}{w}$ is the relaxation length of the suspension chain line on the seabed, and the effective tension force at the cable guide hole of the suspension chain line can be obtained by solving the above two equations iteratively using Newton-Raphson and other methods.

3 Numerical Simulation

3.1 DTU 10MW Semi-submersible Floating Platform Modle

The detailed dimensions of the DTU 10MW semi-submersible floating platform are shown in Fig. 3. The distance between the centre column and the outer column is 37 m. All the columns have upper cylinders and lower cones. The horizontal pontoons connecting the columns are 16 m wide and 7 m high, and the vertical sloshing plate under the horizontal pontoons is 17 m wide, with an additional 0.5 m on each side and a thickness of 0.5 m. Below the centre column, the radius of curvature of the sloshing plate is 10 m. The diameter of the centre column at the base of the tower is 12.05 m. The diameter of the top of the outer columns is 13.4 m, with the bottom of the outer columns being conical in shape. The length of the conical part is 11 m, and the diameter at the contact position with the horizontal float is 15.8 m. The diameter of the circular part of the swinging plate under the outer column is 22.8 m. The total mass of the platform is 21709 t. The main structural parameters are shown in Table 1.

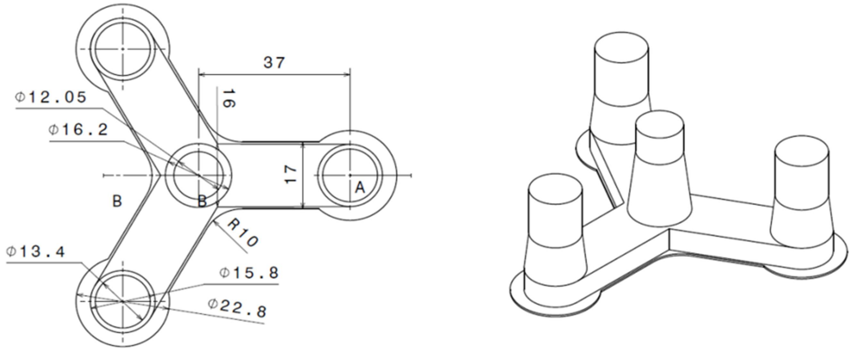

Fig. 3. Main dimensions of DTU 10MW semi-submersible floating platform (unit:m).

Table 1. Summary of the main structural dimensions of the DTU 10MW semi-submersible floating platform.

Parameters	Value	Unit
Mass incl. ballast	21709	t
CM below SWL	15.225	m
Freeboard	11	m
Draft	22	m
Displaced volume	23509	m^3
Pitch inertia	9.430×10^9	kgm^2
Roll inertia	9.430×10^9	kgm^2
Yaw inertia	1.630×10^{10}	kgm^2

3.2 WECs Model

In the selection of wave energy conversion devices, the heave cylindrical buoy-type wave energy generator is chosen due to its numerous advantages, including a simple structure, flexible layout, relatively high power generation efficiency, and wide applicability. Therefore, nine heave cylindrical buoys are integrated with a semi-submersible floating platform. The primary parameters of the heave cylindrical buoys are listed in Table 2. The nine heave cylindrical buoys are evenly distributed in an array formation among the three columns of the semi-submersible platform, as depicted in Fig. 4.

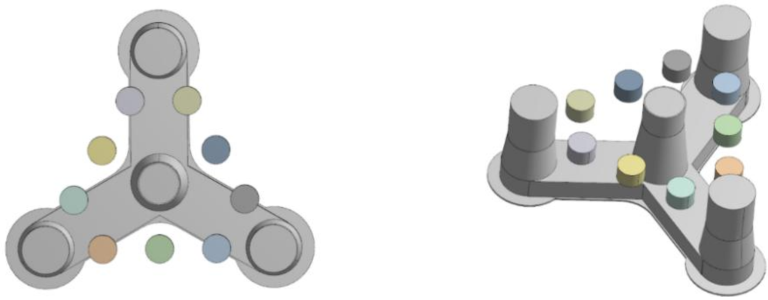

Fig. 4. Top view (left) and general structure schematic (right) of the multi-float WEC coupled with SSFP system

Table 2. Summary of main structural dimensions of multi-float WECs.

Parameters	Value	Unit
Radius	4	m
Height	5	m
Draft	3	m
CM below SWL	1	m
Displaced volume	154.57	m^3
Pitch inertia	9.790×10^5	kgm^2
Roll inertia	9.430×10^5	kgm^2
Yaw inertia	1.240×10^6	kgm^2

3.3 Mooring Model

The specific parameters are summarised in Tab. 3. The overall structure of the multi-float wave energy converter-mooring system-semi-submersible floating platform coupling system is shown in Fig. 5.

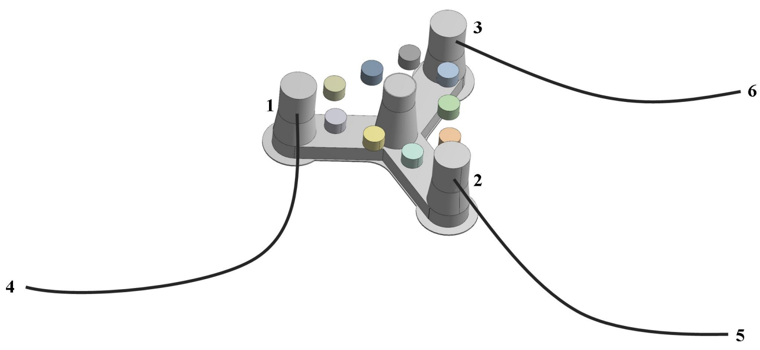

Fig. 5 Schematic diagram of the overall structure of the multi-float WEC - mooring - semi-submersible floating platform coupling system.

Among them, the coordinates of the cable guide holes 1, 2, and 3 are (43.7, 0, 2.75), (-21.85, 37.845, 2.75), and (-21.85, -37.845, 2.75), respectively, and the coordinates of the corresponding anchor points 4, 5, and 6 are (844, 0, -200), (-422, 730.925, -200), and (-422, -730.925, -200).

Table 3. Summary of main structural dimensions of mooring system.

Parameters	Value	Unit
Weight	23	Kg/m
Equivalent cross-sectional area	0.003	m^2
Axial stiffness	2.330×10^8	N/m
Breaking force	3.660×10^6	N
Drag diameter	0.076	mm
Additional mass coefficient	1.0	\
Drag coefficient	1.2	\
Axial drag coefficient	0.4	\

3.4 Calculated Parameters

In order to ensure the long-term operation of the wind turbine and reduce the construction cost, this paper takes the traditional DTU 10MW semi-submersible wind turbine platform as the research object, carries out the stability research of the offshore platform under the extreme sea state, and explores the improvement of the stability of the platform system through the addition of the wave energy device. Considering the extreme marine environment in the actual project, the sea state of one year is selected for simulation. AQWA is used to generate waves using JONSWAP spectrum, with a peak lift factor of 3.3, a meaningful wave height of 6.5 m, a peak period of 0.5233 rad/s, and a wave direction of 0°.

4 Result Analysis

A comparison of the dynamic behavior of the multi-float WECs coupled the SSFP multibody system (red curve) with the motion response time-course curve of the dynamic behavior of the SSFP without WECs (only mooring system coupled to the SSFP, black curve) is shown from Fig. 6. to Fig. 11.

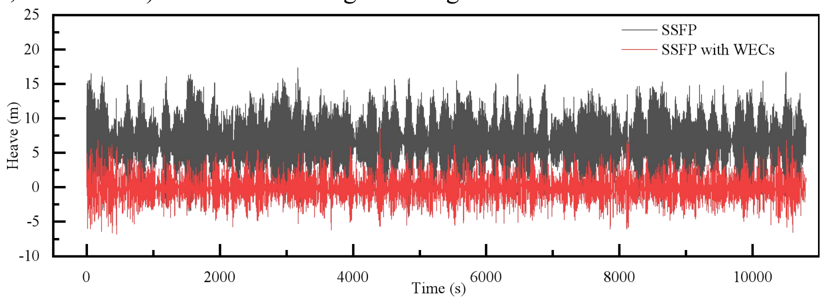

Fig. 6. Comparison of the heave response of SSFP before and after adding WECs.

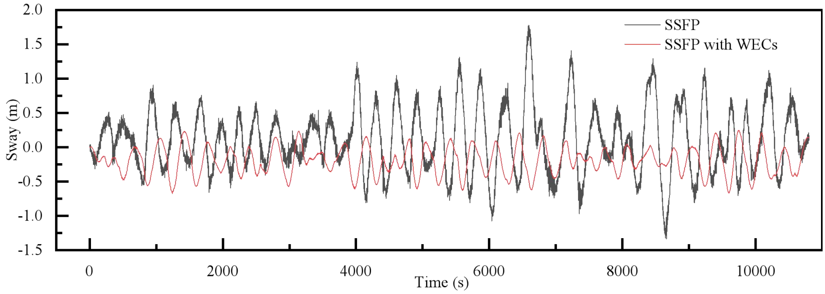

Fig. 7. Comparison of the sway response of SSFP before and after adding WECs.

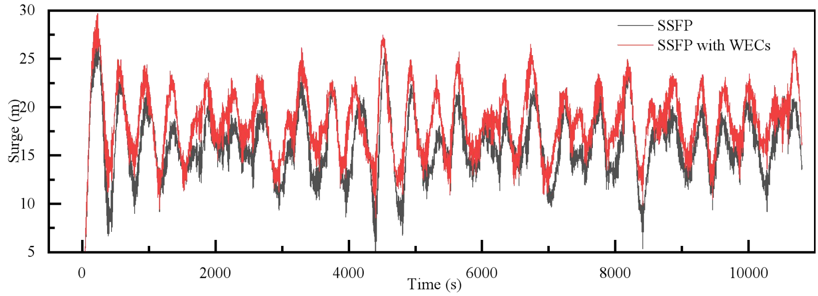

Fig. 8. Comparison of the surge response of SSFP before and after adding WECs.

Fig. 6 - Fig. 8 present the time-history curves of the system's heave, sway, and surge motion responses before and after the introduction of the multi-buoy WECs. As observed in Fig. 6, there is no important alteration in the magnitude of the system's heave motion. However, due to the presence of the multi-buoy WEC, the overall mass of the system increases, resulting in a deeper draught for the semi-submersible floating platform. Consequently, the amplitude of the negative heave motion increases, while the amplitude of the positive heave motion decreases. According to Fig. 7, the WECs effectively suppresses the system's sway motion response. Since the direction of sway motion is perpendicular to the incoming wave direction, it is less affected by wave loads. Additionally, the increased system mass leads to an overall increase in damping, further enhancing the suppression effect on sway motion. Under the given conditions, the maximum sway motion of the SSFP with WECs is plunged from 1.835 m to 0.773 m, representing a reduction of 57.87%. Moreover, the array configuration of the vertical cylinder-shaped buoys in the wave energy converter increases the water-blocking area in the surge (wave inflow) direction, thereby enhancing the longitudinal loads on the system. Consequently, the system's surge motion response is amplified to a certain extent, as shown in Fig. 8.

Fig. 9 - Fig. 11 depict the time history curves of yaw, roll, and pitch motion responses before and after the introduction of the multi-float wave energy converter (WEC). As evident from the figures, the multi-body coupling system consisting of the multi-float WEC and the semi-submersible floating platform effectively suppresses the rotational angles in all three directions. By absorbing wave energy, the WEC

reduces the torques exerted on the platform by waves, thus inhibiting yaw motion. Consequently, the maximum yaw angle is reduced from 3.273° to 1.690°, representing a significant reduction of 48.36%.

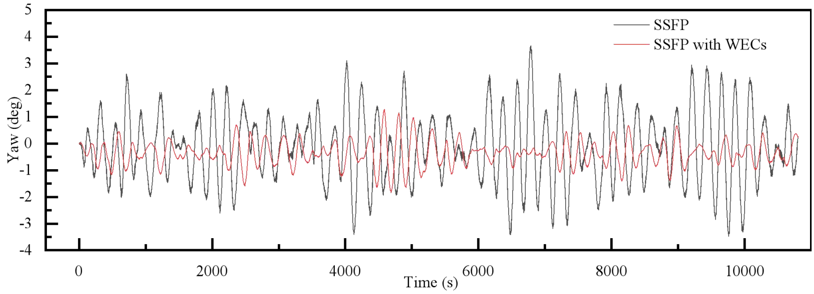

Fig. 9. Comparison of the yaw response of SSFP before and after adding WECs.

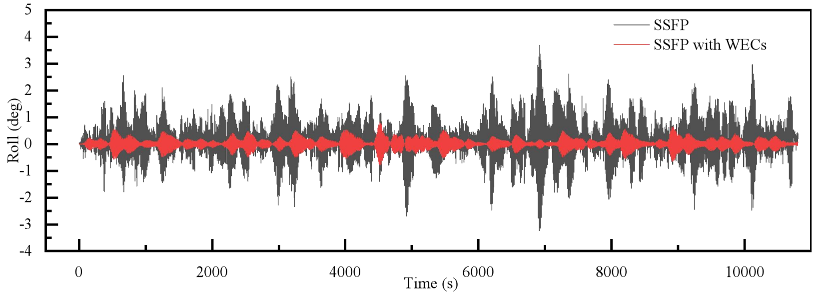

Fig. 10. Comparison of the roll response of SSFP before and after adding WECs.

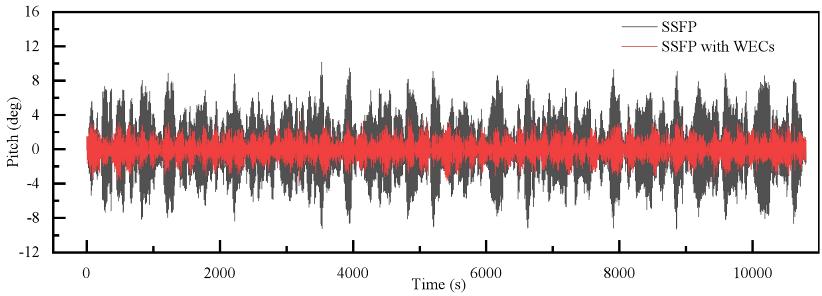

Fig. 11. Comparison of the pitch response of SSFP before and after adding WECs.

Furthermore, the vertically oscillating floats arranged in an array adaptively adjust the damping in the roll motion direction by altering the overall mass and buoyancy distribution of the platform, thereby reducing the roll amplitude and frequency. Notably, the maximum roll angle is decreased from 2.021° to 0.716°, achieving a remarkable reduction of 75.21%.Additionally, since the wave direction aligns with the surge direction, the system's water resistance area increases. Through its own heave motion, the system dissipates wave energy, mitigating the pitch torques imparted by waves and suppressing pitch motion. Consequently, the maximum pitch angle is reduced from 10.266° to 4.079°, representing a substantial decrease of 60.27%.

5 Conclusion

To address the issue of excessive motion responses in various degrees of freedom for deep-sea semi-submersible floating platforms under wave loads, this study presents a novel design of a multi-body coupling system that integrates a floater wave energy converter with a semi-submersible floating wind turbine platform. This system features an array of heave-type cylindrical floaters arranged between the side columns of the platform. The floaters dissipate and convert wave energy through heave motion, effectively mitigating the impact of wave loads. Additionally, the system forms a dynamic coupling with the platform through mooring lines, significantly enhancing the damping in all directions.Numerical analysis results demonstrate that under extreme sea conditions, the system effectively suppresses the motion responses of surge, sway, pitch, and yaw. Specifically, the suppression rates for sway, roll, and pitch motion responses exceed 60%, while the suppression rate for yaw motion response approaches 50%.

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References

1. Yu, M., Cao, F., Wei, Z., Han, M., Shi, H., Chen, H., Tian, H.: Hydrodynamic performance and energy redistribution characteristics of wind–wave hybrid system based on different WEC microarrays. Ocean Engineering 306(15), 118090(2024).
2. Roddier, D., Cermelli, C., Aubault, A., Weinstein, A.: WindFloat: A floating foundation for offshore wind turbines. Journal of Renewable and Sustainable Energy 2(033104), 1-34 (2010).
3. Cheng, Y., Xi, C., Dai, S., Ji,C., Cocard, M., Yuan, Z., Incecik, A.: Performance characteristics and parametric analysis of a novel multi-purpose plat-form combining a moonpool-type floating breakwater and an array of wave energy converters. Applied Energy 292(15), 116888(2021).

4. Sismani, G., Loukogeorgaki, E., Frequency-based investigation of a floating wave energy converter system with mul-tiple flaps. Applied Mathematical Modelling 84, 522-535(2020).
5. Hyebin, L., Sunny, P., Yoon, B.: Performance analysis of multiple wave energy converters placed on a floating platform in the frequency domain. Energies 11(2), 406-420(2018).
6. Rony, J.S., Karmakar, D.: Performance of a hybrid TLP floating wind turbine combined with arrays of heaving point absorbers. Ocean Engineering 282, 114939(2023).
7. Chandrasekaran, S., Sricharan, V.V.S.: Numerical analysis of a new multi-body floating wave energy converter with a linear power take-off system. Renewable Energy 159, 250-27(2020).
8. Yu, Y., Li, Y.: Reynolds-Averaged Navier–Stokes simulation of the heave performanceof a two-body floating-point system. Computers and Fluids 73, 104-114(2013).
9. Taylor, E., Hung, S.: Second order diffraction forces on a vertical cylinder in regular waves. Applied Ocean Research 9(1). 19-30(1987).
10. Howe, D., Nader J.R., Macfarlane, G.: Performance analysis of a floating breakwater integrated with multiple oscillating water column wave energy converters in regular and irregular seas. Applied Ocean Research 99, 102147(2020).