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Numerical simulation on hydrodynamic effects of serrated heave plates in cylindrical FPSO

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ABSTRACT

Heave plates are critical for mitigating offshore platforms' heave motion, yet existing studies mostly ignore their impacts on six-degree-of-freedom (6-DOF) motions. By adopting the CFD method based on the in-house naoe-FOAM-SJTU solver, this paper investigates a 120,000-ton cylindrical FPSO equipped with serrated heave plates in model scale. It systematically compares hydrodynamic characteristics of single- and double-layer configurations under regular and bichromatic wave conditions. The double-layer serrated heave plates effectively suppress the FPSO's heave and pitch motions but amplify its surge motion. The serrated structure enhances vortex shedding and energy dissipation, while flow-structure interaction induces asymmetric velocity fields that account for the increased surge displacement. The findings not only reveal the multi-DOF hydrodynamic coupling mechanism of serrated heave plates, but also provide a reference for the performance optimization of heave plates in other floating structures. This study provides theoretical support for optimal design of heave suppression structures for cylindrical FPSOs.

KEY WORDS: CFD; Cylindrical FPSO; double-layer heave plate; serrated heave plate

INTRODUCTION

Heave plates are widely used to suppress the heave motion of floating offshore structures by enhancing hydrodynamic damping and added mass. Traditionally, heave plates are mostly designed with regular shapes such as circular, square, hexagonal, or porous configurations. This paper adopts a serrated heave plate and further discusses the differences in hydrodynamic performance between single-layer and double-layer serrated heave plates.

Many researchers have studied the hydrodynamic characteristics of heave plates. Zhang et al. (2023) conducted experimental investigations on heave plates of semisubmersible floating offshore wind turbines using the forced oscillation method, and found that thinner heave plates and hexagonal shapes exhibit better damping performance. Rao et al. (2021) carried out numerical and experimental studies on spar platforms equipped with heave plates, confirming that the heave plates installed at the keel achieve the optimal motion suppression effect with negligible scale effects. An and Faltinsen (2013) studied perforated rectangular heave plates and revealed that the hydrodynamic coefficients are more sensitive to the KC number at large submergence depths, and the damping is dominated by edge vortex shedding. Qin et al. (2025) focused on the column boot clearance angle of deep-draft cylindrical platforms, and found that increasing the clearance angle reduced the added mass and natural period, while the damping coefficient increased and the heave RAO decreased at low periods. Ezoji et al. (2022) summarized the hydrodynamic damping of heave plates at low KC numbers and proposed the edge area-to-plate area ratio (Re/a) as a key evaluation parameter. Zhu and Lim (2017) found that the circular heave plates not only enhanced the damped heave period, but also influenced on damped pitch period.

Beyond the traditional offshore oil and gas engineering field, extensive studies on heave plates have been carried out for heaving pontoons and other devices. Srinivasan et al. (2006) described the heave plates as effective design to reduce the wave excitation forces and increase the damping of Truss-Pontoon semisubmersible platform. Wang et al. (2015) studied the hydrodynamic performance of a novel semi-submersible unit with pontoons, which brought heave-roll/heave-pitch coupling effects. Li et al. (2025) conducted Wave-adaptive Rescue Vessel with pontoon and converted pontoon heave dynamics into a solvable second-order mechanical system. Ghadimi et al. (2020) numerically investigated the effect of breakwater on heaving pontoons. They found the breakwater has no effect on the responding frequency but reduce the amplitude of the exciting wave.

Several researchers have also studied cylindrical FPSO with heave plates. Jiang et al. (2020) studied the effect of heave plate width on a cylindrical FPSO, and found that the damping coefficient and damping ratio increase gradually with increasing plate width. Huo et al. (2023) numerically analyzed the hydrodynamic response and slamming impact of cylindrical FPSOs. Subbulakshmi and Sundaravadivelu (2021) used Boundary Element Method (BEM) to investigate single and double damping plates under regular waves, and found that double damping plates yield lower heave added mass due to their excessively small spacing. Amin et al (2022) investigated the motion performance of cylindrical FPSO with interceptor plate. They found that the double face interceptor plate can reduce heave RAO by 50% and pitch RAO by 67%.

Based on the above research foundations, this paper adopts Computational Fluid Dynamics (CFD) method and focuses on the 120,000-ton cylindrical Floating Production Storage and Offloading (CFPSO) with serrated heave plates. Under regular and bichromatic wave conditions, the differences in hydrodynamic characteristics (including motion responses, velocity fields and response amplitude operators) between single-layer and double-layer configurations are compared. The FPSO is subjected to 6-DOF motions and moored using the spring model that has been validated by static stiffness tests. This study analyzes the 6-DOF motion and observes the flow field around the heave plates. An in-depth analysis of the effects of different serrated heave plates configurations on the 6-DOF motions is carried out, presenting the influences of various heave plate designs on the motion performance of the FPSO platform. The serrated structure is expected to enhance vortex shedding by increasing the edge area, while the double-layer design optimizes heave and pitch damping performance but increase the surge motion. The research results are expected to provide a theoretical basis for the optimal design of heave suppression structures for cylindrical FPSO, and also provide a reference for the hydrodynamic optimization of heave plates in other floating structures such as heaving pontoons.

METHODOLOGY

Governing Equation

The method is adopted our in-house solver naoe-FOAM, which is based on the open source software OpenFOAM. The governing equations are described below, which are the incompressible Navier-Stocks equations:

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U}g\nabla(\mathbf{U}-\mathbf{U}_g)\right) = -\nabla p_d - \mathbf{g}g\mathbf{x}\nabla p + \mu\nabla^2\mathbf{U} + \mathbf{f}_\sigma + \mathbf{f}_s \tag{2}$$

Where $\mathbf{U}$ is velocity field, $\mathbf{U}_g$ is velocity of grid nodes; $p_d = p - \rho\mathbf{g}\cdot\mathbf{x}$ is dynamic pressure, $\mathbf{x}$ is the horizontal direction which is based on the Cartesian coordinates; $\mathbf{f}_\sigma$ is the surface tension term in two phases model.

The solution of momentum and continuity equations is implemented by using the pressure-implicit spit operator (PISO) algorithm (Issa, R.I. 1986). The Volume of fluid (VOF) method is applied to capture the two-phase interface. The VOF transport equation is described below:

$$\frac{\partial \alpha}{\partial t} + \nabla g[(\mathbf{U}-\mathbf{U}g)\alpha] = 0 \tag{3}$$

Where α is volume of fraction, indicating the relative proportion of fluid in each cell and its value is always between zero and one:

$$\begin{cases} \alpha = 0 & \text{air} \\ \alpha = 1 & \text{water} \\ 0 < \alpha < 1 & \text{interface} \end{cases} \tag{4}$$

Wave generation and absorption

In order to improve the efficiency of the solution, a generating-absorbing boundary condition (GABC) method proposed by Wellens and Borsboom (Düz et al, 2017) is used to construct a numerical wave pool based on the traditional wave-making and dissipation method. Compared with the traditional source damping zone technology and relaxation zone dissipation technology, the proposed method does not need to use additional computational domains to achieve passive numerical dissipation, nor does it need to modify the control equation of the existing solver, which can greatly improve the computational efficiency while achieving low reflectivity, and has been verified in some wave-structure interaction problems. The following is a brief introduction to the basic principles of this method:

Based on the classical Sommerfeld radiation boundary condition, this method solves the inherent defect of only targeting a single constant wave velocity c, so that it can be better applied to the dispersive wave situation containing multiple wave components in the actual problem. The specific solution is to replace the original constant c with a function c(z) that varies with depth：

$$\frac{\partial \Phi}{\partial t} + c(z)\frac{\partial \Phi}{\partial x} = 0 \tag{5}$$

where is the velocity potential function, Φt is the time, and x is the coordinates along the direction of wave propagation. In order to convert Eq. (5) into a variable in the N-S equation under the viscoflow CFD framework, the Bernoulli equation is used here：

$$p = -\rho g z - \rho\frac{\partial \Phi}{\partial t} \tag{6}$$

where is the total pressure, which is the density of the water. After substituting Eq.(6) into Eq.(5), the boundary conditions expressed as dynamic pressure and velocity U can be obtained p_d**:**

$$-(p_d)_b + \rho c(z)\boldsymbol{n}_b \cdot \boldsymbol{U}_b = S^G \tag{7}$$

where $()_b$represents the physical quantity defined on the boundary plane, which is the source term used to make waves S^G.

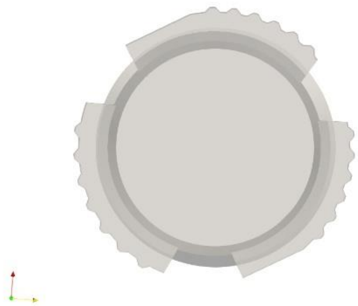
This wave generation and absorption method can achieve a better wave absorption effect without using the relaxation zone, which can shorten the calculation domain, save computational time, and ensure the accuracy of wave simulation, making it suitable for CFD numerical simulation of complex engineering problems.

NUMERICAL SIMULATION

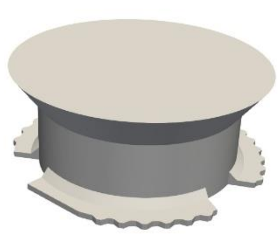
Numerical Setup

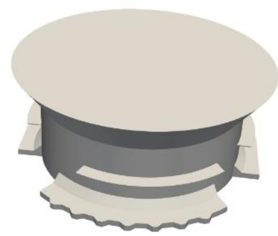
The numerical calculation model uses a 1:60 model scale cylindrical FPSO as the main research object. Three serrated heave plates are equidistantly arranged at the bottom of the CFPSO, with a consistent serrated edge design for all heave plates. Compared with the single-layer heave plate case, the double-layer heave plate has another circular heave plate corresponding to the position of three heave plates at a distance of 16 m in full scale, as shown in Fig.1

Two sets of wave conditions (full scale) are adopted for the numerical simulation, including regular wave and bichromatic wave conditions, both with a significant wave height of 3 m. The bichromatic wave is composed of two wave components with periods of 10 s and 15.5 s, and the regular wave has a single period of 16 s. The detailed parameters of the wave conditions are listed in Table 1.



(a) Schematic diagram of a cylindrical FPSO of three serrated heave plates





(b) Single-layer serrated heave plate (c) Two-layer serrated heave plate

Fig.1 Schematic diagram of numerical models

Table 1. Numerical wave condition (in full scale)

Wave condition	Period of composed wave No.1(s)	Period of composed wave No.2(s)	Wave height(m)
Bichromatic wave	10	15.5	3
Regular wave	16		3

The spring model method is used to simplify the mooring of the CFPSO. This model only considers the tension generated by the axial deformation of the mooring line, ignores the weight of the mooring line itself and its hydrodynamic interaction with the surrounding flow field. The mooring model contains mooring points and anchor points, which are attached to marine structures and move with them, while the anchor points are stationary. The static stiffness of the spring model has been validated by the experiment.

A rectangular computational domain with a length of 21 m, a width of 12 m, and a total height of 7.25 m is adopted for the numerical simulation, with a water depth of 5.25 m, which meets the deep-water wave conditions for the designed wave parameters. The layout of the computational domain is shown in Fig. 2. The mesh generation and local refinement details are shown in Fig. 3, and the total number of grids is about 5 million.

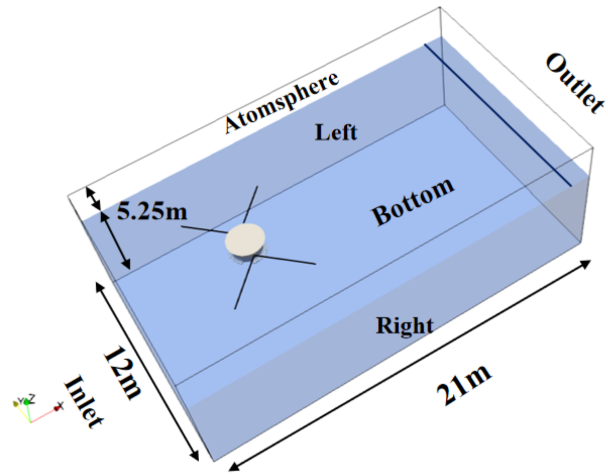
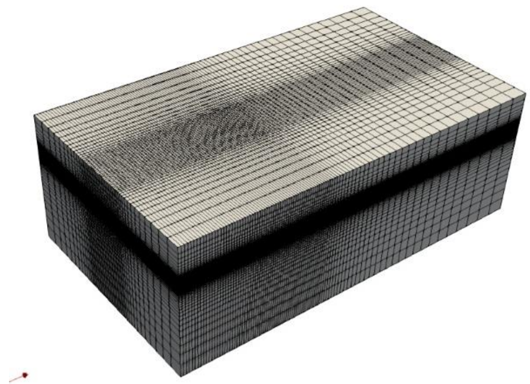
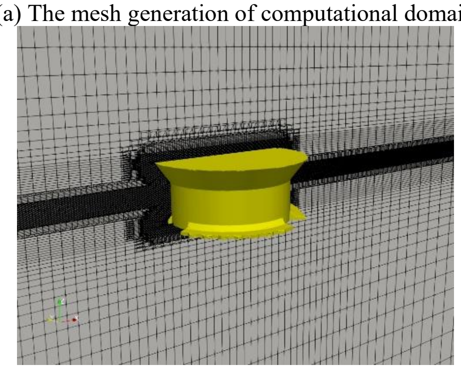


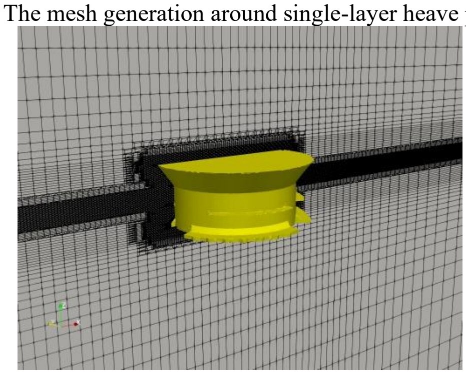
Fig.2 The setup of computational domain



(a) The mesh generation of computational domain



(b) The mesh generation around single-layer heave plate



(c) The mesh generation around two-layer heave plate

Fig.3 The mesh generation of CFPSO

Validation

Before CFD calculation, the static displacement test of the mooring system is carried out to verify the stiffness of the mooring system to ensure that the equivalent stiffness of the mooring used in CFD calculation is consistent with the test. The verification results of the equivalent stiffness of the mooring are shown in Fig. 4, which shows that the equivalent stiffness of the mooring is in good agreement with the test results.

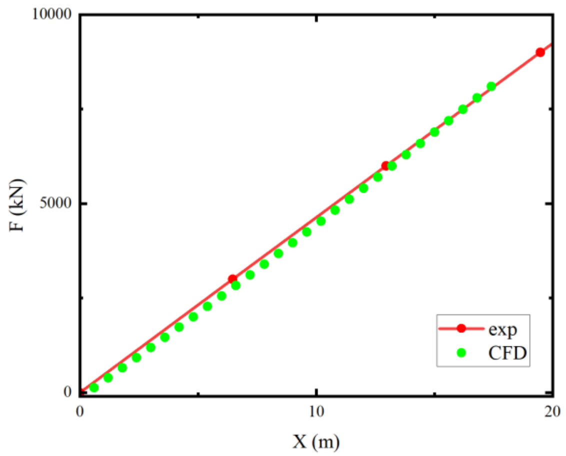


Fig.4 The validation of spring model.

The results of the numerical simulation are validated by comparing the numerical results with experimental results. The experiments were conducted by the experimental team of CNOOC Research Institute at the State Key Laboratory of Shanghai Jiao Tong University. The results are shown in Table 2, with the numerical error of surge motion, heave motion and pitch motion all less than 5%. It has been seen that the numerical methods adopted in this paper is faithful.

Table 2. Numerical validation (in full scale)

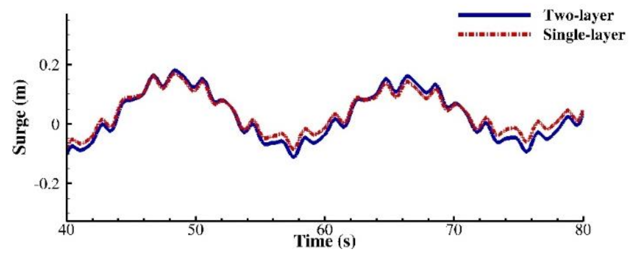
DOF	Numerical results	Experimental results	Numerical error
Surge Motion	0.699m	0.675m	3.55%
Heave Motion	2.044m	2.045m	0.04%
Pitch Motion	0.218 deg	0.222 deg	3.11%

Motions and scattering waves

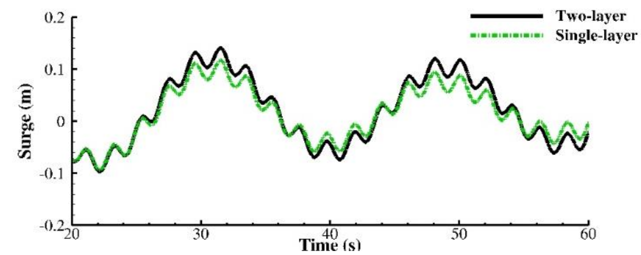
Under the action of regular waves, two different forms of heave plates show similar motion characteristics. As for the surge and pitch motion, a long period (mooring system) and a small period (wave period) can be observed at the same time, while the heave motion only exhibits the small period (wave period), indicating that the surge and pitch periods of cylindrical FPSO are controlled by the mooring system and the wave period at the same time, and the heave motion is mainly controlled by the wave period.

Regarding the surge motion results, the surge motion amplitude of the FPSO fitted with double-layer heave plates is greater than that of the FPSO with single-layer heave plates under both wave conditions. Under the regular wave condition, the maximum surge motion displacement with double-layer heave plates is about 5.8m (full scale). For the heave motion results, the heave motion amplitude of FPSO with double-layer heave plates is obviously smaller and more stable, and the stability of the single-layer heave plate is slightly worse than that of the double-layer heave plate.

With respect to the pitch motion results, the double-layer heave plate shows the most stable pitch control performance in the whole-time domain, and its angular change amplitude is smaller. For the bichromatic wave condition, the pitch angle of FPSO shows obvious periodic fluctuations, ranging from -2 degrees to 3 degrees, and the motion trends of the FPSO with the two types of heave plates are highly synchronized, but there is a distinguishable difference in amplitude.

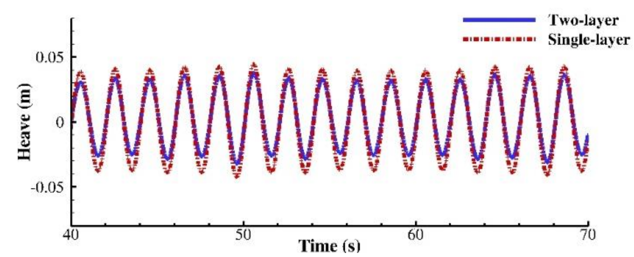


(a) bichromatic wave

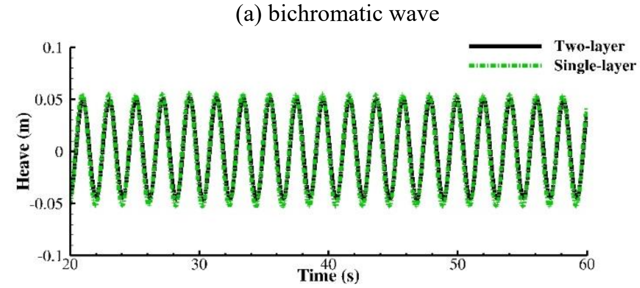


(b) regular wave

Fig.5 The comparison of surge motion between two-layer and single-layer heave plate

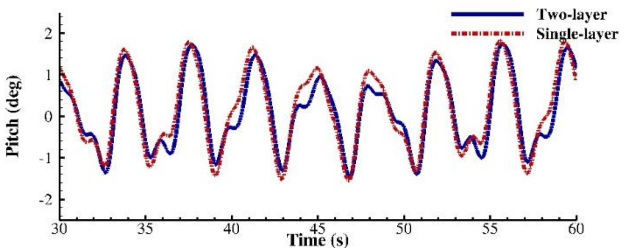


(a) bichromatic wave

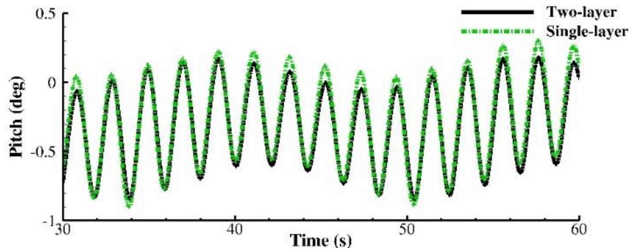


(b) regular wave

Fig.6 The comparison of heave motion between two-layer and single-layer heave plate



(a) bichromatic wave



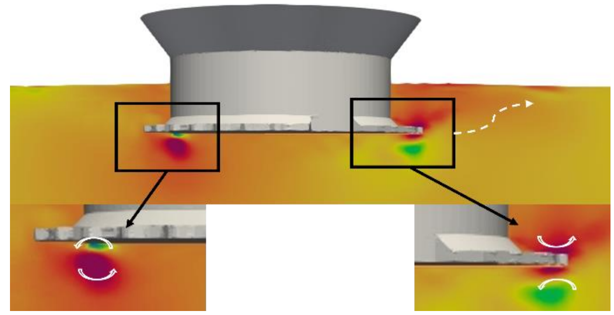
(b) regular wave

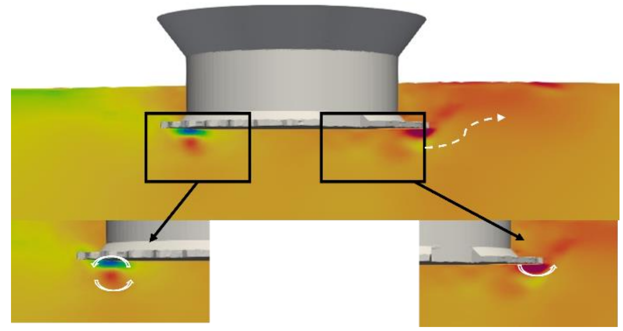
Fig.7 The comparison of pitch motion between two-layer and single-layer heave plate

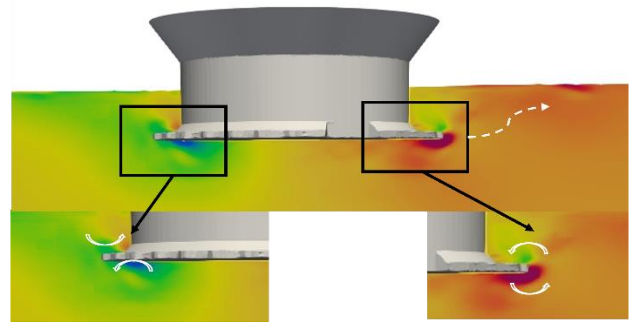
It can be seen that whether it is a bichromatic wave or a regular wave, the double-layer heave plate shows a similar trend compared with the single-layer heave plate --- the heave motion and pitch motion is smaller, but the surge motion is larger. When the FPSO undergoes the heave motion, the heave plate undergoes the heave motion at the same time. The vortex on the side of the plate generates viscous damping, thereby reducing the heave motion of the FPSO. For surge and pitch motion, the role of the heave plate in these motions differs from that in heave motion.

To reveal the hydrodynamic mechanism of the different motion responses caused by the two heave plate configurations, the velocity field around the heave plates of CFPSO under the regular wave is selected for observation. Since the motion over a full period under regular wave is symmetrical, the axial velocity field at four moments with half a period is selected for analysis, as shown in Figs. 8 and 9.

It can be seen that in the axial direction, the heave plate will also produce vortices in motion --- counter-rotating vortex pairs are generated on both the wave-facing side and the wave-leeward side. The vortex pairs generated by the single-layer heave plate are small, and they are generated below the heave plate in the first quarter period. During the last quarter period, positive velocity vortices appear on the upper side of the heave plate and negative velocity vortices on the lower side until the end of the wave period. The vortex pair on the wave-leeward side is not symmetrical, and the forward velocity vortex will continue to extend in the direction of wave propagation until it touches the free surface. At the same time, the vortex pair on the wave-leeward side shows periodic changes: firstly, a positive velocity vortex is formed above the heave plate, a negative velocity vortex is formed below, and then the upper velocity disappears and the lower velocity vortices is transformed into a positive velocity vortex. As the positive velocity vortex below increases, a negative velocity vortex appears above, and finally the vortex pairs around the heave plate gradually become symmetric.


(a) t=1/8T


(b)t=1/4T


(c)t=3/8T

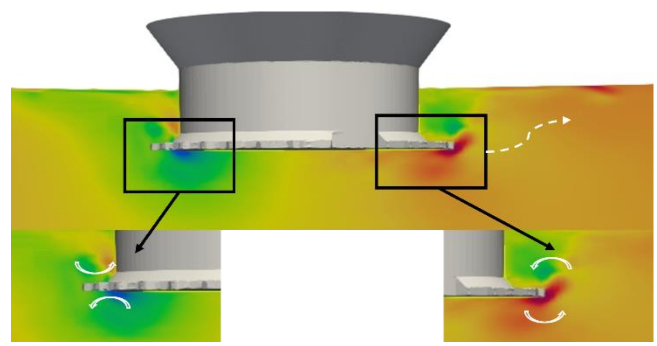
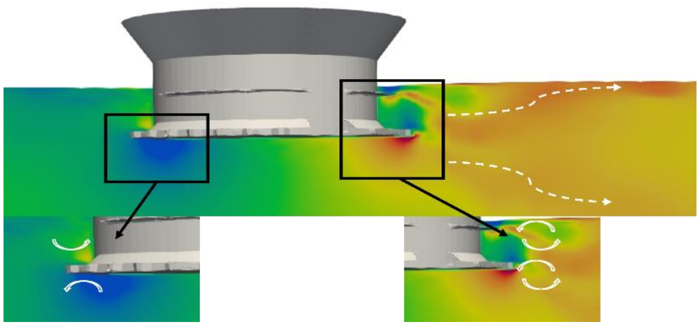

(d)t=1/4T

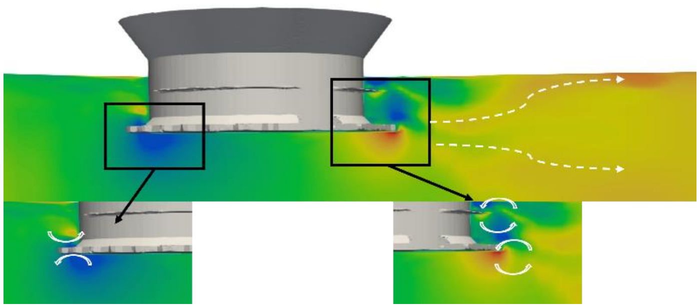
Fig.8 The snapshots of velocity around double-layer heave plates CFPSO

For the double-layer heave plate, the flow field characteristics are significantly different from those of the single-layer heave plate. Although each layer retains a single-plate structural form, the vortex pairs generated by the double-layer configuration differ significantly from those of single-layer heave plate. The wave passes through the gap of the heave plate above and generates a small velocity field that diffuses upward to the free surface. Therefore, the axial velocity generated by the serrated heave plate is less obvious than that of the single-layer heave plate, and has strong asymmetry. The range of velocity vortices under the lower heave plate is much larger than that of the upper velocity vortices in the first quarter period. In the last quarter period, noticeable velocity vortices only exit on one side (either above or below the plate).

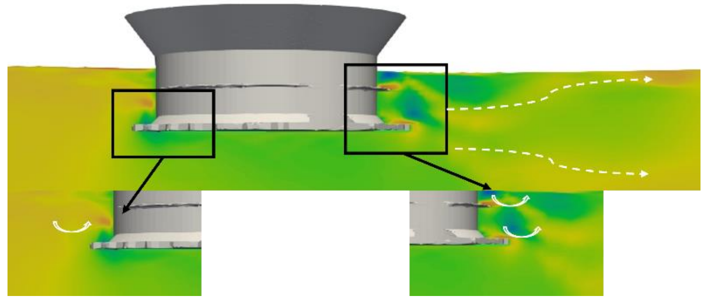
For the wave-leeward side of the double-layer heave plate, the velocity field generated is even more different from that of the single layer - as shown in Fig. 9. It can be seen that the two velocity fields that clearly extend positively to the x-axis come from the upper layer and the lower layer of the heave plate respectively. The upper heave plate generates a large range of vortex and floats to the free surface, which greatly increases the speed of the free surface on the back wave side. At the same time, the lower heave plate will also produce a large range of vortex structure, resulting in an increased flow velocity on the wave-leeward side both at the free surface and within the FPSO's surrounding area. Thus, the FPSO platform will move more easily along the positive direction of the x-axis under the background flow field, leading to a larger surge motion displacement.



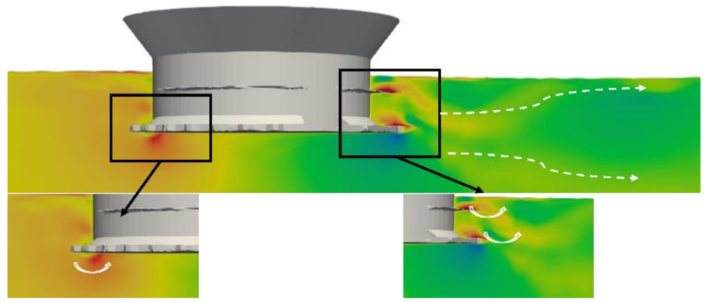
(a) t=1/8T



(b)t=1/4T



(c)t=3/8T



(d)t=1/4T

Fig.9 The snapshots of velocity around double-layer heave plates CFPSO

CONCLUSIONS

In this paper, numerical simulations of cylindrical FPSO equipped with serrated heave plates are carried out under regular waves and bichromatic wave conditions. By comparing the hydrodynamic performance of two configurations (single-layer and double-layer serrated heave plates), the study analyzed the motion responses of the platform with heave, surge and pitch. In this paper, the CFD method is used to analyze the platform with a spring model by using a self-developed solver naoeFOAM-SJTU. The conclusions obtained are as follows:

The motion response of the cylindrical FPSO with different serrated heave plate configurations is basically consistent under both regular and bichromatic waves. Specifically, the double-layer serrated heave plates can effectively suppress the heave and pitch motion of the cylindrical FPSO but will amplify its surge motion.

Flow field observations revealed that vortices are generated around the heave plates during the FPSO's motion; the vortices on the wave-leeward side propagate toward the free surface, enhancing the local velocity field in this region. Compared with the single-layer configuration, the vortices generated by the double-layer heave plates have a larger propagation range, which further promotes the surge motion of the FPSO and leads to a larger surge displacement.

Additionally, the interaction between the upper and lower layers of the double-layer configuration leads to asymmetric flow field distribution, which is the primary reason for the amplified surge motion. This finding suggests that optimizing the spacing between the two layers of serrated heave plates could potentially balance the suppression of heave/pitch motions and the control of surge motion, providing a feasible direction for the engineering design of heave suppression structures for large cylindrical FPSOs. The numerical results obtained in this study also verify the reliability of the CFD method based on naoeFOAM-SJTU in simulating the complex hydrodynamic interactions between serrated heave plates and waves.

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