Numerical Investigation of Hydrodynamic Responses of Point Absorbing Wave Energy Device

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Abstract: To reduce the impact of fossil fuels on the environment, researchers are looking for alternative energy resources. Wave energy is widespread in nature, which is a kind of green renewable energy. Point absorbing wave energy device can effectively transform wave energy, of which the motion response in wave is complex. The movement of wave energy device, the force and energy conversion efficiency will be disparate under different conditions. The main purpose of this paper is to study the hydrodynamic response of cylindrical wave power generation device in different wave conditions, and the influence factors on the force, motion and energy conversion efficiency of the cylindrical floating body are explored. In this paper, a hydrodynamic solver naoe-FOAM-SJTU based on open source CFD software OpenFOAM is applied to simulate the response of a single cylindrical floating body and two cylindrical floating bodies under regular waves respectively. To ensure the accuracy of wave conditions, waves2foam tool box is used to generate stokes waves with different wavelengths. Damping coefficient is used to simulate the effect of motor on wave energy device. By numerical simulation of the response of a single floating body, it is found that the CDF numerical method is reliable for simulation. Through the numerical simulation of the response of double floating bodies with different distance between them, the interaction between the floating body is found, and the effect of different wave conditions on wave energy conversion efficiency is studied.

Keywords: wave energy, point absorber, hydrodynamic response, naoe-FOAM-SJTU solver, conversion efficiency

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1 Introduction

Under the background of the increasing consumption of fossil fuel consumption, as a new type of renewable energy, the renewable energy is more and more concerned by governments and researchers. As a representative non-polluting renewable energy, the wave energy recovery device has been studied for many years. At present, although there are many modes of wave power devices, the overall development of wave power generation devices is still relatively low. There are many factors in this situation, among which the wave energy distribution and the characteristics of wave energy absorbing device are the main restricting factors. Wave energy is widely distributed, but with low density, unstable characteristics and cannot be exploited on a large scale. At the same time, the requirement of the wave energy acquisition device for the mooring system is generally high, which makes the cost of the wave power generation device increased. In addition, the stability of wave energy acquisition device has become the bottleneck of large-scale application of wave energy. Some wave energy collection devices are very efficient, but poor reliability and easy to damage in extreme sea conditions. These factors make the development of wave energy far behind the development of wind energy.

Although many wave energy absorption devices have been developed, especially the famous Salter duck absorption device (Salter, S.H., 1974), the peak absorption efficiency of its wave energy reaches an astonishing 80%, but it cannot be popularized because of its complicated structure and high manufacturing cost. At present, many researchers tend to simple point absorption devices, especially simple cylindrical devices (Kofoed, J.P., 2009).

Separated cylindrical floats are commonly used as floating breakwater for marine engineering (Ozeren, Y. et al 2011). The cylinder is placed on the water surface and perpendicular to the direction of the wave. When the waves reach the floating body, part of the energy is reflected, part of the energy converted into kinetic energy. Some of the kinetic energy will be scattered out, the rest of the energy is stored as electricity or consumption due to the damping effect.

A lot of research has been done on the wave energy absorption device. For the wave energy absorption device, when the damping coefficient is relatively small, the conversion efficiency of wave energy decreases with the increase of wave frequency. When the damping coefficient is large, the wave energy conversion efficiency increases with the increase of wave frequency (Ringwood, J., Butler, S., 2004). The numerical simulation method is used to analyze the damping coefficient of response to the optimal efficiency (Nolan, G.A. et al.,2005). Through the experiment and numerical simulation, the analysis of wave energy absorption device can find the larger the float diameter, the more energy absorption (Pastor, J., Liu, Y., 2014). The characteristics of single and two cylindrical floating body wave energy absorption devices have also been studied (Chen B et al, 2016). In this paper, the characteristics of the wave energy absorption device of two floating bodies will be further studied based on Chen' work.

A clever design can balance efficiency and production costs, so that cylindrical power plants can play the maximum effect. To make the design more reasonable, it is necessary to study

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*Corresponding author Email: dcwan@sjtu.edu.cn the response of cylindrical floating body waves under different wave conditions

In this paper, a viscous flow solver, naoe-FOAM-SJTU, developed based on open source software OpenFOAM, is used to simulate the response of a cylindrical floating body in a wave. For wave simulation, waves2foam solver is used to generate waves. In this paper, the numerical simulation results and the calculation results are compared. Then, the movement and force of the single floating body and two different damping coefficients are compared and analyzed, and the characteristics of the floating body damping movement in the wave are found. Finally, the wave energy conversion efficiency of the cylindrical floating body is calculated, and the variation characteristics of the single floating body and the two-floating body efficiency are analyzed. It provides a reference for the design of point absorbing energy device.

2 Numerical method

2.1 Governing equation

The control equations for incompressible viscous fluids are as follows:

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

$$\frac{\partial \rho \mathrm{U}}{\partial t} + \nabla \cdot \left(\rho\left(U - U_g\right)U\right) = -\nabla p_d - g \cdot x\nabla\rho + \nabla \cdot (\mu\nabla U) \tag{2}$$

In which, U is fluid velocity, U_g is velocity of mesh grid, p_d is dynamic pressure of fluid, the value is equal to difference between the total pressure and the hydrostatic pressure. g is acceleration of gravity, ρ is density of fluid, μ is dynamic viscosity coefficient.

RANS equation is used to solve the equation, and k-ω SST turbulence model is used to solve the problem of RANS equation not closed, and wall function is used in the near wall surface. The finite volume method (FVM) is used to discrete the equation, and the PISO algorithm is used to solve the velocity pressure coupling problem. The free surface is captured by the fluid volume method (VOF).

2.2 Motion of floating cylinders

In this paper, the cylindrical floating body only has heave motion, its motion equation is:

$$\mathrm{m}\ddot{z} + C\dot{z} = G + F_w \tag{3}$$

In which, m is mass of the cylinder, $\ddot{z}$ and $\dot{z}$ are heave speed and acceleration respectively. C is damping coefficient, G is volume force of cylinder, F_W includes wave force and hydrostatic buoyancy. $C\dot{z}$ consists of generator load, transmission resistance and generation loss. In this paper, the value of damping coefficient C is changed to study the motion response and stress of cylindrical floating body under different damping coefficients.

2.3 Wave generation theory

In this paper, the waves2foam (OpenFOAM,2013) wave solver developed by OpenFOAM is used to simulate the stokes wave. It is stokes second order wave by calculation, which equation is :

$$\phi = \varepsilon\phi_1 + \varepsilon^2\phi_2 \tag{4}$$

In which ε is perturbation parameter, φ_1 and φ_2 are first order and second order solution.

By changing the speed inlet and outlet conditions, waves2foam can produce waves and make waves disappear. The control equation of the relaxation region is:

$$\alpha_R(\chi_R) = 1 - \frac{\exp\left(\chi_R^{3.5}\right) - 1}{\exp(1) - 1}\ for\ \chi_R \epsilon [0,1] \tag{5}$$

In which, α_R is relaxation factor, which is a function of χ_R. Its trends are as follows:

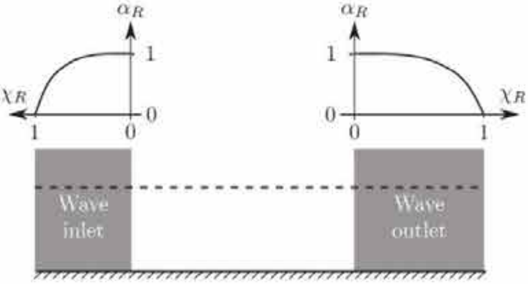


Fig. 1 α_R trend in inlet and outlet region

The effect of relaxation factor is:

$$\phi = \alpha_R\phi_{computed} + (1 - \alpha_R)\phi_{target} \tag{6}$$

In which ϕ is velocity of free surface or liquid parameter.

Fig 1 shows that the relaxation factor will increase from zero to maximum at the entrance. The relaxation area at the entrance and exit constitutes the wave area and the wave suppression area of the computational pool.

3 Numerical model and test conditions

3.1 Physical model and numerical model

The experiment was completed along the coast and state key laboratory of ocean engineering of Dalian university of technology (Chen B et al.,2016). The test apparatus is shown in fig.2. The test pool is 60 meters long, 4 meters wide and 2.4 meters deep. On one side of the pool there is a wave generator, on the other side is wave-absorbing beach. The cylindrical floater model is made of organic glass, 1 meter long and 0.2 meter in diameter. The cylinder is fixed with iron bars to ensure that it has degrees of freedom only in the vertical direction. The model of the cylindrical floating device is shown in figure 3, the model is equal to the actual size.

Fig.2 Experiment device

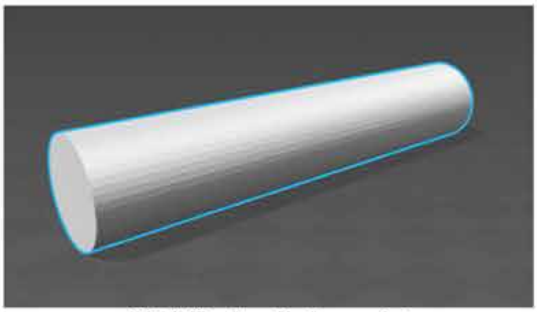


Fig.3 Single cylinder model

3.2 Mesh and computational domain

The naoe-FOAM-SJTU solver is based on OpenFOAM, which provides the user a powerful, convenient and practical utility snappyHexMesh (Niels G.Jm et al.), which can create a high-quality computing grid in a relatively short time. The overview of the compute domain is shown in the figure 4. And the local refinement of the grid near the floating body is given in the figure 5 and figure 6. The model is in the center of the compute domain. The total number of cells is about 1.8 million.

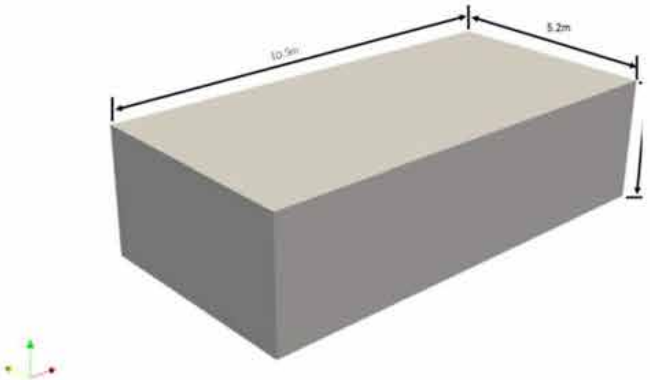


Fig.4 Computational domain

Fig.5 Grid distribution of single cylinder

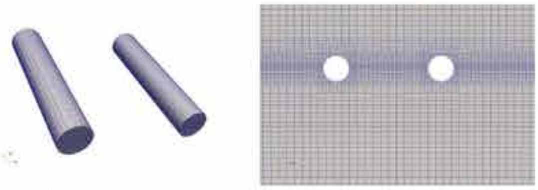


Fig.6 Grid distribution of double cylinder

4 Result and analysis

4.1 Validation of numerical model.

In order to verify the accuracy of the calculation results, this paper will compare with the experimental results and the calculation results of Chen et al.(2016). In Chen's paper, the two-dimensional potential flow theory is used to analyze the calculation results of the cylinder. In this paper, the displacement response of single cylinder under the of wave periods 1.1s and 1.5s waves is compared, as shown in fig. 7 (a)(b). In which, Zm indicates the difference of the maximum value of displacement minus the minimum displacement. Fig.7 shows that when the wave period is 1.1s, the calculated results of 2D are closer to the experimental values than 3D results. The overall trend between experiment and the numerical calculation through naoe-FOAM-SJTU are consistent, while there are certain differences in the specific values. It can be observed that the displacement and wave height calculated by naoe-FOAM-SJTU have a strong linear relationship, that the displacement value is proportional to the change of the wave height. But linear relationship is relatively weak in the experiment results. For the wave period of 1.5s, the results calculated by naoe-FOAM-SJTU are more accurate than the two-dimensional results, and the results of each wave height are in good agreement.

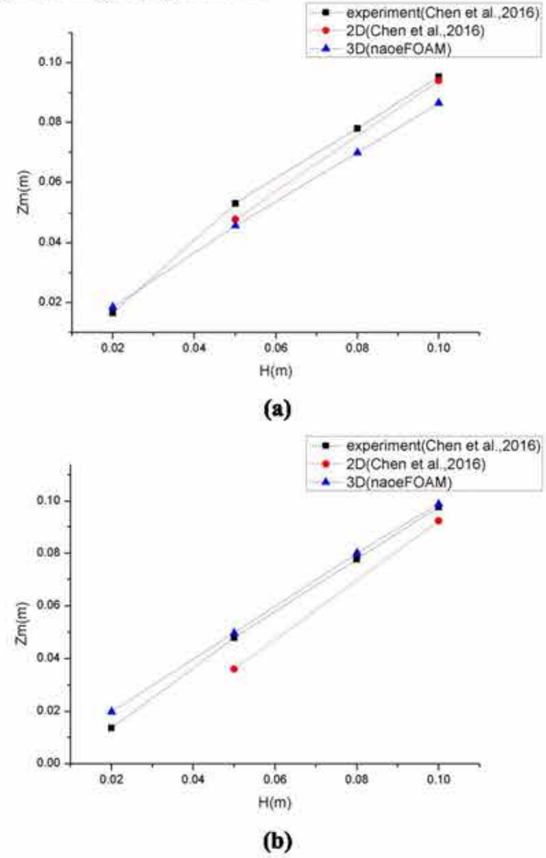


Fig.7 Heave displacement in wave period (a)T=1.1s (b)T=1.5s

Fig. 8 is a time-calendar curve with the wave period of 1.5 s, and the wave height of 0.1 m. Fig. 8 shows the motion of the cylinder in detail, in which the motion of the cylinder is stable in both the experiment and the 3D CFD simulation, and the amplitude gap between the curves is very small. In 2D calculation, the amplitude of heave motion of the cylinder is in fluctuation, which shows that the calculated results are not stable. It probably because the effect of the length of the cylinder is not taken into account in 2D calculations. The waves pass by both sides of the cylinder and diffracted, which is not observed in two-dimensional calculations.

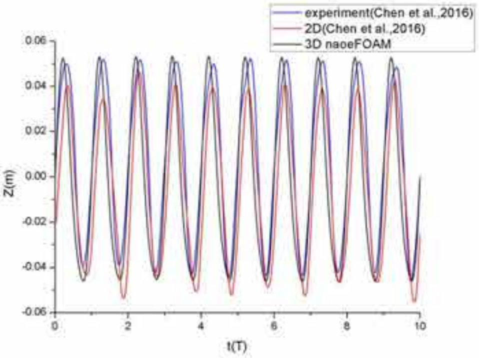


Fig.8 Time series of measured and predicted heave displacement of single cylinder, T=1.5s

Through the comparison of the experimental results and the two-dimensional calculation results, the accuracy of the naoe-FOAM-SJTU calculation results is verified, which lays a foundation for further research.

4.2 Computational results of double cylinder.

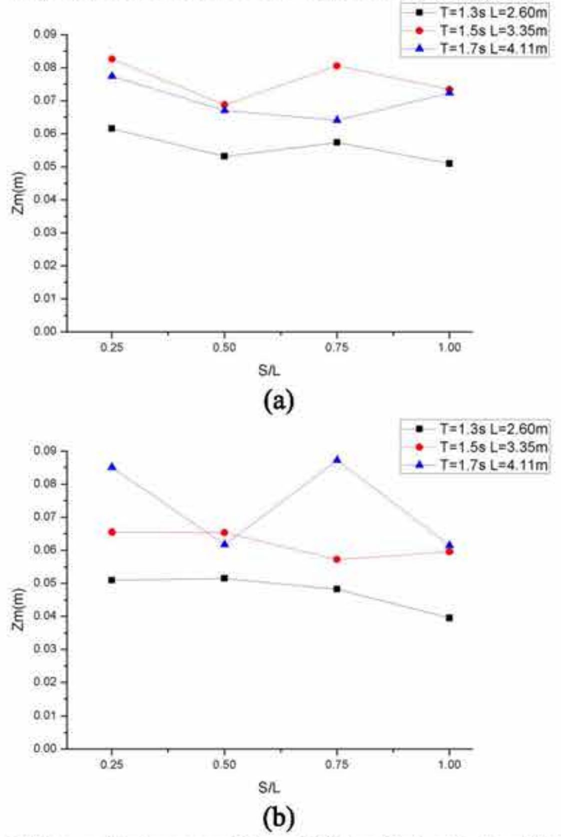
In order to study the influence of the distance between two cylinders on the motion and force of the cylinder, the motion and force of the two cylinders under different wave periods are calculated. The calculation conditions are as shown in table 1. The wave height is 0.1m and damping coefficient is 300 N/(m/s) for all cases.

Table 1 Parameter for numerical simulations

wave period T(s)	wave length L(m)	distance between cylinders S(m)	relative distance S/L
1.3	2.60	0.65	0.25
		1.3	0.50
		1.95	0.75
		2.6	1.00
1.5	3.35	0.84	0.25
		1.68	0.50
		2.51	0.75
		3.35	1.00
1.7	4.11	1.03	0.25
		2.06	0.50
		3.08	0.75
		4.11	1.0

4.2.1 heave motion of cylinder

Under the wave conditions, the floating body movement affects the conversion efficiency of wave energy. Generally speaking, the more vigorous the floating body move, the higher the wave energy conversion efficiency be under the same damping condition. At the same time, the displacement and velocity of the floating body affect the design parameters of the energy conversion device in the floating body, and the optimal sea state corresponding to an energy conversion device is usually unique. This makes it necessary to study the movement and velocity of the floating body.

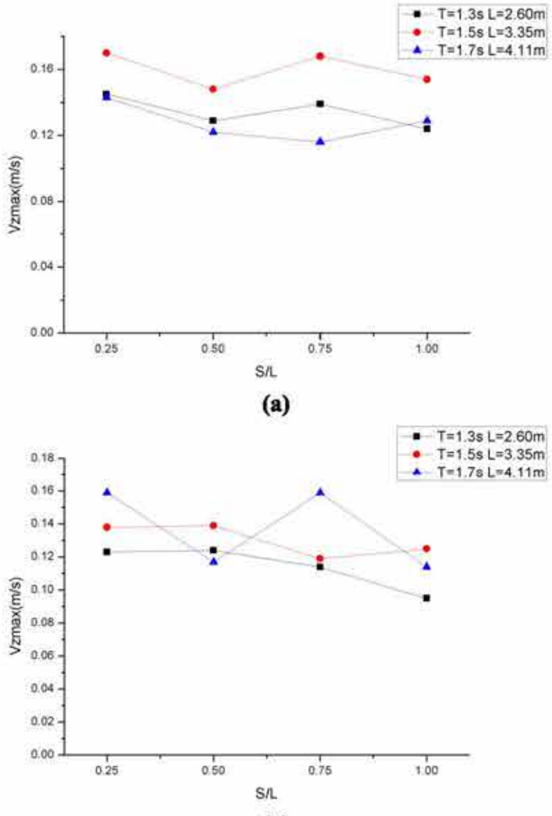


(a)

(b)

Fig.9 Heave displacement Zm of (a) the first cylinder (b) the second cylinder

Fig. 9 shows the variation of the heave displacement with the distance between two cylinders at different wave periods and wavelengths. It is obvious that the heave motion of the first cylinder and the second cylinder is affected by the distance between the two cylinders, which shows that the interaction between the two cylinders is strong. When T=1.3s and T=1.5s, the first cylinder's heave displacement appears a relatively high degree of similarity: the displacement of S/L= 0.25 and S/L= 0.75 is almost equal, so as the case S/L = 0.5 and S/L = 1.0. But when T=1.7s, there is no such trend. Interestingly, for the second cylinder, this phenomenon is reflected at T=1.7s, but not at the other two periods. This phenomenon is probably not accidental, and the mechanism behind it is worth exploring.



(a)

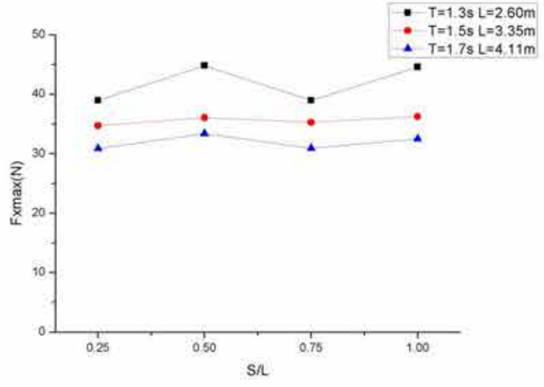
(b)

Fig.10 Maximum vertical velocity Vzmax of (a) the first cylinder (b) the second cylinder

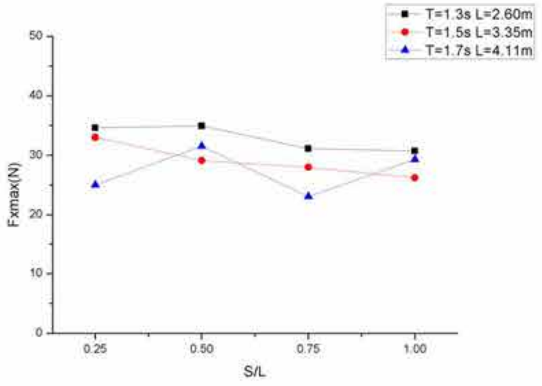
Fig. 10 shows the variation of the maximum velocity of two cylinders with the distance. The variation trends of maximum velocity and the displacement are very similar, but the amplitude is different compared to the displacement.

4.2.2 Wave load on cylinder

The force of the floating body is very important for the oscillating float type wave power generation device. If the peak of the wave force acting on the floating body is too large, it may cause damage to the structure, thus affecting the stability of the device. In addition, as the oscillating float needs to be fixed through the anchor chain, its force condition also affects the chain system parameters and stability.



(a)



(b)

Fig.11 Maximum vertical velocity Vzmax of (a) the first cylinder (b) the second cylinder

Fig. 11 shows the variation of the maximum horizontal force with the distance between the two cylinders. Like the motion, the force of the cylinder is affected by the distance between the two cylinders. For the first cylinder, the horizontal force at different periods and wavelengths is similar to the motion results which are larger when S/L=0.5 and 1.0, smaller when S/L=0.25 and 0.75. This indicates that a half wavelength difference of distance between the two cylinders is likely to affect the phase of the reflected wave. When the distance is half of wavelength, the difference of the reflection wave phase is a wavelength. It explains why the distance difference has a certain similarity in the calculation results of half wavelength. According to the analysis, if the incident wave and the reflected wave phase difference to a certain value, there may be some resonance effect, thus the movement and force of the cylinder reach a peak. For the second cylinder, when T=1.7s, the change rule is similar to the first cylinder, but it does not happen for the other two periods.

4.2.3 Wave energy conversion efficiency

Wave energy conversion efficiency is the key parameter for the wave energy collection device. The primary conversion coefficient can be written as:

$$P_0(t) = \left|F_{damp}\cdot\dot{z}\right| = \left|C\dot{z}\cdot\dot{z}\right| \qquad (7)$$

In which $\dot{z}$ is vertical speed of cylinder, C is damping coefficient, the wave energy converted from t_1 to t_2 can be expressed as:

$$\overline{P_0} = \int_{t_1}^{t_2} P_0(t)dt/(t_2 - t_1) \qquad (8)$$

According to the results of Toyata et al.(2013), the wave energy of unit width is obtained by the following formula:

$$P_{wave} = \frac{\pi}{2kT}\rho g\left(\frac{H}{2}\right)^2\left(1+\frac{2kh}{sinh2kh}\right) \qquad (9)$$

Primary wave energy conversion efficiency is:

$$\eta = \frac{\overline{P_0}}{P_{wave}} \qquad (10)$$

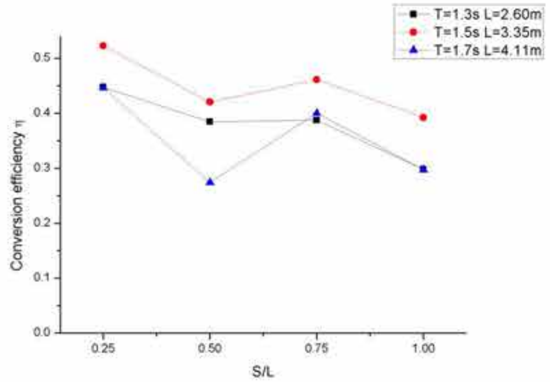


Fig.12 Primary wave energy conversion efficiency

Fig.12 shows the relationship between wave energy conversion efficiency and the distance between two cylinders. The wave energy conversion efficiency of the two cylinders is obviously affected by the distance between two cylinders. By comparison, it is found that the wave energy conversion efficiency is maximum at S/L=0.25. with the increase of distance, the wave energy conversion efficiency first decreases and then increases, then decreases. Its variation is similar to the movement and force, which shows the effect of the interaction between the cylinders on the total efficiency. Overall, as the distance increases, the wave energy conversion efficiency has a general downward trend, which may be caused by wave dissipation. first cylinder wave energy conversion efficiency is significantly higher than the second, and this phenomenon is not observed under the other two wavelengths.

5 Conclusions

In this paper, the naoe-FOAM-SJTU solver based on OpenFOAM is used to simulate the wave response and the energy conversion efficiency of a single cylindrical floating body and two cylindrical floating bodies. In this paper, the accuracy of 3D simulation results is verified by comparing the results of three-dimensional calculation to 2D results and experimental results. Then, the wave response of two cylinders in different periods and different distances is simulated and calculated. The results show that the distance between the two cylinders has a considerable influence on the movement of the cylinder, the force and the conversion efficiency of the wave energy. Motion, force and wave energy conversion efficiency have similar trend with the distance. When the difference between the distance is half a wavelength, some variables are similar, which may be due to the interaction between the reflected wave produced by the second cylinder and the incident wave. This paper finds some interesting phenomena, and the mechanism behind it is worth further research.

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