Numerical Simulation For Hydrodynamic Response Of Wave Energy Converter In Extreme Waves

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***Abstract*— The survivability of wave energy converter(WEC) in extreme sea conditions is key index that affects its overall performance. In this paper, CFD method is used to simulate the response of a cylindrical WEC in waves. The naoe-FOAM-SJTU solver based on the open source CDF platform OpenFOAM is used for the simulation. Focused waves of certain amplitude and period are generated using Waves2Foam solver, and the accuracy of the waves is verified through comparison with experiments. The interaction between the fixed cylinder and floating cylinder with the focused wave is simulated respectively, then the pressure and force of the cylinder together with surface elevation are analysed. The results show that the influence of cylinder motion on surface elevation is significant. The change of wave pressure on the fixed cylinder is more likely to cause damage to the structure. The interaction between the cylinder and the wave affects the amplitude and period of the force on the floating body.**

***Keywords*— naoe-FOAM-SJTU, wave energy converter, focused wave, survivability**

I. INTRODUCTION

Survivability is an inevitable index in wave energy converter design. The UK Energy Research Centre defines survivability as “the ability to survive predicted and surprise extremes in wind, wave and tidal current conditions, in any combination” [1]. Becoming a key issue in the field of marine renewable energy, survivability has attracted more and more researchers’ attention. Since the WEC is directly exposed to the wave load, the survivability is more important. Although some complex wave energy converters are theoretically highly efficient, the reliability is insufficient, which makes maintenance cost of these devices much higher. As a consequent, exquisite design such as “Salter duck”[2], the theoretical wave energy conversion efficiency of which is over 80%, can only exist in the laboratory, and difficult to be applied on a large scale because of its high manufacturing cost and maintenance cost.

Survivability includes long-term survivability and short-term survivability. Long-term survivability generally refers to the ability of WECs to work in general sea conditions for long periods of time. The stability of mechanical devices and electronic devices in wave energy conversion devices will be affected under the wave load over the years, and regular inspection and maintenance are required to maintain the stability of the devices. Short-term survivability refers to the ability of wave energy converter to maintain structural stability in extremely sea conditions. Wave loads, green water, and mooring loads have attracted more attention in the study of short-term survivability. once these conditions occur, WEC structures may be destroyed in an instant.

Focused waves are irregular waves. A series of regular waves peak at the same position at the same time, making the instantaneous wave of irregular waves reach the maximum. Focused wave is the ideal prototype to study the extreme waves. Longuet-Higgins studies the statistical and nonlinear effects of extreme waves in random ocean environment [3]. Chaplin et al. compared the wave loads of regular and focused waves on vertical cylinders by experimental method. It was found that the wave loads of focused waves on vertical cylinders were larger at the same wave height and period [4]. Zhao and Hu carried out a series of numerical simulations on the nonlinear interaction between the focused wave group and the floating body [5].

In this paper, the interaction between the focused wave and the horizontal cylindrical floating body is simulated, the motion and pressure of the WEC under extreme wave conditions are studied, and the short-term survival performance of the wave energy conversion device is analysed. Hydrodynamic performance of wave energy converter under extreme waves is simulated and analysed using CFD method. Naoe-FOAM-SJTU, a marine engineering solver developed based on open source CFD software OpenFOAM, is used for numerical simulation. And wave solver waves2foam is used to generate focused wave.

II. MATHEMATICAL AND NUMERICAL MODEL

A. Governing Equation

The governing equations include continuity equation and Navier-Stokes equations based on incompressible viscous fluid assumption, which are given as

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

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

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.

To describe the free surface of the fluid, the fluid volume method (VOF) [6] method is used to capture the free surface.

Phase parameter is introduced to describe the state of the fluid in a grid, which is given by

$$\frac{\partial\alpha}{\partial t} + \nabla\cdot\left[(U-U_g)\alpha\right] + \nabla\cdot\left[U_r(1-\alpha)\alpha\right] = 0 \qquad (3)$$

Where U_g and U_r represent velocity of the mesh node and velocity of the interface respectively.

B. Numerical wave tank

Wave generation and wave elimination are realized by using the numerical wave solver Waves2foam[7] based on open source CFD toolbox OpenFOAM. Waves2foam generates waves by setting inlet velocity boundary conditions and eliminates waves by setting outlet conditions, where the wave parameters are adjusted by relaxation factors. Relaxation factor is introduced to adjust wave parameters, which is given by

$$\alpha_R(\chi_R) = 1 - \frac{\exp(\chi_R^{3.5})-1}{\exp(1)-1} \; for \; \chi_R \epsilon [0,1] \qquad (4)$$

In which, α_R is relaxation factor, which is a function of χ_R. As is shown in Fig. 1.

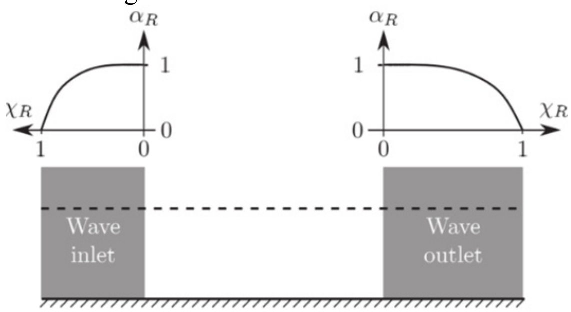


Fig. 1 A sketch of the variation of α_R and χ_R for both inlet and outlet relaxation zones

C. Geometry model and mesh conditions

Specific geometric model configuration is shown in the Fig. 2, the wave tank is 10m in length, 4m in width, 1.5m in height, with water depth of 1m. The relaxation zone of wave maker is at the left side of the wave tank, the length of which is set as 3m long to ensure the sufficient evolution of waves, so as wave eliminator at the right side. The mesh at that free surface is encrypt to ensure the calculation accuracy. The total number of mesh is about 1.1 million, as is shown in Fig. 3.

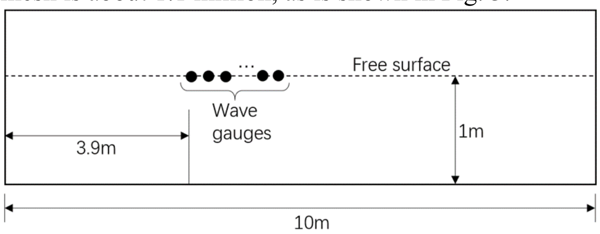


Fig. 2 Configuration of numerical wave tank

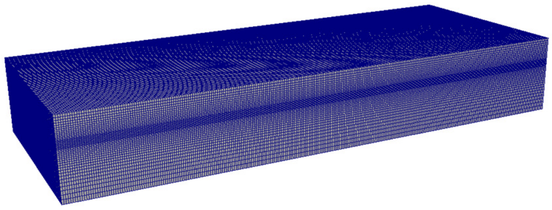


Fig. 3 Mesh distribution of computational domain

III. GENERATION OF FOCUSED WAVE

The focused waves generated in this paper are composed of 29 waves with period range from 0.5s to 1.5s. Each component has the same period interval and amplitude. The parameters are derived from the experimental results of Baldock et al. [8]. The focusing position of the wave is set as 3.9 m away from the left boundary and the focusing time is set as 10s. Due to the interaction of waves, the actual focusing position and focusing time may deviate from the set value. A series of wave gauges are set every 0.05 m to determinate the actual focusing configuration.

Fig. 4 presents time histories curve of wave elevation recorded by each wave gauge. The actual focusing position is the position corresponding to the highest surface elevation obtained by wave gauges. Comparing the surface elevation of each wave gauge, the focusing position is determined to be 4.2m away from the left side, and the focusing time is 10.13s, corresponding to the wave gauge 6.

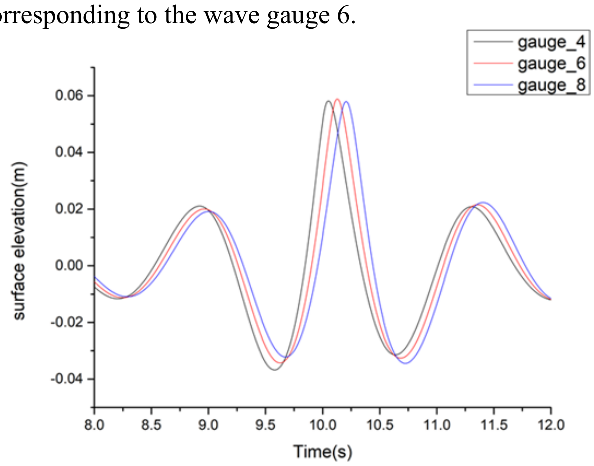


Fig. 4 Surface elevation recorded by each gauge

The relationship between focusing time and focusing position and wave amplitude is shown in Table 1. Both the focusing time and the focusing position of the focused wave change with the increase of the amplitude, which may be caused by the interaction between the wave components. In this paper, there is a linear relationship between the focusing time and the focusing position with the wave amplitude in several conditions. This relationship requires more calculation for verification.

TABLE I
RELATIONSHIP BETWEEN FOCUSING TIME AND POSITION WITH AMPLITUDE

Amplitude(m)	Focusing time(s)	Focusing position(m)
0.03	0	0
0.04	+0.04	+0.1
0.05	+0.09	+0.2
0.06	+0.13	+0.3

Fig. 5 shows the comparison between the numerical simulation results, experimental results and the theoretical results of second-order wave. The numerical simulation results are in good agreement with the experimental results, which ensures the accuracy of the numerical simulation.

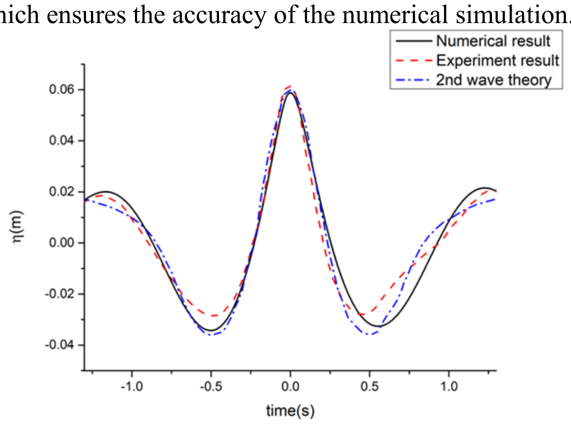


Fig. 5 Comparison between the numerical simulation results, experimental results and theoretical results

IV. INTERACTION BETWEEN WAVES AND STRUCTURES

In this part, the interaction between the focused wave and the horizontal cylinder is studied.

A. Vertical Displacement and Surface Elevation

The cylinder is 1 m long and 0.25 m in diameter, placed at the focal position of the focused wave, 4.2 m from inlet. Its model and nearby mesh distribution is as shown in Fig. 6. In order to study the motion response characteristics of horizontal cylinder in focused wave, fixed cylinder and cylinder with freedom in z-direction are set up respectively.

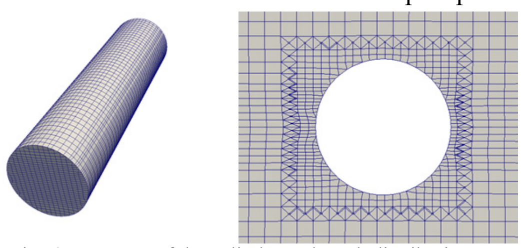


Fig. 6 Geometry of the cylinder and mesh distribution around

The Fig. 7 shows the displacement of floating cylinder. When the peak of the focused wave meets the cylinder, the cylinder moves to the highest point. The maximum displacement amplitude of motion appears at 10.7s. Since the direction of motion of the cylinder is consistent with the wave phase at this time, the displacement amplitude of the cylinder is larger than that of the focusing time.

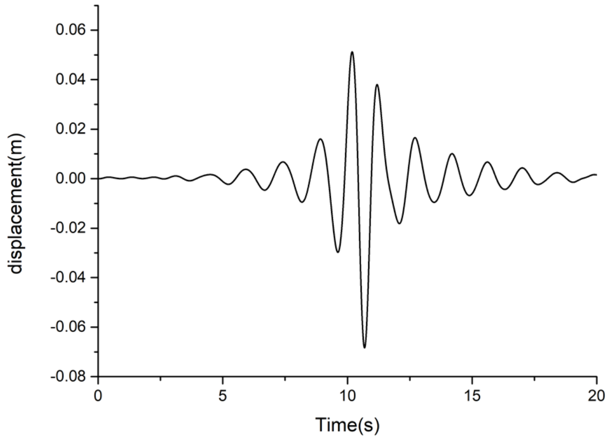
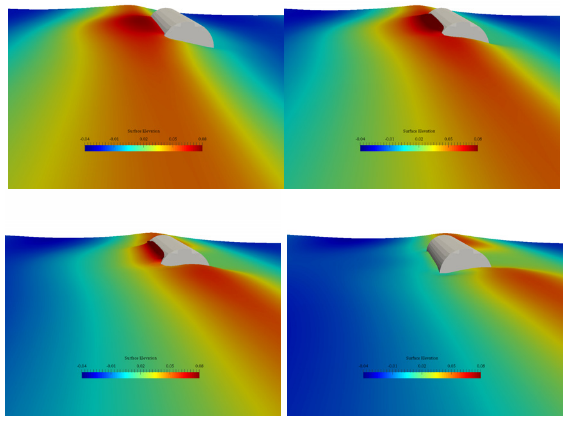
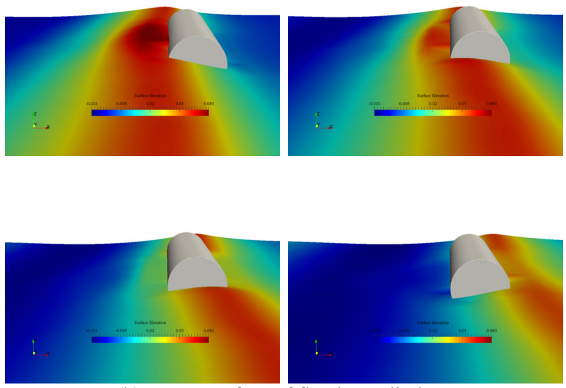


Fig. 7 Vertical displacement of floating cylinder



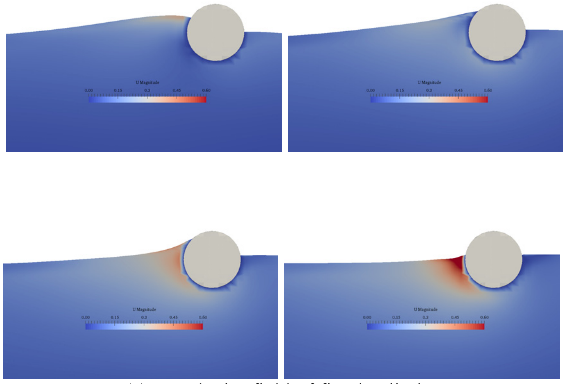
(a) Free surface of fixed cylinder



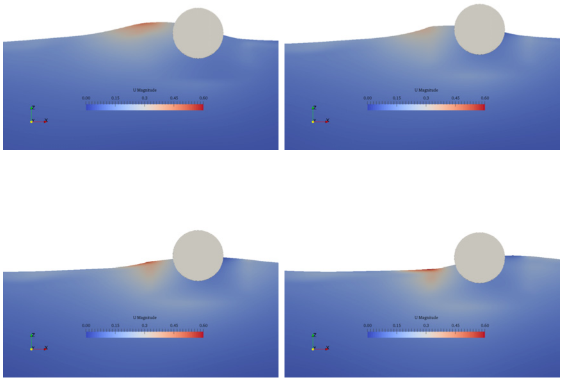
(b) Free surface of floating cylinder

Fig. 8 Surface elevation when the focused wave meets the cylinder

The surface elevation when the focused wave meets the cylinder is shown in the Fig. 8, and the velocity field of the fluid is shown in Fig. 9.



(a) Velocity field of fixed cylinder



(b) Velocity field of floating cylinder

Fig. 9 Velocity field when the focused wave meets the cylinder

The Fig. 10 shows the time series of surface elevation at the front of the cylinder (x=4.05 m). When the wave amplitude is small, there is little difference in surface elevation between different situations. At focusing time, the wave surface rises obviously due to the blocking of the cylinder. Compared with the fixed cylinder, the floating cylinder has a larger wave surface elevation on its front side due to coupling of the cylinder and wave. After the wave crest passes through the cylinder, the difference between the wave surface elevation of the fixed cylinder and that of the non-cylinder is very small and becomes smaller with time. The surface elevation of floating cylinder is obviously different from that of fixed cylinder and non-cylinder. The difference of wave surface after focusing time is mainly due to the wave rising caused by the movement of floating cylinder, which affects the phase of the incident wave.

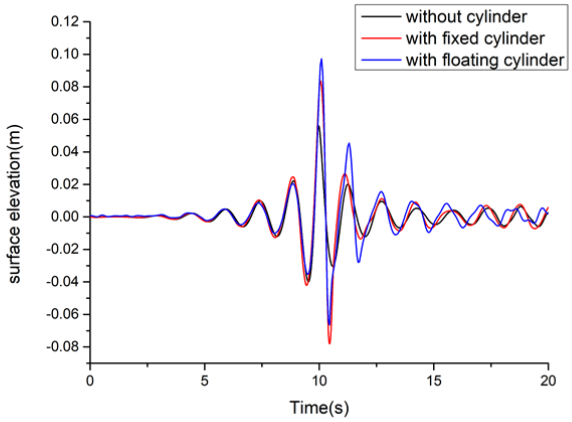


Fig. 10 Surface elevation at x=4.05 m

The Fig. 11 shows the time series of wave surface height at the rear side of the cylinder (x = 4.35 m). Before the focusing time, the surface elevation difference is not big in all three cases. in the case of no-cylinder, the wave surface height is higher because there is no cylinder to stop the wave from moving forward. When the focused wave passes through, the height of the wave surface is the largest in the case of non-cylinder because the wave is not affected. Compared with the fixed wave, the floating cylinder has less blocking effect on the wave. After the focused wave passes through the cylinder, the change of the free surface of the floating cylinder is obviously larger than that of the other two cases，which is mainly due to the wave generated by the movement of the floating cylinder, which overlaps with the original wave and increases the overall amplitude.

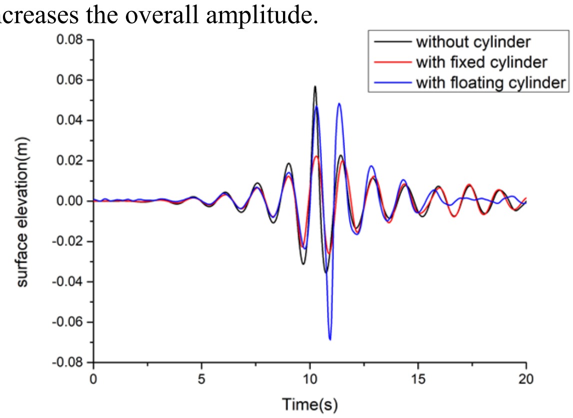


Fig. 11 Surface elevation at x=4.35 m

B. Pressure and Forces

The pressure on the surface of the floating body will destroy the structural stability of the device. Eight pressure sensors are arranged on the surface of the cylinder to study the pressure on the surface of the floating body under the focused wave, as shown in the Fig. 12. The Fig. 13 shows the measurement results of Sensor 1 and Sensor 7, respectively corresponding to the sensors with the largest pressure fluctuation and the largest pressure amplitude.

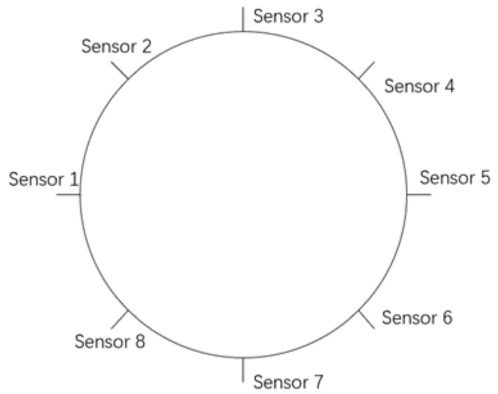
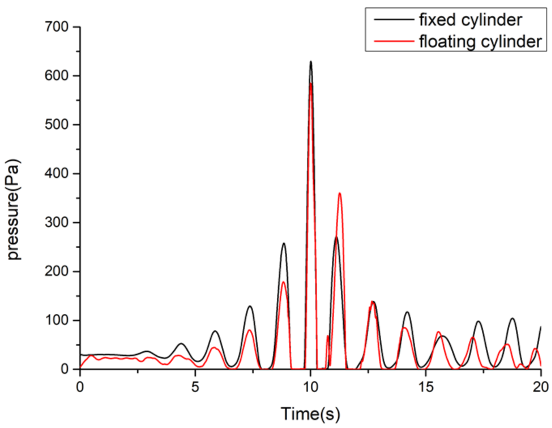
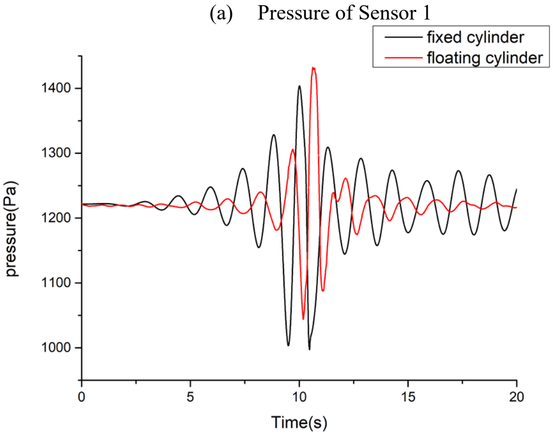


Fig. 12 Location of pressure sensors on the cylinder



(a) Pressure of Sensor 1



(b) Pressure of Sensor 7

Fig. 13 pressure of Sensor 1 and Sensor 7 on the cylinder

For the pressure sensor 1, the pressure on the fixed cylinder at the focusing time is greater than the pressure on the floating cylinder, which means that the movement significantly reduces the maximum pressure on the floating body. Therefore, it can be concluded that the interaction between the floating body and waves can reduce the pressure on the floating body and improve the survivability of the device under some circumstances.

The pressure Sensor 7 records the maximum pressure on the floating body, which appears at the bottom of the cylinder. The pressure on the cylindrical surface at this position is mainly due to the change of free surface. The period and peak value of the pressure on the bottom of the cylinder are different from that of the fixed cylinder because the movement changes the draught of cylinder. The peak pressure on the floating cylinder is greater than that on the fixed cylinder in this case.

The mooring system is required to fix the position of the wave energy converter in actual sea conditions. Therefore, the force on the floating body in waves needs to be studied. The Fig. 14 and the Fig. 15 are the forces on the cylinder in the horizontal direction and vertical direction. The peak value of horizontal force on the fixed cylinder is slightly higher than that on the floating cylinder, while period is almost the same. Due to the movement of the cylinder, the period and amplitude of the vertical force in both cases are quite different, which is similar to the trend of pressure of Sensor 7.

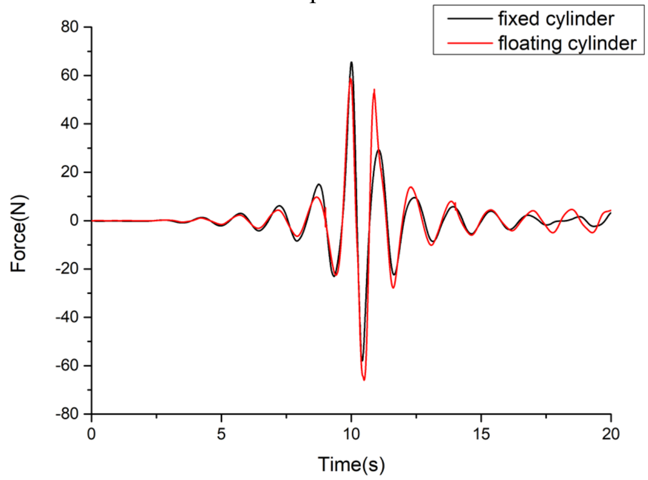


Fig. 14 Horizontal force of cylinder

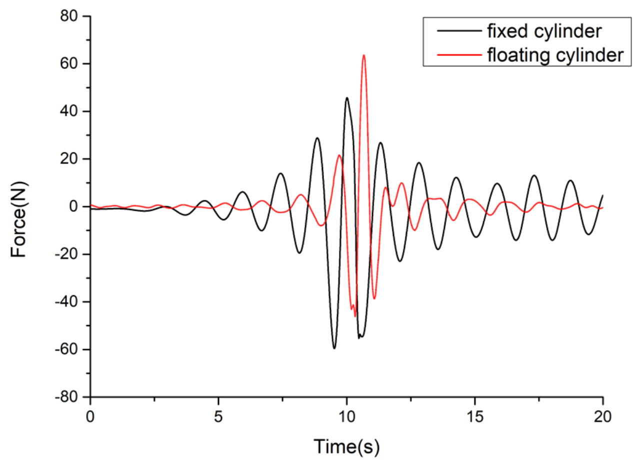


Fig. 15 Vertical force of cylinder

V. Conclusions

In this paper, the ocean engineering solver naoe-FOAM-SJTU developed based on OpenFOAM, an open source CFD software, is used to simulate the hydrodynamic response of a cylindrical wave energy converter in a focused wave. The results show that:

1.The focused wave with specific parameters can be effectively simulated by Waves2foam. The focusing position moves toward wave direction with the increase of wave amplitude, and the focusing time increases at the same time. In these cases, the focusing position and time are linearly related to the wave amplitude, but this relationship requires verification by further calculation.

2.The force and pressure of the cylinder during the focusing time are obviously influenced by the movement. The period and amplitude of pressure on the cylinder at the bottom and vertical force on the cylinder are both affected by interaction between the cylinder and waves. The movement reduces the intensity of the pressure change of the floating body.

3.The surface elevation near the focal point changes greatly due to the influence of the cylinder. The wave generated by the cylinder postpone the maximum amplitude of the surface elevation by half of the period.

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