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Numerical Simulation and Research of Motion Characteristics for Surge-heave Coupled Motion of Moonpool

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Abstract

By application of the Fluent software, the forced surge-heave coupled oscillation of a 2D rectangular moonpool structure is simulated numerically. The influences of different oscillation frequencies, amplitudes and the ratios of the opening on the fluid forces on the moonpool are discussed. It is shown that, when the moonpool is under surge-heave coupled motion, the change of surging amplitude or frequency has different effects on the amplitudes and the waveform of time-history curve of each fluid force and moment, while, the change of heaving amplitude or frequency has only influences on the amplitudes of the vertical fluid force. The amplitudes and the waveform of time-history curve of the horizontal fluid force and moment are almost unaffected by the different ratios of the opening, while the amplitudes of the vertical fluid force decreases with the increase of the opening. The calculation results and the revealed phenomena have important significance for engineering design.

Keywords

Moonpool; Numerical Simulation; Coupled Surge-heave; Motion Characteristics; Fluid Forces.

1. Introduction

With the increasing demand for marine resources, all kinds of engineering vessels and offshore platforms are developing continuously. In order to facilitate the installation of pipeline facilities and protect operations, the offshore drilling platform is usually equipped with a moonpool with an opening at the bottom that runs through the hull. It is necessary to study the hydrodynamic characteristics of the moonpool for the rational design of its structure.

Two natural vibration modes of fluid in the moonpool are divided into the piston mode and sloshing mode by Fukuda[1]. The natural modes of oscillation of the inner free surfaces of the moonpool are determined, under the assumption of infinite water depth via linearized potential flow theory, and the problem is treated in two and three dimensions by Molin[2]. Based on reference[2], by solving the coefficient matrix of potential function via Galerkin method, the semi-analytical solution of natural frequencies and shapes of fluid was obtained, and the influences of geometric parameters of the moonpool on its natural vibration characteristics were discussed by L. Huang et al.[3]. The radiation and diffraction problems of the rectangular moonpool with different opening widths in infinite water of limited depth are studied, and the influences of opening width on the added mass and damping coefficient of the moonpool is analyzed by H.W. Zhou et al.[4]. The radiation and diffraction problems of the rectangular moonpool in front of a straight wall are studied by the method of variation separation, and the effects on the hydrodynamic characteristics of the moonpool caused by different

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opening positions and different distances between the moonpool and the wall are analyzed by H.S Zhang and H.W. Zhou[5].

The above theoretical research methods are all based on linear potential theory, so it is difficult to consider the influence of viscosity and the nonlinear influence of the fluid in the moonpool. Therefore, numerical simulation based on CFD theory is more convenient to accurately research the change of flow field. A method including both numerical simulation and analysis for ship added mass and damping coefficient was outlined for ship oscillating in waves by R.C. Zhu et al.[6]. By application of the Fluent software, the flow filed of a drillship with a step-style moonpool is simulated numerically, and the resistance performance of the drillship is analyzed by Z.Y. Li and H.B. Zhang[7]. By application of the Fluent software, forced oscillations of a rectangular moonpool with or without a straight wall are simulated numerically by H.S Zhang et al.[8]. In the case of each opening ratio, the numerical simulation results are in good agreement with the analytical results[4,5]. It proves the method in reference[8] successfully implements the numerical simulation of the surge and heave motion of the moonpool.

In practical engineering, the ship or offshore platform not only moves in a single mode, but also moves in coupled mode. In this paper, based on reference[8], the forced surge-heave coupled oscillation of a 2D rectangular moonpool structure is simulated numerically. The influences of motion parameters and the ratios of the opening on the fluid forces on the moonpool are discussed.

2. Numerical model

2.1 Structure model of wave tank and moonpool

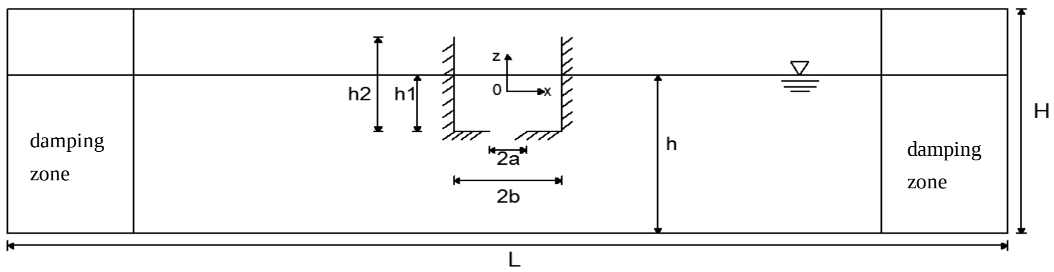

Figure 1. Schematic diagram of numerical wave tank and moonpool

A two-dimensional numerical wave tank is established to simulate the different oscillatory motions of a rectangular moonpool. The upper part of the water tank is air and the lower part is water, the origin of the coordinate axis is located in the center of the moonpool structure, the damping zones are set at both ends of the water tank, see Figure 1. Fluent software was used for numerical simulation, and the basic parameters of the numerical model are shown in Table 1.

Table 1. Basic parameters of the numerical model

parameter	computational domain			moonpool		
	L/m	H/m	h/m	$2b$/m	h_1/m	h_2/m
value	20.0	6.0	3.0	1.0	1.0	1.5

2.2 Grid partition

The grid structure is shown in Figure 2. The annular area set around the moonpool can adapt to the variation of the dynamic grid when the moonpool is under surge-heave coupled motion. Because the fluid is moving violently at the free surface, the grid near the free surface is encrypted. At the bottom and top of the tank, duo to the slight influence of the oscillatory motion, the grid of these areas can be simplified.

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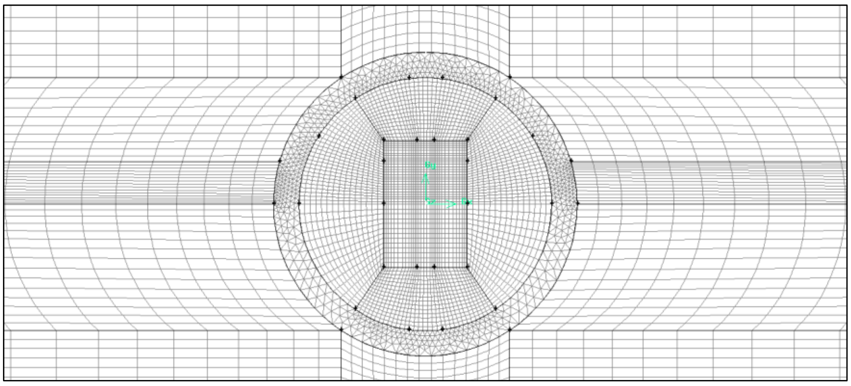

Figure 2. Schematic diagram of grid division

2.3 Numerical model and boundary conditions

In Fluent, the VOF model is used to capture the free surface, RNG $k-\varepsilon$ model is selected as viscous model, PISO is selected as solution method of pressure-velocity coupling. In RNG $k-\varepsilon$ model, the functions of turbulent kinetic energy k and turbulent dissipation rate ε can be expressed in the following forms in reference[9]

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=\frac{\partial}{\partial x_j}(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j})+2\mu_t\frac{\partial u_i}{\partial x_j}S_{ij}-\rho\varepsilon \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho u_j\varepsilon)}{\partial x_j}=\frac{\partial}{\partial x_j}(\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j})+2C_1\frac{\varepsilon}{k}\mu_t\frac{\partial u_i}{\partial x_j}S_{ij}-C_2\rho\frac{\varepsilon^2}{k} \tag{2}$$

Where ρ is density, t is time, u_i and u_j are the velocity components in the the directions of x_i and x_j, S_{ij} is value of the mean strain and μ_{eff} is total viscosity

$$S_{ij}=\frac{1}{2}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}) \tag{3}$$

$$\mu_{eff}=\mu_t+\mu \tag{4}$$

$$\mu_t=C_\mu\rho\frac{k^2}{\varepsilon} \tag{5}$$

Where μ_t is turbulent viscosity, μ is molecular viscosity and its value is 1.003×10^{-3} kg/m·s.

The coefficient C_1

$$C_1=1.42-\frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3} \tag{6}$$

Where η is additional expansion parameter

$$\eta=\frac{Sk}{\varepsilon} \tag{7}$$

$$S=2(S_{ij}S_{ij})^{1/2} \tag{8}$$

Other coefficients: $C_2=1.68$, $C_\mu=0.085$, $\alpha_k=\alpha_\varepsilon=1.39$, $\eta_0=4.38$, $\beta=0.015$.

The wall boundary condition is set on the surface of the moonpool. The oscillation motion of the moonpool is expressed as

$$x_j=x_{j0}\sin\omega t \tag{9}$$

$$\dot{x}_j=x_{j0}\omega\cos\omega t \tag{10}$$

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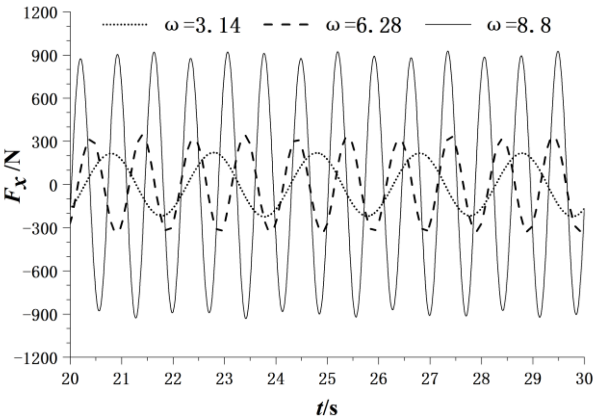
where, x_j is displacement, $\dot{x}_j$is velocity, j=1,2 respectively represents surge and heave motion, x_{j0} is amplitude of the oscillatory motion, ω is circular frequency. According to Equation(10), use the secondary development function of Fluent software to write UDF program to realize the numerical simulation of the surge-heave coupled motion.

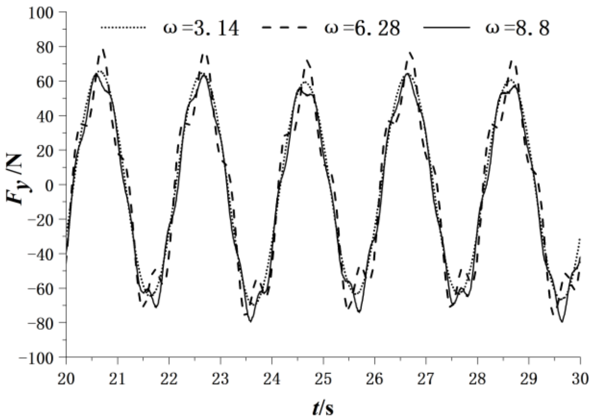
When the moonpool is oscillating, at both ends of the tank, the momentum source method is used to eliminate the waves reflected on the side walls of the tank. The wall boundary condition is set on the left and right sides and the bottom of the tank, the pressure-inlet boundary condition is set on the top of the tank.

3. Influence of oscillation frequency on coupled motion

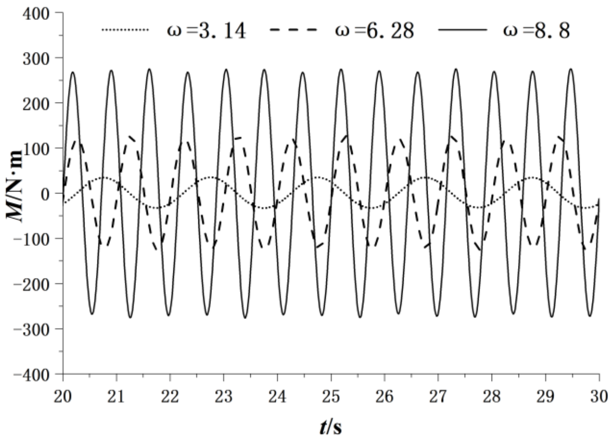
The fluid forces on the moonpool can be divided into F_x, F_y and M, where F_x is horizontal force, F_y is vertical force and M is moment. In order to investigate the influences of oscillation frequency on surge-heave coupled motion, assume the opening ratio of the moonpool *a/b* is 0.2, select different frequencies of surge and heave motion for numerical simulation to discuss the force variation of the moonpool.



(a) Horizontal force



(b) Vertical force



(c) Moment

Figure 3. Comparisons of the forces under surge-heave coupled motion with different surging frequencies

3.1 Influence of surge frequency on coupled motion

Under the coupled motion, the amplitude of surge motion x_{10} is assumed to be 0.01m, and the amplitude of heave motion x_{20} is assumed to be 0.02m, the frequency of heave motion is 3.14rad/s.

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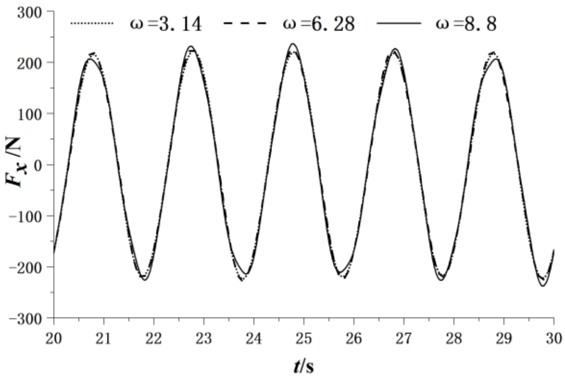
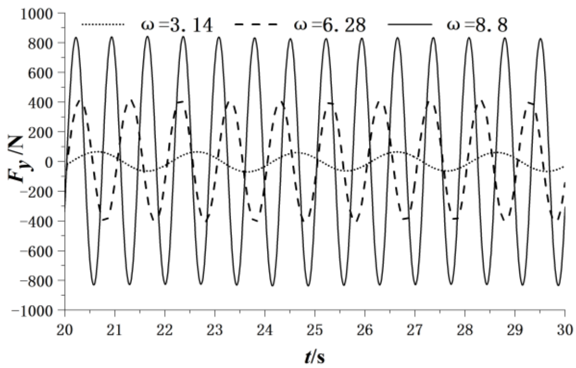
Compare the differences of fluid forces under surge-heave coupled motion, when the frequencies of surge motion are 3.14, 6.28 and 8.8rad/s, see Figure 3. Under the coupled motion, the amplitudes of both F_x and M are greatly affected by the change of surge frequency, while the waveform of their time-history curves is almost not affected, see Figure 3(a) and 3(c). And when surge frequency is 8.8rad/s, the amplitudes of both F_x and M are about 4.5 times that of 3.14rad/s, while the waveform of time-history curves of forces and moment is regular sinusoidal variations.The amplitude of F_y is almost unaffected by the change of surge frequency, but the waveform of its time-history curve is greatly influenced, see Figure 3(b). And when surge frequency is 3.14rad/s, the time-history curve of F_y is almost a regular sinusoidal variation, but with the increase of surge frequency, the nonlinear action at the peak and trough of the wave is gradually enhanced, and the waveform becomes more irregular.

3.2 Influence of heave frequency on coupled motion

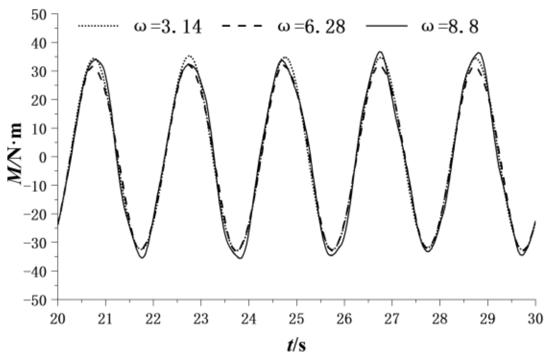
Under the coupled motion, the amplitude of surge motion x_{10} is assumed to be 0.01m, and the amplitude of heave motion x_{20} is assumed to be 0.02m, the frequency of surge motion is 3.14rad/s. Compare the differences of fluid forces under surge-heave coupled motion, when the frequencies of heave motion are 3.14, 6.28 and 8.8rad/s, see Figure 4. Under the coupled motion, the amplitudes of both F_x and M are almost not affected by the change of heave frequency, the waveform of their time-history curves has a slight effect on the position of the peak and trough, see Figure 4(a) and 4(c). The amplitude of F_y is greatly influenced by the change of heave frequency, but the waveform of its time-history curve is almost unaffected, see Figure 4(b). And when the heave frequency is 8.8rad/s, the amplitude of F_y is about 8 times that of 3.14rad/s, while the time-history curves are regular sinusoidal variations.



(a) Horizontal force



(b) Vertical force



(c) Moment

Figure 4. Comparisons of the forces under surge-heave coupled motion with different heaving frequencies

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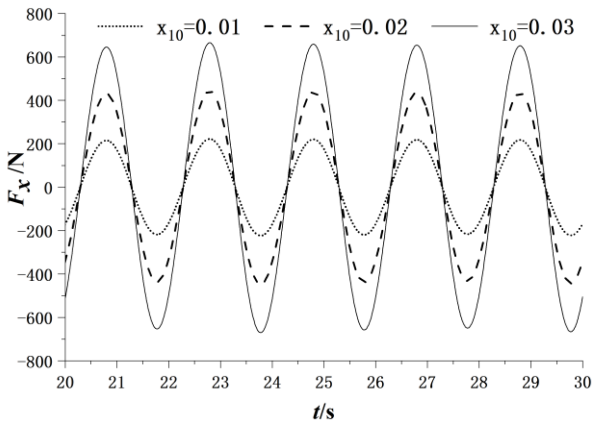
4. Influence of oscillation amplitude on coupled motion

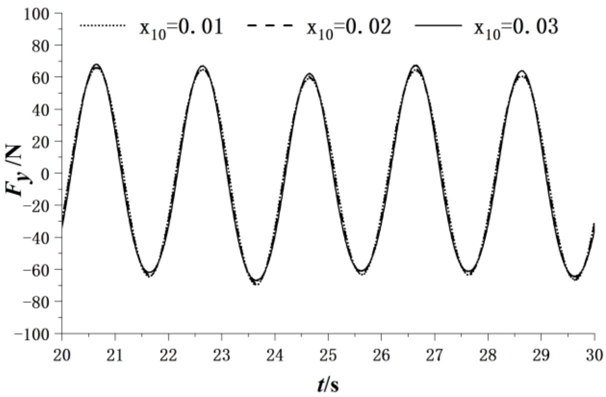
In order to investigate the influence of oscillation amplitude on surge-heave coupled motion, assume the opening ratio of the moonpool *a/b*=0.2, different amplitudes of surge and heave are selected for numerical simulation to discuss the force variation of the moonpool.

4.1 Influence of surge amplitude on coupled motion

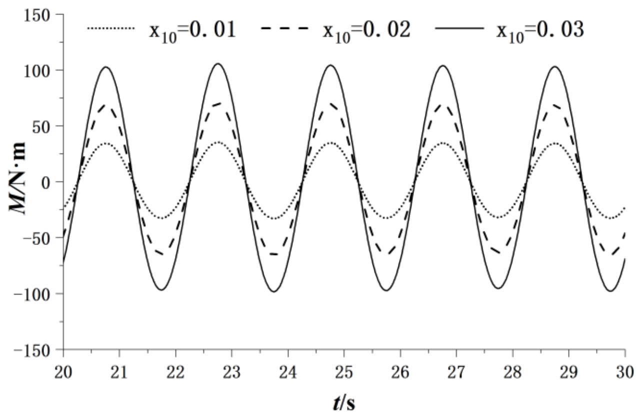
Under the coupled motion, the amplitude of heave motion x_{20} is assumed to be 0.02m, the frequency of both surge and heave motion is 3.14rad/s. Compare the differences of fluid forces under surge-heave coupled motion, when the amplitudes of surge motion are 0.01, 0.02 and 0.03m, see Figure 5. Under the coupled motion, the amplitudes of both F_x and M are greatly affected by the change of surge amplitude, while the waveform of their time-history curves is almost not affected, see Figure 5(a) and 5(c). And when surge amplitude is 0.03m, the amplitudes of both F_x and M are about 3 times that of 0.01m, their time-history curves are regular sinusoidal changes, although surge amplitudes are different. The amplitude of F_y and its waveform of the time-history curve are almost unaffected by the change of surge amplitude, see Figure 5(b).



(a)Horizontal force



(b) Vertical force



(c) Moment

Figure 5. Comparisons of the forces under surge-heave coupled motion with different surging amplitudes

4.2 Influence of heave amplitude on coupled motion

Under the coupled motion, the amplitude of surge motion is assumed to be 0.01m, the frequency of both surge and heave motion is 3.14rad/s. Compare the differences of fluid forces under surge-heave

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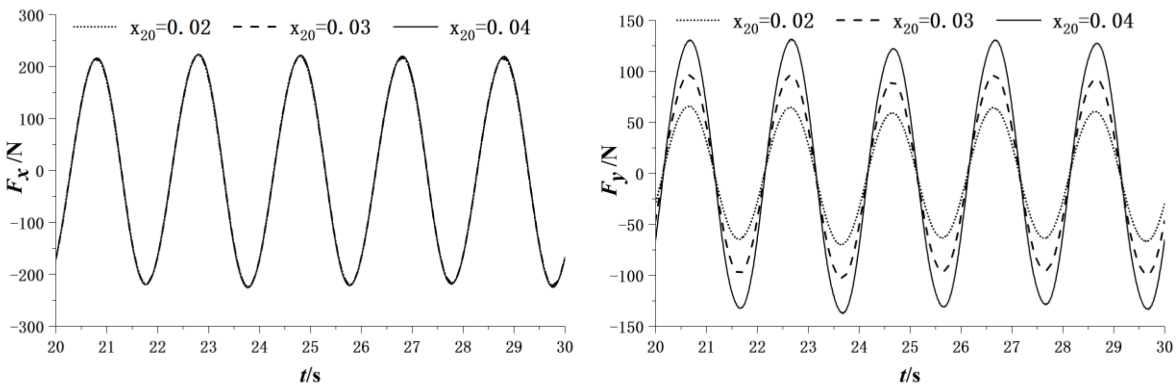
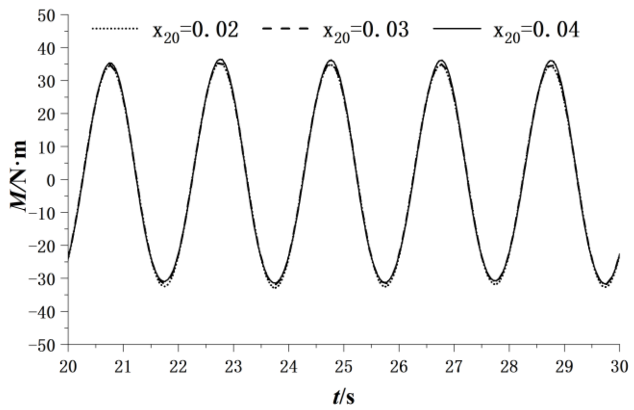
coupled motion, when the amplitudes of heave motion are 0.02, 0.03 and 0.04m, see Figure 6. Under the coupled motion, the amplitudes of both F_x and M and the waveform of their time-history curves are almost not affected by the change of heave amplitude, see Figure 6(a) and 6(c). The amplitude of F_y is greatly influenced by the change of heave amplitude, the larger the heave amplitude is, the greater F_y is, see Figure 4(b). And when heave amplitude is 0.04m, the amplitude of F_y is about 2 times that of 0.02m, while the time-history curves are regular sinusoidal variations. For different heave amplitudes, the time-history curves of F_y are all regular and smooth sinusoidal.



(a) Horizontal force (b) Vertical force



(c) Moment

Figure 6. Comparisons of the forces under surge-heave coupled motion with different heaving amplitudes

5. Influence of the ratio of the opening on coupled motion

In order to study the influences of the ratio of the opening on the forces of the coupled motion, the amplitude of surge motion x_{10} is assumed to be 0.01m, and the amplitude of heave motion x_{20} is assumed to be 0.02m, the frequencies of both surge and heave motion are 3.14rad/s. Compare the differences of fluid forces under surge-heave coupled motion, when a/b is 0.2, 0.4, 0.6 and 0.8, see Figure 7. The amplitudes of both F_x and M and their waveform of the time-history curves are not affected at different ratios of the opening, see Figure 7(a) and 7(c). The amplitude of F_y decreases with the increase of the ratio of the opening, and when a/b=0.8, the amplitude of F_y is only 1/6 of that when a/b=0.2, while the ratio of the opening has little effect on its waveform of the time-history curve, see Figure 7(b).

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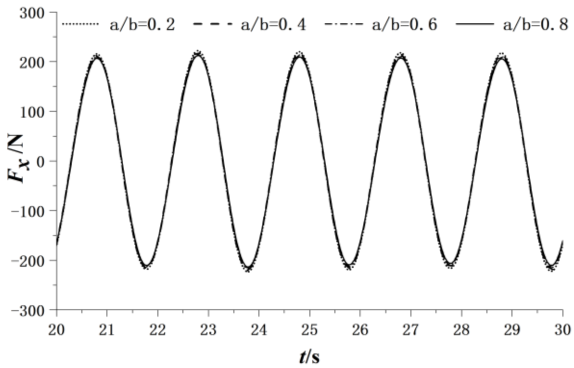
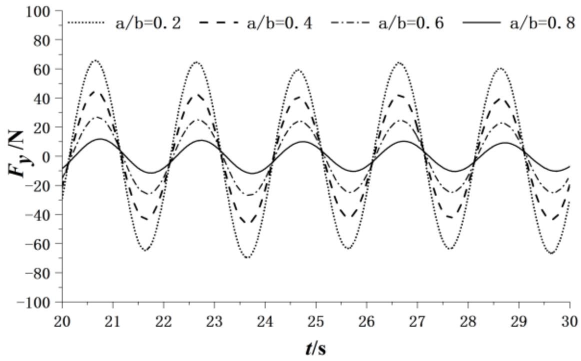
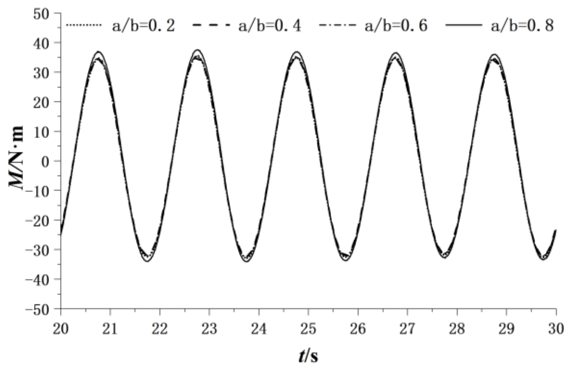


(a) Horizontal force



(b) Vertical force



(c) Moment

Figure 7. Comparisons of the forces under surge-heave coupled motion with different values of a/b

6. Conclusion

In this paper, by application of the Fluent software, the forced surge-heave coupled oscillation of a 2D rectangular moonpool structure is simulated numerically. The influences of different oscillation frequencies, amplitudes and the ratios of the opening on the fluid forces on the moonpool are discussed. The results prove that:

1) The amplitude of vertical force is slightly affected by the change of surge frequency, while the amplitudes of both horizontal force and moment increase with the increase of surge frequency. The time-history curves of horizontal force and moment are weakly affected by the change of surge frequency, while with the increase of surge frequency, the non-linearity of waveform of the time-history curve enhances gradually. The variation of heave frequency has little effect on the amplitude and waveform of horizontal force and moment, while the amplitude of vertical force increases rapidly with the increase of heave frequency.

2) The amplitude of vertical force is slightly affected by the change of surge amplitude, while the amplitude of horizontal force and moment increase with the increase of surge amplitude. The waveform of the time-history curves in all directions are not affected by the change of surge amplitude. The variation of heave amplitude has little effect on the amplitude and waveform of horizontal force and moment, while the amplitude of vertical force increases rapidly with the increase of heave amplitude.

3) The amplitude of horizontal force and moment and the time-history curves are almost unaffected by the opening ratio of the moonpool, while the amplitude of vertical force decreases with the increasing of the opening.

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The research results in this paper need to be compared with the model tests for mutual verification, but the in-depth understanding of the motion law of the moonpool can be used for reference when designing the structure of the moonpool and selecting the parameters of the physical model test, so as to avoid blind tests.

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