Research Article

Zhiyang Zhang*, Weixing Liu, Xiongbo Zheng, Hengxu Liu, and Ningyu Li

Numerical simulation of hydrodynamic oscillation of side-by-side double-floating-system with a narrow gap in waves

<https://doi.org/10.1515/phys-2021-0021>

received December 23, 2020; accepted March 01, 2021

Abstract: In offshore oil and gas exploration and transportation, it is often encountered that the multi-floating structures work side by side. In some sea conditions, there is a strong coupling between the multi-floating structures that seriously affects the safety of offshore operations. Therefore, the prediction of the relative motion and force between the multi-floating structures and the wave elevation around the multi-floating-system has become a hot issue. At present, the problem of double-floating-system is mostly based on linear potential flow theory. However, when the gap width between two floating bodies is small, the viscous and nonlinear effects are not negligible, so the potential flow theory has great limitations. Based on the viscous flow theory, using the finite difference solution program of FLOW3D and using volume of fluid technology to capture the free surface, a three-dimensional numerical wave basin is established, and the numerical results of the wave are compared with the theoretical solution. On this basis, the hydrodynamic model of side-by-side double-floating-system with a narrow gap is established, and the flow field in the narrow gap of the fixed double-floating-system under the regular wave is analyzed in detail. The law of the gap-resonance is studied, which provides valuable reference for the future research on the multi-floating-system.

Keywords: viscous fluid, side-by-side, double-floating-system, narrow gap, hydrodynamic oscillation, shadowing effect

1 Introduction

In recent years, with the further development and utilization of marine resources, multi-floating-system has been widely used in production practice [1–4]. Common multi-floating-system includes oil and gas transmission system [5–7], double barge system in the floating support installation of a large offshore platform [8], warship replenishment system [9], and offshore super large floating system [10–14]. In such structures, the relative distance between two or more floating structures is small, resulting in obvious hydrodynamic effects. In some cases, because of the interaction between waves and multiple-floating-system with a narrow gap, resonance occurs in the narrow gap, the wave elevation increases significantly, and the motion and force of the floating body increase correspondingly. Therefore, there will be a strong coupling problem that seriously affects the stability and safety of the offshore operation. How to effectively predict the hydrodynamic performance of the multiple-floating-system is a hot issue in the field of marine engineering in recent years.

At present, there are two main methods for hydrodynamic interference research in the narrow gap of multiple-floating-system: (1) numerical simulation based on linear potential flow theory and (2) model test. The above method mainly analyzes the force, motion response of the multi-floating-system in the wave, and the wave elevation around the floating body. As the potential flow theory ignores the nonlinear and viscous effects, the calculation result of the wave elevation in the narrow gap at the resonance frequency is too large, resulting in the calculation distortion of the wave drift force. In view of the limitations of potential flow theory, many international scholars have improved this. Huijsmans et al. [15], in the

* **Corresponding author: Zhiyang Zhang**, School of Ocean Engineering, Jiangsu Ocean University, Lianyungang 222002, China, e-mail: zhangzhiyang0530@126.com

Weixing Liu: School of Ocean Engineering, Jiangsu Ocean University, Lianyungang 222002, China

Xiongbo Zheng: School of Mathematical Sciences, Harbin Engineering University, Harbin 150001, China

Hengxu Liu: Yantai Research Institute and Graduate School, Harbin Engineering University, Yantai 265500, China

Ningyu Li: College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

study of the low-frequency slow drift force of the oil and gas transmission system, increased the boundary condition limit in the narrow gap of the two ships, which is equivalent to adding a rigid lid on the free surface of the gap, effectively reducing the peak of the slow drift force at the resonance frequency, but the rise of the free surface does not have a real simulation. The damping lid method is put forward by Chen [16]. By adding damping value at the free surface, the excessive wave elevation in the narrow gap of the double-floating-system is suppressed, and the wave elevation and wave drift force at the resonance frequency are well simulated. Pauw et al. [17] used the damping lid method proposed by Chen to study the hydrodynamic problem of mooring double-floating-system. It is found through experiments that it is difficult to give a pervasive damping value for the case with different narrow gap width. The influence of the damping lid method on the second-order wave drift force is greater than the first-order wave elevation and the motion response. Bunnik et al. [18] corrected the damping lid method and studied the mooring side-by-side liquefied natural gas (LNG) carrier. Damping is added to the free surface inside and outside the narrow gap. This method reduces the mesh dependence and provides better results. Xin et al. [19] used a combination of viscous computational fluid dynamics (CFD) and test to study the hydrodynamic interference of the side-by-side barges. On the basis of the three-dimensional potential flow theory, Zhou et al. [20] studied the hydrodynamic interference of the double-floating-system with different waves' direction by the damping lid method. Using different types of incident waves, i.e., white noise waves, transient wave groups, and regular waves, Zhao et al. [21] investigated both the transient and steady-state resonant responses of the fluid in narrow gaps at model scale, based on the potential flow solvers with the addition of calibrated damping [22].

It can be seen that the linear potential flow theory ignores the viscosity of the fluid, although it does not affect the basic law of hydrodynamic performance but causes an overestimation in the numerical simulation results. The researchers found the importance of viscosity and nonlinearity and tried to refine the results of the linear potential flow theory by the damping lid method, but it must depend on the study of the test and difficult to give a pervasive damping value. Therefore, it is necessary to develop a numerical model based on viscous fluid to study the hydrodynamic oscillation in the narrow gap of multi-floating-system in real marine environment. The details of the research work of this paper are as follows:

- (1) The basic theory of CFD method is introduced in detail.
- (2) Based on the Flow3D finite difference solution program of viscous flow theory, a three-dimensional numerical wave basin is established to simulate the hydrodynamic resonance phenomenon in the narrow gap of the double-floating-system under the action of the wave, and the calculation results are compared with the results of the literature [23–25]. The mesh convergence analysis is carried out on the hydrodynamic model of the double-floating-system, and the optimal mesh division scheme is proposed.
- (3) On this basis, the wave elevation and fluid motion in the narrow gap of fixed double-floating-system are analyzed.
- (4) The influence of narrow gap width and wave period on the wave elevation is analyzed in detail.

2 The basic theory of CFD method

2.1 Fluid flow governing equations

It is assumed that the fluid is incompressible. The governing equations include the continuity equation and the Navier–Stokes equation for incompressible viscous fluid motion. In this paper, the fluid is considered as Newtonian fluid. Because of the unique FAVOR grid processing technology of Flow3D, independent and complex geometry can be defined within the structured grid, so that the simple rectangular grid can be used to represent arbitrary complex geometry, and the shortcomings of the previous finite difference method for building boundary fitting are avoided. The software provides multi-grid nesting and local encryption technology, which can reduce the consumption of memory, provide high accuracy, and greatly improve the calculation efficiency. The continuity equation of FAVOR grid processing technology is different from the classical equation. The continuity equation and momentum equation contain volume and area fraction parameters. The specific expressions are as follows.

Continuity equation:

$$\frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z) = 0. \quad (1)$$

Momentum equation:

$$\begin{aligned} \frac{\partial u}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} + w A_z \frac{\partial u}{\partial z} \right\} \\ = -\frac{1}{\rho} \frac{\partial p}{\partial x} + G_x + f_x, \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z} \right\} \\ = -\frac{1}{\rho} \frac{\partial p}{\partial y} + G_y + f_y, \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial w}{\partial t} + \frac{1}{V_F} \left\{ u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z} \right\} \\ = -\frac{1}{\rho} \frac{\partial p}{\partial z} + G_z + f_z. \end{aligned} \quad (4)$$

In the above formula, V_F is the volume fraction of the flowable fluid in the numerical basin. A_x , A_y , and A_z represent the area fraction of the flowable fluid in the three directions x , y , and z , respectively. u , v , and w are the velocity components in the three directions x , y , and z . (G_x , G_y , G_z) is the acceleration of gravity, and (f_x , f_y , f_z) is the viscous force acceleration of the fluid.

2.2 Turbulence model

Flow3D provides five turbulence models: the Prandtl hybrid length model in the zero-equation model, an equation model, the standard $k-\varepsilon$ model, the RNG $k-\varepsilon$ model, and the large eddy simulation. In this paper, the interaction between wave and three-dimensional structure is simulated, and a series of irregular motion shapes such as wave-breaking and deformation will occur. It is suitable to be simulated using the RNG $k-\varepsilon$ model. Similar to the continuity equation and momentum equation, the volume fraction V_F and area fraction A_x , A_y , A_z are added to the control equation of the RNG $k-\varepsilon$ model in Flow3D.

2.3 Free-surface model

The volume of fluid (VOF) method is used to simulate the free surface. The basic idea is to define a fluid volume function F in each unit of the computational domain, and F is a function of time and space. The core of the VOF method is to reconstruct the moving free surface by solving the transport equation of the fluid volume function. The transport equation of the fluid volume function F is as shown in the following equation (5), and the

Figure 1: Location of variables in a grid cell.

volume and area fraction parameters also need to be considered.

$$\frac{\partial F}{\partial t} + \frac{1}{V_F} \left[\frac{\partial}{\partial x} (F A_x u) + \frac{\partial}{\partial y} (F A_y v) + \frac{\partial}{\partial z} (F A_z w) \right] = 0. \quad (5)$$

2.4 Discretization of governing equations

Flow3D uses the finite difference method to discretize the governing equations and to discretize the space into three-dimensional rectangular staggered grids, as shown in Figure 1. The scalar is defined at the center of the control body, such as the pressure P , the fluid volume function F , the density ρ , the flow volume fraction V_F , and so on, while the velocity u , v , w and area fraction A_x , A_y , A_z are defined at the center point of the edge of the grid.

3 Numerical simulation based on Flow3D

3.1 3-D numerical wave basin

A three-dimensional numerical wave basin is established, and its correctness is verified. When the flow field mesh is divided, the ratio of a cell direction does not exceed 1:3, the ratio of the length to width of the xyz is not more than 1:5, the ratio of the adjacent grid block is best within 1:2, the number of grids in the range of wave height is 10–15, and the 100–120 grids are divided within the wavelength range. The simulation results of the wave are basically the same as the theoretical

Table 1: Boundary condition of numerical wave basin

Boundary	Inlet	Outlet	Side	Bottom	Top
Condition	Velocity-inlet	Outflow	Symmetry	Wall	Specified pressure

values. Based on the above experience [26,27], the free outflow boundary of Flow3D is used for preliminary wave elimination in the outlet of numerical wave basin.

3.1.1 Model building and meshing

The three-dimensional numerical wave basin has a total length of 5 m in the X direction, a width of 2 m in the Y direction, and a height of 1.3 m in the Z direction. The boundary conditions are set as presented in Table 1.

Mesh encryption is required at the free surface ($z = 1$ m), and generally 100 grids are set in the wave height range. The encrypted mesh of the free surface and the

(a)

(b)

Figure 2: The mesh schematic diagram of numerical wave basin. (a) Mesh encryption for free surface. (b) Overall mesh schematic diagram.

Figure 3: Color contour plot of basin after free surface stability.

overall mesh of the three-dimensional numerical wave basin are shown in Figure 2.

3.1.2 Numerical wave generation

A linear regular wave with a wave height of 0.04 m and a period of 0.98 s is selected. The time of simulation is 30 s, and the time step is 1/20 of the wave period (0.049 s). The three-dimensional color contour plot of free surface after the wave stability is shown in Figure 3, and the wave height time history curve at $x = 0$ m is shown in Figure 4. Compared with the theoretical value, it is found that the wave is unstable before 5 s, and the wave is stable between 5 and 19 s. The wave height and phase are basically the same, and the simulation results are good. However, it is affected by the reflected wave after 19 s, which interferes with the normal simulation of the working area. Therefore, using Flow3D to establish a numerical wave basin, only the free outflow boundary condition of the numerical wave basin outlet cannot satisfy the wave

Figure 4: The time history curve of $x = 0$ m.

Table 2: The size of mesh block

Mesh block	Block 1 (ordinary basin)	Block 2 (wave-eliminating block)	Block 3 (ordinary basin)
X direction length	0–5 m	5–8 m	8–10 m
Mesh size	0.04	0.08	0.04

elimination, and there is still the influence of the reflection wave. It is necessary to add the additional wave elimination device to meet the requirements of subsequent numerical simulation.

3.1.3 Numerical wave elimination

The additional wave elimination device adopts wave-absorbing block, which has the advantages of good wave-eliminating effect and low cost. Wave-absorbing block belongs to the method of imitating physical wave elimination and adds a momentum decay source term in momentum equation.

$$S_i = -\left(\frac{\mu}{\alpha}v_i + C_2\frac{1}{2}\rho|v|v_i\right). \quad (6)$$

The first term in the right side of the equation (6) is the viscous loss term, the second term is the inertia loss term, and the S_i is the source term of the momentum equation in the i direction. The $|v|$ is the velocity size, and the $1/\alpha$ and the C_2 are a constant [28–34]. In fact, only the first term at the right side of the equation usually is taken.

The numerical wave basin is divided into three blocks in the X direction, and the meshes are divided into different sizes, as presented in Table 2. The three-dimensional mesh schematic diagram is shown in Figure 5.

Block 1 in the table is an ordinary three-dimensional numerical wave basin, and there is no structure in the basin. Block 2 is a wave-absorbing block, which only plays the role of wave eliminating and does not need to observe the flow field in the block, so the grid can be

Figure 5: The mesh schematic diagram of 3D numerical wave basin with wave-absorbing block.

appropriately sparse. Block 3 is an ordinary basin for testing the effect of wave eliminating.

The length of the wave-eliminating region is about one to two times the wavelength, and the distance from the left side of the wave-absorbing block to the inlet is 5 m. Keep the wave parameters unchanged and also monitor the free surface changes at $x = 0$ m. Figure 6 shows a three-dimensional color contour plot with wave-absorbing device, and the wave height is significantly reduced after the wave passes through the wave-absorbing device. Figure 7 shows the comparison of the wave height before and after wave eliminating and theoretical values at $x = 0$ m. It can be seen that after the improvement of the wave-eliminating method, the wave height of the free surface is hardly affected by the reflected wave. It is in good agreement

Figure 6: Color contour plot of 3D numerical wave basin after wave elimination. **Figure 7:** The comparison of wave height at $x = 0$ m before and after wave elimination.

with the theoretical value. It is feasible and can be used for numerical simulation.

3.2 Numerical simulation validation

The hydrodynamic interference in the narrow gap of the side-by-side double-floating-system is a typical strong nonlinear problem, and its theoretical research remains to be improved, and the reliability of the numerical simulation results needs to be further improved. In order to verify the correctness of the numerical simulation method in this paper, the results simulated in the present model was compared with published numerical and experimental results to examine if they agree well. In 2014, Xu [23] studied the flow field resonance phenomenon in the narrow gap of a double-floating-system under the action of waves by experimental and numerical methods. The case in ref. [23] was numerically simulated using Flow3D software, and the results of the numerical simulation were compared with those in the ref. [23].

3.2.1 Description of numerical simulation case

Referring to the basin size and mesh division in ref. [23], a side-by-side double-floating-system with the gap width of 0.05 m was added at the distance of 3 m from the inlet of the numerical wave basin. The specific parameters of the floating body are presented in Table 3.

To accurately simulate the motion posture of the floating body in the wave, it is necessary to add a nested encrypted mesh block. The nested mesh block can reduce the grid size as much as possible under the premise of fully including double-floating-system, so as to reduce the total number of grids and reduce the computation time. The mesh in the X - Y plane and the overall mesh are shown in Figure 8.

When the coupled motion of wave and double-floating-system is simulated, the floating body drifts

(a)

(b)

Figure 8: The mesh schematic diagram of validation case. (a) The mesh schematic diagram of the X - Y plane. (b) Overall mesh schematic diagram.

away with the wave or collides with other floating bodies, which will lead to the divergence of numerical simulation. Therefore, the horizontal motions of the two floating bodies (swaying, surging, and yawing) are limited in the validation case, and only the vertical motions (heaving, rolling, and pitching) are retained.

3.2.2 Comparison of numerical simulation results

Five monitoring points in the narrow gap of the double-floating-system are defined. The coordinates of monitoring points A–E are presented in Table 4. The location distribution of the monitoring points is shown in Figure 9.

The results of the numerical simulation are compared with the results in the ref. [23] in Figure 10. SIM represents

Table 3: Main scale and hydrostatic parameters of the model

Parameter	Value	Parameter	Value
Length L	1.5 m	Horizontal position of center of gravity (from stern)	0.7395 m
Beam B	0.45 m	Vertical position of center of gravity (form baseline)	0.1272 m
Depth D	0.15 m	I_{xx}	0.62352 kg m ²
Draft T	0.0667 m	I_{yy}	8.9248 kg m ²
Displacement Δ	0.0433 t	I_{zz}	9.2301 kg m ²
Narrow gap width ϕ	0.05 m		

Table 4: Coordinates of five monitoring points

Monitoring points	Point A	Point B	Point C	Point D	Point E
Coordinate	(-0.5, 0, 0)	(-0.25, 0, 0)	(0, 0, 0)	(0.25, 0, 0)	(0.5, 0, 0)

the numerical simulation results in this paper, CAL represents the numerical results of the reference, and EXP represents the model test results of the reference.

It can be seen from the figure that the wave height values at four points of A, B, C, and E are basically consistent with the results in the reference. Except for the difference at the individual peaks, the phase is also in good agreement, and the overall error is within 5%. However, the wave height time history curve at point D differs greatly from the experimental results in the reference and is basically consistent with the numerical results of the ref. [35–41]. It may be that the horizontal motion of the two floating bodies in the CFD numerical simulation is completely limited, while the horizontal motion in the model test is not completely fixed, only by the horizontal mooring system.

The motion results of the double-floating-system are compared with the results in the reference. The motion of the double-floating-system under the action of wave is completely symmetrical. Therefore, the comparison of motion results of one floating body is shown in Figure 11.

The figure shows the time history curve of the vertical motion of the floating body, which is almost identical in phase, and only differs in part of the peak, but within the error tolerance. There are differences in the results of numerical simulation, and the possible reason is that the mesh of the validation case is different from that of the reference. In the reference, mesh refinement is performed on the free surface and in the narrow gap, but the

validation case in this paper is to add a nested mesh around the double-floating-system. Although the way of mesh encryption is different, the purposes are all to observe the free surface and the flow field in narrow gap.

According to the above two sets of comparisons, the results in the reference are in good agreement with the numerical simulation results in this paper within the range of error tolerance, which verifies the accuracy and reliability of the numerical research method in this paper.

3.3 Mesh convergence analysis

According to the hydrodynamic model of the double-floating-system proposed in this paper, before using the Flow3D software to simulate the hydrodynamic interference in the narrow gap, to select the appropriate number of mesh, it is necessary to meet the high numerical simulation precision and less calculation time. Therefore, it is necessary to carry out the mesh convergence analysis.

3.3.1 Description of numerical simulation case

A numerical wave basin with a hydrodynamic model of a double-floating-system is set up. The original point of the coordinate is taken at the middle point of the two floating bodies. The distance between two floating bodies is 0.05 m, the wave height is 0.035 m, and the period is 0.6455 s. Table 5 presents the division schemes of three different grid sizes. The different mesh schematic diagrams of the three-dimensional numerical wave basin are shown in Figure 12. In the simulation of mesh convergence analysis, the horizontal motion (swaying, surging, and yawing) of the two floating bodies is limited, and only the vertical motion (heaving, rolling, and pitching) is retained [42].

3.3.2 Comparison of convergence analysis results

Figure 13 shows the comparison of the motion in the vertical direction of the two floating body and the wave height in the middle of the narrow gap under the three meshing schemes.

It can be seen that the convergence of mesh 2 and mesh 3 is better, the trend of the simulated results is

Figure 9: Layout of monitoring points.

Figure 10: The time history curve of the wave height of the monitoring point. (a) The time history curve of the wave height at A point. (b) The time history curve of the wave height at B point. (c) The time history curve of the wave height at C point. (d) The time history curve of the wave height at D point. (e) The time history curve of the wave height at E point.

Figure 11: Comparison of the motion. (a) Comparison of heave motion. (b) Comparison of roll motion. (c) Comparison of pitch motion.

Table 5: Different mesh division schemes

Mesh	Block 1 (overall mesh size)	Block 2 (nested mesh size)	Total number of mesh
1	0.04	0.02	782,800
2	0.02	0.01	1,323,200
3	0.01	0.005	2,505,336

basically the same, and the phase and peak are also basically consistent. However, the mesh 1 and mesh 2 and 3 have great differences in peak value, and some phases are also biased. The simulation effect is not good. To balance the calculation time and the accuracy of the calculation, the mesh 2 scheme is used to study the gap-resonance problem when the numerical wave basin size and model size are the same.

Figure 12: Schematic diagrams of three different mesh division schemes: (a) mesh 1; (b) mesh 2; (c) mesh 3.

Figure 13: Comparison of convergence results. (a) Comparison of heave motion. (b) Comparison of roll motion. (c) Comparison of pitch motion. (d) Comparison of wave height at the origin of coordinates in the narrow gap.

4 CFD simulation of side-by-side double-floating-system with a narrow gap

4.1 Analysis of flow field in the narrow gap of fixed double-floating-system

The hydrodynamic interference in the narrow gap of the double-floating-system under the action of regular wave

is numerically simulated, and the wave elevation around the fixed double-floating-system and the fluid movement in the narrow gap are mainly analyzed.

4.1.1 Description of numerical simulation case

Two identical homogeneous square box models are selected to simplify the hydrodynamic model of the double-floating-system. The main parameters of the model are presented in Table 6.

Table 6: Main parameters of the model

Parameters	Length	Beam	Depth	Draft	Displacement	Density	Narrow gap width
Value	1.5 m	0.45 m	0.15 m	0.07 m	47.25 kg	466.67 kg/m ³	0.1 m

The narrow gap width is 0.1 m, and the distance from the inlet of the numerical wave basin to the floating body is generally greater than one wavelength (1.5 m). The length of the numerical wave basin is 4.7 m, the width of the basin is 2 m, the depth of the basin is 1.3 m, the water depth is 1 m, and the origin of the coordinates is 2.2 m from the inlet of the numerical wave basin. A linear regular wave with a wavelength of 1.5 m and a wave height of 0.04 m is selected.

4.1.2 Wave elevation in narrow gap

Figure 14 shows the wave elevation around the double-floating-system in a regular wave period ($t = 8.768$ – 9.748 s). At the beginning of a period ($t = 0$), the wave elevation appears at the front of the floating body. The value of the wave height (0.033 m) is about 1.65 times that of the incident wave amplitude (0.02 m), and the wave height enlargement is mainly because of the superposition of the reflected wave and the incident wave. The maximum wave elevation appears at $t = 1/4 T$, and the maximum wave height appears at the front of the narrow

gap of the double-floating-system (about the $1/10$ of the floating body length), and the wave elevation (0.066 m) is about 3.3 times the incident wave amplitude of 0.02 m. At $t = 1/2 T$, as the wave continues to propagate, the amplitude of the wave in the narrow gap continues to decrease. At this time, the peak of the incident wave propagates to the middle of the floating body, and the wave height around the double-floating-system is not large. The flow field in the narrow gap tends to be stable. At $t = 3/4 T$, corresponding to $1/4 T$, the front of the narrow gap of the double-floating-system is the valley value of the wave (about $1/10$ of the total length of the floating body). When $t = T$, the fluid goes back to the state of $t = 0$ at the beginning of the period and begins to repeat the process mentioned above.

The overall effect is that the double-floating-system has a shadowing effect on the flow field in the narrow gap, and the internal flow field of the narrow gap is separated from the external flow field. The flow field at the front of the narrow gap shows strong nonlinearity, and the phenomenon of wave elevation is obvious. The wave elevation in this example mainly occurs at the head of the floating body and the front of the narrow gap of the

Figure 14: Color contour plot of the flow field around the double-floating-system in a complete period: (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

double-floating-system. While other scholars have not found the wave resonance phenomenon at the head of the floating body, the resonance is mainly concentrated in the rear of the narrow gap. The possible reasons for this phenomenon are as follows: (1) the floating body is simplified into a square box model, and the head of the square box is different from the ship; (2) the selected wavelength is too long, the narrow gap width is too small, and the wave cannot pass through the inside of the narrow gap but directly bypasses the double-floating-system. Therefore, to further explore the resonance phenomenon inside the narrow gap, the next section will study the influence of the narrow gap width and wave period on the flow field around double-floating-system.

Figure 15: Wave height distribution along the X-axis direction at $y = 0$.

Figure 16: Color contour plot of the wave elevation around the double-floating-system at $t = 1/4 T$.

When $t = 1/4 T$ and $t = 3/4 T$, Figure 15 shows the distribution of the wave height values in the narrow gap midline ($y = 0$) of the double-floating-system along X-axis direction of the numerical wave basin. Two red dotted lines indicate the position of the head and tail of the floating body. It can be seen that under the coupling of the wave and the double-floating-system, the hydrodynamic resonance phenomenon occurs in the head of the floating body and the front of the narrow gap, and the wave rises obviously (Figure 16). However, the wave height at the tail of the double-floating-system begins to decrease gradually, and after passing through the wave-eliminating region, the wave height rapidly decreases and tends to be stable.

The five monitoring points in the narrow gap of the double-floating-system are selected to analyze the wave elevation in the gap. The coordinate values of the A–E points are presented in Table 7, and the wave height value of the A–E monitoring point is plotted as a time history curve, as shown in Figure 17.

It can be seen from the figure that the numerical simulation results of different monitoring points tend to be stable after 10 s. The wave height value near the A monitoring point is the largest, and the maximum value is about (0.07 m) up to 3.5 times of the incident wave (0.02 m), which is consistent with the results of color contour plot of free surface above. With the continuous propagation of the incident wave along the X-axis direction in the narrow gap, the peak position of the wave elevation in the narrow gap moves along the direction of the X-axis as well, but the peak value of the wave elevation is continuously reduced until the free surface tends to be stable. It can be found that the decrease in the peak value of the wave elevation in the X-axis direction is caused by various factors such as fluid viscous action, wave damping effect, and shadowing effect of the floating body on the flow field in the narrow gap.

4.1.3 Fluid motion in narrow gap

To investigate the fluid motion around the double-floating-system, Figure 18 shows the division of a wave period ($t = 8.768$ – 9.748 s) into eight typical moments. At the midship section ($x = 0$ m) of the double-floating-system, a complete wave period is selected to discuss the velocity and

Table 7: Coordinates of five monitoring points

Monitoring points	Point A	Point B	Point C	Point D	Point E
Coordinate	$(-0.75, 0, 0)$	$(-0.375, 0, 0)$	$(0, 0, 0)$	$(0.375, 0, 0)$	$(0.75, 0, 0)$

Figure 17: The time history curve of wave elevation at monitoring point A–E.

Figure 18: Typical moments for a complete wave period ($t = 8.768\text{--}9.748\text{ s}$).

pressure distribution of the fluid around the double-floating-system, as shown in Figure 19.

At the beginning of the period $t = 0$, it can be seen from Figure 19(a) that the fluid flows from the outside of the two floating bodies through the bottom into the inside of the narrow gap, and the fluid velocity inside the narrow gap is upward, and the free surface is continuously increased. When $t = 1/8 T$, it can be seen from Figure 19(b) that the upward velocity of the fluid in the narrow gap begins to decrease gradually, and the fluid at the bottom of the floating body begins to flow backward to the outside of the two floating bodies. When $t = 1/4 T$, it can be seen from Figure 19(c) that the free surface in the narrow gap reaches the highest, at which time the fluid

velocity is reduced to zero, and the direction is changed to start generating a downward flow velocity. When $t = 3/8 T$, it can be seen from Figure 19(d) that the downward velocity of the fluid in the narrow gap is increasing, and flows to the outside of the double-floating-system through the bottom of the floating body. When $t = 1/2 T$, it can be observed from Figure 19(e) that the downward moving speed of the fluid inside the narrow gap reaches the maximum, and the free surface is basically in the static equilibrium position. When $t = 5/8 T$, it can be seen from Figure 19(f) that the downward velocity of the fluid in the narrow gap begins to decrease. In addition, when most of the fluid flows downward in the narrow gap, the fluid outside the two floating bodies already has the velocity of backflow, indicating that the fluid has started to move from the outside through the bottom of the floating body to the narrow gap. When $t = 3/4 T$, it can be observed from Figure 19(g) that the flow in the narrow gap moves to the lowest point, and the downward velocity gradually decreases to zero and then begins to move upward. When $t = 7/8 T$, it can be seen from Figure 19(h) that the upward velocity of the fluid in the narrow gap starts to increase gradually, and the fluid outside the two floating bodies flows into the narrow gap through the bottom of the floating body, eventually causing the free surface in the narrow gap to rise continuously. When $t = T$, the fluid returns to the state at the beginning of the cycle and begins to repeat the process mentioned above.

4.2 Parameterized study of flow field in narrow gap

Using the control variable method, the narrow gap width of the double-floating-system and wave parameters is selected as variables to observe the wave elevation of the flow field in the narrow gap. The influence of different gap width and different wave periods on the flow field in the narrow gap is explored.

4.2.1 Description of numerical simulation case

The narrow gap width of the double-floating-system is selected as 0.05 m and 0.1 m, the wave height is 0.04 m, and the water depth 1.3 m remains unchanged. The wavelength is 0.25, 0.5, 1, and 1.5 times the length of floating body, respectively, and the numerical simulation cases are presented in Table 8.

Figure 19: Fluid velocity and pressure distribution at the midship section of the double-floating-system in a complete period. (a) $t = 0$; (b) $t = 1/8 T$; (c) $t = 1/4 T$; (d) $t = 3/8 T$; (e) $t = 1/2 T$; (f) $t = 5/8 T$; (g) $t = 3/4 T$; (h) $t = 7/8 T$; (i) $t = T$.

Table 8: Numerical simulation case

Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Narrow gap width (m)	$\Phi = 0.05$	$\Phi = 0.05$	$\Phi = 0.05$	$\Phi = 0.05$	$\Phi = 0.1$	$\Phi = 0.1$	$\Phi = 0.1$	$\Phi = 0.1$
Wavelength (L)	0.25	0.5	1	1.5	0.25	0.5	1	1.5
Wave period (s)	0.49	0.699	0.98	1.2	0.49	0.699	0.98	1.2

4.2.2 Wave elevation of the flow field at four different wave periods when the gap width is 0.05 m

Cases 1–4 are used to compare and analyze the flow field in the narrow gap at typical time. According to the wave parameters and the size of numerical wave basin, the wave propagates to the structure around 3 s and is relatively stable around 8 s. Therefore, a complete wave period after 8 s is selected as a typical time in each case, and the wave period is divided into four typical moments ($t = 0$, $t = 1/4 T$, $t = 1/2 T$, and $t = 3/4 T$). Figures 20–23 show the color contour plot of free surface obtained by numerical simulation.

The following can be seen from the above color contour plot of free surface:

- (1) In case 1, the wave period is 0.49 s. When the incident wave peak propagates to the front of the double-floating-system, the free surface rises significantly because of the superposition of the reflected wave and the incident wave after the wave encounters the floating body. As the wave continues to propagate, the

peak of the wave appears at the head of the floating body, and the height reaches a maximum value of 0.056 m, which is about 2.8 times the incident wave amplitude of 0.02 m. The wave continues to propagate in the narrow gap, and the wave amplitude continues to decrease until the free surface is stable. As the amplitude is reduced slowly and the selected wavelength is shorter, there are multiple peak points in the flow field in the narrow gap.

- (2) In case 2 with a wave period of 0.699 s, when the incident wave peak propagates to the entrance of the narrow gap, the free surface at the entrance of the narrow gap increases obviously. When the peak of the incident wave propagates to about $1/8$ to $1/7$ of the length of the floating body inside the narrow gap, the wave height reaches 0.045 m, which is 2.25 times of the incident amplitude. When the incident wave peak propagates to the middle of the floating body, the wave elevation in the narrow gap is about 0.5–1.5 times the wave amplitude. As the wave continues to propagate, the wave height in the narrow gap continues

Figure 20: Color contour plot of the flow field around the double-floating-system in a complete period (8.81–9.3 s) in case 1. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

Figure 21: Color contour plot of the flow field around the double-floating-system in a complete period (8.2–8.9 s) in case 2. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

Figure 22: Color contour plot of the flow field around the double-floating-system in a complete period (8.72–9.7 s) in case 3. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

to decrease. When the peak of the incident wave reaches the tail of the floating body, there is a peak value and a valley value in the narrow gap.

- (3) In cases 3 and 4, the wave periods are 0.98 and 1.2 s, respectively. The obvious wave elevation is also observed at the entrance of the narrow gap, but the peak value of the wave elevation decreases relative to

the cases 1 and 2, which is about 1.6–1.8 times of the incident wave amplitude. Compared with the case with smaller wave period (cases 1 and 2), the decrease in the wave height in the narrow gap is more rapid. When the wave peak is spread to the middle of the floating body, the free surface of the flow field in the narrow gap tends to be stable.

Figure 23: Color contour plot of the flow field around the double-floating-system in a complete period (8.75–9.95 s) in case 4. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

4.2.3 Wave elevation of the flow field at four different wave periods when the gap width is 0.1 m

The flow field in the narrow gap in the typical time of cases 5–8 is compared and analyzed. Figures 24–27 show the color contour plot of free surface obtained by numerical simulation.

These color contour plot of free surface above can be seen as follows:

- (1) Case 5 with the wave period of 0.49 s is similar to case 1. When the peak of the incident wave propagates to the front of the double-floating-system, the free surface rises obviously, and the wave height of 0.044 m is about 2.1 times that of the incident wave. When the

Figure 24: Color contour plot of the flow field around the double-floating-system in a complete period (8.81–9.3 s) in case 5. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

Figure 25: Color contour plot of the flow field around the double-floating-system in a complete period (8.2–8.9 s) in case 6. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

Figure 26: Color contour plot of the flow field around the double-floating-system in a complete period (8.72–9.7 s) in case 7. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

wave continues to propagate to about $1/10$ to $1/9$ of the length of the floating body in front of the narrow gap, the free surface rises to a maximum value of 0.061 m, which is about three times the amplitude of 0.02 m. Then, the wave amplitude in the narrow gap begins to decrease until the free surface is stable. Because of the short wavelength, there are several

peak points in the flow field in the narrow gap, which is basically consistent with the gap width of 0.05 m. (2) In case 6, the wave period is 0.699 s. When the peak of the incident wave propagates to the front of the narrow gap at a position of about $1/4$ to $1/5$ of the floating body length, the middle of the narrow gap is a wave valley, and the front and rear of the gap have a

Figure 27: Color contour plot of the flow field around the double-floating-system in a complete period (8.09–9.29 s) in case 8. (a) $t = 0$; (b) $t = 1/4 T$; (c) $t = 1/2 T$; (d) $t = 3/4 T$.

wave peak, respectively, and the wave height (0.04 m) is about twice the incident wave amplitude. As the wave continues to propagate, the peak point moves continuously in the narrow gap, and the height of the peak point continues to decrease at a relatively slow speed. When the incident wave peak propagates to the tail of the narrow gap, the wave height of the free surface in the narrow gap is about 0.5 to 1.5 times that of the incident wave.

- (3) In cases 7 and 8, the wave periods are 0.98 s and 1.2 s, respectively. The wave elevation occurs at the head of the double-floating-system and at the entrance of the narrow gap. There is no significant wave elevation in the narrow gap. Moreover, compared with the case with smaller wave period (cases 5 and 6), the decrease in the wave height in the narrow gap is more rapid. When the wave peak is spread to the middle of the floating body, the free surface in the narrow gap has tended to be stable.

5 Concluding remarks

In this paper, the double-floating-system is taken as the research object to study the hydrodynamic interference problem in the narrow gap and try to find the law of

the gap-resonance phenomenon, to explore the internal causes and mechanism. First, a three-dimensional numerical wave basin is established to verify the correctness and feasibility of the viscous CFD method in numerical simulation of gap-resonance problem. The mesh convergence analysis is carried out for the hydrodynamic model of the double-floating-system, and the optimal meshing scheme is proposed. Second, the wave elevation and fluid movement in the narrow gap of fixed double-floating-system are analyzed in detail. Finally, the effects of gap width and wave period on the hydrodynamic interference in the narrow gap of the double-floating-system are investigated. The main conclusions are as follows:

- (1) The narrow gap width is the same, and the flow field movements between the gaps are different under different wave periods. When the incident wave reaches the resonant period of the double-floating-system, the wave continuously reflects in the narrow gap, and the fluid in the narrow gap produces convection with the fluid at the bottom of the floating body, and the free surface in the narrow gap will rise significantly.
- (2) It can be seen from the color contour plot of free surface at different gap width that as the narrow gap width increases, the resonant period of the flow field in the narrow gap of double-floating-system also increases.
- (3) The velocity of the fluid in the narrow gap is faster than the velocity of the fluid outside the double-

floating-system. At the same time, the flow field in the narrow gap is about $1/4$ wavelength ahead of the flow field outside the double-floating-system.

- (4) When the wavelength is too large, the incident wave cannot enter the narrow gap of the double-floating-system, and the wave directly bypasses the double-floating-system to continue to propagate. The double-floating-system has a shadowing effect on the flow field in the narrow gap, and there is no obvious wave elevation in the narrow gap, and the peak value of the wave elevation appears at the head of the double-floating-system.
- (5) When the incident wavelength decreases to less than the floating body length, the wave enters the narrow gap and causes the wave elevation of the flow field in the narrow gap. There may be one or more peak points in the narrow gap, which are related to the aspect ratio L/B and wavelength ratio λ/L .
- (6) With the continuous propagation of the incident wave along the direction of floating body length in the narrow gap, the peak point of the wave elevation in the narrow gap is also moving along the direction of floating body length. However, the peak height of the free surface decreases continuously until the free surface tends to be stable. The gradual decrease in wave height on free surface may be attributed to fluid viscosity, wave damping, and the shadowing effect of double-floating-system on the flow field in the narrow gap and so on.

Acknowledgments: The authors would like to acknowledge the support of National Natural Science Foundation of China (Nos. 52001138; 52071094; 11572094; 5171101175) and National Natural Science Foundation of Jiangsu Province (Nos. BK20201029; 20KJB416005). In addition, the author “Zhiyang Zhang” would like to thank Prof. Zhang for the guidance and assistance in his studies, as well as all the teachers and students of Deepwater Engineering Research Center at Harbin Engineering University.

Conflict of interest: Authors state no conflict of interest.

References

- [1] Newman JN. Wave effects on multiple bodies. *Hydrodyn Ship Ocean Eng.* 2001;4:3–26.

- [2] Fernández-Pousa CR. Perfect phase-coded pulse trains generated by Talbot effect. *Appl Math Nonlinear Sci.* 2018;3:23–32.
- [3] Atangana A, Hammouch Z. Fractional calculus with power law: the cradle of our ancestors. *Eur Phys J Plus.* 2019;134:429.
- [4] Chen L, Cao X, Sun S, Cui J. The effect of draft ratio of side-by-side barges on fluid oscillation in narrow gap. *J Mar Sci Eng.* 2020;8:694.
- [5] Islam MR. Comparative study of numerical simulation and the experimental results for a parallelly connected FPSO and LNG in waves. *International Offshore and Polar Engineering Conference*; 1999.
- [6] Gao J, Chen H, Zang J, Chen L, Wang G, Zhu Y. Numerical investigations of gap resonance excited by focused transient wave groups. *Ocean Eng.* 2020;212:107628.
- [7] Shen W, Chen H, Jiang Y, Gao F. Analysis of resonance characteristics of FSRU and LNG ship under side by side operation. *The Fourteenth ISOPE Pacific/Asia Offshore Mechanics Symposium. International Society of Offshore and Polar Engineers*; 2020.
- [8] Peng JH. *Hydrodynamic interaction of multi-body for offshore float-over installation.* Shanghai, China: Shanghai Jiaotong University; 2011.
- [9] Wang L. Current situation and development trend of foreign naval marine recharge. *Mar Electr Electron Eng.* 2017;6:17–22.
- [10] Wang ZJ, Shu Z, Li RP, Yang JM. Key technical issues in conceptual design of ultra large floating structures. *Ocean Eng.* 2001;19:1–6.
- [11] Zhao W, Pan Z, Lin F, Li B, Taylor PH, Efthymiou M. Estimation of gap resonance relevant to side-by-side offloading. *Ocean Eng.* 2018;153:1–9.
- [12] Zhang H, Zhou B, Zang J, Christopher Vogel, Fan T, Chen C. Influence of narrow gap wave resonance on a dual-body system with WECs and breakwaters. *The Fourteenth ISOPE Pacific/Asia Offshore Mechanics Symposium International Society of Offshore and Polar Engineers*; 2020.
- [13] Jiang SC, Bai W, Tang GQ. Numerical simulation of wave resonance in the narrow gap between two non-identical boxes. *Ocean Eng.* 2018;156:38–60.
- [14] Li B. Multi-body hydrodynamic resonance and shielding effect of vessels parallel and nonparallel side-by-side. *Ocean Eng.* 2020;218:108188.
- [15] Huijsmans RHM, Pinkster JA, Wilde JJD. Diffraction and radiation of waves around side-by-side moored vessels. *Proceeding of the Eleventh International Offshore and Polar Engineering Conference, Stavanger*; 2001;1. p. 406–12.
- [16] Chen XB. Hydrodynamic analysis for offshore LNG terminals, Part 1. Keynote Lecture of 6th International Conference on Hydrodynamics, Perth, Australia; 2005.
- [17] Pauw WH, Huijsmans RHM, Voogt A. Advances in the hydrodynamics of side-by-side moored vessels. *ASME 2007 26th International Conference on Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers*; 2007. p. 597–603.
- [18] Bunnik T, Pauw W, Voogt A. Hydrodynamic analysis for side-by-side offloading. *The Nineteenth International Offshore and Polar Engineering Conference*, 21–26 July, Osaka, Japan; 2009.

- [19] Xin LI, Xu LY, Yang JM. Study of fluid resonance between two side-by-side floating barges. *J Hydrodynamics*. 2016;28:767–77.
- [20] Zhou K, Hu ZQ, Zhao DY. Hydrodynamic interactions between side-by-side offloading FLNG and LNGC under different wave directions. *J Harbin Inst Technol*. 2018;50:114–23.
- [21] Zhao W, Pan Z, Lin F, Li B, Taylor PH, Efthymiou M. Estimation of gap resonance relevant to side-by-side offloading. *Ocean Eng*. 2018;153:1–9.
- [22] Aqsa A. Gully Plugging spillway is an effective gully rehabilitation measure: a case study of district Gujrat-Pakistan. *Big Data Water Resour Eng*. 2020;1:6–9.
- [23] Xu LY. Study on hydrodynamic interference of multiple floating bodies. Shanghai, China: Shanghai Jiaotong University; 2014.
- [24] Gohar R, Tul Ain Q, Muhammad Z, Liulei B, Javed I. An analysis of two-dimensional flow through a water reservoir using mathematical approach. *Environ Contam Rev*. 2019;2:11–3.
- [25] Zhang H, Liu S, Ong MC, Zhu R. CFD simulations of the propagation of free-surface waves past two side-by-side fixed squares with a narrow gap. *Energies*. 2019;12:2669.
- [26] Zhang T. Three-dimensional numerical simulation of wave and its application. Tianjin, China: Tianjin University; 2009.
- [27] Sarwar MT, Hui ZH, Xin YJ, Jiang SW, Yong T, Jie LB, et al. Mitigation techniques to overcome water scarcity issues. *Water Conserv Manag*. 2019;3:30–1.
- [28] Gao W, Wang W. A tight neighborhood union condition on fractional (g, f, n', m) -critical deleted graphs. *Colloq Math*. 2017;149:291–8.
- [29] Bilal Riaz M, Ahmad Asif N, Atangana A Imran Asjad M. Couette flows of a viscous fluid with slip effects and non-integer order derivative without singular kernel. *Discrete Cont Dyn-S*. 2019;12:645–64.
- [30] Ali AJ, Akbar NJ, Kumar MSA, Vijayakumar S, John BA. Effect of cadmium chloride on the haematological profiles of the freshwater ornamental fish, *Cyprinus Carpio Koi* (Linnaeus, 1758). *J Clean Was*. 2018;2:10–5.
- [31] Wang FJ. Computational fluid dynamics analysis: Principles and applications of CFD software. Beijing, China: Tsinghua University Press; 2004.
- [32] Butanda JA, Málaga C, Plaza RG. On the stabilizing effect of chemotaxis on bacterial aggregation patterns. *Appl Math Nonlinear Sci*. 2017;2:157–72.
- [33] Ali R, Hossein H, Parviz M, Abbas G. Lithological mapping in Sangan region in Northeast Iran using ASTER satellite data and image processing methods. *Geol Ecol Landsc*. 2020;4:59–70.
- [34] Gao W, Zhu L, Guo Y, Wang K. Ontology learning algorithm for similarity measuring and ontology mapping using linear programming. *J Intell Fuzzy Syst*. 2017;33:3153–63.
- [35] Jin J, Mi W. An AIMMS-based decision-making model for optimizing the intelligent stowage of export containers in a single bay. *Discrete Cont Dyn-S*. 2019;12:1101–15.
- [36] Chen H, Jiang J, Cao D, Fan X. Numerical investigation on global dynamics for nonlinear stochastic heat conduction via global random attractors theory. *Appl Math Nonlinear Sci*. 2018;3:175–86.
- [37] Sufiyan I, Zakariya R, Yaacob R. Delineation of flood risk zones and 3D modeling in Terengganu river catchment using gis and swat. *Environ Ecosyst Sci*. 2018;2:1–5.
- [38] Erdogan F, Sakar MG, Saldır O. A finite difference method on layer-adapted mesh for singularly perturbed delay differential equations. *Appl Math Nonlinear Sci*. 2020;5:425–36.
- [39] Kang L, Du HL, Du X, Wang HT, Ma WL, Wang ML, et al. Study on dye wastewater treatment of tunable conductivity solid-waste-based composite cementitious material catalyst. *Desalin Water Treat*. 2018;125:296–301.
- [40] Selvi MSM, Rajendran L. Application of modified wavelet and homotopy perturbation methods to nonlinear oscillation problems. *Appl Math Nonlinear Sci*. 2019;4:351–64.
- [41] Wang H, Zhong H, Bo G. Existing forms and changes of nitrogen inside of horizontal subsurface constructed wetlands. *Environ Sci Pollut Res*. 2018;25:771–81.
- [42] Gao J, He Z, Zang J, Chen Q, Ding H, Wang G. Numerical investigations of wave loads on fixed box in front of vertical wall with a narrow gap under wave actions. *Ocean Eng*. 2020;206:107323.