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Research Article

Experimental and Numerical Study of Stratified Sloshing in a Tank under Horizontal Excitation

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The density-stratified liquids horizontal sloshing was tested on a vibration table, and a series of laboratory experiments have been performed to analyze the influence of the excitation frequency on density-stratified liquids sloshing in a partially filled rectangular tank. The MultiphaseInterFOAM solver in OpenFOAM was employed to simulate two-layer fluids sloshing problems. The numerical results of dynamic pressure were validated against the experimental data, showing that the employed model can accurately simulate the stratified liquids sloshing phenomenon. Effects of two-layer fluids liquid depth ratio and total liquid depth on stratified sloshing characteristics were discussed in detail. The response law of the maximum interfacial wave elevation to external excitation frequency was presented in this study. The evolution of the velocity field of density-stratified liquids sloshing is also studied.

1. Introduction

Stratified liquids sloshing refer to the interfacial movement of two or more immiscible fluids in a partially filled container, which are a common phenomenon that widely exists in many industrial and environmental sectors. For example, in the petroleum industry, the crude oil transportation is typically characterized by the delivery of oil-water mixtures in pipelines, because after oil is extracted, it is often necessary to inject water and transport it to processing facilities or offshore refineries [1]. During the transport of the stratified liquids, the sloshing of the stratified liquids is caused by the carrier shaking. Violent sloshing can create highly localized impact force on tank walls or ceiling which may lead to damage of the tank and may even induce sufficient large moment to affect the stability of the vehicle which carries the partially filled container with fluid, especially when the external excitation frequency is close to the resonance frequency. Many researchers have devoted their efforts to the problem of liquid sloshing [2–4] and sloshing mitigation [5–8]. As a top academic pioneer in this field, Faltinsen and Timokha [9] published a monograph and many articles on sloshing.

Stratified liquids sloshing are different from single-layer liquid sloshing. In addition to free surface wave, there is an interfacial wave between two-layer liquids. The period and wavelength of interfacial waves are often significantly different from free surface wave. Stratified liquids sloshing is a typical multiphase flow and multi-interfacial flow motion problems, and the study of the mechanism of nonlinear interfacial motion has been the forefront of computational fluid dynamics research. It is necessary to carry out stratified liquid sloshing research in this study.

Investigations on the stratified liquids sloshing phenomena can be classified as analytical, numerical, and experimental method. However, due to the multiple fluid

interfaces breaking and mixing during violent sloshing and the complexity of the tank structure, only simple analytical models can be established. Under the assumption of ideal fluid and microamplitude theory, Shen et al. [10] used the potential flow theory to derive the self-vibration characteristics of two layers of immiscible fluid in a rectangular container and analyzed the tuned liquid damper (TLD) characteristics of the stratified liquids. They found that the two-layer fluid TLD has better damping performance and broadens the damping frequency band, which can overcome the shortcomings of the effective damping bandwidth of the single-layer fluid TLD. Velesos and Shivakumar [11] studied stratified liquids sloshing in both rectangular and cylindrical containers, extending the number of layers of the layered fluid to the N layer (N can take any positive integer) and determining the correlation of the two system responses. Wu [12] studied the sloshing motion of inviscid density-stratified liquids in a rectangular container based on linear potential flow theory and gave free surface wave height and pressure expressions when density stratification. The results show that the effect of density stratification on the natural frequency of the system is obvious, and many new resonance frequencies will be generated.

With the development of computer and computational fluid dynamics, many researchers have done a lot of research on the numerical simulation of stratified liquids sloshing. La Rocca et al. [13] used potential flow theory to simulate two-layer fluid sloshing in a rectangular tank. Lu and Chai [14] used the VOF method to simulate the oil-water two-layer liquid sloshing of FPSO three-phase separator under different excitations. Wang et al. [15] build governing equations and boundary conditions for continuously stratified liquid sloshing in a cylindrical tank. In their study, new natural frequencies were found, which do not exist for uniform liquid sloshing. Xue et al. [16] simulated the sloshing of a two-dimensional layered flow of oil-water with a free surface based on an improved volume of fluid method and carried out experimental verification. Their research shows that the shape and amplitude time history of free surfaces can be accurately predicted within the tolerance range.

A major feature of the density-stratified liquids sloshing is the presence of interfacial wave due to the density difference, which has seldom been studied [17–19]. Chang et al. [20] studied the internal interfacial waves between two layers of liquids with different densities in a cylindrical container under vertical periodic excitation and found that the internal interfacial wave mode becomes more and more complicated as the density ratio of the upper and lower liquid layers increases. Patel and Natarajan [21] studied the interfacial motion between two layers of a viscous fluid in a rectangular container. Xue et al. [22] numerically studied seiche oscillations of stratified fluids in a closed rectangular tank under various initial inclination angles of the free surface and interfacial layers. Zheng et al. [23] investigated the interaction between two-layered fluid sloshing and porous bottom/sidewall of the tanks. Liu et al. [24] numerically investigated two-layered liquid sloshing in tanks under horizontal excitations. They found that there exist two natural frequencies with the smaller one related to the response of lower layer liquid and the larger one upper layer. However, the research on interfacial wave still lacks high-quality experimental data.

As a computational fluid dynamics (CFD) tool, the OpenFOAM is an open-source library that contains many libraries and codes for solving complex CFD problems, which has been used to study sloshing in our previous work [25]. For multiphase flow, there is already a multiphase incompressible fluid model named multiphaseInterFoam in OpenFOAM. This model, which is coupled with the standard volume of fluid (VOF) scheme, solves the Navier–Stokes equations with the PIMPLE loop.

As discussed above, detailed experimental studies on density-stratified liquids are conducted in this paper. In particular, experimental investigations are required for density-stratified liquids sloshing interfacial wave. The experimental device and numerical model are introduced in section 2 and the experimental results are discussed in section 3. Some conclusions are summarized in section 4.

2. Experimental Rig and Numerical Model

2.1. Experimental Rig and Test Methods. A density-stratified fluid sloshing test platform with the corresponding measurement system, as shown in Figure 1, is developed in the Laboratory of Vibration Test and Liquid Sloshing at Hohai University, China, which is a six-degree-of-freedom motion simulator. The pressure sensor can measure the impact pressure acting on the tank walls. The wave gauge can measure the oil-water interfacial wave elevation. The camera can capture the liquid surface profiles, and the displacement sensor can measure the tank movement displacement. The trolley is fixed to the platform without relative displacement, which is used to measure the hydrodynamics forces of sloshing fluids acting on the tank. All sensors are linked to the data acquisition system, which is used to save and display the measurement data of each sensor in real time without time delay.

The test platform can be used to study the liquid sloshing characteristics under horizontal excitation and input the following motion information to the motion simulator through a computer:

$$x = -a \sin(\omega t), \tag{1}$$

where the motion amplitude a is set to 10 mm.

In the tests, the length of the rectangular tank $L = 0.51$ m, the width $W = 0.15$ m, and the height $H = 0.47$ m. The tank is made of transparent plexiglass panels and can be assumed to be rigid. The arrangement of related instruments is shown in Figure 2. The two wave gauges are, respectively, arranged at a position of 18 mm from the left and right wall surfaces of the rectangular tank and fixed on the tank. Six pressure sensors are successively installed at the left wall of the tank and 11 mm, 30.5 mm, 52 mm, 70.2 mm, 90.2 mm, and 105 mm away from the bilge.

A displacement sensor is adopted in the experimental system to record the time history of the motion simulator

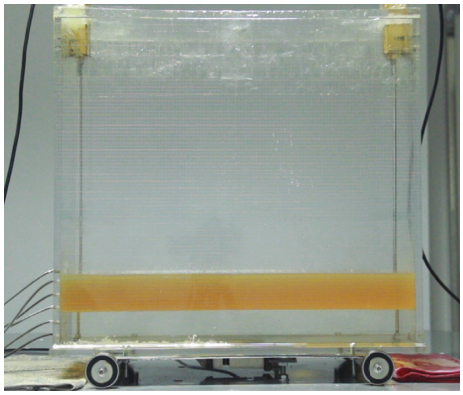


Figure 1: Schematic diagram of oil-water stratified liquids sloshing test device.

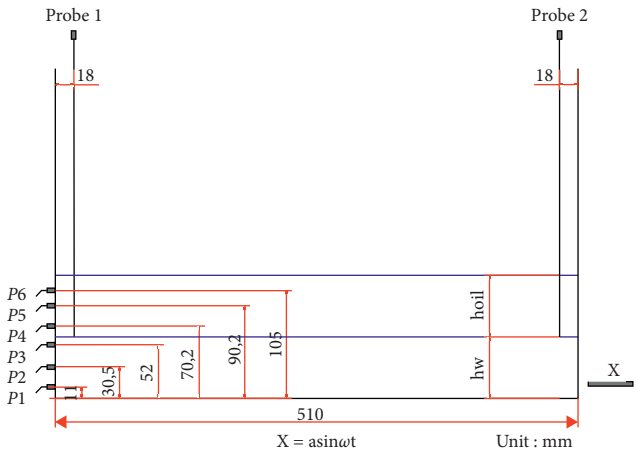


Figure 2: The layout of the test instruments.

which is used to compare with the theoretical or prescribed displacement curve of the motion simulator. This is used to verify that the platform movement can be precisely controlled.

2.2. Mathematical Model. It is assumed that two fluids are incompressible, isothermal, and immiscible, and, in the case of gravity and source terms, the continuity equation and momentum equation are as follows (OpenFOAM6, 2019):

$$\frac{\partial u_j}{\partial x_j} = 0,$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j u_i\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} + \tau_{tij}\right) + \rho g_i + f_{\sigma i}, \tag{2}$$

where u represents the fluid (air, oil, or water) velocity; g_i is the gravitational acceleration; p is the pressure; τ_{ij} is the shear stress, τ_{tij} is the turbulent stress; and $f_{\sigma i}$ is the surface tension.

The density ρ is defined as follows:

$$\rho = \alpha\rho_1 + (1-\alpha)\rho_2, \tag{3}$$

where ρ is 1 inside fluid 1 with the density ρ_1 and 0 inside fluid 2 with the density ρ_2. At the interphase between the two fluids α varies between 0 and 1.

The surface tension $f_{\sigma i}$ is modelled as continuum surface force (CSF). It is calculated as follows:

$$f_{\sigma i} = \sigma\kappa\frac{\partial\alpha}{\partial x_i}, \tag{4}$$

where σ is the surface tension constant and κ is the curvature. The curvature can be approximated as follows:

$$\kappa = -\frac{\partial n_i}{\partial x_i} = -\frac{\partial}{\partial x_i}\left(\frac{\partial\alpha\ \partial x_i}{|\partial\alpha\ \partial x_i|}\right). \tag{5}$$

In order to know where the interphase between the two fluids is, an additional equation for α has to be solved:

$$\frac{\partial\alpha}{\partial t} + \frac{\partial\left(\alpha u_j\right)}{\partial x_j} = 0. \tag{6}$$

The equation can be seen as the conservation of the mixture components along the path of a fluid parcel.

In OpenFOAM, the method proposed by Weller is adopted, which uses an artificial convection term to squeeze the phase fraction near the phase interfacial to counteract the phase interfacial ambiguity caused by numerical dissipation and artificial convection. The term needs to be numerically guaranteed to be zero at the nonphase interfacial. According to the idea of adding artificial convection terms, the VOF model can be expressed as

$$\frac{\partial\alpha}{\partial t} + \nabla\cdot(\alpha U) + \nabla\cdot\left(\alpha(1-\alpha)U_c\right) = 0. \tag{7}$$

The third term in equation (7) is a manually added compressible term, which is 0 in the pure term (non-interfacial) calculation domain. U_C is the modeling speed, which should be compressed in the normal direction of the interfacial instead of tangential; otherwise, it will cause false diffusion. Therefore, the direction of U_C should be the same as n, which can be written as follows:

$$\mathrm{U}_c = f\left(\frac{\nabla\alpha}{|\nabla\alpha|}\right). \tag{8}$$

The compression speed cannot be too large, which is not in line with physics. Therefore, the maximum compression speed is U; then, there is

$$U_c = c|U|\frac{\nabla\alpha}{|\nabla\alpha|}, \tag{9}$$

where c is the controllable compression factor. When $c = 0$, there is no compression effect. The larger c, the faster the compression effect. The final phase equation is

$$\frac{\partial\alpha}{\partial t} + \nabla\cdot(\alpha U) + \nabla\cdot\left(\alpha(1-\alpha)c|U|\frac{\nabla\alpha}{|\nabla\alpha|}\right) = 0. \tag{10}$$

2.3. Mesh Convergence Test. The geometric model used in this study is a two-dimensional rectangular tank, and the extracted data points are also consistent with the layout of the instrument in Figure 2. The fluid velocity is not particularly large during the sloshing process, so a laminar flow model is used. Because the geometric model is a rectangular tank, a structured uniform mesh can be used, as shown in Figure 3, where the mesh sizes in the x and y directions are the same.

In OpenFOAM, the solver used to solve this model is MultiphaseInterFOAM (OpenFOAM6). In order to validate the adopted model, the simulation condition selected is total liquids depth of 10 cm, liquid depth ratio of 1.0, external excitation frequency of 0.90 Hz. The natural frequency of the operating condition is 0.90 Hz. The initial time step is set to 0.001 s and is automatically modified based on the maximum Courant number.

To ensure that the numerical results are independent of the mesh size, mesh independence tests were performed by using four different mesh sizes, as shown in Figure 4. These meshes are labeled I, II, III, and IV, and the mesh sizes are 0.8 mm, 1.9 mm, 1.5 mm, and 2.0 mm, respectively. It can be seen from Figure 4 that when the mesh sizes are 0.8 mm and 1.0 mm, the numerical results of the model change a little. Therefore, a mesh size of 1.0 mm is employed in the following studies.

3. Results and Discussions

3.1. Density-Stratified Liquids Sloshing. It is important to obtain the curves of free surface and interfacial wave response amplitude in a wide range of frequencies for understanding the dynamic characteristics of density-stratified liquids sloshing in a tank. A two-dimensional rectangular tank with width L in the x direction is partially filled with two internally immiscible fluids with density and depth of ρ_1 , ρ_2 and h_1, h_2, respectively. Under the assumption of ideal fluid and microamplitude wave theory, the dispersion relationship between natural frequency and geometric scale and density is deduced according to the equation described by the velocity potential as [10]

$$\omega_{n\pm}^2 = \frac{\left(\alpha_n \pm \sqrt{\alpha_n^2 - \overline{2\gamma_n\beta_n}}\right)}{\gamma_n}, \tag{11}$$

$$\begin{cases} \alpha_n = k_n g\left(\text{th}n_1 + \text{th}n_2\right) + \dfrac{T_{12}k_n^3}{\rho_2}\cdot thn_2 + \dfrac{T_{01}k_n^3}{\rho_1}\cdot\left(\text{th}n_1 + R_{12} + \text{th}n_2\right), \\ \beta_n = thn_1\cdot thn_2\left(k_n g + \dfrac{T_{01}k_n^3}{\rho_1}\right)\left(1 - R_{12}\right)k_n g + \dfrac{T_{12}k_n^3}{\rho_2}, \\ \gamma_n = 2\left(1 + R_{12}\text{th}n_1\cdot\text{th}n_2\right), \end{cases} \tag{12}$$

where T_{01} and T_{12} are the free surface and interfacial tension coefficients, respectively, $\text{th}n_i = \text{th}\left(n\pi h_i/L\right)$. $R_{12} = \rho_1/\rho_2$. Diesel oil density is $\rho_1 = 845\,\text{kg/m}^3$ and water density is $\rho_2 = 1000\,\text{kg/m}^3$. Wave number is $k_n = n\pi/a$. g is the gravity acceleration. $n = 0, 1, 2, \ldots$ is the mode number.

3.2. Effect of Liquid Depth Ratios on Stratified Liquids Sloshing. The natural frequency of stratified liquids sloshing is related to the liquid depth ratio. When the frequency of movement of the tank is close to the natural frequency of the stratified liquids system, there will be severe sloshing and large impact pressure. A series of experimental studies have been performed to analyze the influence of the excitation frequency on stratified liquids sloshing in a partially filled rectangular tank. The total depth of the stratified liquids in the tank is 10 cm. The liquid depth ratio is chosen to be 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6, respectively.

The maximum dynamic pressure on the tank wall during the test is shown in Figure 5. The results show that the maximum dynamic pressure of each pressure measurement point increases with increasing frequency, and when a critical value is reached, the maximum dynamic pressure of the pressure measurement point decreases with increasing frequency. This is consistent with the dispersion relationship derived from the potential flow theory. However, it is worth noting that the maximum dynamic pressure at the test pressure measurement point did not reach the maximum at the natural frequency calculated by equation (11) of the stratified flow dispersion equation, which indicates that the experimental results are somewhat different from the theory due to the nonlinear sloshing. In a stratified liquid sloshing test with a total liquid depth of 10*mm* and different liquid depth ratios, it is found that the actual resonance frequency is between about 1.03 and 1.07 times the theoretical resonance frequencies. The fundamental reason for the difference between the actual resonance frequency and the theoretical resonance frequency is that the theoretical solution is derived under the condition of potential flow theory. It is assumed that the liquid is nonspin and nonviscous. In fact, viscosity is the main reason for system nonlinearity.

3.3. Effect of Total Liquid Depth on Stratified Liquids Sloshing. In addition to the ratio of liquid depth having an effect on the natural frequency of stratified liquids sloshing, the total depth of liquid is also an important parameter for the natural frequency of stratified liquids sloshing, and the effect of total liquid depth on natural frequency is greater than the ratio of liquid depth to the natural frequency, as shown in Table 1 calculated by equation (11). For example, when the total liquid depth is 8 cm, the natural frequency is about 0.82 Hz; when the total liquid depth is 10 cm, the natural frequency is about 0.90 Hz; when the total liquid depth is 12 cm, the natural frequency is about 0.97 Hz.

The liquid depth ratio is 1.0, the total liquid depth h is chosen to be *8 cm*, 10 cm, and 12 cm, respectively, and the corresponding tank filling rates h/L are 15.7%, 19.6%, and 23.5%, respectively. The maximum dynamic pressure on the tank wall is shown in Figure 6. When the external excitation frequency is close to the natural frequency of stratified liquid sloshing, large impact pressure is generated in the system. Through a series of experiments with different liquid depth ratios at different total liquid depths, it can be found that the test results are somewhat different from the theory. When

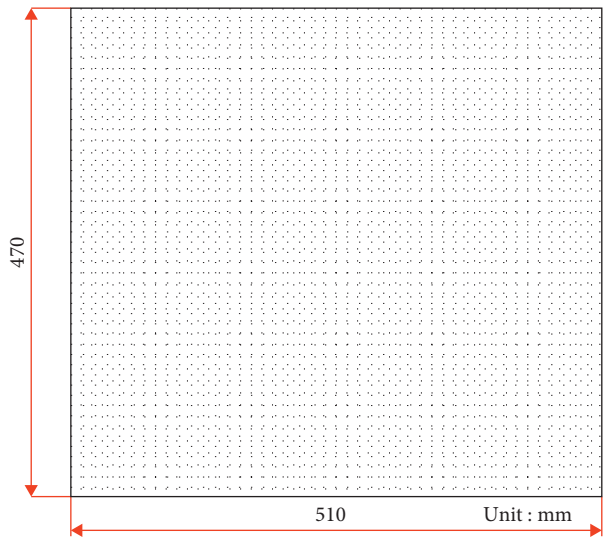


Figure 3: Mesh setup of a two-dimensional rectangular tank (unit: mm).

the total depth of the stratified liquids is 8 cm, the actual resonance frequency is about 1.02 to 1.05 times the theoretical resonance frequency. When the total depth of the stratified liquids is 10 cm, the actual resonance frequency is about 1.03 to 1.07 times the theoretical resonance frequency. When the total depth of the stratified liquids is 12 cm, the actual resonance frequency is about 1.03 to 1.08 times the theoretical resonance frequency. In summary, the actual resonance frequency of the stratified liquids sloshing is slightly larger than the theoretical value calculated from the potential flow theory.

3.4. Characteristics of Stratified Sloshing Interfacial Waves. Considering that the interfacial wave generated when the stratified liquid is sloshing will have a certain impact pressure on the tank wall, the wave amplitude of the interfacial wave is also the focus of research. Figure 7 shows the maximum wave amplitude of the stratified liquid interfacial wave as a function of external frequency. It can be seen that the maximum wave amplitude of the interfacial wave reaches a maximum near the resonance frequency. It is worth noting that when the total depth of the liquid is low (the total depth of the liquid is 8 cm), as the external frequency increases from low to the resonance frequency, the maximum value of the interfacial wave amplitude does not always increase, and there is another peak value of interfacial wave amplitude. This phenomenon occurs when the liquid depth is relatively low. And this tendency also exists in the condition where the total liquid depth is 10 cm and the liquid depth ratio is low, but it is not obvious enough compared with the condition where the total liquid depth is 8 cm. During the test with a low liquid depth ratio, due to the high interfacial wave amplitude, when the interfacial wave reaches the wall, the upper and lower layers of liquid are mixed with each other, making the interfacial blurred, and it is difficult to determine the wave amplitude measurement. This may also be the reason for another maximum value of the interfacial wave amplitude under the condition that the total liquid depth is 8 cm, as shown in Figure 8.

3.5. Dynamic Pressure Prediction. In the following sections, experimental data will be compared with numerical results to validate the accuracy of the numerical model. The test conditions were selected such that the liquid depth ratio is 1.0 and the external excitation frequency is 0.90 Hz. It is noted that the frequency of movement of the tank is equal to the natural frequency of the stratified liquids system, the degree of liquid motion is violent, and its pressure changes with time as shown in Figure 9. It can be seen from Figure 9 that the pressure value measured by each pressure measurement point continuously increases in the first 5 s. This is because the external excitation frequency has suddenly increased from 0 Hz to 0.90 Hz, and the stratified liquids system continuously absorbs externally input energy. When the stratified liquids sloshing reaches a steady state, it can be seen that the pressure versus time curve is nonlinear. Moreover, the numerical results are in good agreement with the experimental data, which shows that the MultiphaseInterFOAM solver in OpenFOAM can be used to solve the stratified liquids sloshing numerically.

By using fast Fourier transform analysis technology, the FFT spectrum is generated for time series of dynamic pressure, as shown in Figure 9. The generated pressure is composed of different frequencies, but the main response frequency is about 0.90 Hz, which is equal to the external excitation frequency. Other secondary response frequencies are integer frequency and cannot be also ignored. This shows that when the external excitation frequency is close to the natural frequency of stratified liquids sloshing, the system produces strong nonlinear interaction. In conclusion, it can be proved that the MultiphaseInterFOAM solver can accurately predict the strongly nonlinear density-stratified liquids sloshing.

3.6. Interfacial Wave Elevation Prediction. Figure 10 shows the comparison of the numerical results of the interfacial wave and the experimental data, and the data is taken on the left side of the wave gauge. The conditions of the experimental data are selected to be consistent with section 3.5. It can be seen in Figure 10 that the numerical simulation results and the experimental results are fair agreements. However, there are still some deviations.

From equations (3) and (7), it can be known that when $\alpha = 0$, the fluid is fluid 1 and when $\alpha = 1$, the fluid is fluid 2. Therefore, between fluid 1 and fluid 2, $\alpha = 0.5$ can be taken as the interfacial between the two liquids; that is, the idea of extracting interfacial waves is to extract the height when $\alpha = 0.5$. Because the distance of the interfacial is very short, rarely the data of α on the mesh points is 0.5. Therefore, the data extracted is the height of the mesh points closest to

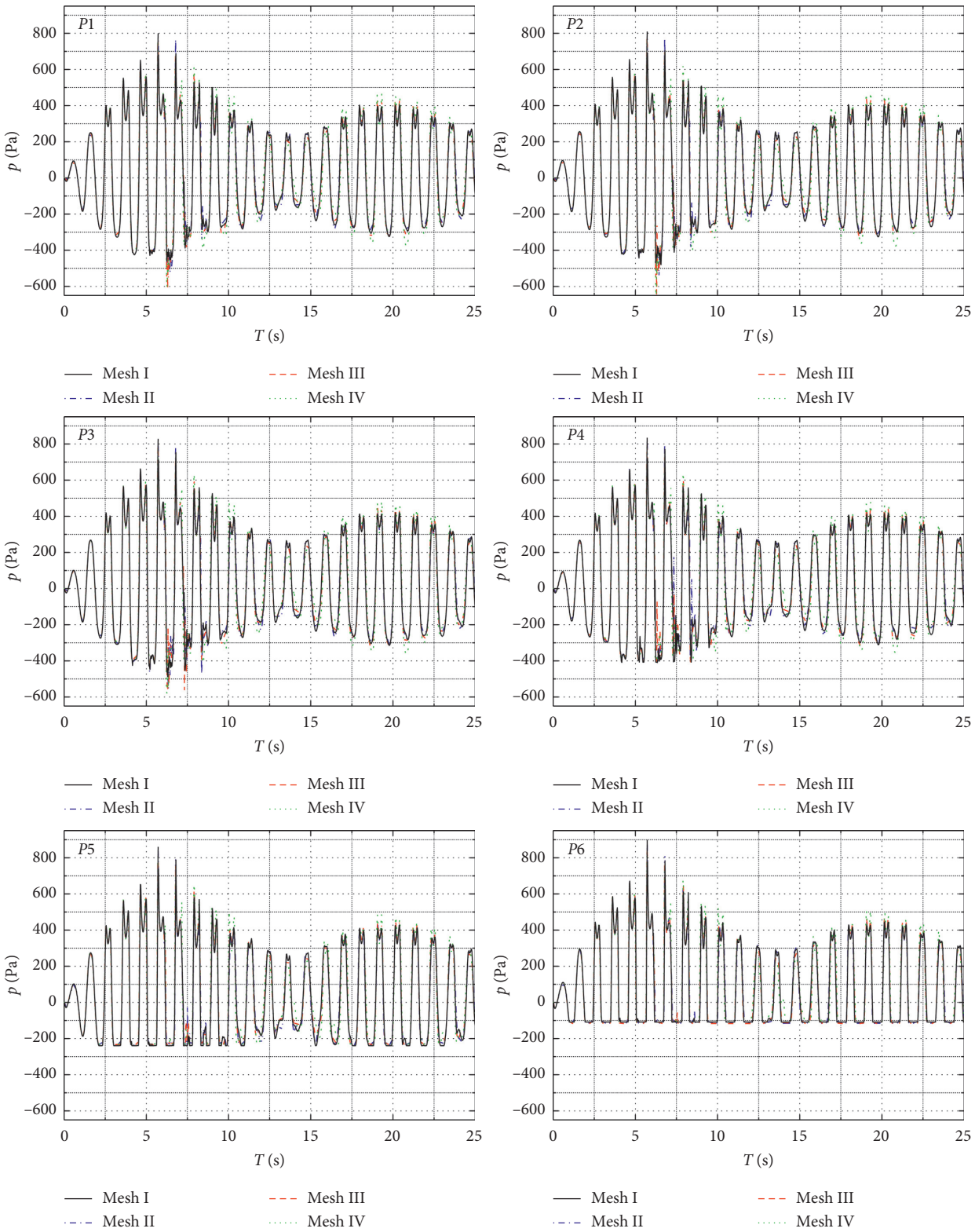


Figure 4: Time histories of pressure: mesh I (black solid), mesh II (blue dot and dash), mesh III (red dash), and mesh IV (green dot).

$\alpha = 0.5$, and this is used as the wave amplitude of the interfacial wave. This may be the reason causing the difference between experimental data and numerical results.

Under this condition, the density-stratified liquid sloshing is a strongly nonlinear problem, and numerical simulations and experiments show the phenomenon of

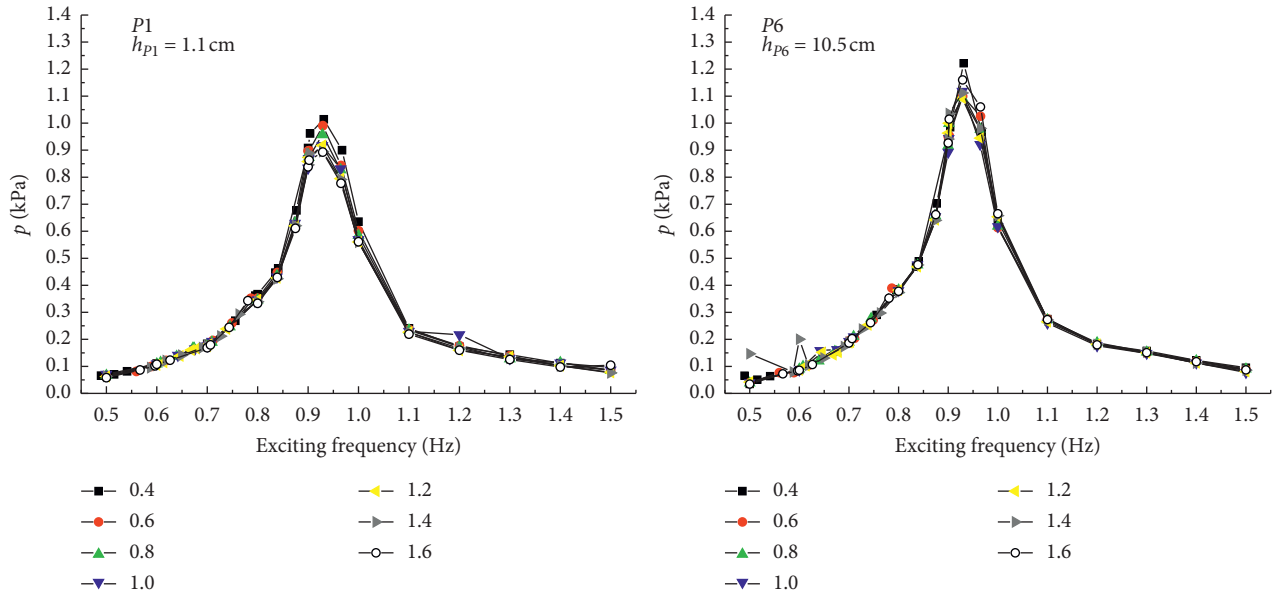


Figure 5: Maximum pressure amplitude with various exciting frequencies.

Table 1: Natural frequencies of stratified liquids sloshing.

Total depth of liquid (mm)	Ratio of liquid depth (h_1/h_2)	Natural frequency (Hz)
8	0.4	0.82
8	0.6	0.82
8	0.8	0.82
8	1	0.82
8	1.2	0.82
8	1.4	0.82
8	1.6	0.82
10	0.4	0.90
10	0.6	0.90
10	0.8	0.90
10	1	0.90
10	1.2	0.90
10	1.4	0.90
10	1.6	0.90
12	0.4	0.97
12	0.6	0.97
12	0.8	0.97
12	1	0.97
12	1.2	0.97
12	1.4	0.97
12	1.6	0.97

mutual mixing between different liquids, as shown in Figure 11 near the right wall. Therefore, the condition for determining the height of the interfacial wave becomes a problem. If the lowest height of the mesh point where $\alpha = 0.5$ is taken, the value of the wave amplitude of the interfacial wave is very low when the liquid moves downwards, as shown in Figure 11 near the right wall. If the highest height of the mesh point where $\alpha = 0.5$ is taken, this obviously does not conform to physics. If the average height of the mesh point where $\alpha = 0.5$ is taken, the value of the wave amplitude of the interfacial wave is very high when the liquid moves up, as shown in Figure 11 near the left wall. Based on the above considerations, the first method is adopted, which is the fundamental reason why the interfacial wave troughs of the numerical result in Figure 10 being greatly different.

3.7. Evolution of Velocity Fields. When the density-stratified liquid sloshing is violent, turbulence and vortex will be generated near the tank wall and interfaces, dissipating most

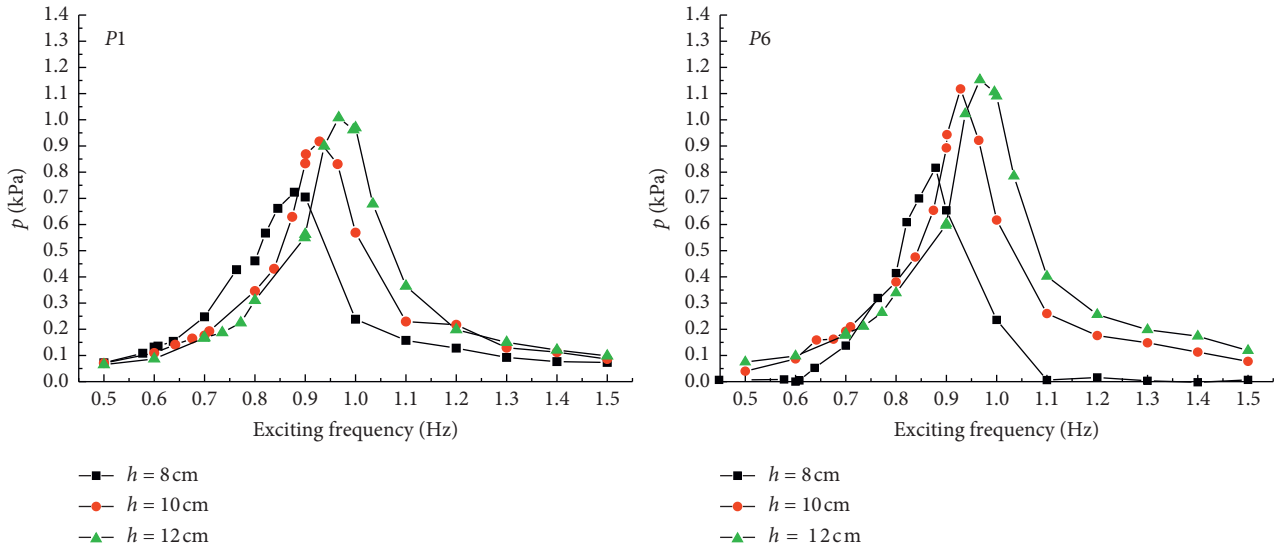


Figure 6: Maximum pressure amplitude at different total liquid depths with various exciting frequencies.

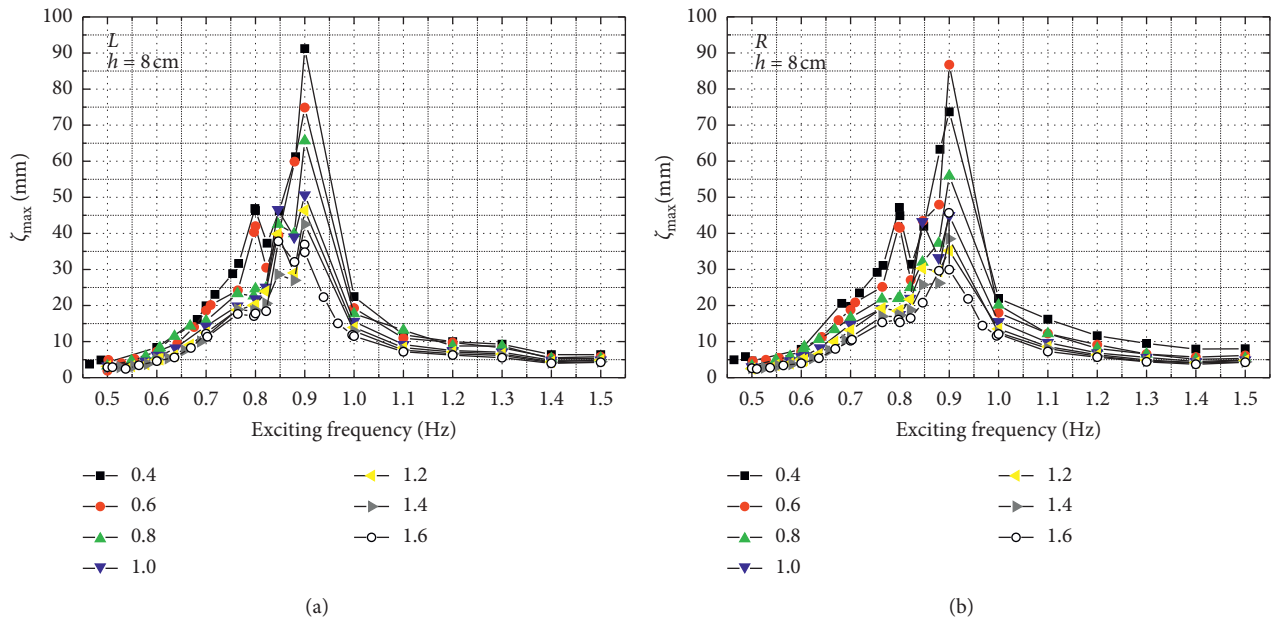


Figure 7: Continued.

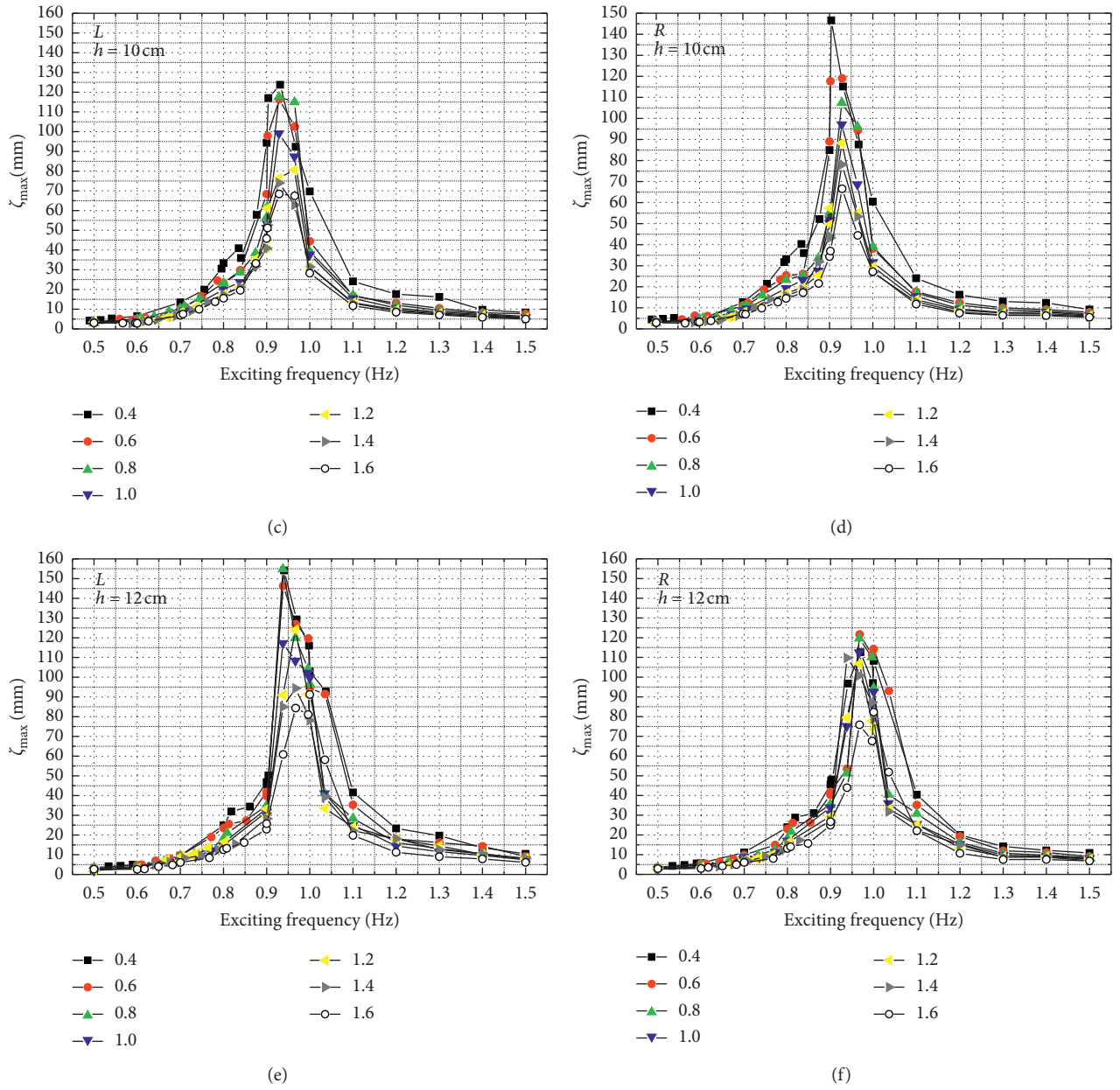


Figure 7: Maximum interfacial wave amplitude with various exciting frequencies. (a) Total liquid depth is 8 cm, left wave altimeter. (b) Total liquid depth is 8 cm, right wave altimeter. (c) Total liquid depth is 10 cm, left wave altimeter. (d) Total liquid depth is 10 cm, right wave altimeter. (e) Total liquid depth is 12 cm, left wave altimeter. (f) Total liquid depth is 12 cm, right wave altimeter.

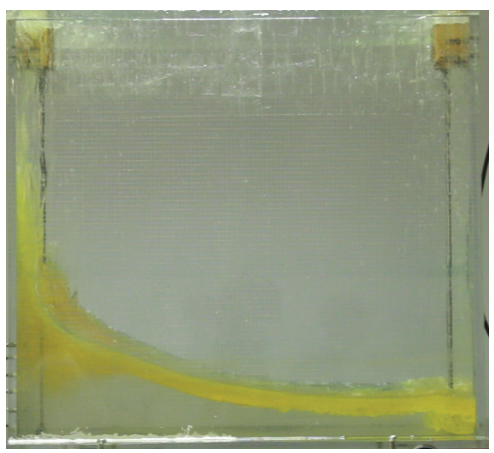
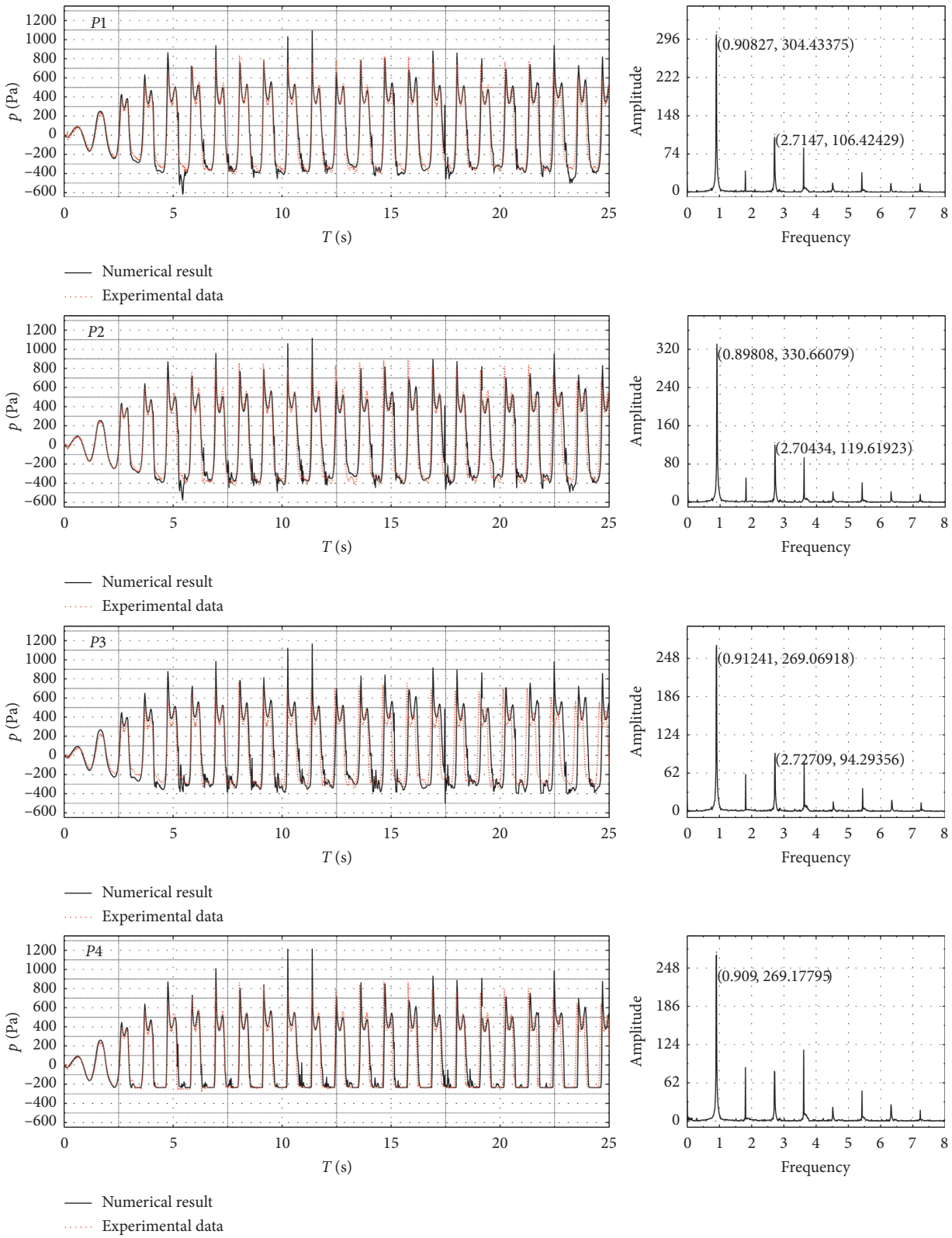
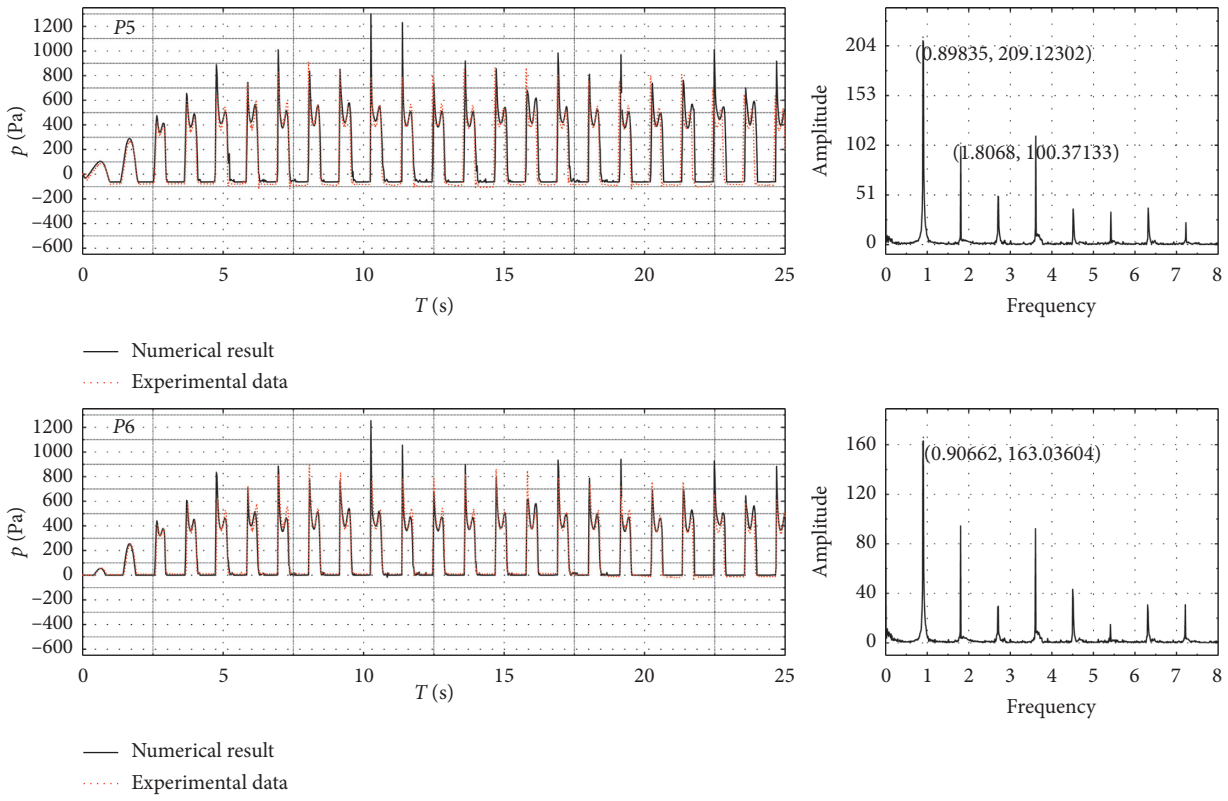


Figure 8: Diesel oil-water mixture at liquid interface.



(a)

Figure 9: Continued.



(b)

Figure 9: Comparison of the pressure between the experimental data and the numerical results and FFT spectrum of the time histories of pressure at tank wall.

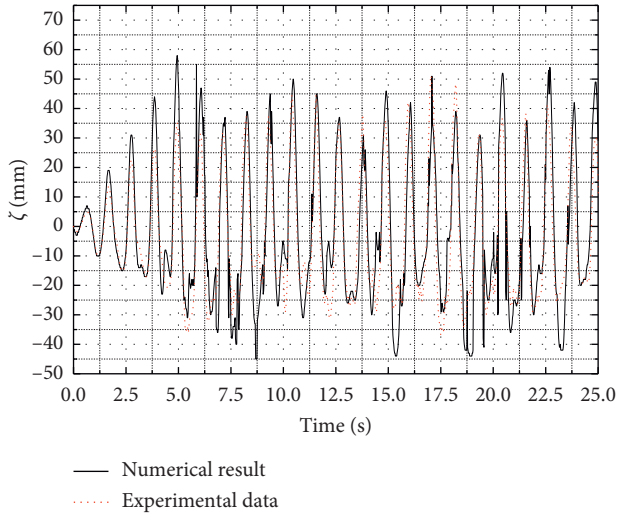


Figure 10: Comparison of time history of interfacial wave between experimental data and numerical results when the total liquid depth is 10 cm.

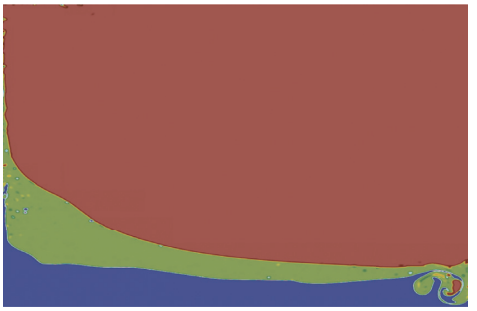
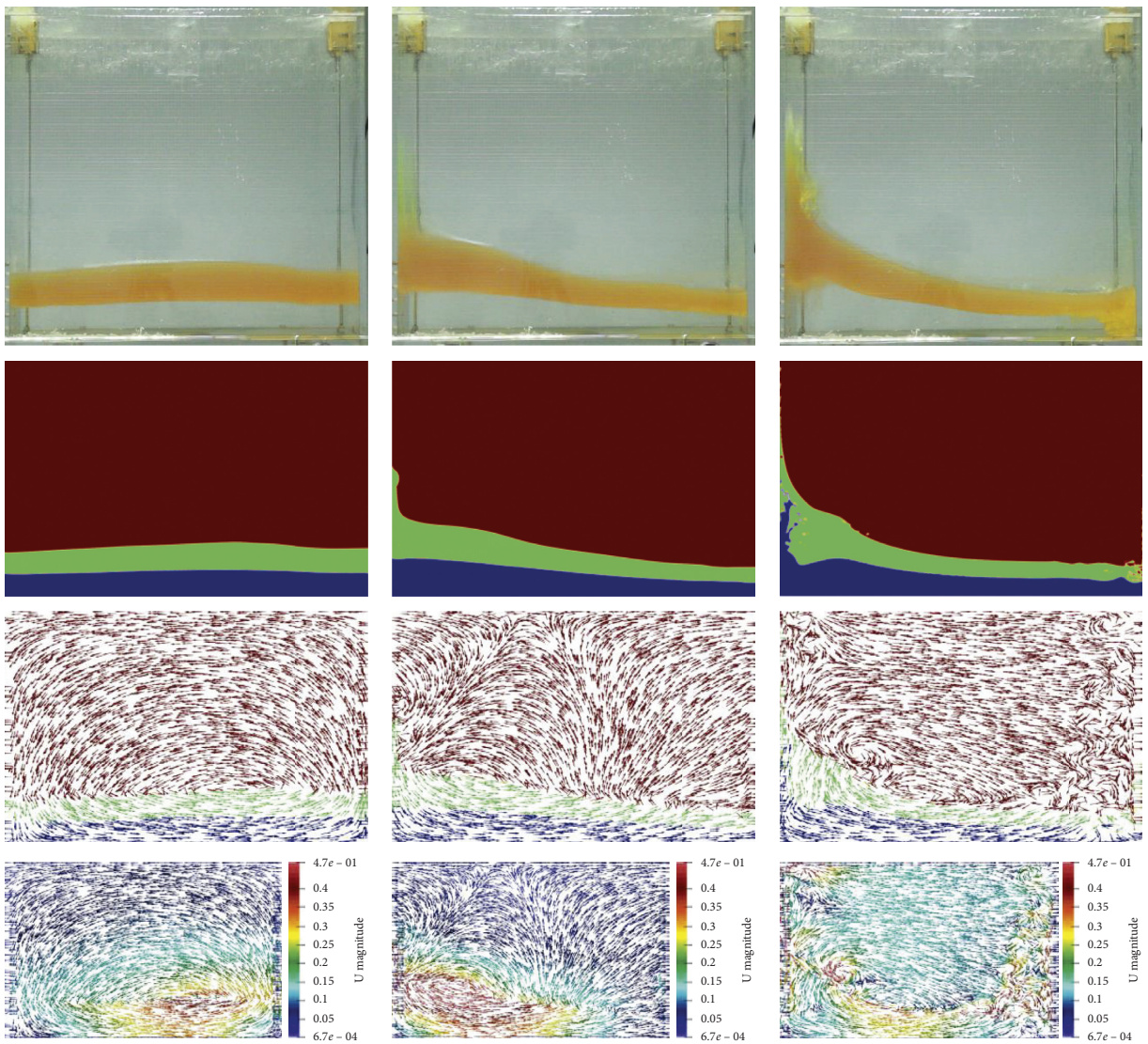


Figure 11: Interfacial mixing ($t = 18.22$ s).

of the energy. The test conditions are still chosen to be the same as in section 3.5. Figure 12 captures the changes in the free surface and interface of the liquid in the tank using the VOF method. According to the comparison of the numerical results and the experimental data, it can be found that the numerical model has a good agreement with experimental data. During the test, it can be clearly seen that when free surface waves and interfacial waves reach or leave the tank wall, the two liquids mix at the interface. From the analysis of numerical results, we can know that vortices are generated at the liquid interface. And this vortex is generated by the upper layer liquid and the lower layer liquid together, not by the single-layer liquid itself. Although the two liquids are mixed with each other at the interface under this condition, the numerical results can still agree with the experimental data for a long time, which shows that the numerical model is very suitable for tracking the free surface wave and interfacial wave.



(a) (b) (c)

Figure 12: Continued.

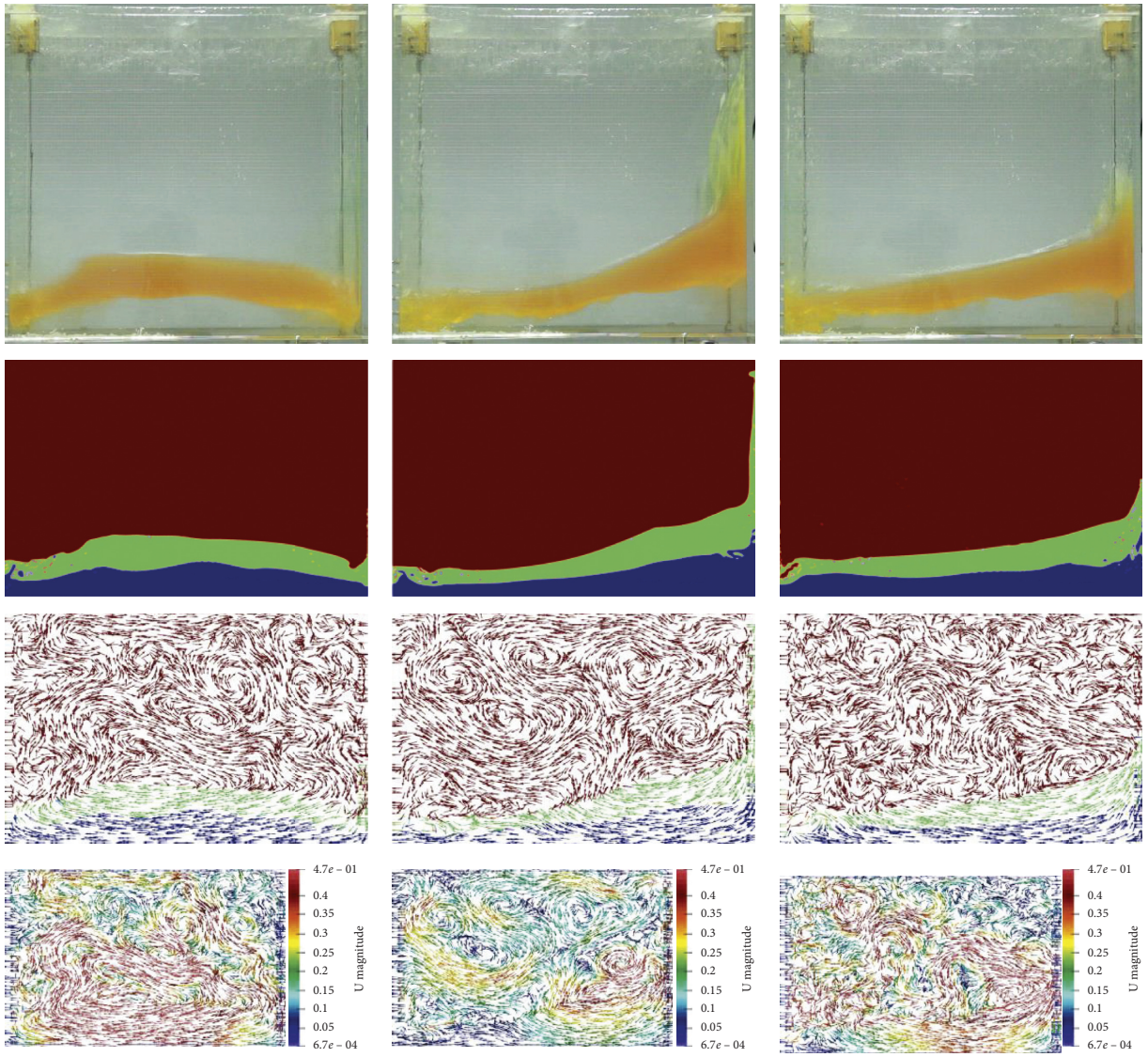


Figure 12: Comparison of free surface and interfacial wave. (a)T = 2.00 s. (b)T = 4.00 s. (c)T = 6.00 s. (d)T = 8.00 s. (e)T = 10.00 s. (f)T = 12.00 s.

4. Conclusions and Further Discussions

The effect of total liquid depth on natural frequency is greater than the ratio of liquid depth to natural frequency. Through a series of experiments with different liquid depth ratios at different total liquid depths, it can be found that the test results are somewhat different from the theory. When the total depth of the density-stratified liquids is 8 cm, the actual resonance frequency is about 1.02 to 1.05 times the theoretical resonance frequency. When the total depth of the stratified liquids is 10 cm, the actual resonance frequency is about 1.03 to 1.07 times the theoretical resonance frequency. When the total depth of the stratified liquids is 12 cm, the actual resonance frequency is about 1.03 to 1.08 times the theoretical resonance frequency.

The maximum wave amplitude of the interfacial wave reaches a maximum near the resonance frequency. It is worth noting that when the total depth of the liquid is low (the total depth of the liquid is 8 cm), as the external frequency increases from low to the resonance frequency, the maximum value of the interfacial wave amplitude does not always increase, and there is another peak value of interfacial wave amplitude. This phenomenon occurs when the liquid depth is relatively low. During the test with a low liquid depth ratio, due to the high interfacial wave amplitude, when the interfacial wave reaches the wall, the upper and lower layers of liquid are mixed with each other, making the interfacial blurred, and it is difficult to determine the wave amplitude measurement. This may also be the reason for another peak value of the interfacial wave amplitude under the condition that the total liquid depth is 8 cm.

By comparing the numerical results with experimental data, it is validated that the MultiphaseInterFOAM solver in OpenFOAM can accurately simulate density-stratified

liquids sloshing, and the VOF method is used. Because the liquids at the interface are mixed with each other, the method of extracting interfacial waves becomes complicated, which needs further research.

During the test, it can be clearly seen that when free surface waves and interfacial waves reach or leave the tank wall, the two liquids mix at the interface. From the analysis of numerical results, we can know that vortices are generated at the liquid interface. And this vortex is generated by the upper layer liquid and the lower layer liquid together.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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