Research Article

Effect of Double-Side Curved Baffle on Reducing Sloshing in Tanks under Surge and Pitch Excitations

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Sloshing is associated with the structural safety of liquid storage vessel. Installing the baffles inside the containers would be beneficial for the mitigating the damage due to the severe sloshing. In this study, an innovative type of double-side curved baffle was proposed to evaluate its effect on reducing sloshing in a rectangular tank under surge and pitch excitation. For comparison with conventional baffles, effects of the vertical baffle and the T-type baffle on mitigating sloshing were also studied experimentally and numerically by analyzing the free surface wave elevation as well as the hydrodynamic pressure on the tank wall. The effective stress at the double-side curved baffle along the height direction of the baffle is much smaller than that at the T-type baffle although they have the same mitigation effect on sloshing wave heights. The sloshing-induced effective stress on the double-side curved baffles was analyzed by varying their radian. Findings show that the effective stress on the baffle tends to decrease with the increase in the radian. The velocity field was presented to observe effect of the baffles on sloshing with the aid of ADINA and laboratory experiments conducted on a hexapod motion platform.

1. Introduction

Liquid sloshing means severe motion of a free surface liquid inside a partially filled container, which is an unsteady and highly nonlinear phenomenon with frequency jump, shift in resonant frequency, super-harmonic resonance, responses at higher harmonics, and fractional harmonics of forcing frequency and thus difficult to describe in full detail [1]. Any liquid storage containers may produce sloshing in a certain condition in addition to the fully filled liquid storage tank or no liquid tank. All kinds of numerical methods are employed to study sloshing. Wu et al. [2] analyzed the liquid sloshing in a 3D tank by using the finite element method (FEM) based on the fully nonlinear wave potential theory. Kim [3] simulated sloshing in the 2D/3D liquid containers by using the finite difference method (FDM). Celebi and Akyildiz [4] used the volume of fluid (VOF) techniques to track the free surface of the fluid and studied the nonlinear sloshing phenomenon of the liquid in the partially filled rectangular

tank. Chen and Xue [5] and Xue et al. [6] performed a series of numerical simulation by using OpenFOAM to investigate the influences of filling levels, external excitation frequency, amplitude, and tank shape on liquid sloshing. Zang et al. [7] derived an axisymmetric boundary element method based on the assumptions of inviscid, irrotational, incompressible liquid, and small amplitude by using the weighted residual method and Green's theorem. Zang et al. [8] firstly proposed an isogeometric boundary element method based on the nonuniform rational B-splines (NURBS) to study the liquid sloshing in the tank with porous baffles.

The slamming induced by sloshing may result in the deformation of the tank wall and even damage. Lots of investigations were conducted to find ways to inhibit liquid sloshing and reduce impact loads. Installing the baffles inside the liquid tanks is considered to be a simple and effective method in mitigating sloshing [9–11]. Abramson [12] first predicted the dynamic pressure on internal baffles and tank walls induced by liquid sloshing. Akyildiz and Ünal [13]

experimentally studied the pressure distribution of a three-dimensional (3D) rectangular tank under different water depths, baffles, and external excitation frequencies and concluded that the baffles can significantly reduce fluid motion. Xue et al. [14] numerically studied the seiche oscillations of layered fluids in a closed rectangular tank and concluded that the vertical baffle accelerated the wave decay for both free surface wave and interfacial wave and also affected the dominant response frequencies of the seiche oscillations. Liu and Lin [15] developed a 3D two-phase fluid flow model to simulate liquid sloshing in a tank with vertical baffles. Their results indicated that vertical baffles have a significant effect on reducing the impact pressure. Wang et al. [16] concluded that the baffles with relatively large length have significant effects on suppressing sloshing force. Meanwhile, they thought that circular arc angle instead of right angle may slightly increase the sloshing force acting on the rectangular annular tank. Xue and Lin [17] investigated the damping mechanism of the ring baffle in reducing sloshing in a rectangular tank by using an in-house NEWTANK model. Akyildiz [18] and Jung et al. [19] studied the effect of vertical baffle height on liquid sloshing by changing the ratio of vertical baffle height to the initial liquid depth. Jin et al. [20] studied experimentally effect of different horizontal porous baffles on liquid sloshing under different external excitation frequencies and amplitudes. Cho et al. [21] studied sloshing with porous baffle by considering two porous baffle positions, namely, one at the center of the rectangular tank and the other at both walls of the tank. Xue et al. [22] studied experimentally the effectiveness of immersed bottom-mounted vertical baffles, vertical baffles flushing with free surface, surface-piercing bottom-mounted vertical baffles, and perforated vertical baffles in suppressing sloshing pressure. Chu et al. [23] investigated the characteristics of liquid sloshing with multiple vertical baffles installed on the bottom of the rectangular tank by varying the external excitation frequency, baffle number, and height. Ünal et al. [24] studied numerically the liquid sloshing in a closed and partially filled two-dimensional (2D) rectangular tank with T-type baffle under rotating excitation. Effect of the factors such as rotation angles, filling levels, and baffle heights on hydrodynamic pressure on tank walls and free surface wave elevations was analyzed. Yu et al. [25] experimentally studied effect of suppressing sloshing by using two perforated floating baffles under different solidity ratios, filling levels, and excitations. Zheng et al. [26] experimentally studied wave interaction with coral reef-flat that can be seen as porous media in a wave basin. Xue et al. [27] numerically studied effects of porous media layer on mitigating sloshing in a membrane LNG tank.

To the authors' best knowledge, the double-side curved baffle has ever been seldom proposed to evaluate its effectiveness in mitigating sloshing. The objective of this research is to discuss the effects of double-side curved baffle and T-type baffle on sloshing mitigation under surge and pitch excitations. Automatic dynamic incremental nonlinear analysis (ADINA) software has been widely used to study sloshing problem. Eswaran et al. [28] studied the sloshing in cubic tanks with ring baffle and horizontal-cum-vertical

baffle by using ADINA software. Cheng et al. [29] used ADINA to simulate three different volumes of storage tanks having different liquid height under the earthquake. Wang et al. [30, 31] used ADINA to simulate the characteristic of liquid sloshing in a rigid cylindrical tank with multiple rigid annular baffles internal. This study would be also performed with the aid of the well-known finite element software ADINA and the hexapod motion platform sloshing tests.

This study is organized as follows. In Section 2 and Section 3, the sloshing experimental platform and numerical model ADINA are introduced briefly. A series of laboratory experiments are carried out in a rectangular tank installed with vertical baffle and T-type baffle, respectively. Both baffles are located at the bottom center of the tank with the same height. The effects of two baffles on suppressing sloshing under the same submerged water depth are discussed by changing the tank movement style and excitation frequencies. In Section 4, the ADINA is employed to simulate sloshing in the rectangular tank with T-type baffle and double-side curved baffle, respectively. The simulation results are compared with the experimental data obtained in Section 3 for validating the accuracy of ADINA in simulating sloshing problems. In Section 5, effects of radians of double-side curved baffles on suppressing sloshing in the rectangular tank are analyzed numerically. Finally, the main conclusions are summarized.

2. Experimental Set Up and Procedure

2.1. Experimental Description. The experiments were conducted in Laboratory of Vibration Test and Liquid Sloshing at Hohai University of China. A hexapod motion platform, which is able to perform six degrees of freedom (DOF) harmonic and random motions according to a predesigned input, is utilized to generate the forced motions of the liquid tank, as shown in Figure 1. The rectangular tank, which is 0.6 m in length, 0.65 m in height, and 0.3 m in width, was fixed on the center of the experimental platform, as shown in Figure 2. A laser displacement sensor was used to record the movement of the platform and the tank, and an angular displacement sensor was fixed in the middle of the platform to record the rotation angle of the platform and the tank. Two capacitive wave probes, which are 0.02 m away from the left and right tank wall, respectively, were installed inside the rectangular tank. Five pressure sensors were located on central line of the left side tank wall. The distance between each pressure sensor was 0.04 m, and the distance between the pressure sensors and the tank bottom is $P1 = 0.03$ m, $P2 = 0.07$ m, $P3 = 0.11$ m, $P4 = 0.15$ m, and $P5 = 0.19$ m, respectively. The range of the wave probe and pressure sensor was 60 cm with a precision of $\pm 0.5\%$ F·S and 50 KPa with a precision of $\pm 0.1\%$ F·S, respectively. The time series of free surface elevation and pressure was recorded by a SDA3000 sensor data acquisition system at an optional sampling rate of 100 Hz or 1000 Hz. Two types of the baffles including vertical baffle (Case1) and T-type baffle (Case2) were installed in the middle of the tank bottom, respectively, as shown in Figure 2. The ratio

FIGURE 1: Hexapod motion platform.

FIGURE 2: The rectangular tank model and layout of the sensors and the baffles.

0.43 of water depth to tank length, namely, a finite water depth of 0.258 m was considered in experiments. The first-order resonant frequency of the tank with different baffle was obtained by the response curve of the maximum wave elevation to the corresponding external excitation frequencies, as shown in Table 1.

The motion of the tank was subjected to the following sinusoidal function, namely, the surge excitation with $x = A \sin 2\pi ft$ and pitch excitation with $\theta = \theta_0 \sin 2\pi ft$, where the amplitude is $A = 0.002$ m and $\theta_0 = 1^\circ$, respectively. The coupled motions under surge and pitch excitation were also conducted by using $x = A \sin 2\pi ft + \theta_0 \sin 2\pi ft$ with the same amplitude 0.002 m and 1° . The experimental parameters are summarized in Table 2.

2.2. Instruments Calibration. In this study, the real horizontal and rotational motion displacement of the hexapod motion platform is recorded by a laser displacement sensor and an angular displacement sensor. To verify the accuracy of the platform movement, the predesigned theoretical displacement was compared with the experimental measurement data by the sensors, as shown in Figure 3, and good agreement is obtained.

3. Effects of Motion Style on the Maximum Wave Amplitude Response to Frequencies under Different Baffles

3.1. Surge Excitation. The maximum wave amplitude of sloshing in the tank with vertical baffle and T-type baffle under surge excitation was obtained experimentally. The tank movement is with $A = 0.002$ m. Figure 4 shows comparisons of the maximum wave amplitude response frequencies between Case 1 and Case 2 under surge excitation. It observed that the maximum wave amplitude of Case 1 is smaller than that of Case 2 when the external excitation frequencies f are smaller than $0.99f_0$ (f_0 is the first-order resonant frequency). When f is equal to f_0 , the maximum wave amplitude of Case 1 has a huge jump, and the maximum wave amplitude of Case 1 is larger than that of Case 2 with the increasing of f . The effect of T-type baffle on reducing sloshing is better than that of vertical baffle under surge excitation in proximity of resonant frequency.

3.2. Pitch Excitation. Figure 5 shows that the maximum wave amplitude comparison of Case 1 and Case 2 under pitch excitation, which was subjected to the following

TABLE 1: The first-order resonant frequency of the tank with different baffles.

First-order resonant frequency (Hz)	Case 1	Case 2
	0.8	0.77

TABLE 2: Experimental parameters.

Case	Water depth (m)	Excitation amplitude	Excitation frequency f (Hz)
1	0.258	$A = 0.002$ m, $\theta = 1^\circ$	0.76–0.84 ^a , 0.72, 0.88
2	0.258	$A = 0.002$ m, $\theta = 1^\circ$	0.73–0.81 ^a , 0.69, 0.8 [°] 5

Notes: a indicates that the frequency interval is 0.01 Hz.

FIGURE 3: Displacement comparisons between the experimental measurement data and theoretical data: (a) surge excitation with $A = 0.002$ m, $(f) = 1$ Hz; (b) pitch excitation $\theta_0 = 1^\circ$, $(f) = 1$ Hz.

FIGURE 4: Comparison of the maximum wave amplitude response to frequencies between Case 1 and Case 2 under surge excitation.

sinusoidal function, $y = \theta \sin 2\pi ft$, where θ was the amplitude of the pitch excitation and $\theta = 1^\circ$. From Figure 5, it can be seen that the change of the maximum wave amplitude under different frequencies of Case 1 and Case 2 is opposite to the change of the maximum wave amplitude under surge excitation. The maximum wave amplitude of Case 1 is larger than that of Case 2 when f is smaller than f_0 , and situation becomes totally different when f is larger than f_0 . However, the peak of the maximum wave amplitude does not occur at f_0 , no matter Case 1 or Case 2. For Case 1, the peak of the maximum wave amplitude occurs at $0.96f_0$, and the peak of the maximum wave amplitude occurs at $1.05f_0$ for Case 2. In

terms of the maximum wave amplitude change, the damping effect of the tank with vertical baffle and T-type baffle is similar.

3.3. Coupled Excitation of Surge and Pitch. Figure 6 shows the maximum wave amplitude comparison of Case 1 and Case 2 at different frequencies under coupled excitation of surge and pitch. The excitation was subjected to the function, $y = A \sin 2\pi ft + \theta \sin 2\pi ft$. The trend of change is roughly the same as that of the maximum wave amplitude under pitch excitation. However, the value of maximum

FIGURE 5: Maximum wave amplitude comparisons of the tank with vertical baffle and the tank with T-type baffle under pitch excitation.

FIGURE 6: Comparisons of maximum wave amplitude of sloshing in the tank with vertical baffle and with T-type baffle under coupled excitation of surge and pitch.

wave amplitude is smaller than that under pitch excitation; it is because the initial motion direction of surge and pitch excitation is opposite under the coupling state set in this study. Besides, the peak of the maximum wave amplitude which occurs near the resonant frequency is $0.98f_0$ for Case 1 and is $1.00f_0$ for Case 2.

In summary, when the external excitation is surge, the maximum wave amplitude varies dramatically for Case 1; when the external excitation frequency f is equal to the resonant frequency f_0 , the maximum free surface elevation has a jump. For Case 2, the maximum free surface elevation changes gently. The damping effect of the vertical baffle is better than that of the T-type baffle when f is less than $0.98f_0$; however, the damping effect of the T-type baffle is better than that of the vertical baffle when f ranges from $0.98f_0$ to $1.1f_0$. When the external excitation is pitch excitation and coupled excitation of surge and pitch, the damping effect of the T-type baffle is better than that of the vertical baffle when f is less than f_0 , and the damping effect of the vertical baffle is better than that of the T-type baffle when f is larger than f_0 . Therefore, the T-type baffle is a better tool in reducing sloshing when f is less than f_0 ; the vertical baffle

is a better tool in reducing sloshing when f is larger than f_0 under surge and pitch excitations.

Since the liquid sloshing is violent in the range of $0.95f_0 \sim 1.05f_0$, the statistical analysis on the impact pressure data in the range of $0.95f_0 \sim 1.05f_0$ is carried out in this study. The impact pressure response curve to external excitation at different pressure sensors positions is shown in Figure 7. The curve in (i) represents the impact pressure of the tank with the vertical baffle at different positions under a range of external excitation, and the curve in (ii) represents that of the tank with the T-type baffle. Figure 7(a) shows the comparison of the tank with the vertical baffle and with the T-type baffle under surge excitation of $A = 0.002$ m. Figure 7(b) shows that under the pitch excitation of $\theta = 1^\circ$, and Figure 7(c) shows that under the coupled excitation of surge and pitch of $A = 0.002$ m and $\theta = 1^\circ$. Findings show that the impact pressure reaches the maximum near the resonant frequency, no matter what kind of baffle, which pressure measuring points. The pressure at p5 is generally greater than the pressure at any other positions. The reason is that the location of p5 is close to the top of the baffle, where the baffle has little inhibition effect on sloshing, and the

FIGURE 7: The impact pressure response curve to external excitation at different positions: (a) surge excitation, $A = 0.002$ m; (b) pitch excitation, $\theta = 1^\circ$; (c) coupled excitation of surge and pitch, $A = 0.002$ m, $\theta = 1^\circ$, where (i) represents the impact pressure of the tank with the vertical baffle at different positions under a range of external excitation and (ii) represents that of the tank with the T-type baffle.

liquid sloshing intensity at p5 is greater than that at other measuring points. In addition, the impact pressure at each measuring point of the tank with T-type baffle at different external excitation frequencies is smaller than that at each corresponding measuring point of the tank with vertical baffle at different frequencies. The sloshing mitigation effect of the T-type baffle is found to be better than that of the vertical baffle in this study.

4. Sloshing Mitigation Effect of Double-Side Curved Baffle

The sloshing mitigation effect of the double-side curved baffle is rarely reported. In this study, the double-side curved baffle was proposed to study its effect in reducing sloshing. The double-side curved baffle was placed in the middle of the tank bottom. The top and bottom width of this baffle is 0.1 m,

the middle waist width of the baffle is 0.006 m, and the radius of the arc is 0.136 m, as shown in Figure 8. Considering that the experiment is time-consuming and expensive, the software ADINA was adopted to carry out numerical studies. The sloshing mitigation effect of the double-side curved baffle under surge excitation with external excitation amplitude $A = 0.002$ m, pitch excitation with external excitation amplitude $\theta = 1^\circ$, coupled excitation of surge and pitch with $A = 0.002$ m and $\theta = 1^\circ$ as well as the external excitation frequency is 0.73 Hz are studied, respectively. For comparison, T-type baffle was also studied together.

4.1. Introduction of ADINA. The Arbitrary Lagrange Euler (ALE) method is adopted to solve the fluid-structure coupling problem in ADINA software. By tracking the true position of the free surface, the ALE method can realize the analysis of the fluid-structure coupling problem by the interaction between solid and liquid being transferred to each other through the coupling surface [32]. The basic equation is as follows:

$$f = \frac{\partial f}{\partial t} \Big|_x + \frac{\partial f}{\partial x_i} c_i = \frac{df}{dt} + c \nabla f, \quad (1)$$

where f is the convection velocity described by a certain physical quantity and c_i is the convection velocity described by the Euler method. $c_i = u_i - w_i$, where u_i is the material velocity of the fluid particle, w_i is the velocity of the grid in the reference coordinate system, and x is the reference coordinate in the reference coordinate system.

The Navier–Stokes equations for the incompressible viscous fluid described by the ALE method are derived as follows:

$$\text{Equation of continuity: } \frac{\partial u_i}{\partial x_i} = 0,$$

$$\text{Equation of motion: } \frac{du_i}{dt} + c_j \frac{\partial u_i}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i,$$

$$\text{Equation of constitutive: } \sigma_{ij} = -\frac{p}{\rho} \delta_{ij} + \nu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right),$$

$$\text{The boundary conditions: } \begin{cases} u_i = \hat{u}_i, & \text{on } S_w, \\ \sigma_{ij} m_j = \hat{\sigma}_i, & \text{on } S_f, \\ p = \hat{p}, & \text{on } S_f, \end{cases}$$

$$\text{The initial conditions: } u(x, 0) = u_0(x), \quad (2)$$

where S_w and S_f are wet wall surface and free surface; ρ , p , and ν are fluid density, pressure, and kinematic viscosity coefficients; f is the volume force; and m_i is the normal vector components outside the boundary.

According to the kinematics relation, the only constraint condition of grid point velocity on the free liquid surface is as follows:

FIGURE 8: Dimensions of the double-side curved baffle (unit: m).

$$u_i m_i = w_i m_i. \quad (3)$$

In ADINA, flow-condition-based interpolation (FCBI) is a special case in the finite volume method, which locally satisfies the conservation of mass and momentum, and satisfies the windward condition by interpolation of velocity. The following is the process of solving Navier–Stokes equations using FCBI unit. Considering the incompressible fluid in a two-dimensional region, satisfying the essential and natural boundary conditions, the velocity $v(x, t) \in V$ and the pressure $p(x, t) \in P$ are required to make the following:

$$\nabla \cdot (\rho v) = 0, \quad (x, t) \in \Omega \times [0, T], \quad (4)$$

$$\frac{\partial \rho}{\partial t} v + \nabla \cdot (\rho v v - \tau) = 0, \quad (x, t) \in \Omega \times [0, T].$$

Initial conditions and boundary conditions are as follows:

$$\begin{aligned} v(x, t) &= {}^0 v(x), \\ p(x, t) &= {}^0 p(x), \quad x \in \Omega, \\ v &= v^s, \quad (x, t) \in \overline{S_v} \times (0, T], \\ \tau \cdot n &= f^s, \quad (x, t) \in S_f \times (0, T], \end{aligned} \quad (5)$$

where $\tau = \tau(v, p) = -pI + \mu[\nabla v + (\nabla v)^T]$, ρ is the liquid density, μ is the viscosity coefficient, the boundary of region $\Omega \in \mathbb{R}^2$ is $S = \overline{S_v} \cup S_f$ ($S_v \cap S_f = \emptyset$), T is the time range under consideration, v^s is the given velocity on the boundary $\overline{S_v}$, f^s is the given normal force on the boundary S_f , and n is the unit normal vector on the boundary.

The Petrov–Galerkin variable formula was used for the subspace V_h, U_h, W_h of V and P_h, Q_h of P . Find $v \in V_h$, $u \in U_h$, $p \in P_h$ so that for any $w \in W_h$, $q \in Q_h$ has

$$\int_{\Omega} w \left[\frac{\partial p}{\partial t} u + \nabla \cdot (\rho u v - \tau(u, p)) \right] d\Omega = 0, \quad (6)$$

$$\int_{\Omega} q \nabla \cdot (\rho u) d\Omega = 0.$$

To define the space, Figure 9 shows the grid cells in a natural coordinate system. In order to obtain the matrix corresponding to the usual two-dimensional geometric model, isoparametric transformation is used. Figure 9 shows a typical set of 9-node elements (Figure 9(a)) and subelements (Figure 9(b)), which are defined by the four nodes in the 9-node element for speed interpolation. Each 9-node cell can be thought as consisting of four 4-node cells.

For the definition of space U_h , subunits are considered. The temptation function in U_h is defined as

$$\begin{bmatrix} h_1^u & h_4^u \\ h_2^u & h_3^u \end{bmatrix} = h(\xi) h^T(\eta), \quad (7)$$

where $h^T(\eta) = [1 - y, y]$, ($y = \xi, \eta$, $0 \leq \xi, \eta \leq 1$).

Similarly, the unit in space P_h (Figure 9(a)) is considered.

$$\begin{bmatrix} h_1^p & h_4^p \\ h_2^p & h_3^p \end{bmatrix} = h(t) h^T(s), \quad 0 \leq t, s \leq 1. \quad (8)$$

The temptation function in V_h is defined by the flow conditions at each boundary of the subunits. For the flux passing through ab edge, the test function is

$$\begin{bmatrix} h_1^v & h_4^v \\ h_2^v & h_3^v \end{bmatrix} = [h(x^1), h(x^2)] h(\eta) h^T(\eta), \quad (9)$$

where $x^k = (e^{q^k} \xi - 1/e^{q^k} - 1)$ and $q^k = (\rho \bar{u}^k \cdot x^k / \mu)$.

$\bar{u}^k \in U^k$ is the velocity at the center point of the cell boundary under consideration; similarly, the temptation function for flux through bc edge can be constructed and so on. Although the flow conditions at the cell boundary may differ, these functions satisfy $\sum h_i = 1$. The unit in space Q_h is a step-size function. Considering Figure 9(a), for example, at node 2 there is

$$h_2^q = \begin{cases} 1, & (r, s) \in [(1/2), 1] \times [0, (1/2)], \\ 0, & \text{other.} \end{cases} \quad (10)$$

Similarly, the weight function in space W_h is also a step-size function. For example, consider node 1 in the subunit as follows:

$$h_1^w = \begin{cases} 1, & (\xi, \eta) \in [0, (1/2)] \times [0, (1/2)], \\ 0, & \text{other.} \end{cases} \quad (11)$$

4.2. Verification of Numerical Results. The first-order resonance frequency of the tank installed with different baffles at a water depth of 258 mm was calculated through

frequencies/mode of ADINA. The calculated results were compared with the first-order resonance frequency obtained by sweeping frequency in the experiments, as shown in Table 3, and the results are pretty close.

ADINA was used to simulate sloshing in the rectangular tank with baffles, and the time history of the free surface elevation was obtained. Figure 10 shows the comparison of the free surface elevations of the liquid tank with baffle during sloshing obtained by experiment and ADINA simulation. Figure 10(a) shows the comparison of free surface elevation in first 10 seconds of a rectangular tank installed the vertical baffle under surge excitation with excitation amplitude $A = 0.002$ m and excitation frequency $f = 0.72$ Hz. The solid line represents the wave height obtained by the experiment, and the dashed line represents the numerical result. Basic trends are consistent although difference exists. For further validation, Figure 10(b) shows that of the rectangular tank with the T-type baffle under surge excitation with $A = 0.002$ m and $f = 0.69$ Hz. The results shows that the free surface elevations obtained by experiments and ADINA simulations agree fairly. In Figure 11, the change of free surface waveform of both numerical and experimental tests is shown at different time. Fairly agreements are also obtained, indicating that the ADINA is capable of predicting sloshing in a tank with the baffles.

4.3. Sloshing Mitigation Effects of Double-Side Curved and T-type Baffle under Different Excitation Styles. Figure 12 shows the comparisons of time history of wave height under different excitation styles. The external excitation frequency of 0.73 Hz, the surge excitation amplitude of 0.002 m, and the pitch excitation amplitude of 1° are kept the same. The black line represents the wave height time history of the tank with T-type baffle, and the red line represents that of the tank with double-side curved baffle. Figure 12 shows that the change of free surface wave elevation of the tank with T-type baffle, and the tank with double-side curved baffle is very similar under different motion style. Besides, the variation trend of free surface wave amplitude under the coupled excitation of surge and pitch is similar to that under pitch excitation. The reason is that the surge excitation amplitude is small, which make the influence of surge excitation be almost nonexistent.

In order to further compare the effects of T-type baffle and double-side curved baffle on reducing liquid sloshing, several stress measuring points are selected on baffles, and the effective stress of the corresponding stress measuring points on the two types of baffles is compared. At the top of baffles, four stress measuring points are selected along the width of the baffles, which are named as p_{11} , p_{12} , p_{13} , and p_{14} , respectively. Six stress measuring points are selected along the height direction of the baffles, which are named as p_{15} , p_{16} , p_{17} , p_{18} , p_{19} , and p_{10} , respectively. The location of each stress measuring point is shown in Figure 13. The external excitation is surge, and the amplitude is 0.002 m, and the frequency is 0.69 Hz. The results are compared in Figures 14 and 15. From stress distribution of measuring points in the direction of the baffle height, the effective stress of T-type baffle in measuring

FIGURE 9: (a) 9-node element; (b) subelement.

TABLE 3: The comparison of 1st resonant frequency obtained by ADINA and experiments.

Case	Water depth (m)	$f_{1st,ADINA}$ (Hz)	$f_{1st,Experiment}$ (Hz)
1	0.258	0.820	0.800
2	0.258	0.775	0.770

FIGURE 10: Comparisons of the free surface elevations of the experimental data and ADINA simulation under surge excitation: (a) Case 1: $f = 0.72$ Hz, $A = 0.002$ m; (b) Case 2: $f = 0.69$ Hz, $A = 0.002$ m. FIGURE 11: Evolution of free surface profile at (a) $(t) = 2$ s; (b) $(t) = 3.1$ s; (c) $(t) = 3.5$ s; (d) $(t) = 4.3$ s.

FIGURE 12: Comparisons of time history of wave height under different motion styles of the tank with T-type baffle and double-side curved baffle and $(f) = 0.73$ Hz: (a) surge excitation with $A = 0.002$ m; (b) pitch excitation with $\theta = 1^\circ$; (c) coupled excitation of surge and pitch with $A = 0.002$ m and $\theta = 1^\circ$.

FIGURE 13: Layout of stress measurement points (unit: m).

FIGURE 14: Comparison of effective stress in the vertical direction of different baffles: (a) tank with T-type baffle; (b) tank with double-side curved baffle.

FIGURE 15: Comparison of effective stress in horizontal direction of different baffles: (a) tank with T-type baffle; (b) tank with double-side curved baffle.

point p_{19} is the largest and then followed by p_{18} and p_{17} . The largest effective stress of double-side curved baffle is in p_{18} , and p_{19} and p_{17} are then followed. In addition, the effective stress distribution of each stress measuring point of the T-type baffle is much larger than that of the corresponding measuring point of the double-side curved baffle. From stress distribution of measuring points along the width of baffles, the effective stress of each measuring point of the T-type baffle is roughly the same, while the effective stress of each measuring point of the double-side curved baffle increases with the increase in the distance between the measuring point and the edge of the baffle.

Figure 16 shows the evolution of velocity fields installed with double-side curved baffle under different motion styles. The baffle installed in the tank changed the moving direction of the fluid when sloshing occurred. The liquid hits the baffle, and the double-side curved baffle leads the liquid to move along the arc of the baffle. It can be seen from Figure 16 that vortices are formed on both sides of the flange of the baffle. All of these contribute to the dissipation of the energy when liquid sloshing. The existence of the baffle separates the liquid

from the left and right sides of the rectangular tank and restricts the sloshing of the liquid. Therefore, the velocity amplitude of the liquid is very small in the water depth below 0.206 m, which is the height range of the baffle, and sloshing is also not violent. The maximum velocity occurs at the junction between the liquid and the top of the baffle, and it may be that as the height rises, the liquid is less and less restricted by the baffle, and as the water depth gets closer and even more than 0.206 m, the sloshing becomes more and more violent. In addition, the liquid moves along the arc of the double-side curved baffle and passes over the baffle when moved to the top of it, and then the slamming happens.

From Figures 12(b), 12(c), 16(b), and 16(c), it can be seen that there is almost no influence of the surge excitation on sloshing, and the liquid mainly exhibits the characteristics of the sloshing under pitch excitation when the coupled excitation amplitude is $A = 0.002$ m and $\theta = 1^\circ$. In order to analyze the effect of coupling excitation on liquid sloshing, the amplitude of surge excitation is increased to 0.01 m, and the characteristics of liquid sloshing under the coupled excitation of surge and pitch are analyzed.

FIGURE 16: Evolution of velocity field under (a) surge excitation; (b) pitch excitation; (c) coupled excitation of surge and pitch.

FIGURE 17: Comparisons of time history of free surface wave under (a) surge excitation; (b) coupled excitations of surge and pitch.

FIGURE 18: Evolution of velocity field under coupled excitations of surge and pitch, $A = 0.01$ m and $\theta = 1^\circ$.

Figure 17 shows the comparisons of time history of free surface wave under surge excitation and coupled excitations of surge and pitch when the surge excitation amplitude increases to 0.01 m. Since the initial direction of liquid movement is opposite under the excitation of surge and pitch, the wave generated under surge excitation and wave generated under pitch excitation will overlap and collide with each other, which caused sloshing wave energy dissipation and then suppressed the liquid sloshing.

The velocity field shown in Figure 16(c) has different characteristics comparing with that shown in Figure 18. When the external excitation amplitude is $A = 0.002$ m and $\theta = 1^\circ$, the maximum flow velocity occurs at the interface between the liquid and the top of the double-side curved baffle (as shown in Figure 16(c)). When the external excitation amplitude is $A = 0.01$ m and $\theta = 1^\circ$, the maximum flow velocity occurs not only at the interface between the liquid and the top of the double-side curved baffle but also at the edges of the baffle and the wall of the rectangular tank (as shown in Figure 18). It may be that wave generated by the surge excitation and wave generated by pitch excitation meet and counteract in the middle position of the liquid, while the wave near the wall of the rectangular tank and the edge of

baffle do not. Therefore, the flow velocity in the liquid decreases, while the flow velocity at the edge increases.

5. Effect of Radian on the Damping Effect

In order to find out whether the radian of the double-side curved baffle has an effect on reducing sloshing, four kinds of double-side curved baffle with different radians are proposed in Figure 19. The height and the top width of the baffle remain the same, only the radians of the baffle are changed, and the radians are 0.132 m, 0.136 m, 0.140 m, and 0.153 m, respectively. Eleven stress measuring points are arranged on baffle, four of which are distributed on the top of the baffle, and the rest are distributed along the curved edge of the baffle, as shown in Figure 20.

The ADINA is used to simulate the liquid sloshing of these four different radian baffles when water depth is 0.258 m, the surge excitation amplitude is 0.002 m, and the external excitation frequency is 0.69 Hz. The time history of free surface wave elevation for four kinds of double-side curved baffle with different radians is shown in Figure 21. The change of the radian of the double-side curved baffle has little influence on the wave elevation. Figures 22 and 23 show

FIGURE 19: Double-side curved baffle with different radians (unit: m).

FIGURE 20: Layout of stress measurement points (m).

FIGURE 21: Contrast of wave heights on free surface of different radian baffles.

FIGURE 22: Comparison of effective stress in the vertical direction of different radian baffles: (a) $r = 0.132$ m, (b) $r = 0.136$ m, (c) $r = 0.140$ m, and (d) $r = 0.153$ m.

FIGURE 23: Continued.

FIGURE 23: Comparison of effective stress in horizontal direction of different radian baffles: (a) $r = 0.132$ m, (b) $r = 0.136$ m, (c) $r = 0.140$ m, and (d) $r = 0.153$ m.

comparison of the effective stress at different measuring points distributed along the curved edge of the baffle and comparison of the effective stress at different measuring points distributed at the top of the baffle with different radians. It can be seen from Figure 22 that the effective stress corresponding to p_{31} , p_{41} , p_{51} , p_{61} , and p_{71} under different radians gradually decreases with the increasing of radians. When the radian is equal to 0.132 m, the effective stress at measuring point p_{31} is the largest and then followed by p_{41} , p_{51} , p_{61} , and p_{71} . When the radian is equal to 0.153 m, the situation becomes exactly the opposite. In addition, the difference between the maximum and minimum values of the effective stress obtained by each stress measuring point (p_{41} , p_{51} , p_{61} , and p_{71}) also decreases with the increasing radian. It can be seen from Figure 23 that the effective stress at measuring point p11 increases slightly with the increasing radians, while the effective stress at other measuring points remained basically unchanged. On the whole, sloshing mitigation effect increases with increasing the radian of the double-side curved baffle.

6. Conclusions

Sloshing mitigation effects of the vertical baffle, the T-type baffle, and the double-side curved baffle are investigated in this study by comparing the maximum wave amplitude, effective stress distribution, and evolution of velocity field under different excitation parameters. Some conclusions have been drawn as follows.

It was proved to be in this study that the damping effect of the T-type baffle is better than that of vertical baffle. From the perspective of the maximum wave amplitude changing with the external excitation frequency, when the tank is excited by surge excitation, the antisloshing effect of the T-type baffle is better than that of the vertical, and when the tank is excited by pitch excitation and coupled excitation of surge and pitch, the damping effect of this two kings baffles is about the same. According the hydrodynamic pressure on the tank wall under resonant frequency, when the tank is fitted with T-type baffle, the hydrodynamic pressure at all

measuring points in the tank wall is lower than that when the vertical baffle is installed.

As for the dimension of the baffles set in this study, there is almost no difference in the free surface elevation of T-type baffle and double-side curved baffle under the same sloshing condition. However, when the external excitation is surge excitation and the amplitude of excitation is 0.002 m, the frequency of excitation is 0.69 Hz and the effective stress at the double-side curved baffle along the height direction of the baffle is much smaller than that at the T-type baffle. And, the effective stress at the double-side curved baffle along the width of the baffle is larger than that at the T-type baffle.

By changing the radian of the double-side curved baffle, it was found that the effective stress on the baffle tends to decrease with the increase in the radian on the whole.

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.

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