Numerical Simulation on the Sloshing Characteristics of Gas-liquid Flow in Cargo Tank and Anti-sloshing Methods

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Abstract. With the rapid development of society, the demand for liquid carrier ships and vehicles is increasing rapidly. Under the action of external load, the liquid in the tank would move relative to different degrees and produce hydrodynamic pressure on the local part of the liquid bulkhead, which will cause local damage or complete destruction of the structure, and then lead to leakage or other safety accidents. In this paper, computational fluid dynamics method is used to simulate the sloshing characteristics of the liquid in the cargo tank, and the instantaneous characteristic data of the free surface displacement fluctuation of the sloshing liquid are monitored. Through the pressure acquisition system, the hydrodynamic pressure distribution acting on the side wall of the cargo tank under external excitation is obtained. Through the free surface displacement fluctuation and the maximum hydrodynamic pressure acting on the side wall, the severity of liquid sloshing in cargo tank under external excitation is evaluated. The effects of different baffle combinations on liquid sloshing in cargo tanks are studied and discussed. The effects of baffles with holes on liquid sloshing are also discussed.

Keywords: Cargo tank; sloshing; Resistance of the shaking; gas-liquid two-phase flow.

1. Introduction
Liquid sloshing is a ubiquitous fluid movement phenomenon, generally occurs in a container with a certain free surface, usually it is the relative movement of two or more immiscible (or Minimal miscibility) fluids in a limited space, with complex liquidity, randomness and nonlinearity. Along with the sloshing of the liquid, the movement of the liquid would show plane sloshing, wave overturning, rotation, mixing, etc. In recent years, with the changes in energy structure, the rise of LNG and LPG tankers and spot-supply tankers caused by uneven distribution of gas has further made sloshing a hot research issue worldwide. On the other hand, since it is impossible to reach full load during transportation, there will always be a free liquid surface, which will cause sloshing under external excitation. To solve various problems caused by sloshing during transportation, many scholars at home and abroad have actively carried out related researches on liquid sloshing. The complexity, randomness and nonlinearity of the sloshing problem bring many problems to the study of the problem. However, in recent decades, many effective research methods have been developed, which can be divided into theoretical analysis method, numerical simulation method and physical model experiment method[1-3].

Liu and Lin [4,5] established a completely nonlinear numerical model of liquid sloshing in a three-dimensional rectangular container based on the VOF method, simulated the joint movement of the three-dimensional container in two horizontal directions, and were able to simulate and analyze the breaking and rolling of waves. Firouz-Abadi and Haddadpouretal [6] established a numerical model based on the boundary element method, in which reduced-order modeling technology was used, and
mainly study the different modal shape distribution of liquid sloshing in the container. Wu and Chen [7] studied liquid sloshing under resonance conditions. Research on anti-sloshing measures, Arafa [8] studied the liquid sloshing in a container with horizontal and vertical partitions and analyzed the changes of the natural frequency of the container with different partitions in different partitions. Goudarzi and Sabbagh-Yazdietal [9] analyzed the liquid sloshing in a container with horizontal and vertical partitions through numerical simulation and physical experiments, And mainly studied the damping strength of the partition against liquid sloshing. Faltinsen and Timokha [10] used the domain decomposition method to construct an asymptotic method suitable for the antisymmetric liquid sloshing mode, and studied the complex relationship between the natural frequency of the partition and the water depth, the number of partitions, and the position of the partition.

In this paper, a numerical simulation method is used to establish a computational fluid dynamics model of gas-liquid two-phase sloshing, to study the influence of the geometrical characteristics and structural form of the tank (with or without baffles and the number and placement of baffles) on the sloshing characteristics.

2. Numerical Simulation Method

2.1. The Numerical Model
In this paper, volume of fluid model and RNG turbulence model are used to study the sloshing process of fluid in cargo tank under excitation, and the mechanism of factors affecting the severity of sloshing in cargo tank is analysed, and corresponding measures are taken to restrain the sloshing.

2.2. The Boundary Conditions
(1) Free surface condition. Kinematic boundary conditions: assuming that fluids are kept on the free surface; dynamic boundary conditions: assuming that the pressure acting on the free surface is atmospheric pressure.
(2) When the flow field is excited by a certain kind of excitation, the displacement fluctuation will occur on the free surface, and the wave will propagate outward until it meets the wall.
(3) Due to the rigid structure of the cargo tank, the normal velocity component of the flow mass point at the bottom plate is 0.
(4) The velocity boundary condition on the walls are set to no slip boundary condition.

2.3. Geometry Model and Discretized Schemes
The model is a 60×60×30 mm rectangular tank with a water depth of 21 mm, that is, the liquid carrying rate is 70%. The surface of the cargo tank is set as the wall, and then the tank is filled with liquid. Constant acceleration is set in the negative direction of Z axis and positive direction of X axis as external excitation. The sloshing characteristics of liquid in cargo tank under external excitation are simulated.

The convergence criterion is set to 0.001 for the simulation cases to ensure a high calculation accuracy. Spatial discretization schemes are critical for the solution process. Therefore, the second order upwind scheme is adopted. The time step is set to 0.01 s, which guarantees that the Courant–Friedrichs–Lewy (CFL) number always remains below 0.5. The number of grids is approximately 200 000 which grid independence was verified.

3. Analysis of Liquid Sloshing Characteristics in Cargo Tanks

3.1. Analysis of the Free Surface Displacement of Liquid Sloshing in the Cargo Tank
The external excitation load received by the cargo tank by setting accelerations in the x-axis and z-axis directions, where the x-axis is set to 2.5m/s² and the z-axis is set to 9.81 m/s² (default gravitational acceleration). The setting of the acceleration is mainly based on the seismic intensity table. This article simulates the sloshing of the cargo tank under the seismic intensity of magnitude 8.
As shown in Figure 1, the sloshing situation of the liquid in the cargo tank at different times. Obviously, under the action of the excitation load, after a period, the liquid in the cargo tank sparks to the top of the tank [11,12]. Under the reaction force of the impact of the tank wall and the action of gravity, the liquid cargo starts to move to the left, and then is excited laterally. The liquid moves to the right, and in cycle. During the sloshing process, the right-side wall of the cargo tank is subjected to continuous swaying power, and the liquid will roll over and produce bubbles, which will cause potential hazards to the cargo tank.

![Figure 1](image1.png)

**Figure 1.** Liquid sloshing in the cargo hold at different times.

From Figure 2, the time characteristics of free liquid level fluctuations. Because no turbulence control measures have been taken, the liquid cargo tank sloshing under certain incentives [13,14]. When t=0.1s, the liquid cargo reaches the top of the tank under the lateral excitation and produces an impact force with the right-side wall of the tank. The reaction force of the impact force is opposite to the direction of the lateral excitation. The fluid sloshed back and forth in the cargo tank, and then generated continuous stress on the right-side wall, causing the cargo tank to deform or even rupture.

![Figure 2](image2.png)

**Figure 2.** Displacement of a point on a free surface at different times.

3.2. Analysis of Liquid Sloshing Liquid Hydrodynamic Pressure in the Cargo Tank

Figure 3 shows the time characteristics of the hydrodynamic pressure (gauge pressure) at the monitoring point on the right-side wall of the cargo tank. From the figure, when t=0.1s, the pressure rises sharply to the highest value (this time is also the time when the free surface displacement reaches the maximum value), and finally with the sloshing of the liquid in the cargo tank, the hydrodynamic pressure stabilizes at a constant value.

![Figure 3](image3.png)

**Figure 3.** Dynamic water pressure changing with time.

![Figure 4](image4.png)

**Figure 4.** Time Characteristics under different loading rates.
3.3. Sloshing Characteristics of Cargo Tanks at Different Loading Rates
The fluctuation of the free surface displacement (the violent degree of sloshing) of the liquid in the cargo tank at different heights of the liquid level is studied, and the most sensitive value of the liquid level (the liquid loading rate of the cargo tank) to the sloshing of the cargo tank is obtained. It can be seen from Fig. 4 that the sloshing severity of cargo tanks at different liquid level heights is not linearly distributed with the liquid level height, but there is an extreme value. When the liquid loading rate in the cargo tank is less than 30%, an extreme value appears; when the liquid loading rate in the cargo tank is between 60% and 70%, an extreme value appears in the fluctuation of the free liquid surface of the cargo tank. It can be concluded that when the liquid loading rate of the cargo tank is about 70%, the liquid in the cargo tank is most sensitive to sloshing under external excitation. On the other hand, when it is less than 30%, it can be that the frequency under the external excitation is close to the natural frequency of the liquid in the cargo tank, leading to severe sloshing under resonance. Therefore, 70% liquid loading rate is selected to simulate the suppression characteristics of different forms of baffles on liquid cargo tank sloshing.

4. Effect of Damping Baffle on Sloshing in Cargo Tank
Under the action of external excitation, the intensity of sloshing in the tank can be properly controlled by setting baffles along the moving path of liquid cargo. This can not only have the effect of shock absorption, but also can be used as a sacrificial structure. The design configuration and location of these baffles need to be simulated and optimized in detail. The liquid sloshing suppression characteristics of horizontal baffle, vertical baffle and symmetrical three plates in cargo tank under external excitation are studied.

4.1. Cargo Tank with Middle Vertical Baffle
A baffle \((x = 0.03m)\) with a height of \(0.018m\) is placed in the middle of the tank. The liquid carrying rate in the cargo tank is 70% (i.e. the liquid level at rest is 0.021 m). It can be seen from Figure 5 that under the external excitation, the free surface displacement rises to the highest point and reaches the peak value near \(t = 0.1s\). At this time, due to the reaction force of the right side wall of the cargo tank and the blocking effect of the baffle placed in the middle of the tank, the displacement of the free surface of the liquid in the cargo tank begins to decrease, and then under the action of the transverse excitation, the free surface starts to surge upward until it collides with the side wall, and thus goes on and on. The first peak is caused by the impact pressure, and the latter series is caused by the change of free surface. It is obvious that the peak value of impact pressure is much greater than the latter, which indicates that violent sloshing will occur near the natural frequency of the liquid and the side wall of the cargo tank will also be subject to huge impact pressure. Compared with that without baffle, the peak value of free surface displacement with baffle decreased, and the fluctuation range of free surface decreased with time \((\Delta = 1mm\) with baffle, \(\Delta = 4mm\) without baffle). These fully show that the installation of positioning baffle can effectively reduce the free surface fluctuation of the cargo tank and inhibit the liquid sloshing in the tank.

4.2. Cargo Tank with Three Symmetrical Baffles
The sloshing characteristics of the liquid are studied when three baffles are symmetrically placed at the bottom of the cargo tank. As shown in Figure 6, the width of the model is 30mm, the thickness is...
2mm and the height is 18mm. The liquid carrying rate in the cargo tank is 70% (i.e. the liquid level at rest is 21mm).

It can be seen from Figure 7 that under the external excitation, when \( t = 0.2s \), the free surface displacement rises to the maximum value. At this time, due to the reaction force of the right side wall of the cargo tank and the blocking effect of the symmetrical baffle placed at the bottom of the tank (the moving direction is opposite to the force direction), the free surface displacement of the liquid in the cargo tank begins to decrease; then, under the action of transverse excitation, the free surface starts to move upward until it collides with the side wall, which goes on and on [15]. Compared with the free surface displacement fluctuation without baffle, it can be found that the time when the free surface displacement fluctuates to the maximum value is delayed than that without baffle; the peak value of free surface displacement is also reduced (the peak value of free surface of cargo tank without baffle plate reaches the tank top under the external excitation, which can effectively avoid the phenomenon after placing baffle); with the pushing of time, the free surface displacement peak value of the tank without baffle plate reaches to the tank top of the tank. The fluctuation range of the free surface displacement is smaller. All these show that the positioning baffle can effectively inhibit the sloshing of the liquid cargo tank.

Compared with the setting of the middle vertical plate, the maximum free surface displacement of the middle vertical plate is relatively small in terms of the peak value of the free surface displacement. It can be seen that the vertical plate in the middle of the tank has a better effect on the sloshing of the tank.

4.3. Influence of Vertical Baffle Position Setting

The effects of the middle vertical baffle and the symmetrical baffle on the sloshing characteristics of the liquid in the cargo tank under external excitation were discussed. It is concluded that the effect of the middle vertical baffle on the sloshing of the liquid is better. This section will discuss the influence of the position of vertical baffle at the bottom of the tank on the liquid sloshing characteristics of the tank. Due to the external excitation, the liquid in the cargo tank will start to move to the right side wall. Therefore, in this section, vertical baffles will be placed on the left and right side walls close to the cargo tank, with the positions of \( x = 15\text{mm} \) and \( x = 50\text{mm} \). The basic size of the baffle is consistent with the setting of the middle vertical baffle. As shown in the Figure 8, we can get the following conclusion: placing transverse baffles on the left and right sides of the cargo tank cannot effectively reduce the free surface displacement fluctuation in the cargo tank, and the positioning baffle on the left side of the cargo tank has the worst suppression effect, because the external excitation load is applied in the positive direction of X axis, and the liquid in the tank sloshes to the right side of the tank under the external excitation. In other words, most of the liquid is concentrated on the right side. Compared with the three methods, the horizontal baffle placed in the middle of the tank can effectively restrain the liquid sloshing in the tank under the external excitation load.
Figure 8. The time characteristic diagram of level displacement fluctuation under various baffles.

5. Influence of Throttling Baffle on Sloshing in Cargo Tank

It is found that the fluctuation of free surface displacement can be suppressed by increasing the height of transverse baffle in cargo tank. Based on the purpose of reducing the force acting on the side wall of the cargo tank, we conjecture to drill a hole at the bottom of the transverse baffle, study, observe and analyze whether the hole can play the role of pressure drop (similar to the role of throttle orifice); on the other hand, if the transverse baffle is completely placed at the bottom of the cargo tank, it will block the flow of liquid on both sides of the baffle and feed the liquid in the tank. The loading and unloading of the container has brought new problems. Based on the above two points, the mechanism of suppressing liquid sloshing in cargo tank under external excitation will be studied by opening a hole at the bottom of the positioning baffle, that is, setting throttling baffles with different diameters, and comparing with the positioning baffle, the differences and advantages and disadvantages are analyzed. Two kinds of throttling baffles with different diameters (i.e. $d = 3$ mm, 10 mm) are set. The size and placement position of the baffle are consistent with the vertical baffle in the previous study, that is, the baffle is 18 mm in height, 2 mm in thickness and 60 mm in width, and its placement position is horizontally placed in the middle of the cargo tank.

5.1. Throttle Baffle with Hydraulic Diameter of 3mm

In this section, a semicircular hole is drilled at the bottom of the horizontal vertical baffle in the middle of the cargo tank. The diameter of the hole is 3mm (i.e. $1/20$ of the baffle width). The transverse excitation is still simulated by constant acceleration along the x-axis and z-axis directions. The liquid carrying rate of the cargo tank is 70% (i.e. the static liquid level height is 21mm).

As shown in Figure 9 under the action of external excitation, when $t = 0.1$s, the free surface displacement in the cargo tank reaches the maximum value due to the impact force generated by transverse excitation; as time goes on, the free surface displacement reaches the peak again and again due to the action of liquid gravity and the blocking effect of the baffle placed on the bottom of the cargo tank. It is obvious that the former peak is caused by the impact pressure, and the latter series is caused by the change of free surface. The former peak is much larger than the latter. Compared with the free surface displacement of the cargo tank with a hole baffle ($d = 3$mm) and that of the transverse baffle (untreated), it can be seen that the fluctuation of the time characteristics of the two tanks is roughly the same, that is, the hole does not affect the blocking effect of the transverse baffle on the liquid sloshing in the cargo tank.

Figure 9. Scheme of time characteristics of free surface displacement fluctuation in cargo tank.
5.2. Throttling Baffle with Hydraulic Diameter of 10 mm

As shown in Figure 10, when \( t = 0.15s \), under the action of external excitation, the free surface displacement of the cargo tank rises to the highest point. At this time, under the influence of the reaction force of the right wall of the cargo tank, the liquid begins to move in the negative direction of the X axis, that is, the free surface begins to drop. During the descending process, due to the obstruction of the throttle orifice and the acceleration along the positive direction of the X axis (reaction force and transverse direction. The direction of the excitation is opposite), so that the liquid in the cargo tank drops to a certain height value, and then starts to move in the positive direction of the x-axis, so as to cycle. The throttling baffle reduces the fluctuation of the free surface in the cargo tank to a certain extent (mainly from the maximum value of the free surface displacement and the fluctuation range of the free surface displacement with time), and effectively reduces the liquid sloshing degree in the cargo tank.

In order to study the effect of orifice on liquid sloshing, a comparison was made between throttling baffle and vertical baffle. As shown in Figure 11, the free surface displacement of the tank with throttling baffles and vertical baffles reaches the maximum at almost the same time. However, the free surface displacement of vertical baffle is 0.5mm less than that of throttling baffle. With the passage of time, the fluctuation range of the free surface of the two is almost the same, and finally it sloshes at the same height. It can be seen that: setting throttle \( (r = 5mm) \) on the positioning baffle reduces the blocking effect of baffle on liquid sloshing in cargo tank, that is to say, it weakens the damping effect of baffle itself on liquid sloshing under certain external excitation.

![Figure 10](image1.png)

**Figure 10.** Time characteristics at monitoring point.

![Figure 11](image2.png)

**Figure 11.** Time characteristics under vertical baffle and throttle Orifice plates.

6. Conclusion

In this paper, three-dimensional rectangular tank is taken as the research object, and a series of problems are studied and discussed, such as the numerical simulation method of sloshing characteristics, the structure of the tank (with or without surge bulkhead) and the influence of the combination of various types of baffles on the sloshing characteristics.

1. The numerical simulation method, control equation and boundary conditions of sloshing in liquid cargo tank are discussed. At the same time, the severity of sloshing under different liquid carrying rates is studied, so as to find out the standard liquid carrying rate and prepare for the follow-up research. With the free surface displacement fluctuation and the maximum hydrodynamic pressure acting on the sidewall as the evaluation indexes, the sloshing severity of the cargo tank under different liquid loading rates was studied. With the increase of liquid loading rate in the cargo tank, the free surface displacement fluctuation becomes more and more intense.

2. The results show that the peak value of the middle vertical baffle is the minimum in terms of the maximum value of the free surface displacement, and the fluctuation range of the free surface displacement of the middle vertical baffle is relatively minimum, that is, it is the most stable. The positioning baffle and symmetrical baffle on the left and right sides have no obvious inhibition effect on the free surface displacement fluctuation of the liquid in the cargo tank under the external load. Comprehensive comparative analysis: the setting of the middle vertical baffle plate is the most effective for the sloshing suppression of the liquid in the cargo tank.
(3) The research and analysis on the drilling of the horizontal baffle at the bottom of the cargo tank shows that the drilling at the bottom of the horizontal baffle cannot play a role in pressure drop; on the contrary, with the increase of the bottom aperture of the baffle, the fluctuation value of the free surface displacement in the cargo tank and the maximum hydrodynamic pressure acting on the right side wall also increase. That is to say, when the aperture increases to a certain value, the inhibition effect of transverse baffle on liquid sloshing in cargo tank will be weakened. When \( d = 3 \) mm, the free surface displacement fluctuation and the maximum hydrodynamic pressure acting on the right-side wall of the cargo tank are approximately equal to those of the untreated transverse baffle. That is to say, a semicircular hole with a diameter of 3 mm can be set at the transverse baffle to improve the loading and unloading of liquid in the cargo tank.

**References**

[1] Li YL, Su M, Li H, Deng R, Wang KP, Hu Z. Numerical research on time domain ship motions coupled with sloshing at different liquid levels and forward speeds[J]. *Ocean Engineering*, 2019, 178, 246-259.

[2] Yu Y, Zhao T, Duan M, Zhou T, Xu J, Su Y, Zhong Z, Liu H. Experimental investigation on the underwater soft yoke mooring system considering sloshing[J]. *Ships and Offshore Structures*, 2019, 14 (3), 309-319.

[3] Du Y, Wang C, Zhang N. Numerical simulation on coupled ship motions with nonlinear sloshing[J]. *Ocean Engineering*, 2019, 178, 493-500.

[4] Liu D, Lin P. Three-dimensional liquid sloshing in a tank with baffles[J]. *Ocean Engineering*, 2009, 36 (2), 202-212.

[5] Liu D, Lin P. A numerical study of three-dimensional liquid sloshing in tanks[J]. *Journal of Computational Physics*, 2008, 227 (8), 3921-3939.

[6] Firouz-Abadi R, Haddadpour H, Ghasemi M. Reduced order modeling of liquid sloshing in 3D tanks using boundary element method[J]. *Engineering Analysis with Boundary Elements*, 2009, 33 (6), 750-761.

[7] Wu C-H, Chen B-F. Sloshing waves and resonance modes of fluid in a 3D tank by a time-independent finite difference method[J]. *Ocean Engineering*, 2009, 36 (6), 500-510.

[8] Arafa M. Finite element analysis of sloshing in liquid-filled containers[J]. *Production Engineering and Design for Development (PEDD'07)*, 2006, 793-803.

[9] Goudarzi M, Sabbagh-Yazdi S, Marx W. Investigation of sloshing damping in baffled rectangular tanks subjected to the dynamic excitation[J]. *Bulletin of Earthquake Engineering*, 2010, 8 (4), 1055-1072.

[10] Faltinsen O, Timokha A. Natural sloshing frequencies and modes in a rectangular tank with a slat-type screen[J]. *Journal of Sound and Vibration*, 2011, 330 (7), 1490-1503.

[11] Zhao W, Yang J, Hu Z, Xiao L, Tao L. Hydrodynamics of a 2D vessel including internal sloshing flows[J]. *Ocean Engineering*, 2014, 84, 45-53.

[12] Zhang HS, Wu PF, Liu WB. The analysis of second-order sloshing resonance in a 3-D tank[J]. *Journal of Hydrodynamics*, 2014, 26 (2), 309-315.

[13] Zhao W, Yang J, Hu Z, Xie B. Hydrodynamics of an FLNG system in tandem offloading operation[J]. *Ocean Engineering*, 2013, 57, 150-162.

[14] Wang C-Y, Teng J-t, Huang GP. Numerical simulation of sloshing motion inside a two-dimensional rectangular tank by level set method[J]. *International Journal of Numerical Methods for Heat & Fluid Flow*, 2011, 21 (1), 5-31.

[15] Ebrahimian M, Noorian MA, Haddadpour H. Equivalent mechanical model of liquid sloshing in multi-baffled containers[J]. *Engineering Analysis with Boundary Elements*, 2014, 47, 82-95.