

Simulation and Experimental Analysis of the Sloshing in the Anti-rolling Tank

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Abstract. Roll motion of ship is known to be critical degree of freedom because it has very small damping, and different roll-damping devices are designed to reduce roll motion. The anti-roll tank(ART) is one kind of important ship roll-damping device widely used today, the roll damping moment is created by the sloshing of liquid in the tank. The sloshing in the tank is very complex and has free surface effect. This paper study the free-oscillation of the sloshing, roll, and roll coupled with sway motion of ship through simulation and experimental analysis to understand the actual working state of ART in detail. So that the result can help design the structure of ART, assess the anti-roll effect and take experimentation on ship with ART on the sea.

Keywords: anti-roll tank, sloshing, roll, sway, Fluent.

1. Introduction

The anti-roll tank is one type of the ship-damping devices successfully used all over the world. It is applicable to reduce the roll motion at any speed, especially fits for the ships at low speed even zero speed. The idea of liquid sloshing absorber systems described for the roll stabilization of ships has been realized for a long time. The sloshing of the ART is caused by the roll motion and coupling sway motion when a ship is sailing on the sea. Sometimes only pure roll motion is considered, it is not sufficient if sway motion is not added. In addition, the free-oscillation sloshing of liquid in the tank is also a classic motion when studying the ART characteristic in the lab. Through the research of the free-oscillation, roll, and roll coupled sway motion the actual working state of ART can be understood in detail. So that the research can be beneficial to design the structure of ART, assess the anti-roll effect and take experimentation on ship with ART on the sea. In the paper the Fluent of CFD simulation software is used to study sloshing in the ART.

2. Expatiation of ART Theory

Considering the liquid level of the right wing tank in Fig.1, suppose the liquid level $z_0 = 0$ when the liquid level of the right wing tank is equal to the portside, and at other time it is defined by z .

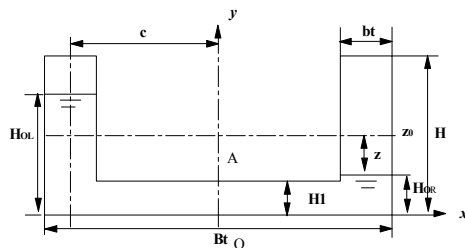


Fig.1: The structure of the tank.

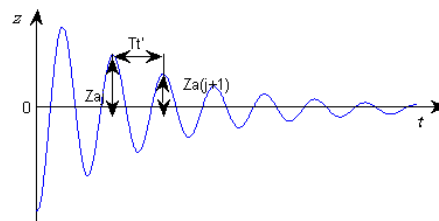


Fig.2: The liquid level of the right wing tank.

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So the differential equation of the liquid flow is

$$\ddot{z} + 2\nu_t \dot{z} + \omega_t^2 z = 0 \quad (1)$$

The solution of the differential equation

$$z = z_m e^{-\nu_t t} \cos(\omega'_t t - \theta) \quad (2)$$

where ω'_t denotes the damping frequency and z_0 denotes the initial liquid level, $\omega'_t = \sqrt{\omega_t^2 - \nu_t^2}$,

$$z_m = z_0 \sqrt{1 + \left(\frac{\nu_t}{\omega'_t}\right)^2}, \quad \cos \theta = \frac{1}{\sqrt{1 + \left(\frac{\nu_t}{\omega'_t}\right)^2}}.$$

The damping coefficient can be confirmed from the reduction between two amplitudes of the liquid level. In Fig.2, the amplitude and the $(j+1)$ amplitude can be denoted to

$$z_{aj} = z_m \cos \theta e^{-j\nu_t \frac{T'_t}{2}} \quad (3)$$

$$z_{a(j+1)} = z_m \cos \theta e^{-(j+1)\nu_t \frac{T'_t}{2}} \quad (4)$$

The $(j+1)$ reduction between the two amplitudes is

$$\begin{aligned} \delta z_{a(j+1)} &= z_{aj} - z_{a(j+1)} = z_m \cos \theta e^{-j\nu_t \frac{T'_t}{2}} (1 - e^{-\nu_t \frac{T'_t}{2}}) \\ &= z_{mj} (1 - e^{-\nu_t \frac{T'_t}{2}}) \end{aligned} \quad (5)$$

We can see the reduction between two amplitudes of the liquid level is proportioned to the initial liquid level amplitude of the surge from Eq.7.

The surge period T'_t is

$$T'_t = \frac{2\pi}{\omega'_t} = \frac{2\pi}{\omega_t} \frac{1}{\sqrt{1 - \left(\frac{\nu_t}{\omega_t}\right)^2}} = T_t \frac{1}{\sqrt{1 - \left(\frac{\nu_t}{\omega_t}\right)^2}} \quad (6)$$

where T_t denotes the natural period.

From Eq.6 we can know the damping enlarged the natural period. But actually the increment is very tiny, so the natural period can be approximatively calculate with $T'_t \approx T_t$, so the equation will turns to

$$\frac{\nu_t T'_t}{2} = \frac{\nu_t T_t}{2} = \frac{2\pi\nu_t}{2\omega_t} = \pi n_t \quad (7)$$

where n_t denotes the dimensionless roll damping coefficient.

Take Eq.7 into Eq.5 and spread $e^{-\pi n_t}$ to series. The items higher than simple are omitted, so the equation turns to

$$\frac{\delta z_{a(j+1)}}{z_{aj}} = \pi n_t \quad (8)$$

Eq.8 presents the relationship between the amplitude of the liquid level and the dimensionless roll damping coefficient. Thus the dimensionless roll damping coefficient n_l can be accounted from the damping curve by simulation or experiment.

The roll angle and fluid motion are mutually influenced after installing anti-roll tank. System of “Ship-anti-roll tank” is simplified to coupling oscillations of two degree of freedoms that is double pendulums system. Then we can use two coordinates to describe system of “ship- anti-roll tank” (Tao Yaosen, 1985). Both roll angle φ and liquid level z in the right wing tank are generalized coordinates in the U-tube anti-roll tank.

The differential equations of roll motion and fluid oscillation in the tank on the basis of the anti-roll theory are as follows:

$$\left. \begin{aligned} \ddot{\varphi} + 2v_{\varphi}\dot{\varphi} + w_{\varphi}^2\varphi - \beta\ddot{z} - \alpha z &= w_{\varphi}^2\vartheta_e \sin wt \\ \ddot{z} + 2v_i\dot{z} + w_i^2z - b_i\dot{\varphi} - cw_i^2\varphi &= 0 \end{aligned} \right\} \quad (9)$$

where v_{φ} and v_i denote the damping coefficients of the ship and the tank; w_{φ} and w_i denote the natural frequencies of the ship and the tank.

When the ship is sailing on the sea, it behaves sway motion by the forces of the wave and the control system. This sway motion is composed of two parts: one part is directional; the other is periodic. When the sway velocity does not change rapidly, the effect to the liquid flow by the directional sway motion is not much. The research of the sway motion couple with roll is established in the periodic sway.

3. Sloshing in the tank

Take the 8000 kW rescue and salvage vessel for example. The proportion of the tank model and the practical tank is 1:10. The simulated process of the tank model Sloshing movement is as Fig. 4 and the bench test of the Sloshing movement is as Fig.5. The Fluent software is used to finished the simulation, and VOF (Volume of Fluid)method is applied.

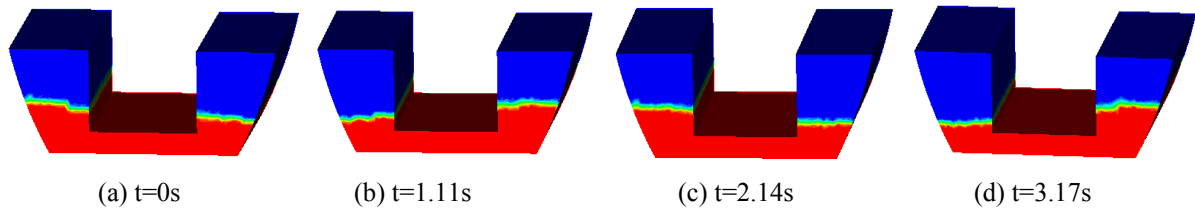


Fig.4: The simulation of Sloshing movement in the tank.

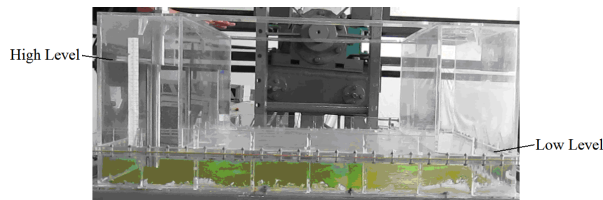


Fig.5: The bench test of the Sloshing movement.

Here the liquid level of the right wing tank is analyzed in Fig.6. The simulated and experimental changes of the liquid level are as shown in Fig. 7.

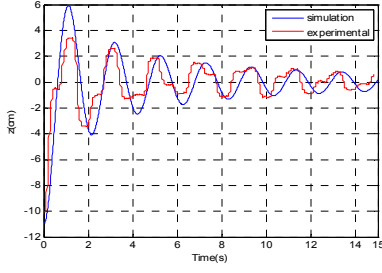


Fig. 6: The liquid level of the right wing tank.

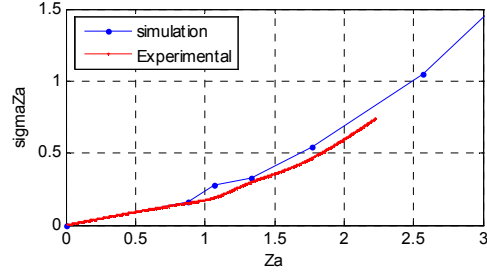


Fig. 7: The relation of $\delta_{z_{\alpha(j+1)}}$ with $z_{\alpha j}$.

The natural period of the model tank can be calculated:

$$T_{tSimu} \approx T'_{tSimu} = 2.04s \quad (10)$$

$$T_{tExp} \approx T'_{tExp} = 1.99s \quad (11)$$

The changes of $\delta z_{\alpha(j+1)}$ with $z_{\alpha j}$ are calculated according to Eq.5, as is shown in Fig. 7.

So the liner damping coefficient can be computed:

$$n_{tSimu} = \frac{\delta z_{\alpha(j+1)}}{\pi z_{\alpha j}} = 0.1303 \quad (12)$$

$$n_{tExp} = \frac{\delta z_{\alpha(j+1)}}{\pi z_{\alpha j}} = 0.1316 \quad (13)$$

From Eqs.10~13 we can see the result of the simulation can tally the experimental result well.

3.1. Roll motion

The simulation and experimental analysis of roll motion can analyze the liquid flow when the tank rolls in different periods (Theresa Kleefsmann,2000; E.F.G.van Daalen,K.M.T.Kleefsmann,J.Gerrits,H.R.Luth, A.E.P.Veldman,2001).

The equation of the roll angle is:

$$\varphi = \varphi_m \cos \omega t \quad (14)$$

The equation of the liquid level in the right wing tank is:

$$z = z_m \cos(\omega t - \alpha) \quad (15)$$

where α denotes the phase difference of the liquid level and the roll angle.

Here we suppose the roll motion is active, and the change of the liquid flow is driven. Take $\varphi_m = 10 \text{ deg}$ for example, and the roll periods are chosen from 1.57s to 6s. The anti-roll moment and the liquid level are analyzed emphatically. The angular lag is an important criterion to check the capability of the tank. When $\alpha = 90 \text{ deg}$, the anti-roll effect reaches to the best. With the same time, the roll period is the natural period of the tank (Xiaoyong AI, Guobin LI, Hong ZHANG and Lihua LIANG, 2004).

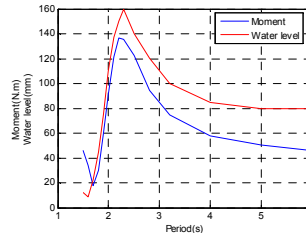
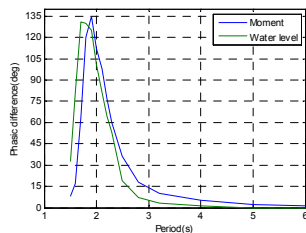


Fig. 8: The simulated angular lag of different periods. Fig. 9: The simulated crest value of different periods.

Fig. 8 shows the simulated angular lag in different periods. From this figure we can see the angular lag changes of the moment and the liquid level are not accurately the same. But they kept the same direction and the differences between them are very tiny. They show the same information: there are two synchronous roll periods, and they are contiguous. So the responses of the moment crest value and the liquid level crest value in different periods should be checked, too.

Fig. 9 shows the simulated crest value in different periods. The maximum values appear at almost the same periods.

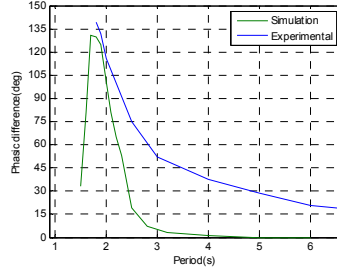


Fig. 10: The contrast of the simulated and the experimental results.

The analyses of Fig. 8 and Fig. 9 are all based on the simulation. And the bench test sustained the simulated result. Fig. 10 is the contrast of the simulated and the experimental liquid level angular lags. Though the liquid level sensor has considerable lag and error, the directions of the results are similar.

3.2. Roll coupled with sway motion

From the research of the Sloshing motion and the roll motion of the tank we can say that the simulated results can reflect the actual instance reasonably. Considering the restriction of the test bench equipment, the analysis of the roll coupled with sway motion aims at the simulated result.

The roll motion can be described as

$$\varphi = \varphi_m \cos \omega t \quad (16)$$

The corresponding periodic sway motion can be described as (Wei SUN, Lihua LIANG, Hong ZHANG, 2006)

$$y = y_m \cos(\omega t + \theta) \quad (17)$$

where θ denotes the phase difference of the sway motion and the roll motion.

Take $y_m = 5cm, \varphi_m = 10deg$ for example, the simulation parameter are selected with $\theta = 0, \pi/4, \pi/2, 3\pi/4$ and $\omega = 2.0, 2.5, 2.86, 3.2, 4Hz$.

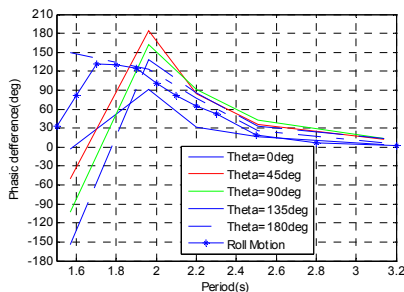


Fig. 11: The angular lag of different periods.

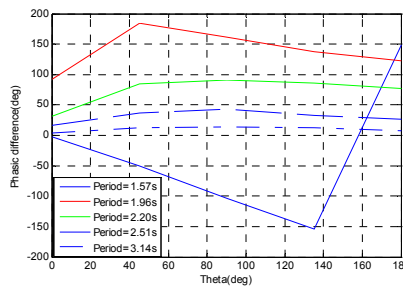


Fig. 12: The angular lag of different θ .

Fig.11 shows that the difference of the two synchronous roll periods enlarges gradually in the subsection of $0 < \theta < \pi/2$. And in the subsection of $\pi/2 < \theta < \pi$, the small synchronous roll period decreases rapidly until it disappears.

Fig. 12 shows that the phase difference θ affects the roll coupled with sway motion evidently in the subsection of $0 < \theta < \pi/2$, and the effect becomes negligible with θ increases continuously.

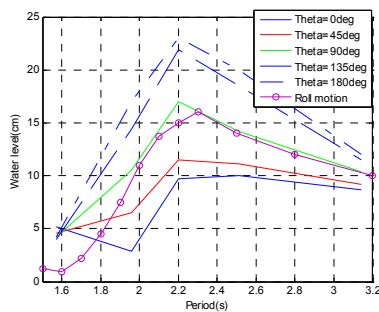


Fig. 13: The crest value of different periods.

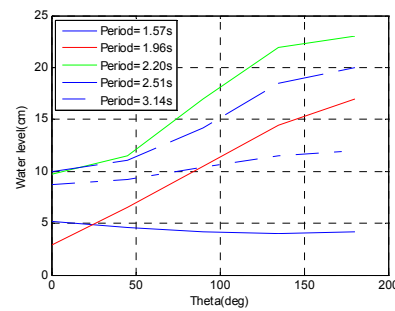


Fig. 14: The crest value of different θ .

Fig.13 shows that the difference of the roll damping reduces gradually in the section of $0 < \theta < \pi$. At the time of $\theta = \pi/2$, the damping is almost the same with roll without sway.

Fig. 14 shows the reduction of the damping enlarges gradually in the subsection of $0 < \theta < \pi/2$. And in the subsection of $\pi/2 < \theta < \pi$, the small synchronous roll period decreases.

4. CONCLUSIONS

From the study of simulation and experimental analysis, we can obtain these conclusions:

- The simulation by Fluent CFD can calculate and analyze the liquid flow accurately. And the result of the simulation inoculates the experiment well.
- The natural periods and the damping coefficient can be calculated from the Sloshing motion of liquid.
- The ordinary characteristic of the tank can be understood in detail from the simulation and the experimental analysis.
- The difference of the two synchronous roll periods enlarges gradually in the subsection of $0 < \theta < \pi/2$. And in the subsection of $\pi/2 < \theta < \pi$, the small synchronous roll period decreases rapidly until it disappears. The phase difference θ affects the roll coupled with sway motion evidently in the subsection of $0 < \theta < \pi/2$, and the effect becomes negligible with θ increases continuously.

The difference of the roll damping reduces gradually in the section of $0 < \theta < \pi$. At the time of $\theta = \pi/2$, the damping is almost the same with roll without sway. The reduction of the damping enlarges gradually in the subsection of $0 < \theta < \pi/2$. And in the subsection of $\pi/2 < \theta < \pi$, the small synchronous roll period decreases.

5. References

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