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Experimental Study on the Influence of External Excitation Frequency Change on Liquid Sloshing Impact in Elastic Tank

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Abstract. The sloshing impact of liquid in elastic tank under combined excitation was studied by physical model experiments, and the sloshing impact characteristics of liquid on the side wall of tank with low liquid loading rate under different external excitation frequencies were analyzed. The results show that under the combined excitation of rolling and pitching motion, the sloshing impact load at the free surface is the largest, while the sloshing impact load far from the free liquid surface is smaller. However, when the external excitation frequency of rolling and pitching motion is located at the resonant frequency and larger than resonant frequency, the sloshing impact load in individual regions appears abnormal phenomenon. When the external excitation frequency of rolling and pitching moves from far away from the resonance frequency to near or even slightly beyond the resonance frequency, the sloshing impact load at the free liquid surface presents a small decline stage, a sharp rise stage and a small rise stage, respectively.

1. Introduction

In recent years, many scholars at home and abroad have carried out a series of studies on liquid sloshing in elastic tanks. Faltinsen and Timokha [1], based on Wagner potential flow theory and Timokha beam theory, established a hydroelastic beam theoretical model for two-dimensional liquid sloshing in an elastic liquid tank under horizontal excitation by using an uncoupled solution method. The theoretical results are compared with the experimental results; Eswaran [2] used finite element method to study the effect of vibration reduction of diaphragm in elastic liquid tank. Assuming that the liquid in the tank is non-viscous fluid, the influence of different baffle forms on sloshing pressure is analyzed; based on physical experiments, Li chenguang [3] studied the effect of elastic deformation on free surface wave forms under resonance and non-resonance conditions; Jiang Meirong [4] analyzed the variation characteristics of free surface wave height and slogging pressure under resonant and non-resonant conditions under horizontal harmonic excitation based on material model test; Tang Jie [5] studied the longitudinal excitation, compared and analyzed the liquid fluctuation in rigid compartment and elastic compartment under low liquid depth and general liquid depth, and concluded that the elastic effect of low liquid depth launching was obvious, while the elastic effect of general liquid depth launching was weakened. The above scholars have made an in-depth study on liquid sloshing in the elastic tank under the condition of single-degree-of-freedom external excitation. However, under actual sea conditions, the ship will undergo complex motions due to the influence of wind, waves and currents. The liquid in the tank is swayed by external excitation of multiple degrees of freedom and the liquid sloshing problem arises. However, there are few reports on the sloshing problem of three-dimensional elastic liquid tank with multiple degrees of freedom.

The paper takes a FPSO ship as a prototype. The physical model is established by using the knowledge of geometric similarity. Using the method of model experiment and considering the hull rolling motion with the compound incentive pitching motion, the researchers carry out the liquid sloshing experiment of three-dimensional elastic liquid tank under compound excitation and discuss and analyse the influence that the change of external excitation frequency has on liquid sloshing impact characteristics in the elastic compartment. The study can provide theoretical reference for the design of the ship's tank structure and to ensure the safe operation of ships.

2. Model test system

Figure 1 shows the experimental system of composite sloshing of the elastic liquid tank.

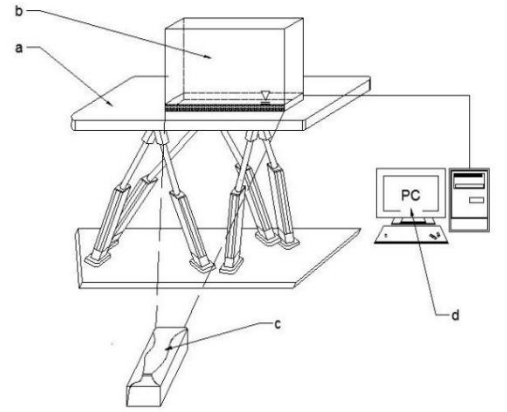

Fig.1 Model test system, (a) sloshing platform system, (b) model tank; (c) high speed camera, (d) data acquisition system of sloshing pressure

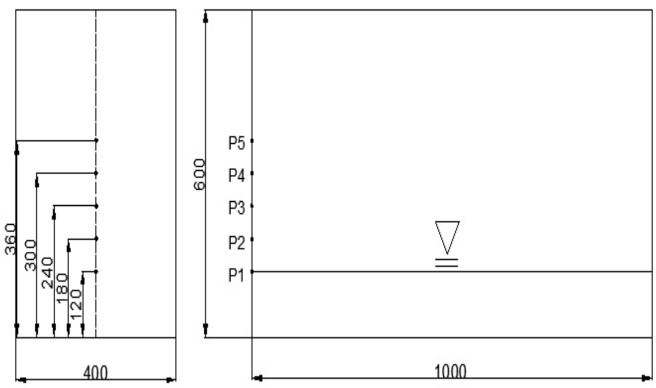

Fig.2 Model tank schematic (unit: mm)

2.1 Experimental facility

In order to analyze the characteristics of liquid sloshing impact and the variation of bulkhead pressure in three-dimensional elastic liquid tank under different external excitation frequencies, the paper takes the middle cargo hold (50m×20m×30m) of FPSO as the prototype tank. The model tank is built with a scale ratio of 1/50. The left and right sides and the top cover of the model tank are made of soft acrylic plates. Its thickness is 4.8mm and other surfaces are made of the acrylic sheets whose thickness is 12mm. In the experiments, tap water was selected as liquid medium at room temperature in summer.

The sloshing platform system consists of six degrees of freedom sloshing platform and its control system. The maximum load of the platform is 1t, which can simulate the coupling motion of rolling, pitching, bow rolling, rolling, pitching, heave and these six kinds of motion of the ship at sea.

In order to collect the sloshing pressure caused by liquid sloshing, five monitoring points were set on the left side of the model tank and one monitoring point was set on the right side. The sloshing pressure acquisition system is composed of piezoresistive pressure sensor model CYB-301 and PLC data acquisition unit model EM9636M. The acquisition unit can convert the electrical signal output by the pressure sensor into digital signal so as to complete the process of pressure acquisition. The range of the pressure sensor is 10KPa, the accuracy is 0.1%FS, and the resolution of the data acquisition unit is 0.01kpa.

2.2 Selection of external excitation frequency

Under external excitation, the natural frequency of liquid in the tank is f_n [1]. The natural frequency of sloshing liquid in rectangular tank can be calculated by Faltinsen's expression of n-order natural frequency:

$$f_n = \frac{1}{2}\sqrt{\frac{ng\tanh\left(\frac{n\pi h}{L}\right)}{\pi L}}$$

L is the length of the tank in the direction of motion and the unit is m. *h* is the liquid level and the unit is m. *g* is the acceleration of gravity and the unit is m/s^2. *n* is the number of modes. This paper considers the diversity of wave motion frequencies under actual sea conditions. The external excitation frequency is set as $0.2f_1$、$0.4f_1$、$0.6f_1$、$0.8f_1$、$1f_1$、$1.2f_1$.

2.3 Experimental condition

There are many ways to influence ship motion, but roll and pitch motion are the main ones. Therefore, the combined motion of pitch and roll is selected as the external excitation form in this experiment. The sloshing center of pitch and roll is located at the center of the tank bottom. The free liquid level is horizontal when the tank is at rest.

In smooth sea condition, the roll and pitch Angle of the ship is in the 0 to 10°. Therefore, external excitation amplitude takes a value between 0 and 10°, like 3°. The specific experimental conditions are shown in Table 1:

Tab.1 Experiment condition

Carrier fluid rate/（*h/H*）	External excitation form	Roll excitation frequency/（Hz）	Pitch excitation frequency/（Hz）	Excitation amplitude/（°）
0.2	Pitch and Roll compound excitation	0.106	0.24	3
		0.212	0.48	
		0.318	0.72	
		0.424	0.96	
		0.530	1.20	
		0.636	1.44	

3. Results and discussion

3.1 Frequency domain characteristics of sloshing impact loads

From the above analysis of the free surface waveform, it can be seen that under different external excitation frequencies, the severity of liquid sloshing in the tank is different, and the liquid sloshing impact load will change. This section focuses on the analysis of liquid sloshing shock load characteristics in elastic tank at different external frequencies. After the previous data demonstration, it is found that the sloshing impact load at the free surface monitoring point (P1) is the largest at different external frequencies. Therefore, the sloshing impact load of the free liquid level monitoring point is selected for analysis. The result is shown in Fig.3.

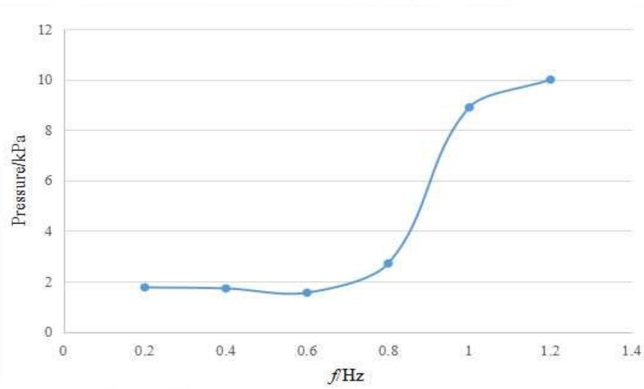

Fig.3 Frequency history of sloshing load at free surface

It can be seen from the Fig.3 that when the external excitation frequency of the roll is $0.2f_1$, $0.4f_1$, $0.6f_1$, the sloshing load at the free liquid level monitoring point shows a small downward trend. At $0.6f_1$, $0.8f_1$, $1f_1$, the sloshing load at the free surface monitoring point rises sharply. In the stages $1f_1$ and $1.2f_1$, the sloshing load at the free surface still shows an upward trend, but the amplitude of the increase is greatly reduced. Analyze the reasons, as can be seen from Tab 1. In the stages $0.2f_1$-$0.6f_1$ ($0.2f_1 \leq f \leq 0.6f_1$). The external excitation frequency of the pitching motion is greater than the external excitation frequency of the rolling motion. Therefore, the pitching motion has a greater influence on the sloshing load at the free surface. The movement of the tank is affected by both the rolling motion and the pitching motion. When the liquid in the tank sloshes, the waveform changes in combination with the free surface. The free surface waveform at this stage is mainly standing wave. As the external frequency of the roll motion increases, the first-order natural frequency of the liquid in the chamber gradually approaches. Rolling motion enhancement, but the effects of pitching motion are weakened. Therefore, in the stages $0.2f_1$-$0.6f_1$ the sloshing load at the free surface shows a small downward trend.

In the stages $0.6f_1$-$1f_1$ ($0.6f_1 < f \leq 1f_1$). The free sloshing load liquid level drastic rises. The reason is that the external excitation frequency of the roll motion and the pitch motion gradually reach their respective first-order resonance frequencies. From the waveform change can known the free surface waveform in the tank is different. The closer to the first-order natural frequency of the liquid in the tank, the greater the complexity of the free surface waveform and the increased kinetic energy of the liquid in the tank. During the sloshing process, the liquid accelerates and impacts the bulkheads on both sides, so the sloshing load at the free liquid level rises sharply.

In the stages $1f_1$-$1.2f_1$ ($1f_1 < f \leq 1.2f_1$). The sloshing load at the free surface is still rising. The free sloshing load liquid level still shows an upward trend. But rising range appear decrease trend. The reason is that the external excitation frequency of the roll and pitch motion is greater than the respective first-order resonance frequency. However, the composite excitation of roll and pitch motion is still near the first-order resonance frequency. From the change of waveform can know about that liquid motion is nonlinear in the tank is obvious at this time. And accompanied by a large number of liquid topping phenomenon occurs. The cumulative kinetic energy of liquid in the tank continues to increase. Accelerate the impact of the liquid on the bulkhead. Therefore, the sloshing load at the free liquid level rises slightly.

3.2 Spatial characteristics of sloshing impact loads

The sloshing load at the bulkhead was captured by a pressure sensor mounted on the side bulkhead. It can know about the layout of the pressure sensor is shown in Fig 2. This section mainly analyzes the spatial distribution of sloshing loads of P1-P5 at different external frequencies. From Figure 4 can find Figure 1-5 corresponds to P1-P5 one-to-one.

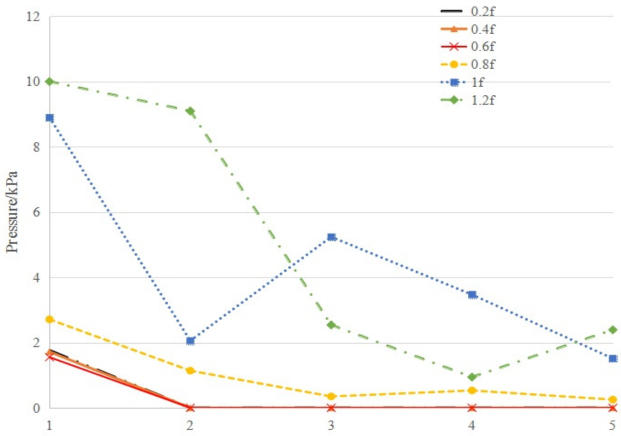

Fig.4 Impact pressure distribution on the left bulkhead

It can be seen that the sloshing impact load at the point P1 of the external excitation frequency of $0.2f_1$-$1.2f_1$ is the largest, that is, the maximum sloshing impact load at the free surface. The smaller the sloshing impact load away from the free surface. Besides in the stages $1f_1$ and $1.2f_1$, there are anomalies in individual monitoring points. First, the external excitation frequency of the roll and pitch motion is in the period of $0.2f_1$-$0.6f_1$. At this time, the external frequency is far from the natural frequency of the liquid in the tank, and no resonance occurs. The pressure at the monitoring point of P2-P5 is zero. At this time, the liquid in the tank mainly impacts the monitoring point at the free liquid level, so the sloshing impact load at the free liquid level is the largest. In the phase $0.8f_1$-$1.2f_1$, the resonant phenomenon occurs as the external excitation frequency gradually approaches or even exceeds the natural frequency of the liquid in the tank. However, due to the small carrier liquid rate, the monitoring point of the free surface is affected by the large sloshing impact load. However, when the resonance phenomenon occurs, the free surface waveform in the tank becomes more complicated, and gas-liquid mixing occurs. At $1.2f_1$, the free surface waveform of the tank exhibits irregular waves, and the gas-liquid mixing phenomenon is intensified. Therefore, when the external excitation frequency is $1f_1$, the sloshing impact pressure at P2 is less than the sloshing impact pressure at P3. When the external excitation frequency is $1.2f_1$, the sloshing impact pressure at point P5 is greater than the sloshing impact pressure at P4.

4. Conclusion

Liquid sloshing in tank is a hot research topic in ship and ocean engineering. In this paper, by means of physical model experiments, the impact characteristics of liquid sloshing in elastic tank under different excitation frequencies are studied by changing the external excitation frequencies of rolling and pitching motions under low liquid loading rate. It is found that under the combined excitation of rolling and pitching motions, the sloshing impact load is the largest at the free surface and get smaller when far away from the free surface. However, when the external excitation frequency of rolling and pitching motion approaches the first-order resonance frequency gradually, or even when the external excitation frequency is slightly larger than the first-order resonant frequency, the position of largest sloshing load gets different; with the external excitation frequency approaching the first natural frequency of the liquid in the tank, the sloshing impact load at the free surface in the tank decreases slightly, rises sharply and rises slightly.

Acknowledgments

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