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Experimental study on characteristic of sloshing impact load in elastic tank with low and partial filling under rolling coupled pitching

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ABSTRACT

A series of experiments covering lowest three natural frequencies of rolling coupled pitching were conducted to investigate liquid sloshing with low liquid depth. The test results show that the most violent liquid sloshing in rolling and pitching is located in the vicinity of the first order natural frequency (f_1). When the excitation frequency of rolling and pitching is located between $0.98f_1$ and $1.113f_1$, roof-bursting phenomenon of liquid appeared, and the maximum impact pressure is at $1.09f_1$. When the external excitation frequency is at $1.113f_1$, the number of sloshing shocks decreases sharply. Furthermore, the space distribution of the impact pressure on the left bulkhead and the top bulkhead was analyzed. It is concluded that with low liquid filling, the impact load is greater near the free surface and the top of tank, and the impact position of the side bulkhead increases with the increasing of the frequency near the resonant frequency.

1. Introduction

Floating Production Storage and Offloading (FPSO) is the offshore petroleum factory, and the crude oil extracted from the seabed can be preliminarily processed and stored in FPSO, so it is inevitable that the tank carries partial liquid during its operation. When the external excitation frequency approaches the natural frequency of the liquid in the tank, it will lead to severe sloshing of the liquid. The sloshing liquid will produce huge slamming loads on the inner structure of the tank, and the bulkhead structure will respond to the slamming loads. Actually, the bulkhead structure would undergo elastic deformation and even cause damage to the structure of the tank, which is hidden dangers for safe operation.

Currently, a lot of scholars from all over the world have studied the problems of liquid sloshing in elastic tank. With the developing of computer technology, numerical simulation has become the main method to study liquid sloshing problems. It is numerically investigated liquid sloshing in elastic tank with System Coupling Module by Zhou and Zhu (2014), the influence of different thickness and material on sloshing load was analyzed; Based on MSC Dytran, the coupling effect in the elastic tank was calculated by Zhu and Liu (2012), and the effects of different external excitation parameters and loading rate on sloshing load of the tank were analyzed under surge excitation. Besides, the influence of bulkhead deformation on the linear pressure of bulkhead was analyzed through numerical study of 2-D flexible side bulkhead sloshing by Strand and Faltinsen (2017). The Automatic Dynamic Incremental Nonlinear Analysis (ANIDA) was also used to simulate small amplitude liquid sloshing in elastic tank by Chen and Meirong (2013), and the results was compared with the results of rigid tank. It is concluded that the elastic tank bulkhead had a certain buffering effect on sloshing impact. In addition, the MLParticles-SJTU internal solver based on Moving Particle Semi-implicit Method (MPS) and combined with Finite Element Method (FEM) which was developed by Zhang and Wan (2017) was used to deal with liquid sloshing in an elastic tank, and the evolutions of free surface, variation of impact pressures, dynamic responses of the structures in both time and frequency domains were presented. However, due to the highly non-linear effect of liquid sloshing, the theoretical analysis and numerical simulation of liquid sloshing are not perfect (Zhu et al., 1999; Wan, 2010; Yung et al., 2009). The experimental method can effectively remedy the defects of theoretical analysis and numerical simulation.

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Physical model experiments were carried out to study the resonant and non-resonant problems of liquid sloshing in rigid and elastic tank by Jiang et al. (2014a,b) and it is concluded that the results of elastic and rigid tank under non-resonant conditions are closed to the theoretical values, while the results of elastic under resonant conditions are less than the rigid ones compared with the theoretical values. In order to study the problem of liquid resonant sloshing in elastic tank further, another some experiments were carried out under finite liquid depth in elastic side tank. The results show that the top of tank is susceptible to large sloshing load. The influence of elastic deformation on free surface under resonant and non-resonant was analyzed through experiment by Li (2015). The above-mentioned scholars mainly analyze the factors affecting liquid sloshing load in elastic tank under single-degree-of-freedom. However, in actual sea conditions, ships are affected by wind, wave and current, which can cause complex motion, and the liquid sloshing in tank is affected by multi-degree-of-freedom external excitation at the same time. But there are few reports on the characteristics of liquid sloshing impact load in elastic tank under multi-degree-of-freedom excitation.

The similarity theory is used to construct a model test bench based on the prototype of a medium cargo tank of FPSO in this paper. The experiments were conducted by considering external excitation of rolling coupled with pitching to study the problems of sloshing impact in elastic with the lowest three natural frequencies. The change of free surface wave height, the frequency domain of sloshing impact load and its space characteristics and the number of sloshing shocks is analyzed to obtain the characteristics of sloshing impact load, which provides theoretical reference for ship load calculation and tank structure design.

2. Experiment set up

The experimental system of sloshing of the whole elastic tank is shown in Fig. 1, (a) the sloshing platform system, (b) the model tank (its size is shown in Fig. 2), (c) the high-speed camera, (d) the sloshing pressure acquisition system.

2.1. Model tank

In this paper, one of the middle cargo tanks of FPSO ship (50 m × 20 m × 30 m) was selected as the prototype tank, and the model tank was built with a scale ratio of 1/50, as shown in Fig. 2.

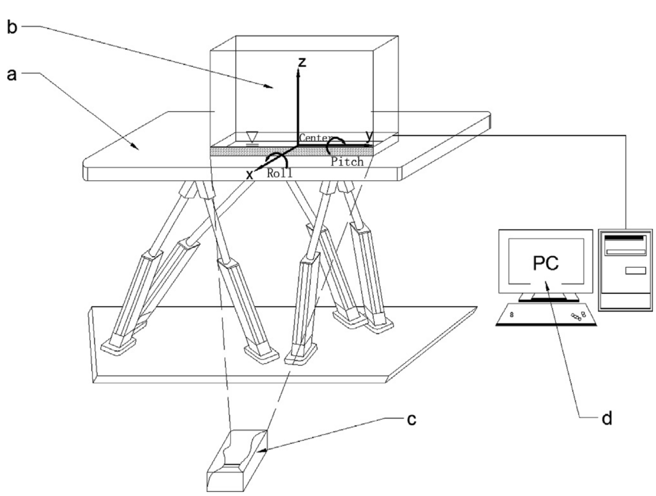

Fig. 1. Model test system, (a) sloshing platform system, (b) model tank; (c) high speed camera, (d) data acquisition system of sloshing.

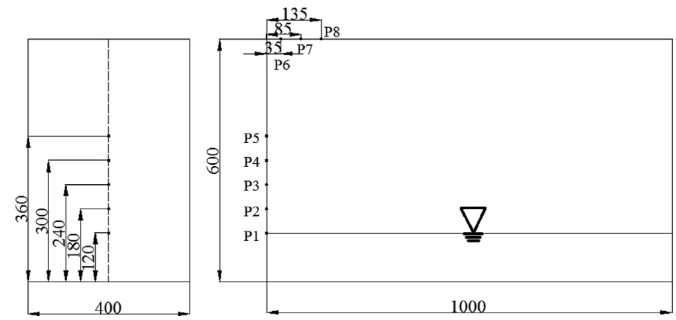

Fig. 2. Model tank schematic (unit: mm).

The model tank is made of acrylic plates with softer materials and different thicknesses. Formula for calculating flexural stiffness of materials is shown as belowEqn 1:

$$EI_z = E\frac{bh^3}{12} \tag{1}$$

where E is the elastic modulus, I_z is rectangular section moment of inertia, b is the width of the rectangular section, h is the height of the rectangular section. The calculation shows that the bending stiffness of the side wall of the tank with thickness of 12 mm is 39 times greater than that of the side wall with thickness of 4.8 mm. Therefore, the tank made of 12 mm acrylic plate can be used as rigid tank, and the tank made of 4.8 mm acrylic plate can be used as elastic tank. There is a similar conclusion conducted by Tang et al. (2017). Hence, the acrylic plate with 4.8 mm thickness is used for the left and right sides of the tank and the top cover 4.8 mm to make up the elastic tank, and the acrylic plate with 12 mm thickness is used for the other surfaces.

2.2. The liquid setting

Many scholars study liquid sloshing in liquid cargo tanks by model test method. Water is used as the liquid medium during the experiment. However, under violent sloshing conditions, serious gas-liquid mixing phenomena is likely to occur in the tank, and the gas-liquid mixing phenomena has an impact on the measurement of sloshing impact load. Therefore, in order to fully investigate the sloshing impact characteristics of crude oil in the tank of FPSO ship during crude oil transportation, the principle of similarity criterion (Wu, 2016) is applied in this paper and it doesn't consider the liquid density. So, the lubricant was selected as the experimental liquid, and the viscosity is 0.056 Pa s, and the details are shown in Table 1.

2.3. Instrument set up

The external vibration platform consists of a six-degree-of-freedom sloshing platform and its control system shown as Fig. 3. The maximum load of the platform is 1t. It can simulate the coupled motions of rolling, pitching, bow, sway, surge, pendulum of ships at sea.

In order to get the sloshing impact pressure generated during the sloshing process, monitoring points are set on the left side and the top of the model tank respectively (Wei et al., 2014). The

Table 1
The physical properties of liquid.

Liquid	Viscosity (Pa·s)	Density (kg/m^3)	Temperature (K)
Lubricant	0.056	870	300

Fig. 3. The external vibration platform.

sloshing pressure acquisition system is composed of a piezoresistive pressure transducer CYB-301 and a PLC data acquisition unit EM9636M shown as Fig. 4. The acquisition unit can convert the electrical signals from the pressure sensor into digital signals, thus completing the pressure acquisition process. The range of pressure sensor is 10 KPa, which is the same as some experiments conducted by Jiang et al. (2014a,b), and the precision is 0.1% FS, and the resolution of data acquisition unit is 0.01 KPa.

The duration and rise time of sloshing impact pressure caused by liquid sloshing are very short, which is generally in the order of milliseconds. According to Nyquist sampling theorem, the frequency of data acquisition instrument is set to be at least twice the highest characteristic frequency concerned in actual measurement. Thus, it is suggested that the sampling frequency of pressure sensor and data acquisition system should be at least greater than 5 kHz (Wei et al., 2014), and the pressure acquisition frequency of all experiments in this paper is 10 kHz. Furthermore, prior to the experiments, all sensors of pressure were calibrated properly.

Pressure sensor Data acquisition

Fig. 4. The system of pressure data acquisition.

2.4. The setting of natural frequency

The natural frequencies of sloshing liquids in a rectangular tank, f_n, can be calculated by the equation given by Faltinsen et al. (1978):

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

where n is the mode number of the internal sloshing, L is the length of tank in moving direction, g is the gravitational acceleration and h is the filling depth of the tank. The mode number is considered from one to three in this paper.

2.5. Experimental conditions

FPSO may roll, pitch, bow, sway, pitch and heave at sea, among which the rolling and pitch (Wang and Jin, 1998) motions are the main ones affecting the motion of ships with the influence of wind, waves and currents. At present, many abroad and native scholars have carried out in-depth studies on liquid sloshing in tank under single-degree-of-freedom external conditions, but the problems of multi-degree-freedom liquid sloshing has not yet been solved. Thus, the combined motion of pitch and roll as the external excitation is chosen to study the problems of liquid sloshing in the tank with elastic side wall. However, because of the complexity of sea condition, the phase difference between rolling and pitching is not undefined in actual sea condition, so, there is no phase difference between the two external excitation in this paper. Besides, the sloshing centers of pitching and rolling are located at the bottom of the tank, and the free liquid level is in a horizontal state when the tank is still. The rolling and pitching directions, the sloshing center are given and shown as Fig. 1.

In this study, the tank was driven with a sinusoidal oscillating motion ($\theta = A\sin(2\pi ft)$) along the rolling and pitching excitation, where A is the excitation amplitude and f is the external frequency of oscillation which is identical to the fundamental sloshing frequency for a given filling level. The external amplitude is 3°, which is adopted by Wenchang Qiu et al. considering the good condition of sea (2005). According to Eq. (2), the lowest three natural frequencies of rolling are 0.53 Hz, 1.0 Hz, 1.38 Hz respectively, and the lowest three natural frequencies of pitching are 1.24 Hz, 1.93 Hz, 2.41 Hz respectively. The liquid loading rate is chosen as 20% to study the characteristics of sloshing impact effectively, and the frequency experiments were done. The frequency of rolling is from 0.477 Hz to 1.116 Hz, besides, the frequency of pitching is from 1.38 Hz to 2.41 Hz. The experiment was repeated three times in each group, in order to study how the coupled external excitation frequency affects the motion of liquid in tank, so the average rolling interval was 0.024 Hz, the average pitching interval was 0.034 Hz. The detail experimental condition is shown in Table 2.

3. Results and discussion

3.1. The analysis of wave height of free surface

According to the frequency experiments, the frequency history wave height of liquid sloshing in elastic tank is gotten and analyzed, shown in Fig. 5.

With the increase of the external excitation frequency of rolling and pitching, the wave heights on both sides of the tank increase rapidly. When the external excitation frequency f/f_1 of rolling and pitching increases from 0.98 to 1.09, the liquid in the tank reaches the top of the tank, and the liquid in the tank slams on the top of the

Table 2
The details of experimental condition.

Loading rate (percent)	External frequency of rolling (f/f_1)	External frequency of pitching (f/f_1)	External amplitude (degree)	Excitation time (sec)
20	0.9 0.92 0.94 0.96 0.98 1.0 1.045 1.09 1.136 1.18 1.23 1.27 1.32 1.36 1.41 1.45 1.50 1.54 1.59 1.63 1.68 1.72 1.77 1.82 1.86 1.91 1.95 2.0 2.04 2.09 2.13 2.18 2.22 2.27 2.31 2.36 2.4 2.45 2.50 2.54	0.9 0.92 0.94 0.96 0.98 1.0 1.03 1.06 1.085 1.11 1.14 1.17 1.2 1.23 1.255 1.28 1.31 1.34 1.37 1.40 1.425 1.45 1.48 1.51 1.54 1.57 1.595 1.62 1.65 1.68 1.71 1.74 1.765 1.79 1.82 1.85 1.88 1.91 1.935 1.96	3	120

tank. With the external excitation frequency f/f_1 of rolling and pitching motion increasing from 1.09 to 1.36, wave heights on both sides of the tank decrease rapidly. When the external excitation frequency f/f_1 is between 1.36 and 3, the wave heights of free surface tend to be stable. This is because the external excitation frequency gradually tends to the first natural frequency in the tank, and the tank continues to slosh, the cumulative kinetic energy of the liquid in the tank increases, which cause the height of the liquid climbing along the bulkhead to increases, and the wave height of the free surface increases rapidly. During the $0.98f_1$-$1.09f_1$ stage, the liquid impinges on the top of the tank. With the increasing of the external excitation frequency f/f_1 of roll and pitch motion between 1.09 and 1.36, larger than the first natural frequency, the velocity of the tank gradually exceeds the velocity of the liquid in the tank, and the height of the liquid climbing along the bulkhead decreases rapidly. Meanwhile, the frequency f/f_1 between 1.36 and 3, the velocity of the tank is much faster than liquid in the tank he fluctuation of free liquid level stable.

3.2. The frequency characteristics of sloshing impact load

In this paper, statistical methods are used to analyze the impact loads due to highly random and discrete. The impact load is defined as the peak value of impact load at free surface. The pressure sensor is arranged to capture the sloshing impact pressure on the bulkhead, and the data are derived by the data acquisition instrument. So, the frequency characteristics of the sloshing impact load under the combined excitation of rolling and pitching are obtained by statistical method, shown as Fig. 6.

It is seen that with the external excitation frequency of rolling and pitching approaching the first natural frequency, the impact load of sloshing at the free surface increases gradually, and reaches the first peak at $0.96f_1$. When the external excitation frequency f/f_1 is between 0.96 and 1.09, the impact load of sloshing decreases first and then increases sharply, reaching the second peak. However, the external excitation frequency of rolling and pitching motion continues to increase, the impact load of sloshing decreases rapidly, and the impact load of sloshing shows a small fluctuation state after $1.36f_1$.

The reason is that when the external excitation frequency of rolling and pitching motion approaches the first natural frequency, the rolling motion plays a dominant role. The velocity of the liquid in the tank increases and the cumulative kinetic energy increases, so the sloshing impact load increases gradually. As the external excitation frequency f/f_1 is between 0.96 and 1.09, the rolling motion is restrained by the pitching motion, which causes the sloshing impact load start to decrease. But the external excitation frequency f/f_1 approaches 1.09, the sloshing impact load increases suddenly. The reason that can be obtained by combination the change of free surface waveform is that the rolling and pitching motions affect the sloshing of the liquid in the tank together, and the accumulated kinetic energy of the liquid in the tank increases again, so the sloshing impact load increases sharply. Then the external excitation frequency is larger than the first natural frequency, and the velocity of tank is bigger than liquid in the tank, which leads the sloshing impact load decrease. After $1.36f_1$, it can be seen that the waveform of liquid movement in the tank tends to be stable, showing a small marching wave state combined with the change of waveform.

3.3. The space distribution of sloshing impact load

As the external excitation frequency approaches the first natural frequency, the sloshing impact load increases through the frequency characteristics of sloshing impact load. So the frequency, which is between $0.96f_1$ and $1.09f_1$, was selected to analyze the space distribution of sloshing impact load, among which 1–5

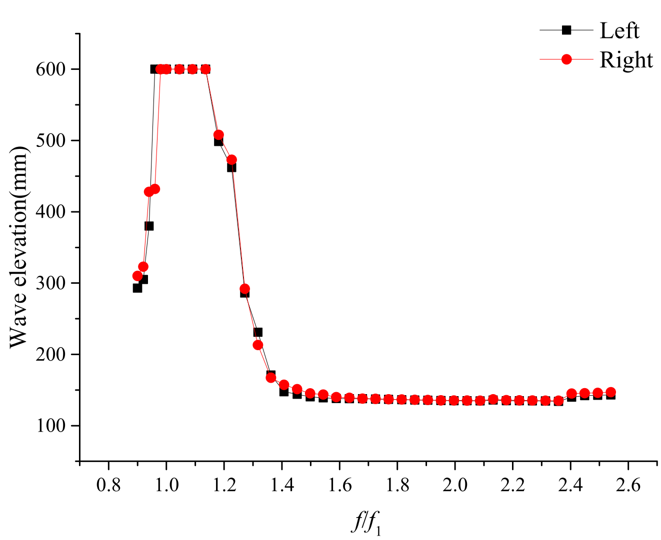

Fig. 5. Relationship between wave elevation and oscillation frequency.

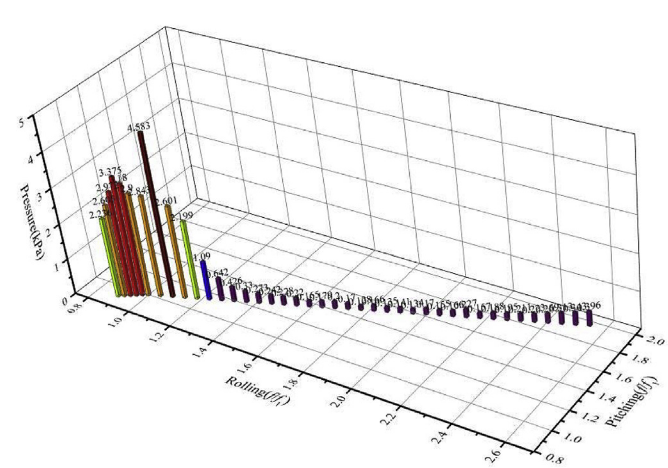

Fig. 6. The relationship between sloshing impact and oscillation frequency in left side of the tank.

represents P1–P5 monitoring point on the left bulkhead and 6–8 represents P6–P8 monitoring point on the roof.

As can be seen from Fig. 7, when the external excitation frequency of rolling and pitching motion approaches the first natural frequency with low and partial filling ($h/H = 20\%$), the impact load of the left bulkhead sloshing concentrates at the free surface, which is at P1. However, when the external excitation frequency is slighter great than the first resonant frequency, the location of the liquid impact bulkhead is different, which can occur at P2 and P3, besides, the top of the tank had larger impact at the same time. The reason for this phenomenon is that when the external excitation frequency gradually increases to the first resonant frequency, the sloshing degree of the liquid in the tank increases, the kinetic energy accumulated increases, and the liquid in the tank mainly impacts the location of P1. Meanwhile, the liquid climbs along the bulkhead, impacts the roof of the tank and the top of the tank near the left bulkhead is subjected to a larger sloshing impact load at the same time. The external excitation frequency continues to increase, and exceed the first natural frequency. When the external excitation frequencies of rolling motion are 0.554 Hz, 0.602 Hz and 0.626 Hz respectively, and when the external excitation frequencies of pitching motion are 1.234 Hz, 1.302 Hz and 1.336 Hz respectively, the position of the liquid impacting the bulkhead is at P2 and P3. The reason is that when the external excitation frequency is greater than the resonant frequency, the liquid sloshing is intense, the cumulative kinetic energy increases, the rolling and pitching motion coexist, and the liquid impacts the side bulkhead randomly, the peak value of sloshing impact load appears at P2 and P3, so the location of liquid impact bulkhead is different.

3.4. *The analysis of number of liquid impact bulkhead*

Because the liquid sloshing in tank is a random process, and the impact pressure has randomness, the POT method was selected to deal with the sloshing impact pressure at the free surface, and the number of sloshing shocks at the first three natural frequencies with low liquid loading rate was analyzed. The number of shocks is determined by the pressure threshold and time interval, based on the research results of Loysel et al. (2012) and Peregrine (2003), 2 kPa is chosen as the pressure threshold of 1/50 model tank, and the time interval is 0.1s. Therefore, the number of sloshing shocks of liquid at the first three natural frequencies is shown in Fig. 8.

As shown in picture, with the frequency of external excitation approaching the first natural frequency, the number of liquid

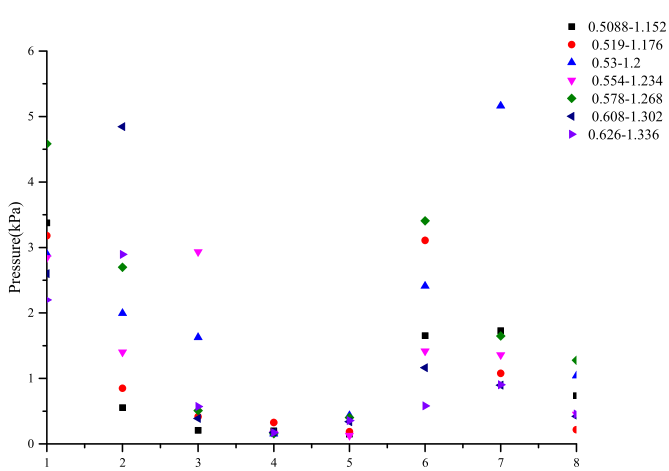

Fig. 7. The space distribution of sloshing impact load.

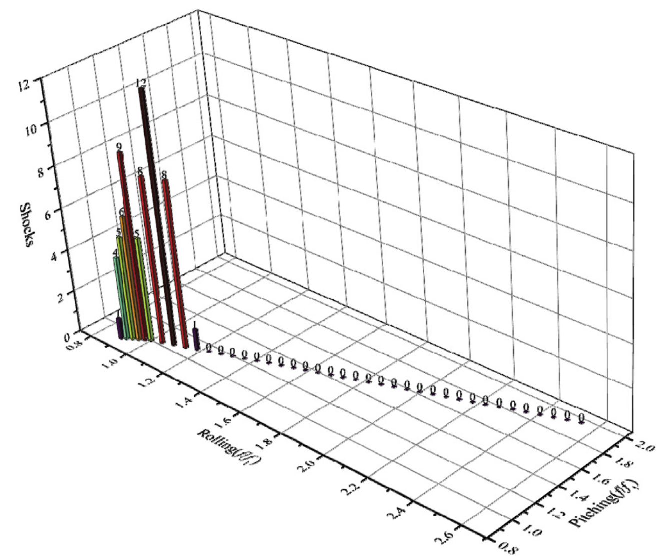

Fig. 8. The frequency domain analysis of sloshing shocks.

impact increases, and when the first natural frequency exceeds, the number of sloshing shocks decreases first and then increases sharply. Besides, the frequency of external excitation of rolling and pitching motion is at 0.602 Hz and 1.302 Hz, the number of sloshing shocks decreases rapidly. After $1.22f_1$, the number of sloshing shocks were zero. The analysis shows that when the external excitation frequency approaches the first natural frequency of the liquid, the cumulative kinetic energy of the liquid in the tank increases, and the number of sloshing shocks increases with the acceleration of the impact on the side bulkhead during the liquid movement. When the external excitation frequency continues to increase, the number of sloshing shocks first decreases, then increases sharply and then decreases rapidly when the external excitation frequency is larger than the first natural frequency, which affected by rolling coupled pitching excitation. After $1.22f_1$, it can be seen that the free surface waveform in this stage is dominated by small marching waves, combined with the change of free surface wave height and frequency domain characteristics. According to the determination method of the number of sloshing shocks, the sloshing impact pressure at the free surface does not reach the pressure threshold, so the number of sloshing shocks is zero.

4. Conclusion

In this paper, the characteristics of sloshing impact loads in elastic tank under coupled excitation at low liquid loading rate are studied through physical model tests. It is concluded that under the combined excitation of rolling and pitching, the sloshing impact loads at free liquid level are the largest when the external excitation frequency is at $1.09f_1$ by analyzing the frequency domain characteristics of sloshing impact loads at free liquid level. It can also be found that near the first natural frequency, the free surface and the top of the tank are subjected to large sloshing impact loads combined with the characteristics of wave height variation and the space distribution of sloshing impact loads. When the external excitation frequency exceeds the first natural frequency and is closed to the first natural frequency, the position of the liquid impact side wall in the tank will rise. On the whole, under the low liquid loading rate, the liquid in the tank mainly impacts the side wall at the free surface.

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