EXPERIMENTAL STUDY OF CHARACTERISTICS OF MOTIONS OF A LARGE MOORING SHIP IN LONG-PERIOD WAVES

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ABSTRACT

By inviting the method of physical model tests, the characteristics of mooring ships’ motion responses in transverse long-period waves have been studied under different conditions, including such elements as loading conditions, wave heights, and specific patterns of mooring, etc. The results indicate that: the mooring ship’s movements of surge, sway and yaw have got natural periods of their own; the movement of sway is a kind of periodic motion. The ratio of the natural period of sway and the natural rolling period of the mooring ship is within 1.11~1.23. The peak value of sway grows along with the increase of the wave period; the regularities of the LNG ship’s movement of heave are basically the same along with the periodic changes of waves, although the loading conditions are different. The peak value of heave is greater than the wave height; the ship’s movement of pitch is affected little by the changes of periods of the transverse waves; the movement of roll is a kind of periodic change. The ratio of the natural periods of roll and the natural rolling period of the mooring ship is within 1.23~1.48. The peak value of roll grows along with the increase of wave period.

I. INTRODUCTION

The movements of a mooring ship are not only significant indicators used to evaluate the operating conditions of a mooring ship, they are also the important parameters used to determine the strained condition of mooring lines and the effects a mooring ship has upon a pier. The mooring ship may have harmonic rolling motions or even more violent motions when the wave period upon it is equal or close to its natural period. Excessive ship motion may affect considerably the normal loading and unloading operations [1, 5], as well as the security of a mooring system and the stability of a pier structure. Therefore, it is essential to make clear the characteristics of motion responses of mooring ships under different loading conditions. Thus, every endeavor can be made to minimize the harmonic rolling motions under the effects of waves upon mooring ships in port design and operation management.

The characteristics of motion responses are the inherent nature of a mooring ship without regard to the pattern or size of waves that acting on the ship. In fact, it depends on the factors like ship types, loading conditions, mechanical properties of mooring lines and fenders, patterns of mooring, and fender layouts, etc. As early as in 1989, Yang [11] has pointed out in his research results that when changing the mooring lines and fenders on the premise that the lines are moored non-specifically and the fenders are used within the usual range, the ship’s responses to frequency will not be affected obviously. Besides, many scholars have recently carried out researches on the motions of mooring ships under the effects of swells and long-period waves: Van der Molen et al. [10] has carried out a numerical simulation to a mooring ship’s motions induced by long-period waves at Tomakomai Port in Japan. He [9] has also fulfilled another simulation study on the movements and loads of an LNG mooring ship under the effects of swells at Withnell Bay of Australia. Sakakibara Shigeki et al. [6, 7] has pointed out that long-period waves may induce dramatic motions of any mooring ship. Ken-ichi Uzakid et al. [8] has explored the causes to mooring ships’ drastic motions of surge and heave and advanced some relative countermeasures. Based on the analysis of a physical model test of mooring ships under the effects of long-period waves and the data got by measuring the movements of prototypes, Ligteringen et al. [4] proposed an estimation formula used to calculate the movements of mooring ships in long-period waves. Besides, due to the trend of up-sizing on ships, the changes in a ship’s size and its hydrodynamic characteristics will inevitably lead to changes in the ship’s characteristics of motion responses. Therefore, the conclusions drawn in Yang’s study mentioned above are not fully applicable to today’s large ships [11]. Therefore, it is necessary to study the characteristics of motion responses of large mooring ships. In this paper, a physical model experiment was performed on a 266,000m³ mooring LNG ship for further study and discussion on the characteristics of motion responses under the effects of long-period waves.

II. DESIGN OF THE EXPERIMENT

1. Simulations of the Mooring Ship

The model scale was set 1:60 in accordance with the re-
quirements of *Wave Model Test Regulation* [12]. The experiment was performed on a 266,000 m$^3$ LNG ship moored to an island berth. The dimensions of the ship are given in Table 1. The model was built based on the 3D hull shape definition of a prototype LNG ship at a geometric scale of 1:60; the weight balance method was used to meet different requirements of load and weight distribution; the LNG ship’s main particulars such as its center of gravity, the periods of roll and pitch, etc. were consistent with similar dynamic conditions.

### 2. Simulations of the Structure of Island Berth

In the same way, the simulations of the structure of island berth were fulfilled by reducing the prototype on the geometric scale 1:60. The simulation of island berth structure can ensure both the geometric similarity and the similarity of the location of caisson piers, as well as the stability of caisson pier. In addition, the outer shells of the caisson piers are made of wood, filled with gravels and small lead weights inside. The top of each caisson pier is connected with the upper wooden part of the berth, which has formed a unity. A number of weights can be evenly added to the surface of the upper structure to make the overall structure of the berth rigid and stable enough. The layout of the berth is shown in Fig. 1.

### 3. Simulations of Mooring Lines

The mooring lines used for mooring the LNG ship were arranged in a symmetrical way by the number of 3:2:3:2. That is to say, there were 3 ropes for both head line and stern line, 2 for both additional head line and stern line, 3 for both forward breast line and after breast line, and 2 for head spring line and stern spring line (Line Numbers refer to Fig. 1). When the locations of mooring dolphins and positions of the ship’s mooring pipes are fixed, the length of lines will automatically satisfy geometric similarity. In the experiment, the nylon ropes with a diameter of $\Phi = 75$mm were chosen for use. Two strands of the ropes were twisted into one mooring line, and two of three strands of the ropes were twisted into one mooring line and the other strand was directly used as another line. The lines used for simulations are made of cotton ropes, the mass of whose per unit length can satisfy gravity similar rule, as well as which are allowed sufficient spare length for use. The lines were hung heavy weights in advance to make them lose elasticity completely. When simulating the lines, the elastic similar rules of lines should be taken into consideration. Wilson Equations can be used for the calculation of the force-deformation of simulating lines. The elastic pieces of steel were adopted to simulate the elasticity of the lines. In the experiment, an initial tension of 100 KN was loaded on each line in accordance with the prototype lines. The Fig. 2 shows the curve graphs of force-deformation of forward breast and after breast lines, which manifests good simulation results.

### 4. Simulations of Fenders

The main similarity conditions of fenders refer to the similarity of the curves of force-deformation and energy-deformation of fenders between the prototype and the model. The standard SUC-2250H cell rubber fenders were taken into use with a layout of two in one row. When simulating the layout of two in one row was simulated into the layout of one cell rubber fender in one row. The simulation results shown

![Fig. 1. Berth layout and diagrammatic illustration of mooring patterns of the LNG ship.](image)

![Fig. 2. The modeling results of force-deformation curves of breast lines.](image)

![Fig. 3. Force-deformation curves to the modeling results of fenders.](image)
in Fig. 3 shows that the rubber fenders achieved better results.

III. EXPERIMENT

1. Experiment Equipments and Measuring Instruments

The experiment was conducted in an ocean environmental flume of the State Key Lab of Coastal and Offshore Engineering (SLCOE), Dalian University of Technology, China. The flume is 40 meters long, 24 meters wide and 1.2 meters deep. A piston type wave maker system designed and constructed by SLCOE is installed at one end of the flume, which can generate multidirectional complex waves of both low-frequency and high-frequency according to different test requirements. Wave absorbers are arranged at the other end of the flume to absorb incoming waves to avoid wave reflection.

In the experiment, the wave data were collected by adopting the DS30 system developed by Beijing Research Institute of Water Conservancy Technology (BRIWT). The system can handle up multipoints of wave surface simultaneously and then process data analyses; the wave measurement instrument spans the range of 35cm, and the proportional error is less than 0.5%. The measurement of a mooring ship’s movement employs the system dedicated to model ship tests with twin CCD optical six-component movement measurement, which is also developed by BRIWT. Such system employs non-contact measurement method to avoid added mass and friction that generated by using the traditional contact one. The system can also be used to simultaneously measure six-component movements.

2. Experiment Conditions and Simulations of Waves

In the experiment, some dynamic factors such as currents and wind loads, etc., which affect the motion of a mooring ship, were not taken into account. The water in the flume is 0.24 meters deep. The direction of waves is transverse which is the most unfavorable to a mooring ship. The characteristic parameters of the long-period waves in the experiment can be referred to Table 2. The irregular waves used in the experiment are the ones simulated by the internationally recognized JONSWAP spectrum.

IV. RESULTS AND DISCUSSION

1. Surge

Fig. 4 has illustrated the experimental results of the changes of the mooring ship’s movement of surge with the changes of the wave period under the effects of transverse waves: it gradually grows with the increase of wave period. When the ship is half loaded at the wave period of 32s, the harmonic rolling motions of surge appear, and the value of surge increases significantly; the movement of surge experiences attenuation both before and after the peak value. It’s about 50% of the peak value when the maximum attenuation appears. When the mooring ship is fully loaded, no peak value appears under the experimental working conditions. However, when the wave period is greater than 40s, the movement of surge has rapidly increased with the increase of wave period.

2. Sway

As shown in Fig. 5, under the effects of transverse waves, the mooring ship’s movement of sway has periodic intermittent motions with the increase of wave period: when the ship is ballasted, the harmonic rolling motions of sway appear when the wave period is 12s, 24s and 40s respectively. The ratio of the natural rolling period of the mooring ship and the natural periods of sway is 1 : 1.11 : 2.22 : 3.69; the peak value of sway grows with the increase of wave period. While under the laden condition, the wave period will grow with the increasing amount of loading upon the harmonic rolling motions of sway appear. The harmonic rolling motions of sway appear twice at the wave period of 18 (20) s and 38s respectively. The ratio of the natural rolling period of the mooring ship and the natural periods of sway is 1:1.11 (1.23): 2.34.; the sway’s second peak value is significantly greater than the first one. As seen from Figure 3 and 4, the movement of sway attenuates when the mooring ship’s harmonic rolling motions appear for the second and third time, and the value of the maximum attenuation is about 35% of its peak.

3. Heave

The experimental results of the changes of mooring ship’s movement of heave in transverse waves with different periods have been manifested in Fig. 6. Along with the periodic changes of waves, the regularities of the LNG ship’s movement of heave are basically the same under different loading conditions. The peak values of heave appear at different wave periods: at 40s when ballasted the ship and at 32s when laden it. Under the effects of waves with the period less than 6s, the movement of heave is less than one third of wave height [3]; while under the effects of long-period waves, the peak values of heave are basically equal or even greater than the wave heights.

| Table 2. Characteristic Parameters of Waves in the Experiment |
|---------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| $H_{1/3} \text{m}$ | $T_P \text{/s}$ | 20    | 22    | 24    | 26    | 20    | 22    | 24    | 26    |
| 0.3    | 28    | 30    | 32    | 34    | 36    | 38    | 40    | 45    | 50    |
| 0.5    | 10    | 12    | 14    | 16    | 18    | 20    | 22    | 24    | 26    |
| 0.8    | 10    | 12    | 14    | 16    | 18    | 20    | 22    | 24    | 26    |
4. **Pitch**

From Fig. 7, it can be seen that the ship's movement of pitch is affected little by the changes of wave periods in transverse waves.

5. **Roll**

The experimental results of the changes of roll in transverse waves with different periods have been shown in Fig. 8. The mooring ship's movement of roll has harmonic rolling motions twice under each of the loading conditions—the ballasted and the laden: when ballasted the peak values of roll appear at 14s and 32s respectively. The ratio of the natural rolling period of the mooring ship and the natural periods of roll is 1:1.29:2.95; with the increasing loading of the mooring ship, the wave period grows at the peak values of roll. The values of wave period at the peak values of roll are 20s and 40s respectively. The ratio of the natural rolling period of the mooring ship and the natural periods of roll is 1:1.23:2.46; the peak values of roll grows along with the increase of wave period: it increases by about 15% when the mooring ship is ballasted and increases by about 30% when laden. It is because the parameter of stabilizing height under the laden condition is less than that under the ballasted one. When the mooring ship is fully loaded, the rough waves are more likely to roll the ship along.

![Fig. 4. Changes of motion responses of the mooring ship's surge with wave periods](image)

![Fig. 5. Changes of motion responses of the mooring ship's sway with wave periods](image)

![Fig. 6. Changes of motion responses of the mooring ship's heave with wave periods](image)
6. Yaw

Fig. 9 gives the experimental results of the changes of yaw in transverse waves with different periods. The general changing trend of the mooring ship’s movement of yaw is on gradual rise along with the increase of wave period. Under the experimental working conditions with different loadings, the harmonic rolling motions of yaw appear just once: at 30s when ballasted and at 32s when laden.

V. CONCLUSION

In this paper, a physical model experiment was employed for research. The characteristics of motion responses of an LNG mooring ship in transverse long-period waves are studied under different loading conditions. The conclusions are drawn as follows,

● The movement of pitch and roll have their own natural periods. Apart from them, the mooring ship’s movements of surge, sway and yaw also have got their own natural periods respectively;

● The movement of sway has a kind of periodic intermittent motion. The ratio of the natural period of sway and the natural rolling period of the mooring ship is within 1.11~1.23, which roughly grow exponentially along with the increase of wave periods; the peak value of sway grows with the increase of wave period;
Along with the periodic changes of waves, the regularities of the LNG ship’s movement of heave are basically the same under different loading conditions. The peak values of heave differ when the wave period changes due to the ship’s different loading conditions; under the effects of waves with different heights, the peak value of heave is greater than the wave height; 

- The ship’s movement of pitch is affected little by the changes of wave period in transverse waves; 
- The movement of roll has a kind of periodic motion. When the movement of roll is at peak values, the ratio of the natural period of roll and the natural rolling period of the mooring ship is within 1.23–1.48, which roughly grow exponentially along with the increase of wave period; the peak value of roll grows with the increase of wave period.

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REFERENCES