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

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Key words: a mooring large ship, long-period waves, transverse waves, characteristics of motion responses, natural period of a moored ship.

ABSTRACT

By using the method of physical model tests, the characteristics of mooring ship's 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 had their own natural periods; the movement of sway was a period motion. The ratio of the natural period of sway and the natural rolling period of the mooring ship was within 1.11~1.23. The peak value of sway grew along with the increase of the wave period; the regularities of the LNG ship's movement of heave were basically the same along with the periodic changes of waves, although the loading conditions were different. The peak value of heave was greater than the wave height; the ship's movement of pitch was affected little by the changes of periods of the transverse waves; the movement of roll was a kind of periodic change. The ratio of the natural periods of roll and the natural rolling period of the mooring ship was within 1.23~1.48. The peak value of roll grew along with the increase of wave period.

I. INTRODUCTION

The movements of a mooring ship are not the 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 disregard of 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 ship's 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 achieved by measuring the movements of

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Table 1. Dimensions of the 266,000 m^3 LNG ship.

Parameters	Unit	Laden	Ballasted
Length Over all	m	345	
Length between Perpendiculars	m	320	
Breadth	m	55	
Depth	m	27.2	
Draft	m	12	9.6
Displacement Volume	t	184008	147206
Height of gravitational center	m	24	19.2
Height of center of buoyancy	m	6.6	5.2
Metacentre Radius	m	24.2	26.9
Transverse moment of inertia	M^4	66523380	54549023
Longitudinal moment of inertia	M^4	1.15E+09	9.42E+08
Stabilizing height	m	6.8	12.9
Natural Period of Roll	s	16.24	10.83
Natural Period of Pitch	s	9.48	8.53

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 upsizing 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]. It is then necessary to study the characteristics of motion responses of large mooring ships. In this paper, a physical model experiment was performed on a 266,000 m^3 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 requirements 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 ship 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

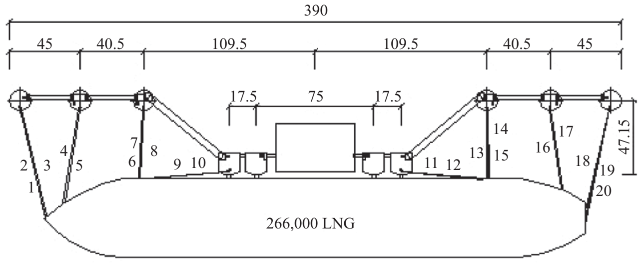

Fig. 1. Berth layout and diagrammatic illustration of mooring patterns of the LNG ship.

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 symmetrically by the number of 3:2:3:2, i.e., three ropes for both head line (Nos. 1-3 on Fig. 1) and stern line (Nos. 18-20), two for additional head line (Nos. 4, 5) and stern line (Nos. 16, 17), three for forward breast (Nos. 6-8) line and after breast line (Nos. 13-15), and two for head spring line (Nos. 9, 10) and stern spring line (Nos. 11, 12). 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 Φ = 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 was 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. 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

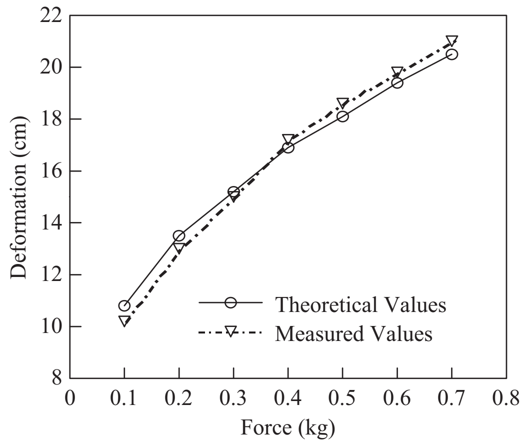

Fig. 2. The modeling results of force-deformation curves of breast lines.

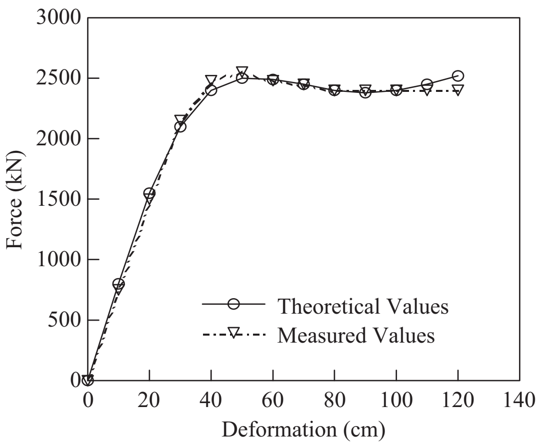

Fig. 3. Force-deformation curves to the modeling results of fenders.

into use with a layout of two in one row. The layout of two in one row was simulated into the layout of one cell rubber fender in one row. The simulation results either show or showed that the rubber fenders achieved better results (Fig. 3).

III. EXPERIMENT

1. Experiment Equipments and Measuring Instruments

The experiment was conducted in an ocean environmental flume of the State Key Laboratory 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 was installed at one end of the flume to generate multidirectional complex waves of both low-frequency and high-frequency according to different test requirements. Wave absorbers were arranged at the other end of the flume to absorb incoming waves to avoid wave reflection.

Table 2. Characteristic Parameters of Waves in the Experiment.

$H_{1/3}$/m	T_P/s								
0.3						20	22	24	26
	28	30	32	34	36	38	40	45	50
0.5	10	12	14	16	18	20	22	24	26
	28	30	32	34	36	38	40	45	50
0.8	10	12	14	16	18	20	22	24	26
	28	30							

In the experiment, the wave data were collected by adopting the DS30 system developed by the Beijing Research Institute of Water Conservancy Technology (BRIWT). The system can handle multipoints of wave surface simultaneously and then process data analyses; the wave measurement instrument spans a range of 35 cm, and the proportional error is less than 0.5%. The measurement of a mooring ship's movement employs the system developed by BRIWT and designed for model ship tests with twin CCD optical six-component movement measurement. Such system employs non-contact measurement method to avoid added mass and friction that generated by using the traditional method with contact measurement. 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 was 0.24 meters deep. The direction of waves was transverse which is the most unfavorable to a mooring ship. The characteristic parameters of the long-period waves in the experiment are listed in Table 2. The irregular waves used in the experiment are the ones simulated by the universally accepted JONSWAP spectrum.

IV. RESULTS AND DISCUSSION

1. Surge

Fig. 4 illustrates 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: the movement gradually grows with the increase of wave period. When the ship is half loaded at the wave period of 32 s, 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 is 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 40 s, the movement of surge has rapidly increased with the increase of wave period.

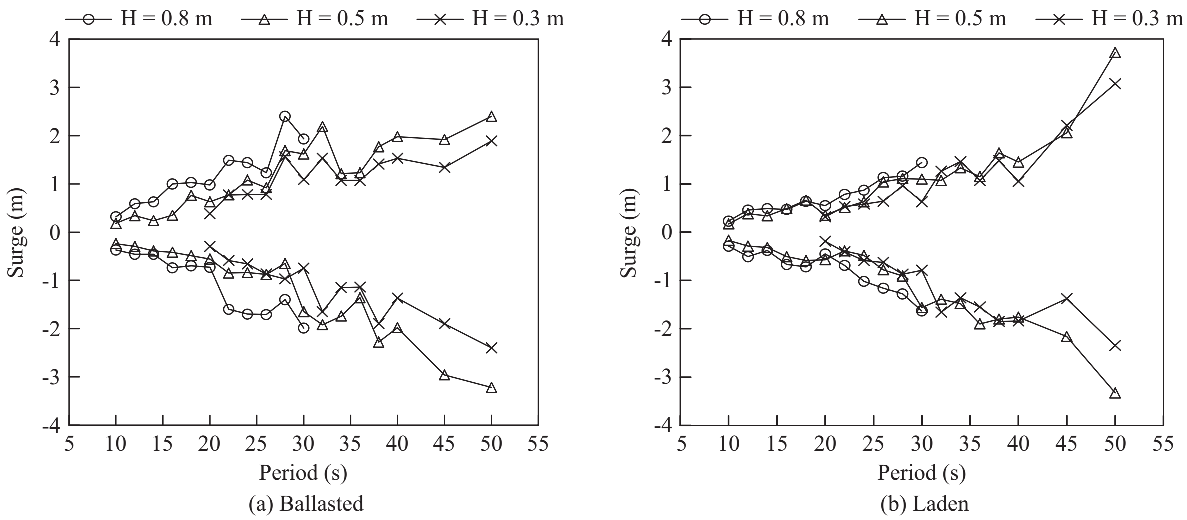

Fig. 4. Changes of motion responses of the mooring ship's surge to wave periods.

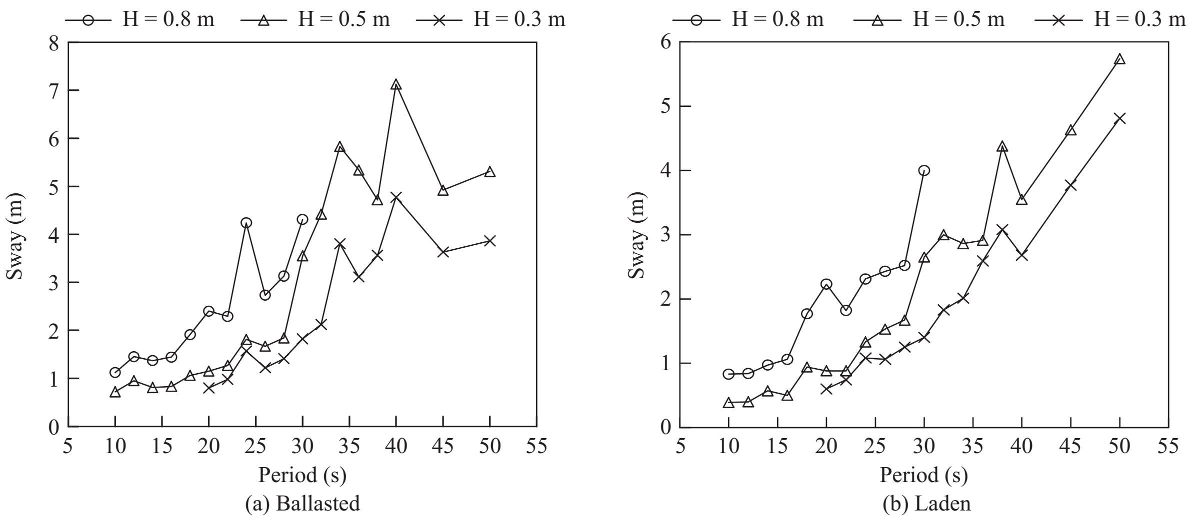

Fig. 5. Changes of motion responses of the mooring ship's sway to wave periods.

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 12 s, 24 s and 40 s 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 appearance of harmonic rolling motions of sway. The harmonic rolling motions of sway appear twice at the wave period of 18 (20) s and 38 s 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 Figs. 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 are 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 40 s when ship is ballasted and at 32 s when ship is laden. Under the effects of waves with the period of less than 6 s, 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 to or even greater than the wave heights.

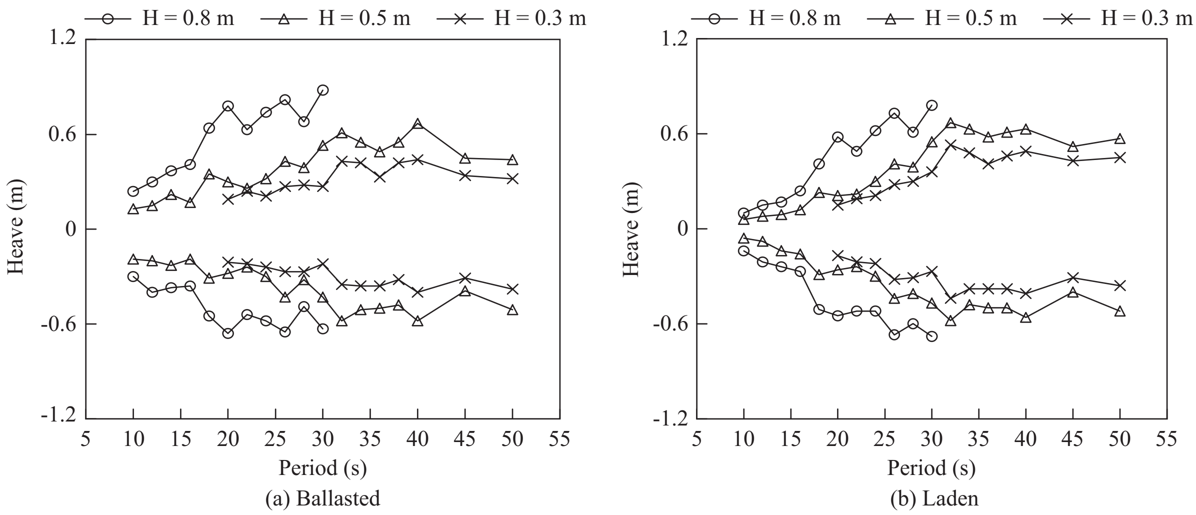

Fig. 6. Changes of motion responses of the mooring ship's heave to wave periods.

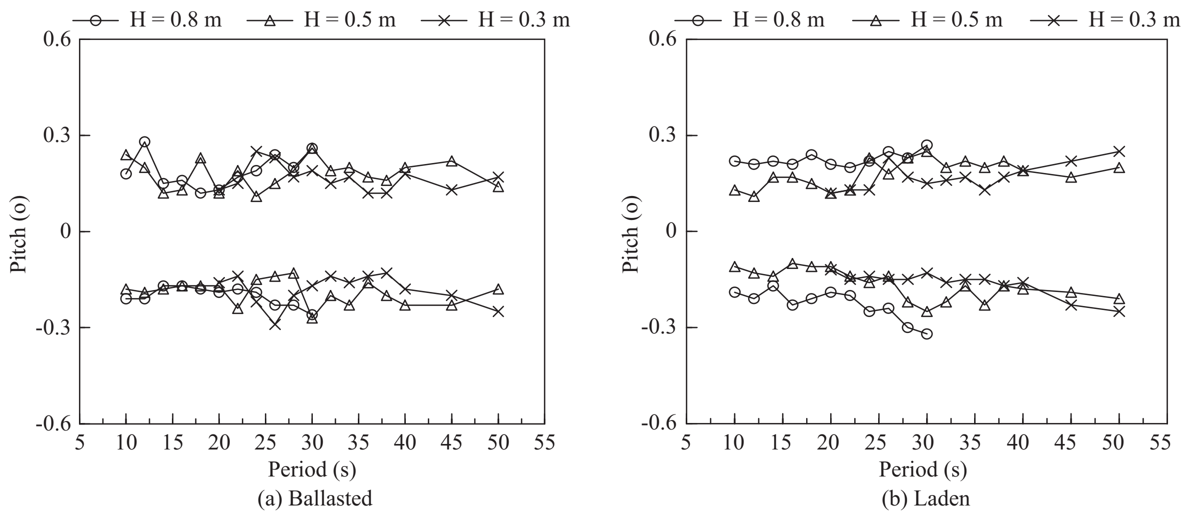

Fig. 7. Changes of motion responses of the mooring ship's pitch to wave periods.

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 32 s 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 20 s and 40 s 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 condition. When the mooring ship is fully loaded, the rough waves are more likely to roll the ship along.

6. Yaw

Fig. 9 illustrates 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 30 s when ballasted and at 32 s when laden.

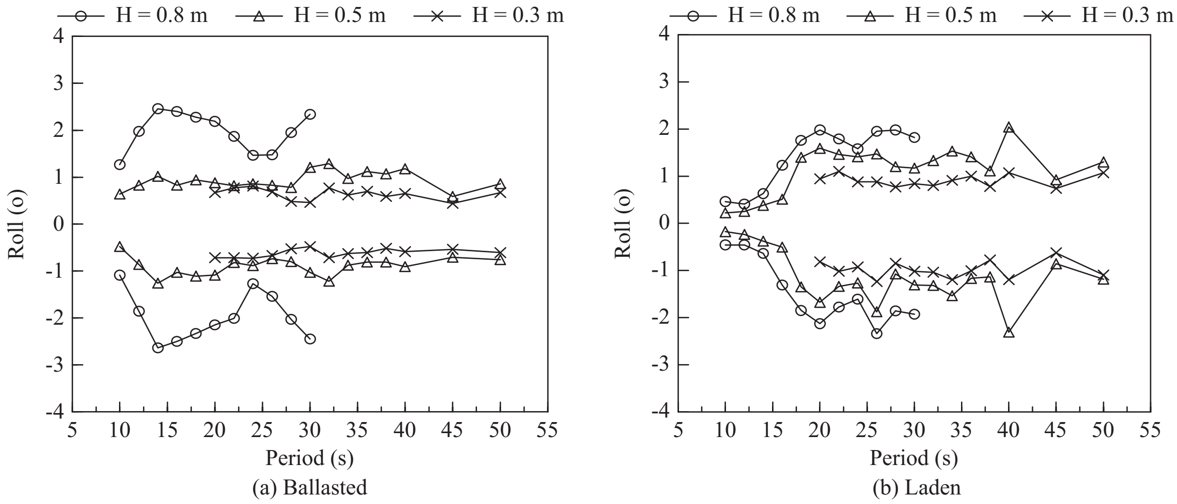

Fig. 8. Changes of motion responses of the mooring ship's roll to wave periods.

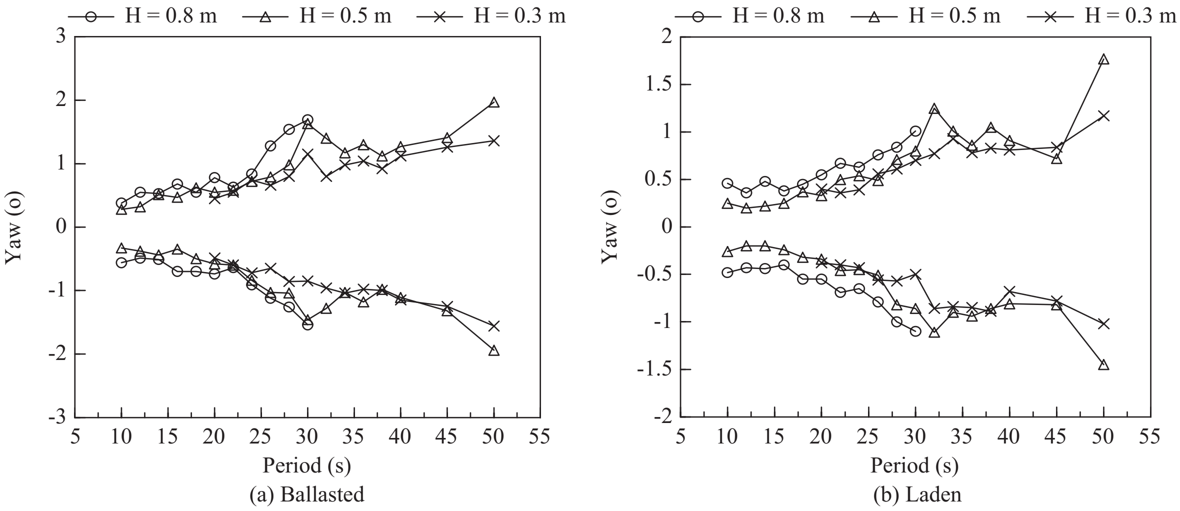

Fig. 9. Changes of motion responses of the mooring ship's yaw to wave periods.

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 were studied under different loading conditions. The conclusions are drawn as followings:

- 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 their own natural periods respectively.
- The movement of sway is a 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 little affected by the changes of wave period in transverse waves;
- The movement of roll is a 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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