A Comparative Study on the Motions of a Mooring LNG Ship in Bimodal Spectral Waves and Wind Waves

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Abstract. By adopting the method of a series of physical model tests, a study has been conducted to compare the motion responses of a mooring ship under the action of bimodal spectral waves and pure wind waves. The results show that the low-frequency waves in the bimodal spectrum waves control the motion responses of the mooring ship. When the energy of bimodal spectral waves equals the one of pure wind waves, the amount of mooring ship motions under the action of bimodal spectral waves is significantly larger than that of pure wind waves. Under such circumstances, even when the energy of the low-frequency waves accounts for only 20% of the total energy of the bimodal spectral waves and the low spectral peak period is 12s, the movement quantity of sway can reach 1.5 times in bimodal spectral waves than in pure wind waves. The movement quantities of surge, heave, and roll in bimodal can reach more than 2 times of those in pure wind waves. Under the action of transverse waves, the mooring ship's movement of pitch is not affected by the wave height of bimodal spectral waves and the period of low-frequency bimodal spectral waves.

1. Introduction

Since the 21st century, with the economic and trade exchanges among countries in the world as well as the development and utilization of marine resources by human beings, the global shipping industry has developed rapidly. In order to reduce the cost of freight transportation, the large-scale transportation of ships has become the development trend of the shipping industry. Therefore, the berths of the terminals have also become larger. In order to meet the draft requirements of large ships, the number of large offshore open docks is further increasing.

The research results from many domestic scholars show that bimodal spectral waves spread most sea areas of China: the results from Zou Wenfeng et al [1] show that when the typhoon "Phoenix" hits the eastern waters off Taiwan Island, typhoon waves whose period is 18s can be found in the sea area off the Zhoushan Islands. When the typhoon waves spread, long-period waves appear earlier than billows in the Bohai Sea. According to the study conducted by Geng Baolei et al [2], upon the hits of typhoon "Son-Tinh", large periodic waves appeared in the Qiongzhou Strait are actually the swells caused by the typhoon. Yang Bin et al [3] analyzed the measured wave data and found that bimodal spectral waves appeared in the northeastern Zhoushan Island caused by the typhoon.

Many scholars at both home and abroad have recently carried out researches on the motions of mooring ships under the effects of swells and long-period waves: Yang Xian-zhang [4] has studied the effects of long-period waves have upon the motion characteristics of mooring ships. Van der MOLEN et al. [5] has carried out a numerical simulation to a mooring ship's motions induced by long-period waves at Tomakomai Port in Japan. He [6] 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. [7] has pointed out that long-period waves may induce dramatic motions of any mooring ship. Shi Xian-ying et al. [8] have done series of model tests to study the motion-response characteristics of mooring large natural gas (LNG) ships under the action of long-period waves. Besides, Shi Xian-ying et al. [9] have also studied the law of motion responses of mooring ships under the effect of mixed waves. However, there is no comparison study of motion responses of mooring ships in both bimodal spectral waves and wind waves.

In this paper, a series of physical model experiments of a mooring ship were performed on a 266,000 m3 LNG ship to investigate and compare its motions under a specific mode of mooring condition but different loading conditions, under the transverse action of waves with the total energy but different in ratios of bimodal spectral waves and wind waves.

2. Design of the experiment

2.1. 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.

2.2. Simulations of the Mooring Ship

The model scale was set 1:60 in accordance with the requirements of Wave Model Test Regulation [10]. 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.

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

Parameters	Unit	Laden	Ballast
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
Natural Period of Roll	s	16.24	10.83
Natural Period of Pitch	s	9.48	8.53

2.3. 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. The layout of the berth is shown in Figure 1.

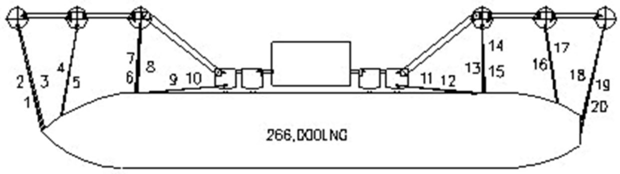


Figure 1. The Berth Layout and the Diagrammatic Illustration of Mooring Patterns of the LNG Ship

2.4. Simulations of Mooring Lines

When simulating the lines, the elastic similar rules of lines should be taken into consideration, and the Wilson formula can be used for calculating the force~deformation of the simulating lines. The elastic pieces of steel were adopted to simulate the elasticity of the lines. Figure. 2 shows the curve graphs of force~deformation of forward breast and after breast lines, which manifests good simulation results.

2.5. Simulations of Fendersu

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 simulation results shown in Figure. 3 show that the rubber fenders achieved better results.

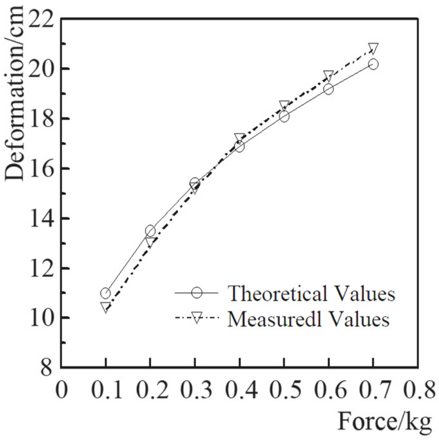


Figure 2. The Modeling Results of Force~Deformation Curves of Breast Lines

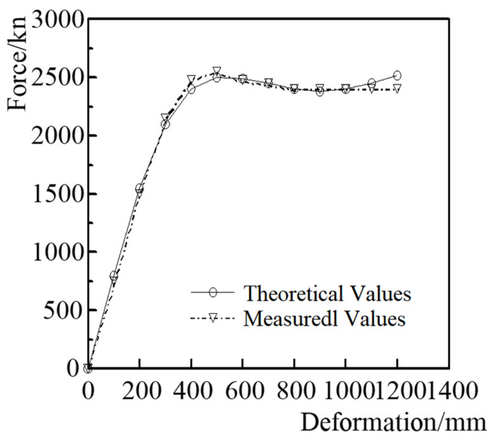


Figure 3. Force~Deformation Curves to the Modeling Results of Fenders

2.6. Simulations of Waves

In the experiment, wind waves used in the experiment are the ones simulated by the internationally recognized JONSWAP spectrum.

The bimodal spectral waves were generated by a six-spectrum parameter [11]. A six-parameter spectrum can be obtained by combining two three-parameter spectrums in both low and high frequency parts of the waves respectively. The equation is given by

$$S(\omega)=\frac{1}{4}\sum_{j}\frac{\left(\frac{4\lambda_j+1}{4}\left(\omega_{mj}^4\right)\right)^{\lambda_j}}{\Gamma(\lambda_j)}\frac{H_{sj}^2}{\omega^{4\lambda_j+1}}\exp\left[-\frac{4\lambda_j+1}{4}\left(\frac{\omega_{mj}}{\omega}\right)^4\right] \quad (1)$$

Where j = 1, 2 represents the low and high frequency parts. There are totally six parameters in the equation, and each change of a parameter, according to the spectrum shape of actual measurement, may minimize the difference between theoretical and measured values of the spectrum.

In the experiments, the significant wave height of long-period waves and the significant wave height of bimodal spectral waves were set the same (That is to say, the total energy of the long-period waves and the bimodal spectral waves are the same). The period of the high-frequency peak of Bimodal Spectral waves was fixed to 6s, and the period of low-frequency peak was fixed within the range from 12 to 24s; the spectral peak period of long-period waves equals to the one of the low-frequency part of bimodal spectral waves. The characteristic parameters of bimodal spectral waves and wind waves used for the test are given in Table 2. As shown in Figure.4, an illustration of the bimodal spectral waves that generated by employing the method of six-parameter spectrum, the theoretical spectrum is seen better fitted the measured one.

Table 2. Characteristic Parameters of Waves in the Experiment

Wave Types		H1/3(m)	Tp (s)					
wind waves		1.1	6					
bimodal spectral waves	high frequency	1.0	6					
	low frequency	0.5	12	14	16	18	20	24
	high frequency	0.8	6					
	low frequency	0.8	12	14	16	18	20	24
	high frequency	0.5	6					
	low frequency	1.0	12	14	16	18	20	24

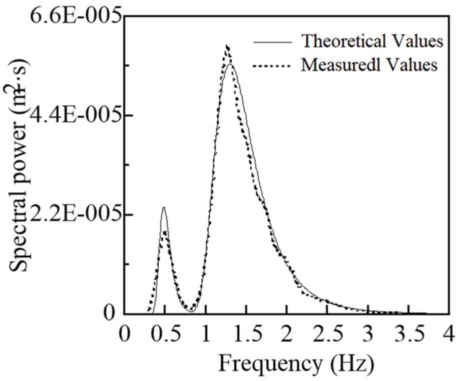


Figure 4. Comparison of Simulated and Measured Values of Bimodal Spectral Wave

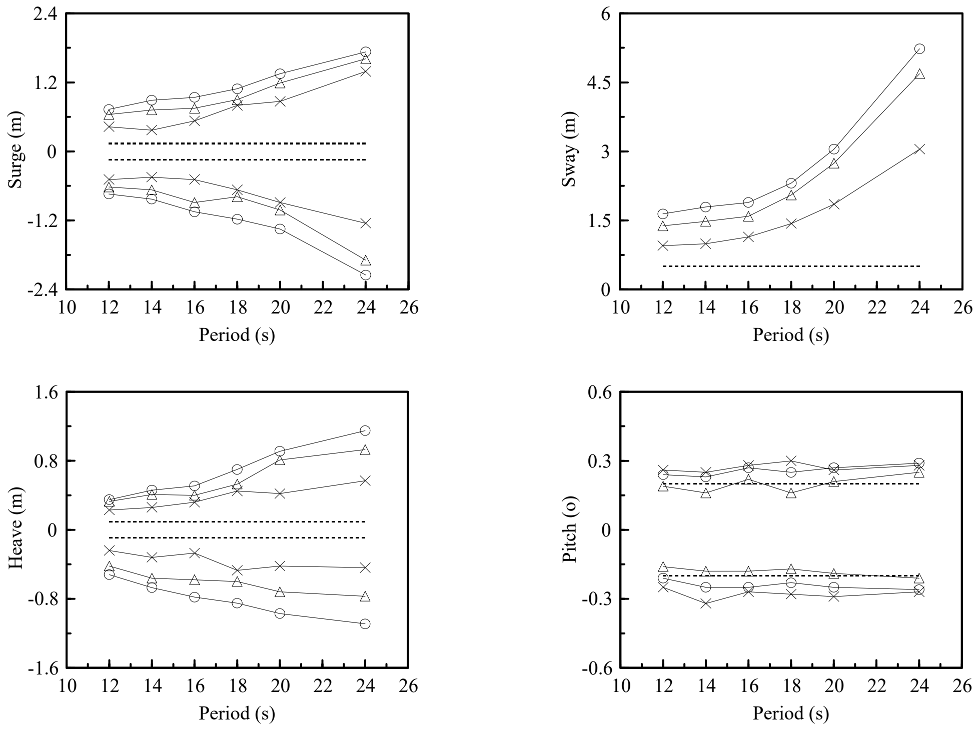
3. Results and discussion

In Figure 5 and Figure 6, the experimental result of the mooring ship's movements in bimodal spectral waves is compared to the one of the same ship's movements in wind waves on condition that the total energy is the same and the period of low-frequency spectral peak is set within the range from 12 to 24s.

It should be noted that the horizontal axis in both Figure 5 and 6 is set for the period of low-frequency spectral peak of bimodal spectral waves. The effective wave heights of the bimodal spectral waves composed in the test equal to the ones of the wind waves. Besides, the peak period of the wind waves is 6s, which is indicated by the horizontal dotted line given in the figures. Therefore, the periods cannot be compared. The six movements of the mooring ships, including surge, sway, heave, pitch, roll and yaw, in both the bimodal spectral waves and the wind waves can be compared except their periods.

It can be seen from Figure 5 and Figure 6 that when the total energies of the bimodal spectral waves and the wind waves are the same in value, the movements of the mooring ship are also significantly increased, even though the proportion of the high-frequency wind wave energy in the bimodal spectral waves is 80%. Under the effects of bimodal spectral waves, the movements (except the movement of pitch) of the mooring ship are much larger than the ones under the effect of unimodal spectral waves. It can be seen that the low-frequency waves in the bimodal spectral waves serve as an effective control for the movements of the mooring ship. Within the condition tested, when the energy of the low-frequency waves in bimodal spectral waves is 20% of the total, the peak period of the low-frequency waves is 12s, the movements of sway and yaw of the mooring ship in bimodal spectral waves can reach 1.5 times or more than those in wind waves. The 3 movements of surge, heave, and roll of the mooring ship can reach 2 times or more than those in wind waves.

When the proportion of the low-frequency wave energy accounts for 50% of the total, the movements (except the movement of pitch) of the mooring ship in bimodal spectral waves is significantly increased compared with the situation when the ratio of low-frequency energy accounts for 20%. When the period of the low-frequency waves is 12s, the movements of sway and roll of the mooring ship in bimodal spectral waves can reach 2 times or more than those in wind waves. The movement of surge is 4 times or more than that in wind waves. The movement of heave is 3 times or more than that in wind waves. However, the movement of yaw only increases slightly.



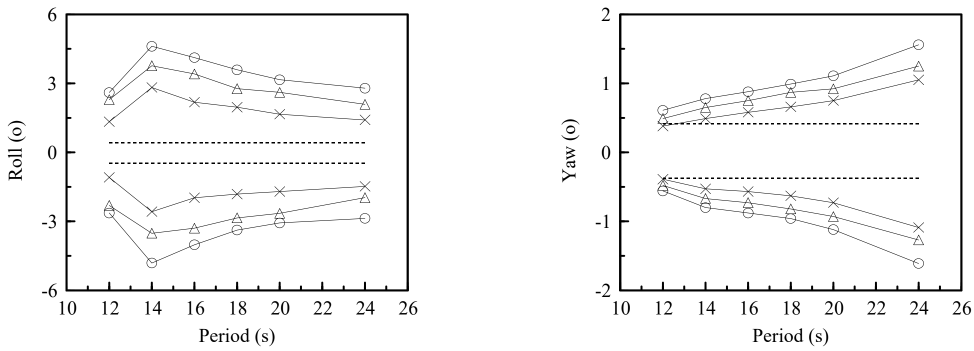


Figure 5. Comparison of Values of Movements of the Mooring Ship in Bimodal Spectral Waves and Wind Waves under the Ballasted Condition

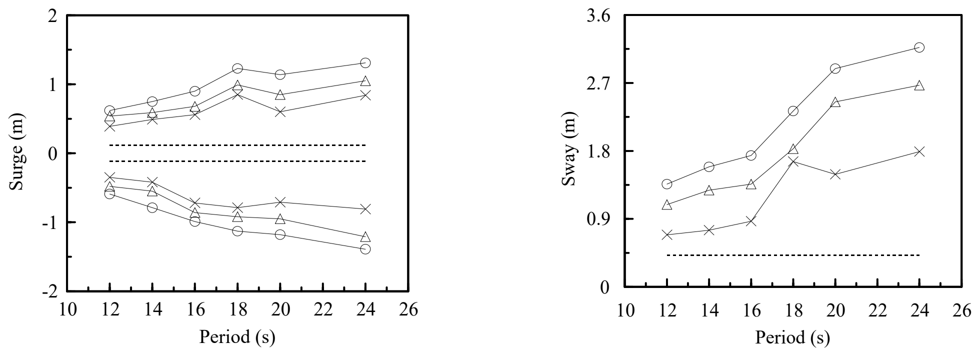
(Legend：- - -wind waves；

-○- 80% contribution of the low-frequency wave energy to the Bimodal Spectral waves；

-△- 50% contribution of the low-frequency wave energy to the Bimodal Spectral waves；

-×- 20% contribution of the low-frequency wave energy to the Bimodal Spectral waves)

When the proportion of the low-frequency wave energy accounts for 80% of the total, the movements (except the movement of pitch) of the mooring ship in bimodal spectral waves is significantly greater than that in wind waves. When the period of the low-frequency waves is 12s, the movements of sway, heave and roll of the mooring ship in bimodal spectral waves can reach about 3 times of those in wind waves. The movement of surge is 5 times or more than that in wind waves. The movement of yaw is 2 times of that in wind waves. When the period of the low-frequency waves is 24s, the movements of sway and roll of the mooring ship in bimodal spectral waves can reach 7 times or more than those in wind waves. The movements of surge and heave can reach 10 times or more than those in wind waves. The movement of yaw can reach 5 times or more than that in wind waves.



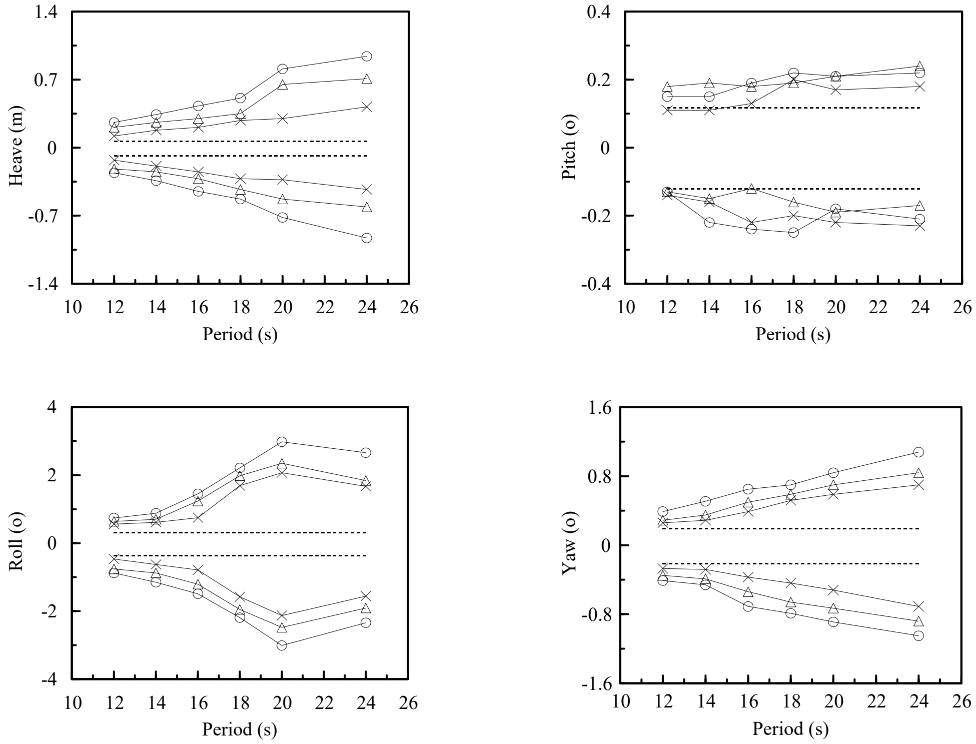


Figure 6. Comparison of Values of Movements of the Mooring Ship in Bimodal Spectral Waves and Wind Waves under the Laden Condition
(Legend as in Figure.7)

Furthermore, within the specific test value range, the mooring ship's movement of pitch is within the range of 0.1° ~ 0.3° in the three kinds of Bimodal Spectral waves with different energy ratios of high and low-frequency waves. In general, under the action of transverse waves, the mooring ship's movement of pitch doesn't change significantly with the changing of the low-frequency spectral peak period of Bimodal Spectral waves. Such a phenomenon goes the same for the situation that the mooring ship's movement of pitch in different transverse waves with different wave heights is independent of the value of transverse wave period [11].

4. Conclusions

In this paper, a study has been conducted to compare the movements of a mooring ship in unimodal spectral waves and bimodal spectral waves with the same total energy but different proportion of high-frequency and low-frequency waves. Within the range tested, the following conclusions are drawn:

(1) The low-frequency waves in bimodal spectral waves serve as an effective control for the movements (except the movement of pitch) of the mooring ship.

(2) The movements of the mooring ship in bimodal spectral waves are significantly greater than those in wind waves, and their difference values magnify with the increase of the energy of low-frequency waves.

(3) Under the action of transverse waves, the mooring ship's movement of pitch is not affected by the wave height of bimodal spectral waves and the period of low-frequency bimodal spectral waves.

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