Experimental Study on the Hydrodynamic Influence of Marine Data Buoy with Different Mooring Systems in Northern Part of Weihai

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Abstract. The hydrodynamic of marine data buoy and its mooring system has an important impact on its reliability, viability and adaptability at sea. In this paper, the physical model test verification, is adopted for studying hydrodynamic of data buoy, by using the measured data in the northern sea area of Chu Island, Weihai, Shandong Province, China. The hydrodynamic performance of three different mooring systems, i.e. slack type, inverted S type and tension type, under the action of wind and waves coupling is studied. The model test of the buoy was carried out at the Environmental Laboratory in the National Ocean Technology Center of the Ministry of Natural Resources of China, and the scale of the model is determined to be 1:5, according to the laboratory test capacity and buoy prototype size. The results show that the inverted S type mooring system has higher reliability, while the tension type mooring system can obtain more accurate observation data, and the performance of the slack mooring system is between the two, among the three types of mooring systems. The research results can provide a reference for the design of other marine buoys and their mooring systems, and the validated numerical simulation method can be applied to the study of the survival performance of the buoy in long-term and extreme sea condition.

Keywords: Marine data buoy, Mooring system, Hydrodynamic, Physical model test.

1. Introduction

Marine data buoy is the basic means of long-term, continuous and real-time mon-itoring of the marine environment, and it is an important technical guarantee to en-sure national marine security, improve the level of marine scientific research, and en-hance the ability of disaster early warning. Therefore, it has higher requirements for the service life of mooring lines and adapting to the marine environment. Due to the influence of wind, wave, and current, the marine data buoy will inevitably be swaying, which will affect the service life and work efficiency of the buoy and its mooring sys-tem. However, the severe natural environment will cause large-scale displacement and even overturning of the buoy. In recent years, with the development of new technology, more and more kinds of data buoys can be used for carriers and data acquisition [1-2]. Therefore, to study the hydrodynamic characteristics of the buoy, verify whether the buoy can work and survive in the worse sea conditions, and improve the measurement accuracy of the observation elements, has become the front issue of the design and de-velopment of the buoy [3-5]. Since the end of the 1940s, various countries have been engaged in the research and development of marine buoys. The National Data Buoy Center (NDBC) in the United States has been engaged in the research and development of technologies such as buoys, mooring systems， and sensor integration into commu-nication since its inception. As a leader in the field of marine research, the Woods Hole Oceanographic Institute (WHOI) has many years of experience in the development of marine buoys.

Chu Island sea area in the north of Weihai, Shandong Province, China, has a maximum water depth of 70m, needs to arrange 4.6 m height marine data buoys to observe the hydrology and meteorology of the sea area in a long-term and real-time manner. Because the Chu Island sea area needs to build a national marine test site to serve the scientific and technological innovation and achievement transformation of marine instruments and equipment in China, the requirements for the data of marine environmental background field are high. In 2013 and 2015, the National Ocean

Technology Center used multi parameter buoy and the Wave Rider to carry out wave observation for a whole year. Different mooring systems were used, and the observa-tion results were quite different. Considering that the water depth of the sea area is about 70m, which is between shallow sea area and medium depth sea area, the design of buoy mooring system should be based on the characteristics of local actual sea con-ditions. Therefore, it is necessary to study and analyze the influence of different types of mooring systems on the hydrodynamic performance of buoy under the action of wind and waves coupling, so as to determine the most appropriate type, which can meet the requirements of survival at sea.

Many scholars have studied the coupling dynamics between the buoy model and the chain in the early stage, and developed its coupling model, and simulated and an-alyzed its motion in the time domain analysis[6-8]. Duggal and Heyl [9-10] used the coupled nonlinear time-domain analysis method to predict the motion response of the deep-water buoy in the surge, heave and pitch di-rections, and the accuracy of this method was verified by experiments. Orszaghova et al [11] had carried on the theoretical analysis and the experimental verification to the submerged moored buoy, and analyzed its chain stress and the buoy motion under the action of regular wave and the irregular wave. Yang et al [12] studied the dynamic and mechanical characteristics of power cables in wave energy conversion (WEC) system. The results show that the large curvature response usually occurs near the high wave height and resonance wave period. More often, the buoy is used as the carrier, carrying wind turbine, tidal current turbine, wave converter and so on. This kind of tur-bine-buoy coupling objects are increasingly used in actual marine engineering [13-16], and the research methods adopted for these coupling objects are variable. Most of its research methods, first of all, carry out theoretical analysis on the carrying object, buoy and its mooring system, then verify the nu-merical calculation results by physical model test.

In this paper, the physical model test method is used to analyze the influence of different mooring systems on the hydrodynamic of buoy in the Weihai sea area, and the most appropriate scheme is selected according to the analysis results.

2. Condition of Weihai Sea Area

The sea area where the marine data buoy deploys is located in the northern sea area of Chu Island, Weihai City, Shandong Province, China, and there have four dis-tinctive seasons. Compared with the inland at the same latitude, it has the characteris-tics of abundant rain, moderate temperature and mild climate, and it is the temperate monsoon climate. The maximum water depth is about 70m. According to the statistics measured by the Weihai Meteorological Observation Station in 2008, the annual aver-age wind speed is 4.7m/s, the frequency of annual wind speeds greater than 5.4 m/s is 28.8%, and the frequency of wind speeds greater than 8.0m/s is 8.3%. In 2013 and 2015, the National Ocean Technology Center observed the waves in the sea area through the wave sensors mounted on the multi-parameter integrated buoy. According to the ob-servation data in 2013, the annual average effective wave height is 0.56m, corre-sponding to the period of 4.18s. The monthly statistics are as shown in Tab.1.

The layout plan of the mooring system refers to the NDBC regulations. The buoy mooring system can be divided into three standard types: shallow sea area, medium depth sea area, and deep-sea area. In shallow sea area with a water depth of less than 6m, the full mooring system is adopted, and the ratio of depth-to-length of the mooring system is determined by the strength of tidal current, the value is 1: (3~5) generally. For medium depth sea area with a water depth between 60~600m, the mooring method of semi-tension chain and nylon rope mixed in series is generally adopted, and the ratio of depth-to-length is 1: 0.9. In deep sea area with a water depth of more than 600 m, the inverted S type mooring system is adopted, which is composed of chain, floating ball, polypropylene cable, etc., and the ratio of depth-to-length is 1: (>1.25).

Considering that the marine data buoy deployment water depth is 60-70m, which is between the shallow sea and medium depth sea, it is necessary to study and analyze the hydrodynamic performance of the buoy and its mooring system in three types to determine the best solution.

Tab.1 Measured wave data of Chu Island in 2013.

Month	Significant wave height(m)	Significant wave period(s)	Average wave height(m)	Average wave period(s)
Jan	1.33	5.10	0.88	4.63
Feb	0.82	4.37	0.54	4.12
Mar	0.92	4.50	0.61	4.21
Apr	0.73	4.13	0.49	3.93
May	0.40	3.79	0.27	3.67
Jun	0.22	3.53	0.15	3.50
Jul	0.33	4.39	0.22	4.04
Aug	0.30	4.15	0.20	3.95
Sept	0.57	4.08	0.38	3.88
Oct	0.65	4.08	0.43	3.89
Nov	0.78	4.27	0.45	3.94
Dec	0.81	4.46	0.52	4.11

3. Physical Modeling Test

3.1 Model facilities and instruments

The model test of the buoy was carried out at the Environmental Laboratory in National Ocean Technology Center (NOTC) of the Ministry of Natural Resources of China. The laboratory environment is shown in the Fig. 1(a) and the main test facilities and equipment include:

(1) Multifunctional basin: 130m long, 18m wide, 6m height and 4.5m water deep in the test;

(2) Wave maker: 10unit servo motor driven push plate wave maker, with a maximum wave height of 0.6m and period range of 0.5-5s, controlled by upper computer software, can simulate regular wave and irregular wave of various spectrum types;

(3) Wind maker: Composed of 16unit axial flow fan, with a maximum wind speed of 10m/s;

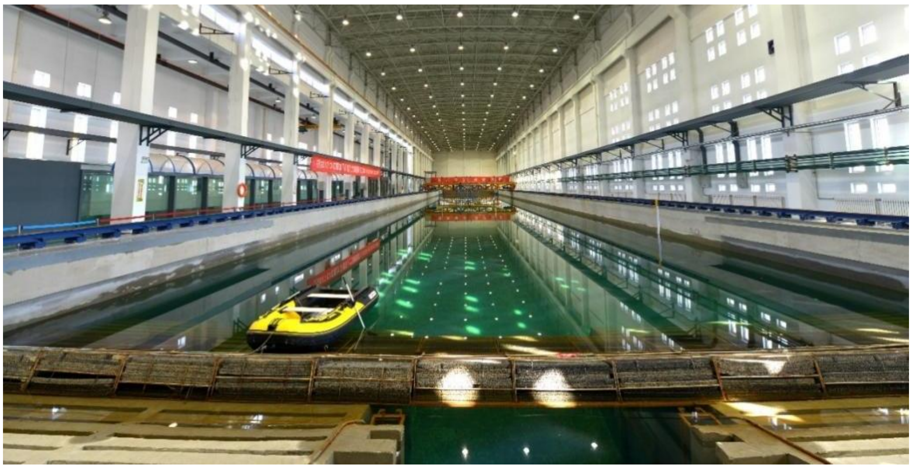
(4) Bilinear BG-II/ 1000mm wave sensor: Range from 0-1m, accuracy is 0.2%;

(5) Testo thermal anemometer 405i: Range from 0-30m/ s, accuracy is ± 0.1m/s + 5%mv;

(6) AML_DDEN underwater tension sensor: Range from 0-250N, accuracy is 0.1%;

(7) Six degree of freedom non-contact attitude measurement system: Composed of three optical lenses, measuring range of 6m × 6m, rotation angle error is ±1.5°, horizontal displacement error is 1.5mm, heave error is 2mm.

The test layout is carried out by the marine industry standard general rules for General Principles of Indoor Dynamic Environment Model Test Methods for Marine Observing Instruments (HY/T 0299-2020). The buoy model is placed 30m away from the wave maker and 20m away from the wind maker. The wave height sensor and anemometer are placed 5m in front of the model. The underwater tension sensor is installed at the connection between the model and the mooring system. The six degree of freedom non-contact attitude measurement system is arranged at the top of the back-wave side of the model, and the distance is about 5m. All the instruments are within the valid period of measurement and calibrated before the test. The specific test layout is as shown in Fig. 1(b):



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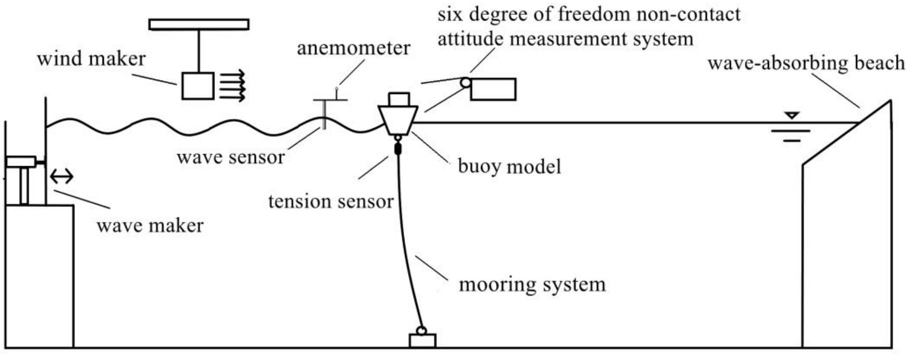

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Fig.1 (a) Marine environmental laboratory of NOTC and (b)Layout of physical model test in wave flume.

3.2 Model and mooring systems

According to the laboratory test capacity and buoy prototype size, the scale of the model is determined to be 1:5. Before the test, the ballast is adjusted first, and the mass, center of gravity and moment of inertia are adjusted to achieve the target value by adjusting the ballast distribution. The upper structure and its sensors are specially considered in the model to ensure a reasonable simulation of the wind area of the prototype. The main parameters of the model and physical test Tab.2 shown:

Tab.2 Main parameters of the marine buoy model.

Object	Unit	Value
Total height	m	0.92
Model depth	m	0.25
Radius	m	0.30
Mass	kg	15.35
Center of gravity	m	0.07
Waterline	m	0.08
Moment of inertia	kg • m^2	0.40

In the physical model test, three mooring systems are adopted, as described in Fig. 1(b) shows those parts, and the weight and size of the chain conform to the similarity theorem with the prototype in the test. The horizontal stiffness of the mooring system is verified before the physical model test.

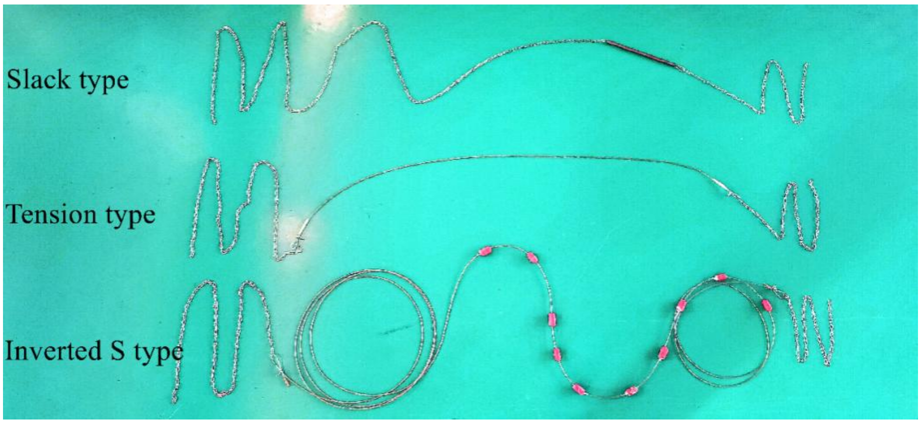


Fig.2 Mooring system in test

Tab.3 Main parameters of the mooring system in physical test

Mooringsystem	Part	Long(m)	Diameter(mm)	Weightinair(kg/m)	Weightin water(kg/m)
Slack type	Chain	4.0	2	0.070	0.063
	Spring	0.3	14	0.283	0.256
	Chain	1.0	2	0.070	0.063
Tension type	Chain	1.0	2	0.070	0.063
	Cable	2.0	3	0.038	0.033
	Chain	1.5	2	0.070	0.063
Inverted S type	Chain	1.0	2	0.070	0.063
	Cable	2.0	3	0.038	0.033
	Buoyancy cable	2.0	3	0.038	0
	Cable	6.0	3	0.038	0.033
	Chain	1.0	2	0.070	0.063

3.3 Test condition

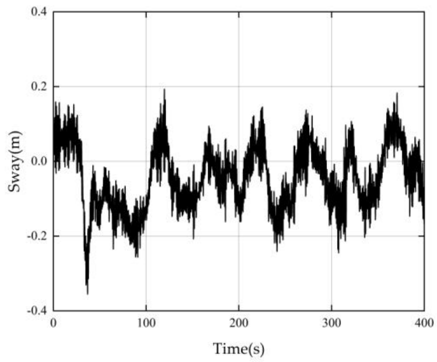
According to the prototype working sea conditions and scale ratio calculation, the test conditions are as shown in Tab.4, three mooring system schemes, 5 testing conditions in each group, and 15 testing conditions in total. In the test, the wind field simulation is carried out first. After the wind field is stable, the irregular wave is carried out. The JONSWAP spectrum is used for irregular wave. The number of waves collected in each testing condition is greater than 100.

Tab.4 Test condition for physical model.

Test	Mooring systems	Significant wave height(m)	Significant wave period(s)	Average wind speed(m/s)
Spring	Slack type/ Tension type/ Inverted S type	0.14	1.85	2.15
Summer		0.06	1.80	0.98
Autumn		0.15	1.85	2.24
Winter		0.20	2.08	2.59
Extreme month		0.27	2.28	4.20

3.4 Test results and analysis

First of all, for the slack type test, the maximum tension of chain is 13.3N, and the model sway slightly in a small range about 0.2m from the origin. Due to the effect of wind, the buoy model first has a surging motion of 1.5m. After the wave acts on the buoy model, it moves in a larger range within 1m. The heaving amplitude of the model is close to that of the wave amplitude, and the wave following property is good. The model has a large rotation motion, the maximum rolling angle is 20° and the pitching angle changes inconspicuously, which is maintained within the range of 4°. The effect of wind has a great influence on the initial yawing angle. After the wind field is stable, the yawing angle is maintained within 40° under the action of wind and waves coupling. The detailed experimental measurement data is shown in Fig. 3:



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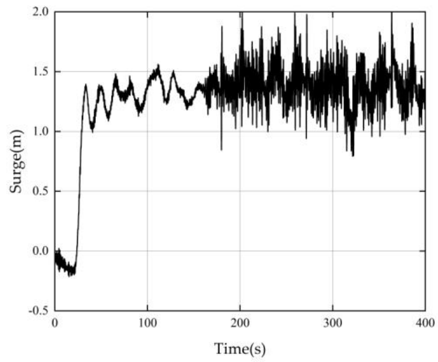

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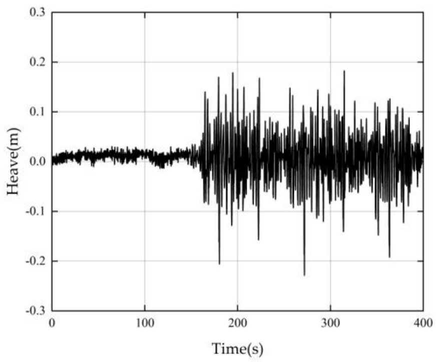

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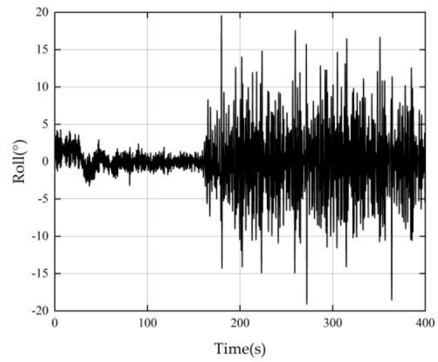

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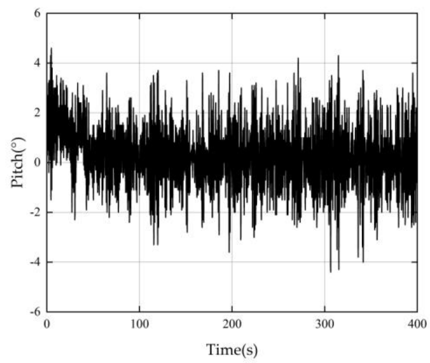

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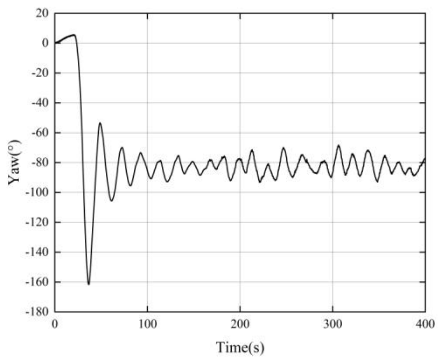

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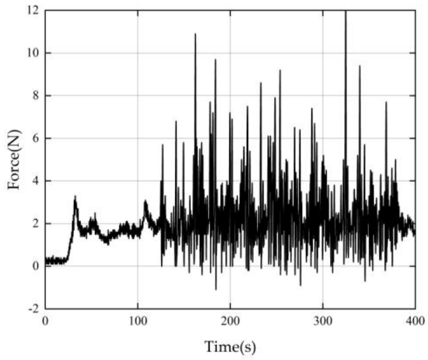

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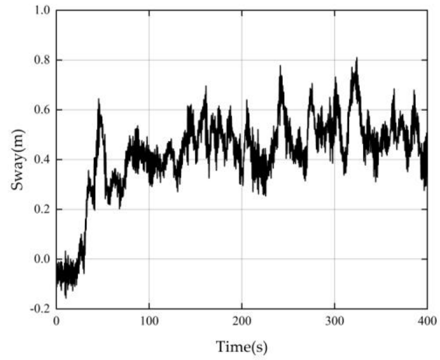
Fig. 3 Results forslack type in physical model test

For tension type tests in Fig.4, the maximum instantaneous tension of the chain exceeds 80N. The motion of swaying and surging of buoy model in a small range. The heaving of the model is obviously affected by the tension of the chain and the displacement towards the underwater direction is large. The rotation motion of the model is relatively small, with an average pitching angle value is 0.69° and a mean rolling angle value is 1.15°. The effect of wind has a great influence on the initial yawing angle. After the wind field is stable, the yawing angle is maintained in the range of 20° under the action of wind and waves coupling.



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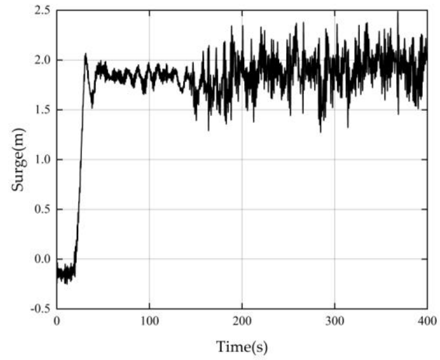

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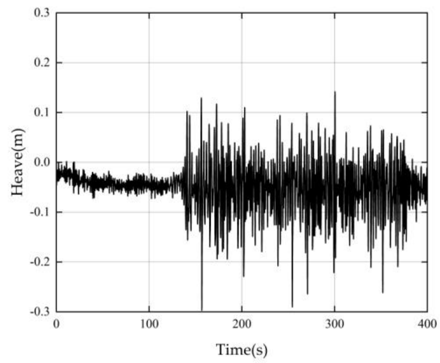

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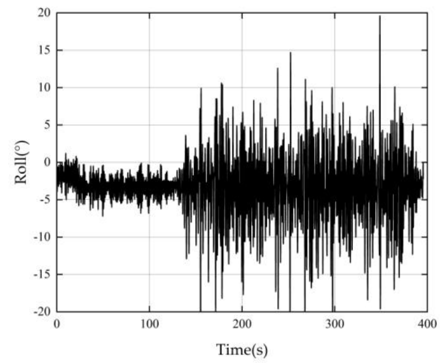

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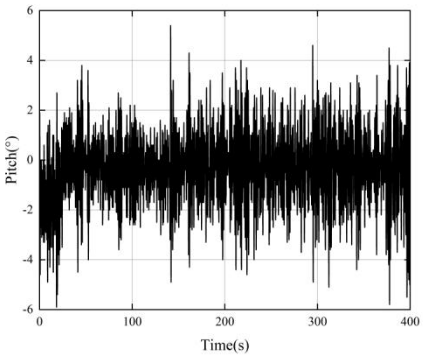

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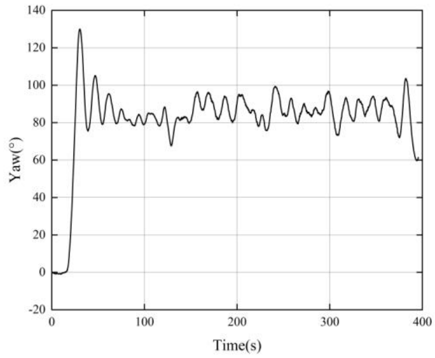

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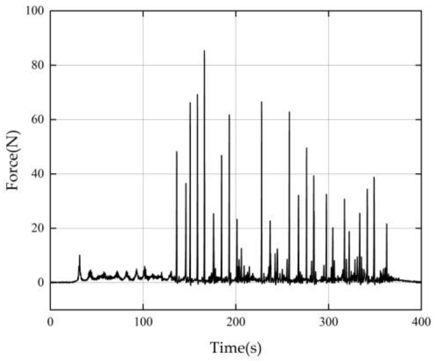

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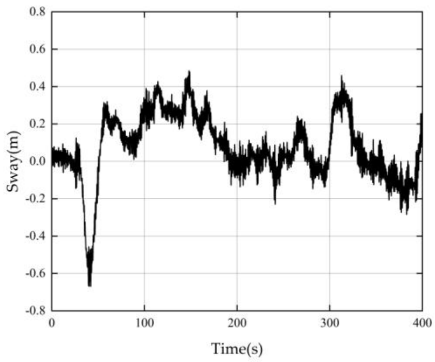
Fig.4 Results fortension type in physical model test

Figure 5 shows the detailed experimental measurement data of inverted S type, and the maximum tensile force of the chain is only 10N. A large amplitude of swaying motion is carried out near the origin of the buoy model. Due to the effect of wind, the model first had a surging motion of about 3m. When the waves acted on the buoy model, it moves over a wide range within 1m. The heaving amplitude of the model is close to that of the wave amplitude, and the model has a good wave following property. The rotation motion of the model is significant, and the maximum rolling and pitching angles are more than 15°; the yawing angle has no obvious stable position, and there is a range of yawing angle about 60° under the action of wind and waves coupling.



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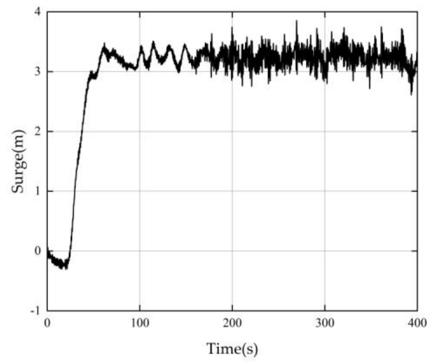

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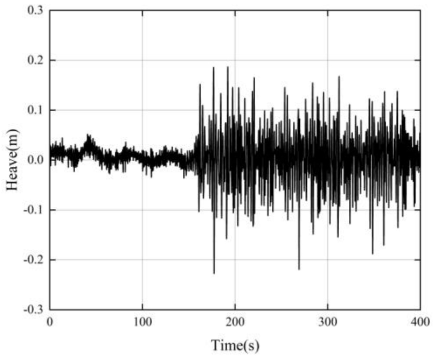

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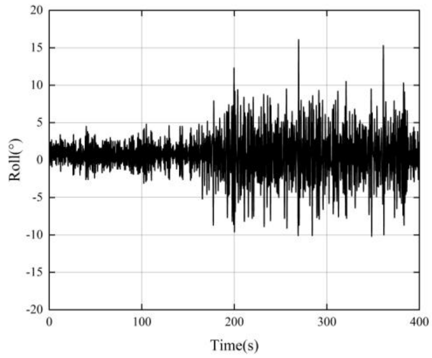

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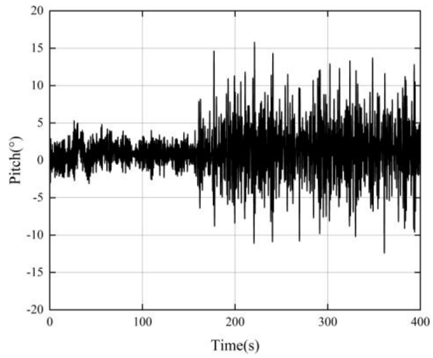

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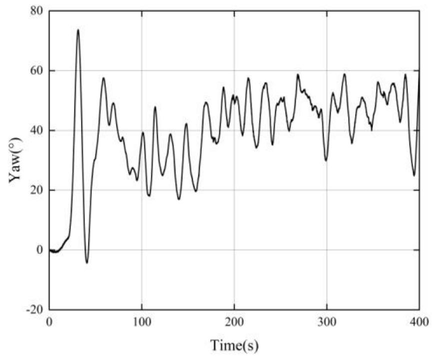

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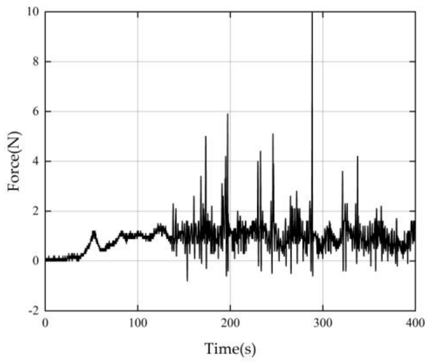

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Fig. 5 Results forinverted S type in physical model test

The results of all physical model test conditions are statistically analyzed and shown in Tab.5. It can be seen that the tension of the inverted S type chain is the minimum, which is 45% of the average tension of the slack type and 37% of the tension type. The rotation motion of the tension type is the smallest, and the rolling angle is 83% of the slack type and 40% of the inverted S type. From this we can conclude:

(1) The tension type mooring system has the best fixed-point observation effect and smaller cruise radius. Simultaneously, due to its smaller rotation angle under the action of wind and waves coupling, the data obtained by the wave sensor and the anemometer are more accurate. However, it has higher requirements for the mooring system, and the chain suffers from large instantaneous

tension, which will cause fatigue in long-term use. Therefore, regular inspection and maintenance should be carried out.

(2) The arrangement of inverted S type mooring system is more convenient. Due to the small tension of chain, it has stronger resistance to extreme environment and longer maintenance period. Nevertheless, the buoy sways violently under the action of wind and waves, so the accuracy of the observation data will be greatly affected. The data should be corrected by relevant algorithms before application.

(3) The hydrodynamic characteristics of the slack type and the reliability of the mooring system are between the above two. When selecting the chain, the analysis and judgment should be made according to the specific situation.

Tab.5 Data statistics ofthe physical model test

Parameter	Slack type					Tension type					Inverted S type				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Average wind speed(m/s)	2.15	0.98	2.24	2.59	4.20	2.15	0.98	2.24	2.59	4.20	2.15	0.98	2.24	2.59	4.20
Significant wave height(m)	0.14	0.06	0.15	0.21	0.27	0.148	0.07	0.16	0.21	0.27	0.14	0.06	0.16	0.21	0.27
Significant wave period(s)	1.85	1.79	1.85	2.08	2.28	1.85	1.81	1.86	2.08	2.28	1.86	1.81	1.86	2.08	2.28
Average force(N)	0.70	0.42	0.80	0.97	2.02	0.24	0.07	0.29	0.33	0.92	0.41	0.04	0.42	0.63	2.48
Maximum force(N)	1.90	0.70	2.00	3.20	13.30	0.70	0.20	1.30	1.30	10.0	1.20	0.40	1.50	5.80	85.3
Average sway(m)	0.02	0.01	0.03	0.04	0.08	0.09	0.06	0.10	0.12	0.14	0.08	0.02	0.09	0.11	0.13
Average surge(m)	0.92	0.24	0.94	1.07	1.26	2.58	1.38	2.56	2.78	2.95	0.54	0.39	0.54	0.62	0.80
Average heave(m)	0.14	0.06	0.15	0.20	0.27	0.15	0.07	0.16	0.20	0.27	0.16	0.07	0.16	0.21	0.28
Average roll (°)	2.14	1.08	2.19	2.38	4.70	3.16	2.08	3.37	3.38	6.82	1.88	1.56	1.88	2.02	4.15
Average pitch (°)	0.97	0.56	0.98	0.98	1.05	2.58	1.58	3.54	3.89	5.21	0.51	0.22	0.51	0.56	0.69
Range of yaw (°)	40	28	41	42	45	46	29	47	48	52	22	14	23	23	23

4. Conclusion

In this paper, the physical model test is used to study and analyze the hydrodynamic performance of marine buoy under the action of wind and waves coupling by using the measured data in Weihai sea area. The advantages and deficiencies of different mooring systems are qualitatively analyzed, and the relatively accurate quantitative analysis results are obtained, which provides a method reference for similar research in the future. The conclusion is as follows:

(1) The physical model test is the main research mean of marine data buoy hydrodynamic performance, which can well predict the motion response of buoy in complex sea conditions.

(2) Among the three types of mooring systems, i.e. slack type, inverted S type and tension type, the inverted S type mooring system has higher reliability, while the tension type mooring system can obtain more accurate observation data, and the performance of the slack mooring system is between the two.

(3) As a public testing platform for national marine instruments and equipment, Weihai National Marine Test Ground has high requirements for marine data buoy, which requires long-term work at

sea and a stable mooring system. It is recommended to adopt tension type mooring system to meet the design and work requirements.

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