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EXPERIMENTAL STUDY OF TWO LARGE-SCALE MODELS' SEAKEEPING PERFORMANCE IN COASTAL WAVES

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Summary

Actual sea waves and vessel motion are an unsteady nonlinear random process. The currently adopted test to simulate wave impact of vessel models in tank can't fully reveal the impact of real sea waves on vessel swing motion. In this paper the buoy wave height meter is adopted to carry out measurements and analyses of the coastal wave environment. The correlation between the coastal wave spectra and the ocean wave spectra is analyzed. The test system is established for remote control and telemetry self-propelled vessel models suitable for the experiment conducted in the coastal areas. The seakeeping performance test is conducted for the same tonnage of round bilge vessel model and the deep-V hybrid monohull of large-scale vessel model under the coastal wave conditions. The experimental results are compared with the test results of small-scale vessel model in the towing tank. The experimental results show that the seakeeping performance of the deep-V hybrid monohull is improved by a wide margin in contrast to that of the round bilge model, and there is a marked difference between the motion characteristics of large-scale vessel models in the coastal wave environment and that of small-scale vessel models in tank.

Key words: *Large-scale model test; seakeeping performance; remote control and telemetry; coastal waves*

1. Introduction

It has already been a tendency to conduct the physical simulation test for large-scale vessel models in natural environment, and the research work in this field is rather sophisticated. This test has been introduced as a new item of testing technology in the reports of ITTC (2008, 2012) in the last few years. Many researchers carried out the simulation tests of the large-scale vessel model or pilot boat for some newly-developed vessels. Loukakis （2005） gave an introduction of large scale model test at sea during the Proceeding of ITTC 2005. Sun (2010) built up the large-scale model system and studied the seakeeping performance of the model at sea. Jacobi and Thomas (2014) studied the slamming behaviour of large high-speed catamarans through full-scale measurements. Suebyiw (2013) studied the application of radio-controlled model testing in coastal waves for the design of a high-speed craft. Coraddu（2013）studied twin screw ships' asymmetric propeller behaviour by means of free running model tests in a lake.

The research content of this paper focuses mainly on the seakeeping performance test. Because it is conducted under the natural sea conditions, the sea wave conditions encountered are three-dimensional non-linear actual sea waves, and the model size is no longer subject to the impact of the testing ground. Thereby, the influence of the model size effect can be reduced greatly, and the motion response of the model can better approach the non-linear motion response of a real vessel under the real sea wave conditions.

According to the model size and the requirement of the model test in the actual sea wave conditions, this paper chooses to conduct the test study under the coastal stormy wave conditions. First of all, measurements and analyses of the sea wave environment are conducted in different coastal areas in China to understand the basic characteristics and rules of the coastal wave environment, which lay a foundation for proceeding with the test study on the motion property of large-scale vessel models. This paper has established a testing system of remote control and telemetry self-propelled model.

Before the study of large-scale model test the seakeeping performance experiment of two small-scale models in towing tank had been carried out. The sections of the two models are given in Figure 1, they are a round bilge hull and a deep-V hybrid monohull which are close in the principal dimensions and displacement. The hybrid monohull has a built-up appendage fixed under the bow which can reduce the longitudinal motion amplitude of the hull. The results of model test in tank indicated that the seakeeping performance of hybrid monohull was better than that of round bilge monohull. For the validation of seakeeping performance especially nonlinear hydrodynamic performance of hybrid monohull in real ocean waves, we started the experimental study of the two large-scale models’ seakeeping performance in coastal waves. Besides, the testing results of large-scale models were compared with that of the small-scale models in towing tank to analyse the difference between the two testing methods.

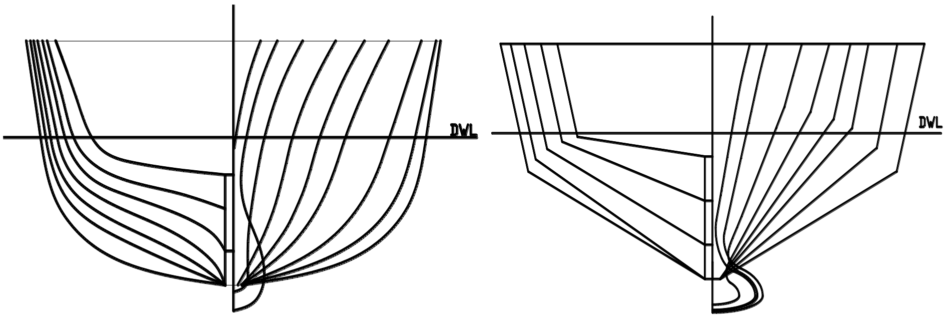


Fig.1 Sections of round bilge hull(left) and hybrid monohull(right)

2. Experimental procedures

2.1 Measurement and analysis of the coastal wave conditions

To decide whether the large-scale model test under the actual coastal wave conditions is viable or not, one of the key techniques is whether the testing conditions match those of the ocean wave conditions. For this purpose, the research team goes to Huludao Harbour sea area, Xiaoheishi sea area and Xiaoping Island sea area in Dalian respectively to investigate and measure the sea wave conditions in these three coastal areas. The wave data are measured by a buoy wave height meter (see Figure 2). The shape of the buoy is spherical, and the bottom is fitted with the iron chain to lower the center of gravity of the wave height meter. The lower part of the ball is immersed in water, and there is a spoiling flap in the middle part of the ball to reduce the swing motion of the buoy. There is an acceleration sensor fitted near the center of gravity within the buoy ball to measure the acceleration time duration of wave surface heaving.

The time interval for collecting data is 0.05s, and each collecting time lasts about 10 minutes. See Figure 3 for the actually recorded acceleration time duration of wave surface heaving. By solving the equation, the correlation function of the acceleration time duration is derived:

$$R(\tau)=\lim_{T\to\infty}\frac{1}{T}\int_0^T\ddot{\zeta}(t)\bullet\ddot{\zeta}(t+\tau)dt \tag{1}$$

In the formula: τ stands for the time interval, and T stands for the limited time of enough length. Then carry out Fourier transform of the above formula, which is further processed by "Hamming smoothing", from which spectral density function of wave surface heaving acceleration is derived:

$$S_{\ddot{\zeta}}(\omega)=\frac{2}{\pi}\int_0^\infty R(\tau)\cos\omega\tau d\tau \tag{2}$$

The wave surface heaving spectra are derived by two quadratures of the acceleration spectra:

$$S_\zeta(\omega)=S_{\ddot{\zeta}}(\omega)/\omega^4 \tag{3}$$

By computing the area beneath the heaving spectra curve of the wave surface m_0 (namely, the variance of the wave surface heaving), we can further obtain parameters such as the significant wave height of the wave ($H_{1/3}$) and mean period from spectarl analysis (Ts).

Fig2 The buoy wave height meter

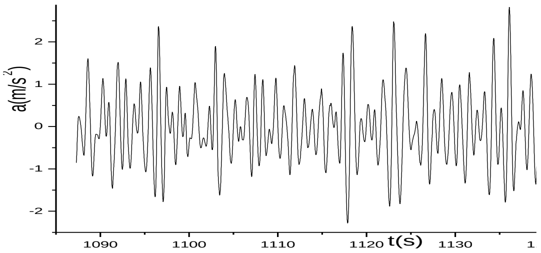


Fig.3 The acceleration time duration of wave surface heaving

The measurements and analyses results of sea waves at different tidal periods and with different wind directions at Huludao sea area and Xiaoping Island sea area in Bohai Sea are performed. The measuring points are all over 1 nautical mile off the coasts and the water depth at the measuring waters is about 10 meters. The by measurements and analyses, it is found that there is relatively great influence of the tide and wind direction on the sea wave. During the flow phase period and the high-tide period, when the wind blows from the sea to the coast, the wave spectra of the measured waters are basically similar to the ocean wave spectra.

Figure 4 shows the wave spectra of Huludao sea area at the high water period. On the very day when the test is carried out at Huludao Harbour (40° 43′ N, 121° 00′ E), the parameters of the tide, wind and water depth, and etc., are as follows:

The time of tide: 01:05 with a height of 76cm; 9:39, 286cm; 16:02, 80cm. The tidal datum plane is 158cm beneath the average sea level, in the time zone: GMT+8;

There is a southerly wind above the sea, with a wind speed of about 5m/s; and a water depth of about 8 meters in the test sea area.

The significant wave heights ($H_{1/3}$) of the three groups of wave data recorded are respectively 0.14m , 0.153m and 0.161m .

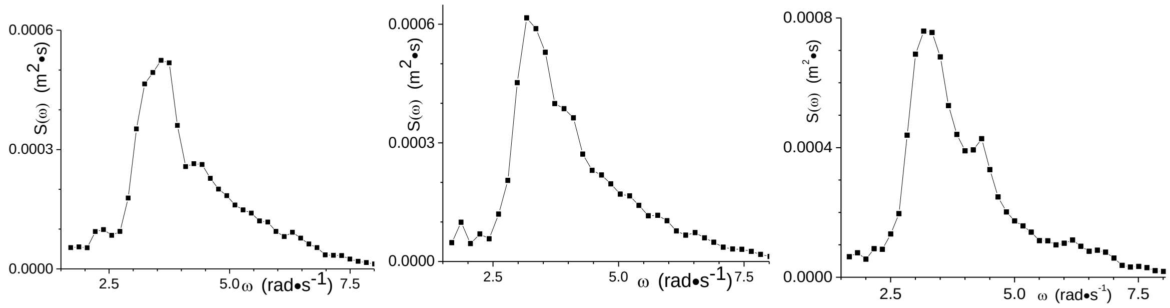


Fig.4 Wave spectra of Huludao sea area

Figure 5 indicates the wave spectra of the coastal flow phase at Xiaoping Island sea area in Dalian City. On the very day when the test is carried out at Xiaoping Island(38° 49′ N, 121° 12′ E), the parameters of the tide, wind and water depth, and etc. , are as follows:

The time of tide: 6:33 with a height of 51cm; 11:57, 323cm; 18:33, 46cm. The tidal datum plane is 163cm beneath the average sea level, in the time zone: GMT+8; with a southerly wind above the sea, and a wind speed of about 4m/s; and with a water depth of about 10 meters in the tested sea area waters.

The statistical significant wave heights ($H_{1/3}$) are respectively 0.279m, 0.264m , and 0.251m .

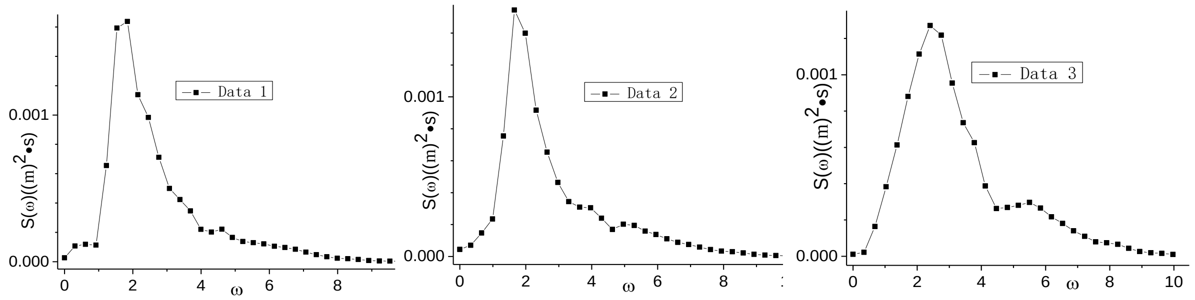


Fig.5 Wave spectra of Xiaoping Island sea area

Comparison of the measured wave spectra with the ocean wave spectra is given in Figure 6.

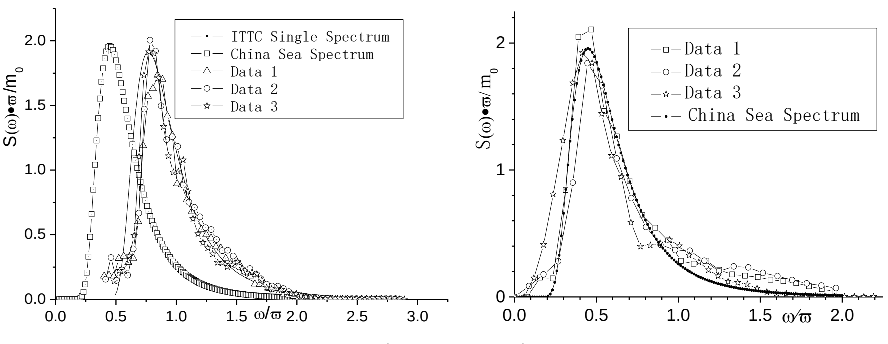
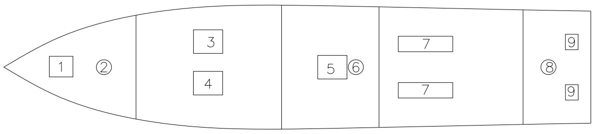


Fig. 6 Nondimensional wave spectra of Huludao(left) and Xiaoping Island(right) sea area

There are usually phenomena of double peaks and multi-peaks for the sea wave spectra during the period of falling tide to that of low tide. Through nondimensional comparison of the off-shore sea wave spectra with the ocean wave spectra, it is seen that the main features of the sea wave spectra during the period of flow phase and that of high-tide are similar to those of the ocean wave spectra in that the central frequencies are basically the same, and the frequency scope and energy distribution are rather wide, closer to those of the actual ocean wave spectra. However, the wave spectra of Huludao sea area is more similar to ITTC Single Spectrum, and the wave spectra of Xiaoping Island is more similar to China Sea Spectrum.

2.2 Establishment of Testing System for Large-scale Vessel Model

For the seakeeping performance test of the large-scale model under the actual wave conditions, the model is the remote control self-propelled one, and the wave is measured by the buoy wave height meter. The equipment and respective characteristcs are shown in table 1, The roll and pitch motion were measured by angular rate top, the course angle of ship model was measured by course top, the vertical acceleration of model bow 1 section, middle mid-ship position and tail 19 section were measured by acceleration sensor; the arrangement of each device in the model is shown in Figure 7.



1-course top 2-bow acceleration sensor 3-remote control and telemetering data transmission radio station 4-data inner test module 5-angular rate top 6-middle acceleration sensor 7-electrical machine and controller 8-tail acceleration sensor 9-steering engine

Fig.7 Arrangement of equipment on self-propelled large scale model

Tab.1 Measurement equipments on the large scale model

Equipment	Type	Range	Precision	Motions	Sampling Frequency/Hz
Angular rate top	MEMSIC VG440	Roll: ±45° Pitch: ±30°	±0.015°	Roll, Pitch	20
Course top	KVH C100	±180°	±0.05°	Course angle	20
Acceleration sensor	Kister 8315	±5g	±0.1%	Vertical acceleration	20

The main parameters of round bilge vessel of four thousand tons and the deep-V hybrid monohull models, with a scale ratio as 1: 19, are shown in table 2. The models have a remote-controlled distance of more than 1km , using 10 storage batteries to provide power. The capability of one battery is 40Ah, and the voltage is 12V. Since the power of the electromotor is 1KW, the batteries could make the model running for more than 3 hours continuously. Model test data was collected and recorded by internal inner test system and external telemetering system at the same time, and a video system installed in the model is used to observe model bow motion and green water condition. Ship model was made of glass steel, and Figure 8 shows pictures of round bilge vessel model and deep-V hybrid monohull model respectively. The model is propelled by screw propellers, with twin rudder to control course, as shown in Figure 9.

Tab.2 Parameters of large scale models

Parameters	L_{WL}	B_{WL}	T	CB	CG	D	I_{xx}	I_{yy}
Units	(m)	(m)	(m)	-	(m)	(kg)	(kgm^2)	(kgm^2)
Round bilge monohull	6.6	0.75	0.22	0.45	0.33	490	1325.53	33.76
Hybrid monohull	6.6	0.8	0.23	0.41	0.33	498	1347.17	39.04

a. Round bilge monohull b. Hybrid monohull

Fig.8 Large scale models

Fig.9 Picture of propellers and rudders

The debugging test of the large-scale model testing system is carried out in calm water in the Songhua River, as shown in Figure 10. Dynamical and static force of the model are adjusted, power system is debugged, and remote control and telemetering system, video system, data inner test system etc. are tested for the model. By benchmarking method, the relationship between model's navigational speed and main engine's rotate speed is measured. The test range pole is set in the shore-side when speed is measured, with the separation distance as 200m. The debugging model with direct route condition entered into velocity measurement area, so that the relationship between navigational speed and rotate speed is measured, the ship model's navigational speeds under seven main engines' rotate speeds are all measured, the measurement results are matched and the relationship curve between the main engine's rotate speed and ship model's navigational speed is obtained, as shown in Figure 11.

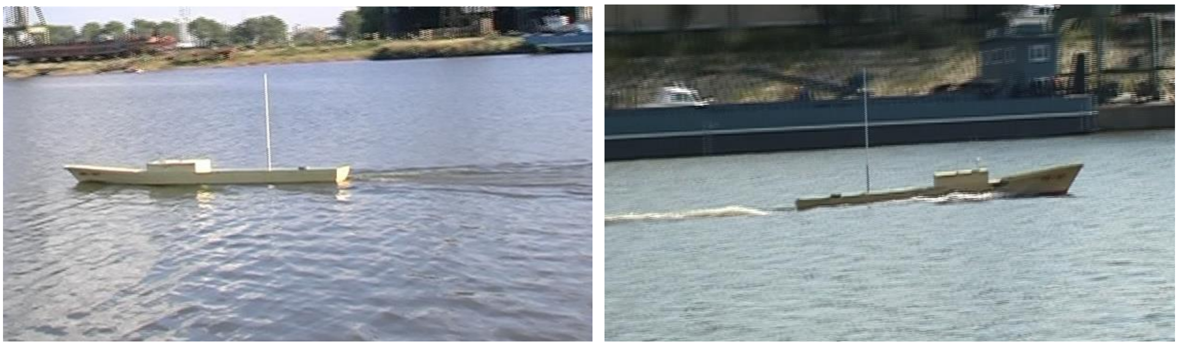


Fig.10 Model test in Songhuajiang River

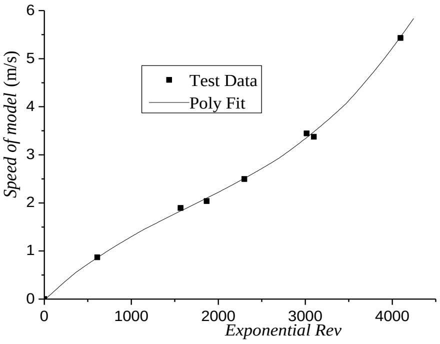


Fig.11 Relationship between speed and revs

2.3 Seakeeping performance Test of Large-scale Ship Model

The two models are tested respectively, for totally 4 days. During the test period, internal wind direction blew from sea surface to coastal side, and tests were conducted between rising tide period and high tide period. Significant wave height compared with actual ship was Class 6 sea condition in the test area after wave height instrument's measurement.

Because near-shore wave was not stable and had strong randomness, test area and wave height instrument should keep proper distance and within 100m of distance to ship model to ensure the motion response of model ship and wave motivation have real-time synchronization, to make wave's data and data measured by wave height instrument coincide when model sailing, and to easily test model's motion of different course angles in the wave in the process of seakeeping performance test. The two models are tested respectively for their motions in different navigational speeds, different wave directions under the equivalently actual ship class 6 sea state ($H_{1/3}$=5~6m), as shown in Figures 12 and 13 which were test video screenshots.

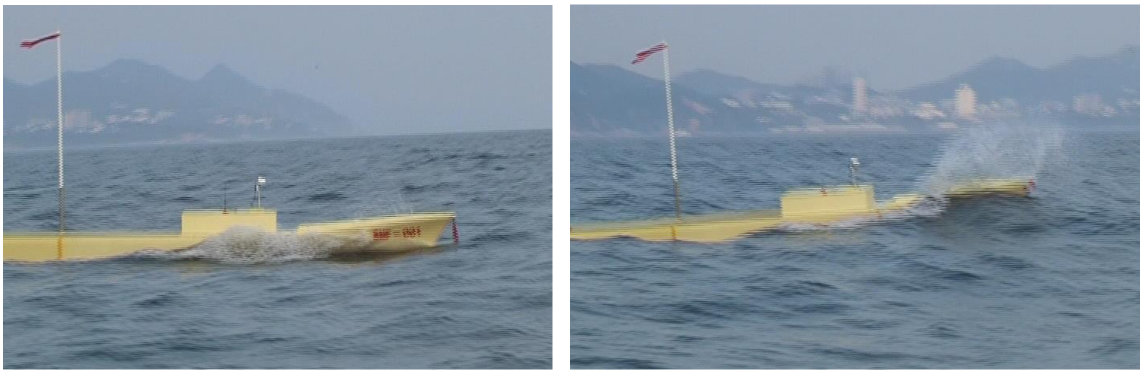

a. head waves b. oblique waves

Fig.12 Large scale model test of round bilge monohull

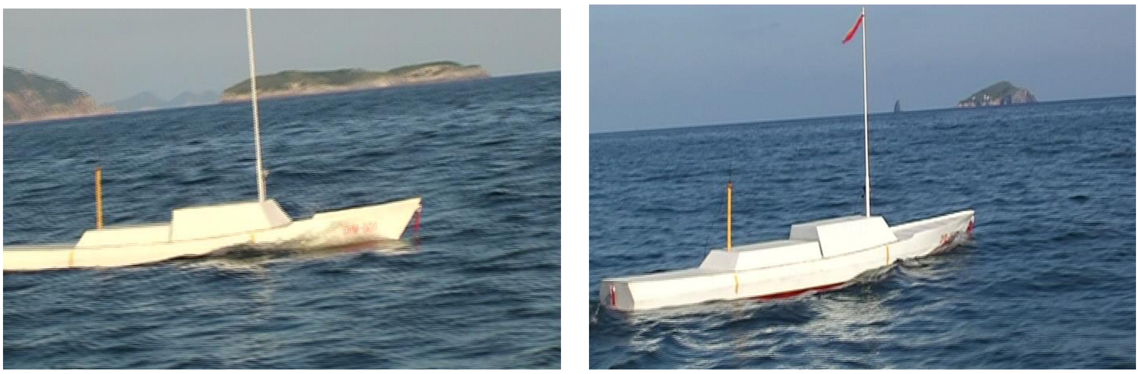

a. head waves b. oblique waves

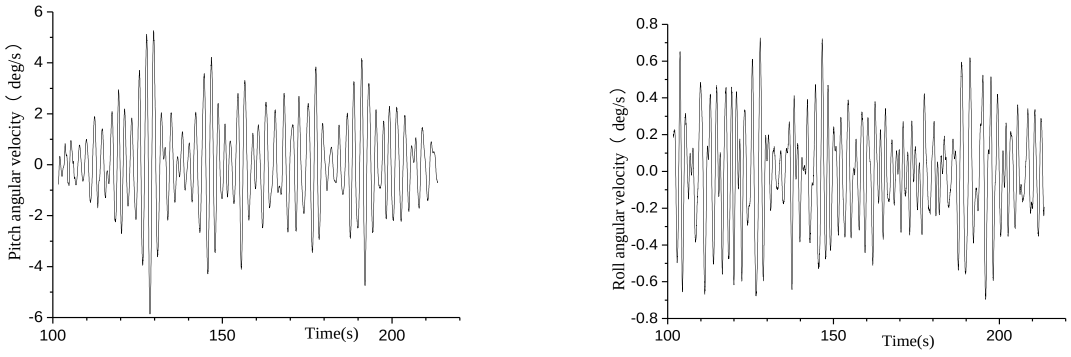
Fig.13 Large scale model test of hybrid monohull

3. Results and discussion

3.1 Test Data Processing for Large Scale Model Test

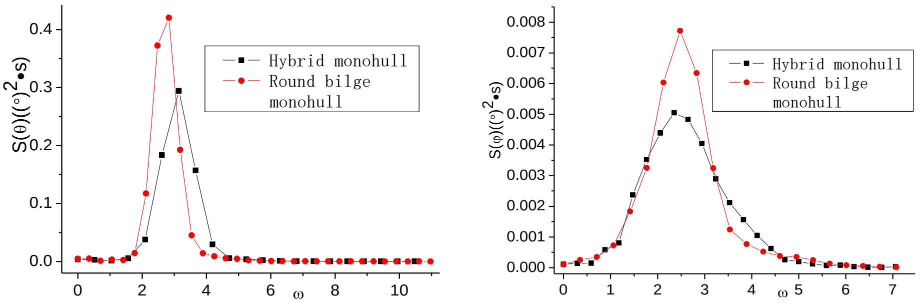
The test data were measured and recorded by model's internal inner test system and telemetering system in the measurement ship at the same time. This paper adopts correlation function method as described above, in which correlation function is calculated by model motion data, which then is processed by Fourier transform, and the swing angular velocity spectrum of model and fixed-point vertical acceleration spectrum can be obtained, in which the swing angular spectrum can be got after angular velocity via one time integral.

Figure 14 shows the time history of pitch and roll angular velocity of large scale test in actual sea wave environment of the round bilge vessel model; Figure 15 shows the spectrum of pitch, roll and bow vertical acceleration of large scale models for speed of 18 knots and 24 knots , whose motion significant value is shown in Table 3.

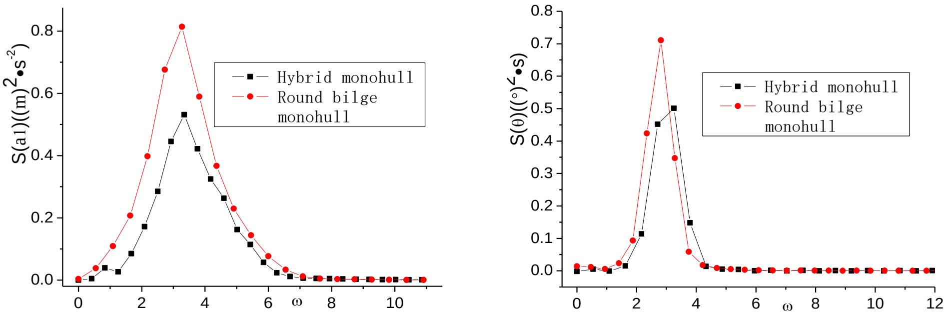


a. Time history of pitch angular velocity of head seas b. Time history of roll angular velocity of head seas

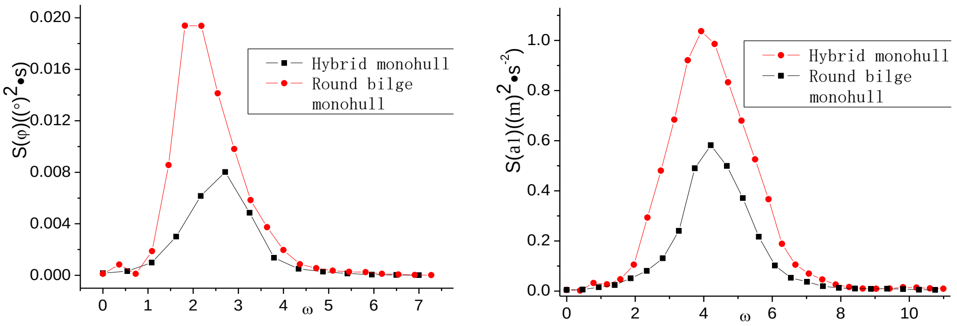
Fig.14 Test data of large-scale model test on the sea



a. Pitch spectrum on the sea at 18kn b. Roll spectrum on the sea at 18kn



c. Bow acceleration spectrum on the sea at 18kn d. Pitch spectrum on the sea at 24kn



e. Roll spectrum on the sea at 24kn f. Bow acceleration spectrum on the sea at 24kn

Fig.15 Spectrum results of large-scale model test

Tab.3 The significant motion amplitude of large scale model test on 6th class wave($H_{1/3}$=5m)

Ships	Speed（kn）	$\theta_{1/3}$（deg）	$A_{bow1/3}$（m/s^2）
Round bilge monohull	18	1.547	2.535
	24	1.6306	3.649
Hybrid monohull	18	1.154	1.825
	24	1.18	2.35

Comparing the motions of hybrid hull model and round bilge vessel model under Class 6 sea condition: for 18 knots, the peak value of pitching angle decreases by 30.02%, and the peak value of head accelerated speed deduces by 34.69%; while for 24 kn , the peak value of pitching angle decreases by 29.52%, and the peak value of head accelerated speed deduces by 44.13%. For 18 knots, the significant value of pitching decreases by 25.4%, and the significant value of head accelerated speed reduces by 28%; while for 24 kn, the significant value of pitching decreases by 27.6%, and the significant value of head accelerated speed reduces by 35.6%.

It is seen from the results of large scale model test that the seakeeping performance of deep-V hybrid hull has been improved greatly as compared with that of round bilge vessel model.

3.2 Comparison of Test Results with Tank Model

Finally the results of large-scale model are compared against result of tank small-scale model (scale ratio 1: 40). The test was conducted in the model ship towing tank of Harbin Engineering University (HEU), and the size of towing tank is 108*7*3.5m. The speed of the tow truck is 0.1~6.5m/s. Wave was made by the rocker flap wave generator, and the model motion of irregular wave height class 6 sea state (significant wave height $H_{1/3}$=5m) was measured by 4DOF seakeeping instrument, the fixed-point acceleration of model was measured by acceleration sensor, and the sensor's position was the same as that in the large-scale model. The parameters of the measurement equipment are shown in Table 4 and Figure16.

Tab.4 Measurement equipments on the small model in tank

Equipment	Range	Precision	Motions	Sampling Frequency/Hz
Wave generator	T: 0.4～4s H_{max}: 0.4m	±0.05°	Course angle	-
Ultrasonic wave height meter	±200mm	±0.1%	-	20
4DOF seakeeping instrument	Heave: 0～±200mm Pitch angle: 0～±15° Roll angle: 0～±50°	±0.1%	Heave, Pitch, Roll	20
Acceleration sensor	±5g	±0.1%	Vertical acceleration	20


a. Towing tank in HEU
b. Wave generator
c. 4 DOF seakeeping instrument

Fig.16 Pictures of measurement equipments

The parameters of small-scale models are shown in Table 5. Figure 17 shows the seakeeping performance in irregular waves of hybrid monohull. Figure 18 shows the time history of pitch amplitude in head seas in tank test. Figure 18 shows the spectrum of pitch and bow vertical acceleration of small-scale models in tank test for speed of 18 knots and 24 knots of actual ship under Class 6 sea condition.

Tab.5 Parameters of small-scale models

Parameters	L_{WL}	B_{WL}	T	CB	CG	D	I_{xx}	I_{yy}
Units	(m)	(m)	(m)	-	(m)	(kg)	(kgm^2)	(kgm^2)
Round bilge monohull	3.125	0.356	0.105	0.45	0.157	52.51	32.05	0.816
Hybrid monohull	3.125	0.381	0.113	0.41	0.157	53.37	32.57	0.944

Fig.17 Picture of seakeeping performance in irregular waves of hybrid monohull

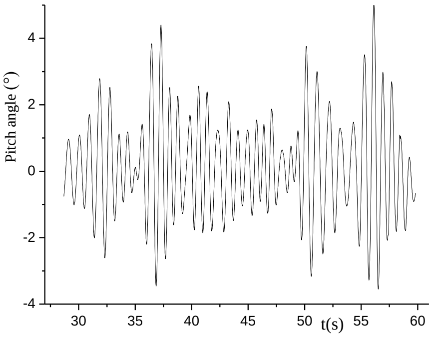
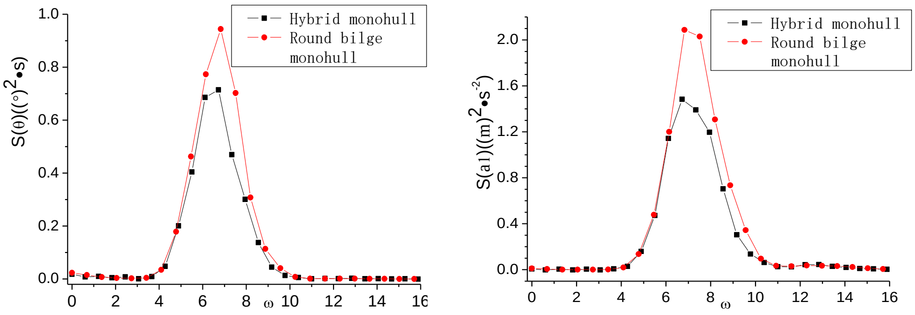
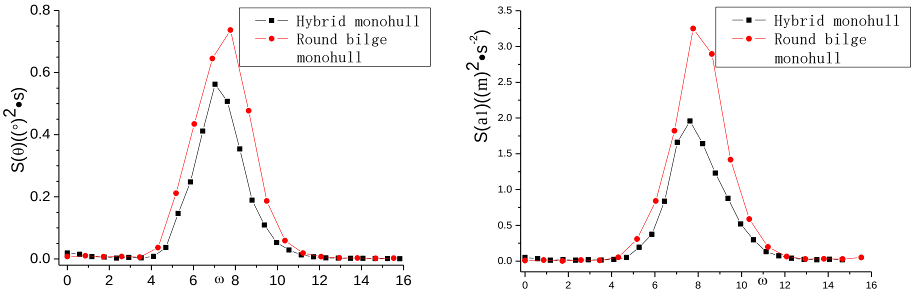


Fig.18 Time history of pitch amplitude in head seas in tank test



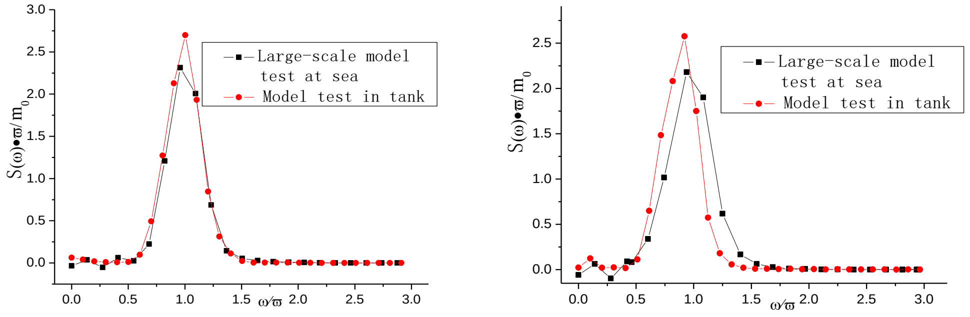
a. Pitch spectrum in tank at 18kn b. Bow acceleration spectrum in tank at 18kn



c. Pitch spectrum in tank at 24kn d. Bow acceleration spectrum in tank at 24kn

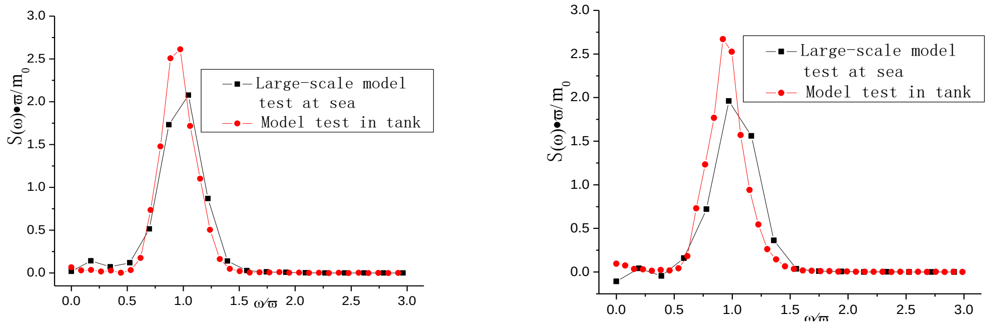
Fig.19 Spectrum results of model test in tank

In this paper, nondimensional comparison is conducted between the test result of tank model and test result of large scale model, and Figure 20 and Figure 21 show the comparisons on pitching scale between the test result of tank model and test result of large-scale model under Class 6 sea condition ($H_{1/3}$=5m).



a.18kn b.24kn

Fig.20 Nondimensional pitch spectra of round bilge monohull



a.18kn b.24kn

Fig.21 Nondimensional pitch spectra of hybrid monohull

Because the actual wave environment is three dimensional and the large-scale model is in the free sailing status when navigating, which is the same as the actual ship; therefore, six coupled degrees of freedom of motions are generated. Compared with tank model test, large scale model test adds the pitching motion, whose six coupled degrees of free motions may be close to that of the actual ship. With dispersion of energy in each free action, the response value of pitching motion and head accelerated speed would appear to be low, which reflects the difference between large scale model test and tank test. However, the wave of vessel model tank is two-dimensional long-crested wave, and the model is sailed under restrictions, which limits the head and pitching motion of vessel model. As a result, the energy is concentrated on certain free motions, and the motion characteristics thereof are inevitably different from those of large scale model test.

Besides, the difference on green water frequency and wave physical phenomenon are also relatively great. From the model test in towing tank we find that the bow deck of hybrid monohull is too narrow to make the wave can climb up to the deck easily. So there have been observed many green water events. In order to reduce green water events of hybrid monohull the bow deck of large-scale model was broadened, as shown in Figure 22, and it became much less than that of small-scale model in tank. However, the two models of round bilge hull are totally the same, so we can see the difference of green water between large-scale model test and small-scale model test from the results of round bilge monohull. Table 6 shows the comparison of green water frequency between tank model test and large-scale model test of actual wave environment under Class 6 sea condition ($H_{1/3}$=5m), while Figure 23 shows the printscreen of green water video of large scale model test and Figure 24 shows the printscreen of green water video of small-scale model test in tank.

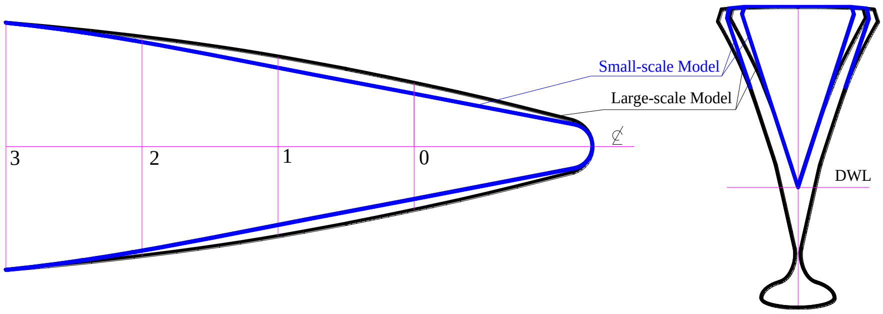


Fig.22 Sketch of the difference between the two models' decks of hybrid monohull

Tab.6 The comparison of green water frequency

Program	Speed/kn	Frequency/Times per minute	
		Round bilge monohull	Hybrid monohull
Small-scale model test in tank	18	3.34	1.79
	24	10.62	8.45
	30	12.18	10.51
Large-scale model test at sea	18	2.6	0
	24	6.1	1.6
	30	9.9	2.7

Fig.23 Picture of green water of large-scale model recorded by videos

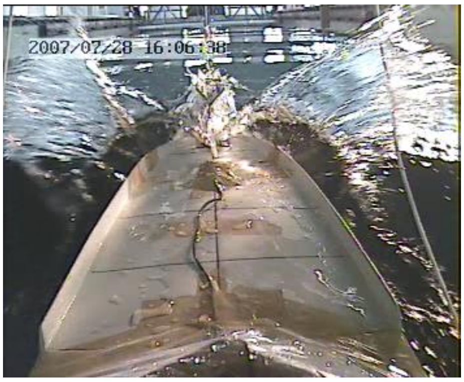


Fig.24 Picture of green water of small-scale model in tank recorded by video

From the above green water frequency and video, it is found that as compared with the small-scale model test in tank, the coupled motion characteristics of large-scale model under three-dimensional wind waving is more obvious. Therefore, its wave frequency is low and its wave physics phenomenon is closer to that of the actual vessel, which has more obvious nonlinear characteristics.

4. Conclusion

The following conclusions could be drawn by the above researches:

(1) By analyzing the measurement of coastal waves in several sea waters, we can find that the coastal wave parameter has relationships with tide, wind direction, water depth. When the wave floods to its climax with the wind blowing from the sea surface to the coastal, and the water depth is more than 8m the wave spectrum shape measured is basically similar to the ocean spectrum, and wave height frequency density complies with the Rayleigh distribution generally. The test system for large-scale remote control and telemetry self-propelled vessel models under actual wave condition established in this paper is stable in operation and reliable in measuring data.

(2) By comparing the large-scale model test result of seakeeping performance property for round bilge vessel model and hybrid monohull model, we find that in coastal waves the seakeeping performance of hybrid monohull has also been improved dramatically compared with that of round bilge vessel. By comparing and analyzing the data collected in the coastal large-scale model test and tank small-scale model test, we find that the response amplitude of pitching motion and bow acceleration is relatively low and its green water frequency is smaller, which shows the difference between large-scale model test in coastal and model test in tank.

(3) For the motions like yaw and sway of small-scale models in tank are restricted, the energy would be concentrated on the other 4 degrees of freedom, while the motions of large-scale models in coastal have 6 degrees of freedom. This is a source of the difference between large-scale model test in coastal and model test in tank. Besides, the different testing environment and measurement instruments can also cause the difference between the two testing methods. However, the major part of the differences maybe due to uncertainty of measurements, especially in case of large scale models. So the measurement uncertainty of large-scale model test should be studied in the future work.

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