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Effect of bow spray strips and Ω-type freeboard on high-speed boats

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Abstract: A high-speed boat may encounter severe wave-making at the bow and become wet at high speed. Some measures can be taken to overcome these disadvantages. In order to compare the effect of bow spray strips and Ω-type freeboards on a high-speed boat, hull wetness, resistance, hull motion, stability and the restoring moment of the heel at high speed of models with these two kinds of auxiliaries were calculated and measured. CFD methods and model tests were adopted. Both of these two auxiliaries can reduce hull wetness, and the model with a Ω-type freeboard has a better initial stability and larger restoring moment of the heel at high speed. A free running model test also indicates that the Ω-type freeboard has a fine performance.

Key words: high-speed boat; Ω-type freeboard; hull wetness; stability; restoring moment of heel; numerical tank test

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0 Introduction

A high-speed boat may encounter severe wave-making at the bow and become wet at part of the bow, and the wet part of the bow will develop toward the midship and stern with the increase of the speed, further increasing the wet surface area and drag of the hull. When the speed of the high-speed boat exceeds a certain critical value, the friction drag will dominate the drag of the hull. At this time, reducing the wet surface area is an effective means of drag reduction. In order to control the bow wave-making, as well as freeboard green water and wetness, we can install spray strips (or splash proof) in the vicinity of the bow or the waterline[1]. The installation of spray (splash) strips is a very simple and easy way to suppress wave. Russia's type 1234 missile boat has splash proof strips installed at the bow to control the bow wave-making and wetness. In addition to the bow spray strips, recently, the Ω-type freeboard design has also arisen. Its main feature is that the freeboard folds outward near the waterline, and sometimes the design is also known as the "Ω ship type". The advantage of this design is that it can also increase the volume of the hull in addition to suppress the wave, which can be used to improve the stability and meanwhile not to widen the hull below the waterline. It is very suitable for some slender high-speed boats. Thompson[2] used similar technology in his patent, and Indonesia's three-body missile boat also uses similar technology on the main hull. The use of Ω-type freeboard and fusion of the anti-green-water auxiliary to the design of hull has gradually become a widely used technique. Compared with the installation of spray (splash) strips, design of Ω-type freeboard needs to integrate into the entire design cycle of the hull.

Wei et al.[3] investigated the effect of an-

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ti–green–water wedge on intilted bow, and confirmed that the wedge can effectively control bow green water and hull wetness of intilted wave piercing boat at high speed. Wang et al.[4] found that there is a difference between the attitude of the free–running model and the test value of the towing tank test when they carried out tests on the low speed direct flight of unmanned free–running model, shown as the trim by stern of the free–running model slightly larger than the measured value of towing tank test. At the same time, Wei et al.[5] also studied the effect of ship navigation attitude on the ship's wetness by numerical tank test. Based on the above research, this paper planned to use the design of Ω–type freeboard on high–speed boat. Ref. [6] discussed the vertical angle problem of Ω–type freeboard preliminarily.

In order to further examine the utilization effect of Ω–type freeboard on high–speed boat, and compare the utilization effect and difference between bow spray strips and Ω–type freeboard, a lathy high speed mono–hull wave piercing boat was used as the parent ship in this paper, and impact of the 2 technical measures on hull wetness, drag, motion, stability and restoring moment of heel at high speed was contrasted through the installation of the bow wedge spray strips and using Ω–type freeboard. Because in the high–speed navigation of sharp bilge planing boat, only the hull bottom below the bilge knuckle line contacts water surface, even only a small part of the stern contacts water surface, and the wet surface area is very small, this research will be focused on and is suitable for high–speed round bilge or near round bilge boat (ship) with a design of slender non–sharp bilge planing boat.

In order to complete the study, based on the numerical tank test, this paper will mainly study the influence of 2 kinds of technologies on hull drag, motion and restoring moment of heel at high speed by solving the URANS equation. Along with the accumulation of technical and academic level, the numerical computational accuracy and reliability have been greatly improved, which is increasingly widely used and recognized in science research and engineering application[7], and has become a very effective means of ship type optimization design in addition to model testing. When the Froude number *Fn* is high, due to that there is a large longitudinal and vertical coupling motion of the hull, in the numerical calculation, in order to forecast the hull performance more accurately, we need to consider the influence of ship's navigation change on the forecast results, and the most effective way of the acquisition and simulation of hull motion is to use dynamic mesh. In addition, this paper will also conduct simple free–running model test to verify the utilization effect of Ω–type freeboard. Through this study, we further reveal the performance of Ω–type freeboard and prove its practical value on high–speed boat.

1 Anti–green–water scheme and calculation principle

In this paper, a 16 m high–speed wave piercing boat[8] was used as the parent ship, and the effect of 2 kinds of anti–green–water technologies was compared by installing wedge spray strips at the bow and converting the freeboard into a Ω–type design, but the part below the hull's waterline maintained unchanged. Ω–type freeboard design is based on the original freeboard, and the freeboard part above the waterline protrudes overboard. The freeboard's knuckle line connects the bow and stern frames, distributed in the range of the ship length. In this study, the protruding width of freeboard is 0.075 times the width of waterline. The schemes of installing bow spray strips and using the Ω–type freeboard are as shown in Fig. 1. Hull sections and side profiles of two methods, i.e., bow spray strips and the Ω–type freeboard are also given in the Fig. 1.

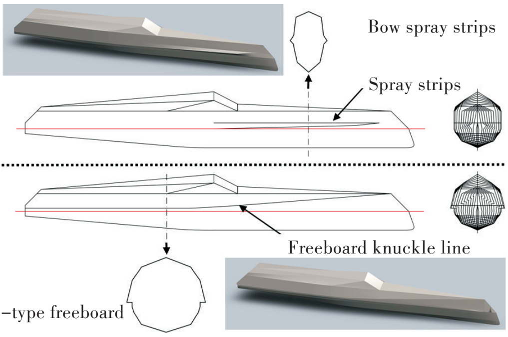


Fig.1 Hull sections and side profiles of two methods

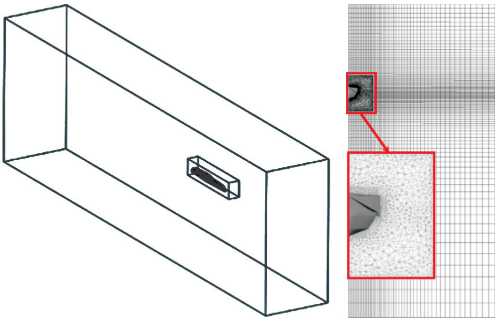
The study in this paper, except the initial stability, was carried out in the model scale. The main dimensions of the model used in the calculation are shown in Table 1, with the scale ratio of 6.

Table 1 Main dimensions of the hull model

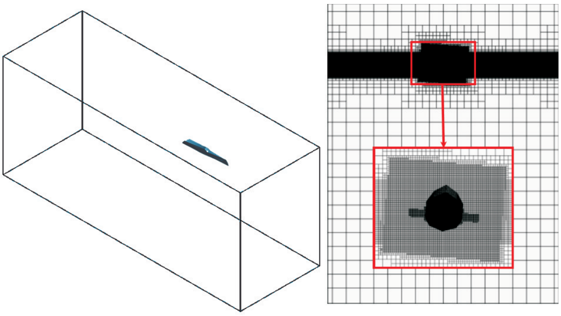
Item	Value
Total length L_{oa} / m	2.746
Length of waterline L / m	2.708
Breadth of waterline B / m	0.333
Draught T / m	0.133
Mass M / t	0.047

In this paper, numerical tank test was used as the main research method to solve the URANS equation, with the viscosity considered. In the theory of viscous flow, the Reynolds-averaged Navier-Stokes equation (RANS) is obtained by averaging the Navier-Stokes equations. In order to close the RANS equation set, the Reynolds stress tensor must be simulated, thus a number of turbulence models are produced. The SST $k-\omega$ model which is frequently used in the shipbuilding industry is chosen for calculation, and the detailed introduction of the model can be found in Ref. [9]. The free surface is captured using the popular Volume of Fluid (VOF) method[10], and it is obtained by setting the volume fraction of water as 0.5.

In order to simulate the motion of hull, it is necessary to use the dynamic meshes for calculation. Usually, the most direct way is to make the ship model surface move, with the spring fairing method and local mesh reconstruction. However, the disadvantage of this method is that negative volume mesh will appear when the mesh reconstruction is conducted to complex models, which leads to the failure of the calculation, and additional computation time will be generated by the mesh reconstruction. Another method is to use the boundary layer meshes as a region, or make the boundary layer meshes and partial surrounding meshes move along with the ship model surface. Combined with the spring smoothing method, this method has no effect on the surrounding meshes of the model, which helps to add and maintain the boundary layer meshes. In this paper, the computational domain was divided into 2 parts in the numerical calculation of hull drag, wave-making and motion, including the dynamic zone moving with the hull and the stationary zone. The dynamic zone adopted the tetrahedral meshes to fit for complex hull surface, and stationary zone used hexahedral meshes with addition of boundary layer meshes to hull surface. Because the hull is symmetrical, half of the hull is taken to establish the computational domain. The division of the computational domain and the mesh section are shown in Fig. 2(a). The mesh nodes between the dynamic zone and the stationary zone are continuous. When the number of the meshes is more than 1.5 million, the influence of the number of meshes on the results is very small[11]. During solving the hull drag and motion, the number of meshes used is more than 2 million, which can meet the requirement of the accuracy of the mesh number. In order to verify the reliability and validity of the calculation method, the test results of a drainage type high speed mono-hull wave piercing boat based on this method were compared with the results of towing tank test. The results show that the method can meet the requirements of ship performance prediction, as shown in Fig. 3. In this paper, the dimensionless processing was conducted for the results of drag, trim (trim by stern was positive) and heaving (upward was positive). In the research on the effect of anti-green-water measures on the hull restoring moment of heel at

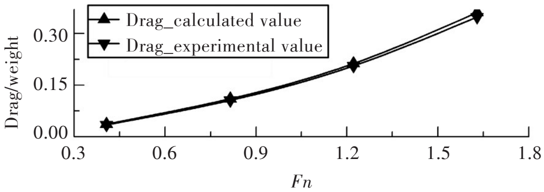


(a) Direct navigation is still water

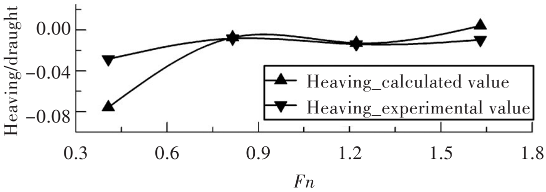


(b) Direct navigation is still water and with heel angle

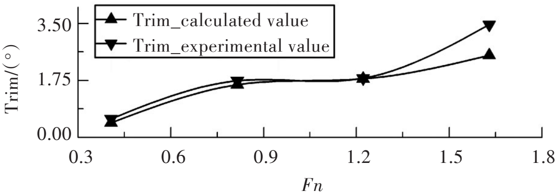
Fig.2 Computational domain settings and meshes



(a) Drag



(b) Heaving

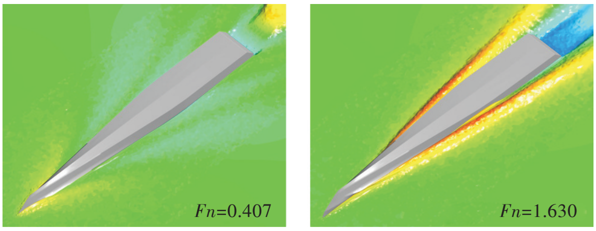


(c) Trim

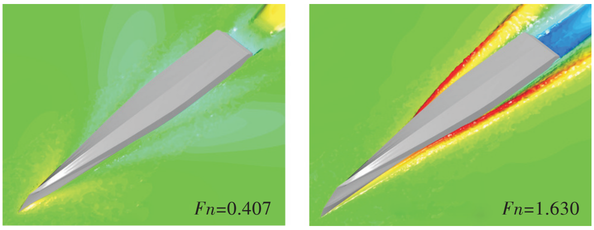
Fig.3 Experimental verification of the calculation method high speed, because the model has a heel angle, the whole ship was used to calculate this part; the model was fixed; 8.4 m/s was selected as the speed node, and the corresponding Froude number was $Fn = 1.630$; measured value 3.45° in the tank test was chosen as the initial trim by stern; heel angles were respectively set to the left inclined 5°, 10° and 15°. The computational mesh was trimmed mesh, and the computational domain and the mesh section are as shown in Fig. 2(b). Due to the asymmetry, the whole boat was used for calculation, and the number of meshes was greater than 3.8 million.

2 Wave-making and hull wetness

The calculation results show that the hull wave-making of the 2 methods has great difference, as shown in Fig. 4. In general, wave-making generated around the hull by Ω-type freeboard is smaller than that by bow spray strips, and the wave-making is further later; compared with Ω-type freeboard, the bow wave-making was more significant for bow spray strips. When $Fn = 0.407$, wave-making generated around the hull has little difference by the 2 methods. And when $Fn = 1.630$, the wave-making difference of 2 methods is mainly shown around the hull, and the reason was analyzed as follows: when the navigational speed increases, green water begins to appear at the bow and continues to strengthen. At this time, the role of bow spray strips with flared design was more and more obvious, and the generated wave-making was more obvious, which was because wave-making generated by bow spray strips spread toward the midship and stern. While confinement of Ω-type freeboard on the bow green water was weak, allowing the bow green water to develop to the midship and bow, and because the bow was intilted, green water was not extruded out of the bow. In this way, the bow wave-making was small.



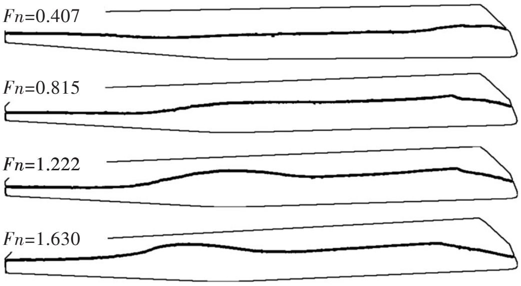
(a) Bow spray strips



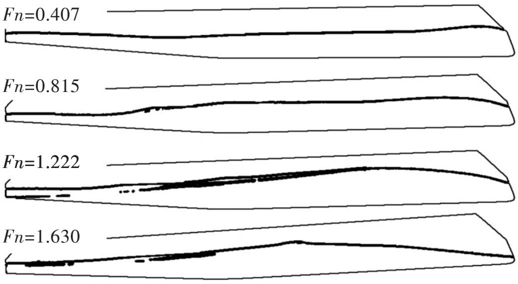
(b) Ω-type freeboard

Fig.4 Comparison between wave-making and spray with two methods

A comparison of the hull surface wetness by 2 methods (Fig. 5) shows that, bow spray strips and Ω-type freeboard can both well control wetness of the bow and freeboard, but the results are obviously different. At $Fn = 0.407$, the bow green water was not obvious, and the roles of 2 methods were almost the same; when $Fn = 0.815$, the bow spray strips suppressed bow green water, and the Ω-type freeboard suppressed the freeboard wetness in the midship and stern; when $Fn = 1.222$, the bow spray strips have been unable to effectively suppress the freeboard wetness in the midship and stern, and Ω-type freeboard indulged bow green water to a certain extent, which effectively restricted the freeboard wetness in the midship; when $Fn = 1.630$, bow spray strips have been unable to effectively limit the freeboard wetness in the midship and stern, and bow green water of Ω-type freeboard was not obvious, which can well limit the freeboard wetness in the midship.



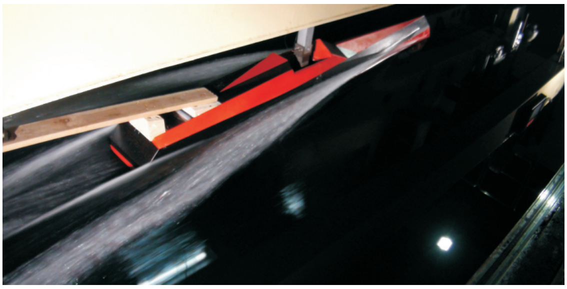
(a) Bow spray strips



(b) Ω-type freeboard

Fig.5 Comparison of the wetted hull surface with two methods

The comparison between the results of the free-running model test and the towing tank test also verified the calculation results of numerical towing tank test. Fig. 6 shows the wave-making and spray of the model at high speed, in which the bow spray strips model was towed by a trailer at high speed, and the Ω-type freeboard model was propelled by the high power brushless motor and the propeller. Fig. 6(a) shows that, spray produced by the bow spray strips model is developed from bow toward stern; Fig. 6(b) shows that the spray generated by the Ω-type freeboard model is developed from midship toward stern. This is consistent with the numerical towing tank test results, and the free-running test also verified the feasibility of Ω-type freeboard. The towing spot of towing tank test was in the center of ship model, and because thrust of free-running test was provided by the propeller, the trim by stern will be more intense. However, the Ω-type freeboard can still play a role, but the bow spray strips will not be able to play the role due to the uplift of the bow.



(a) Bow spray strips(towing speed of towing tank is 8.4 m/s)

(b) Ω-type freeboard(free-running speed of model is 9.2 m/s)

Fig.6 Wave-making, spray and results of model test at high speed with two methods

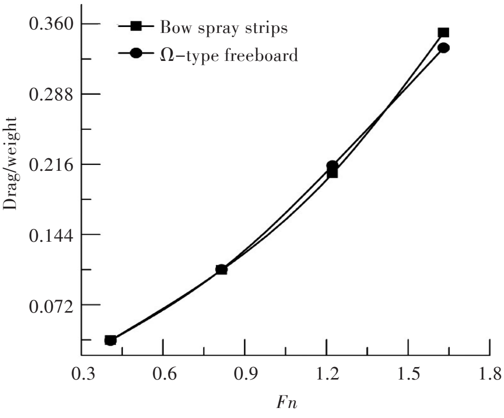
3 Drag and hull motion

In the premise of using the dynamic meshes to acquire navigation motion, bow spray strips and Ω-type freeboard were comparatively analyzed, and the results of drag, trim (trim by stern is positive) and heaving (upward is positive) went through dimensionless processing.

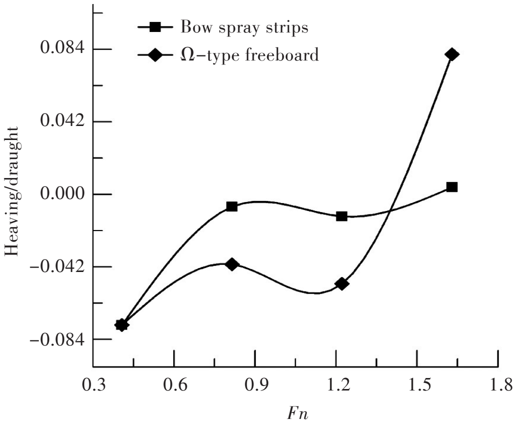
In terms of hull drag, the difference between the 2 methods is mainly reflected at medium and high speed, as shown in Fig. 7(a). At low speed, there was almost no difference between the 2 methods because green water was not obvious. At medium speed, compared to bow spray strips, effect of Ω-type freeboard was slightly better, which was determined by the interaction between Ω-type freeboard and position of side wetness. At high speed, drag reduction effect of Ω-type freeboard was more advantageous than that of bow spray strips. On the whole, the navigational drag difference caused by different ways of anti-green water was not obvious in the calculation range of speed of this paper. If the speed continues to increase, the Ω-type freeboard method would possibly show a larger advantage in speed.

As shown in Figs. 7 (b) and (c), the change of navigation motion of the boat in still water for 2 methods was different. At the lowest speed point, the hydrodynamic force was not obvious, and the navigation motion by 2 methods was almost the same. However, with the increase of the speed, the hydrodynamic forces and their points of action by 2 methods also changed, so the navigation motion was different. When $Fn < 1.4$, barycenter sinkage of Ω-type freeboard was greater than that of bow spay strips. When $Fn > 1.4$, the barycenter of Ω-type freeboard had an obvious uplift, which was caused by the dynamic lift generated by the Ω-type freeboard. At low speed, the trim by stern produced by 2 methods had small difference; in the medium speed range, the trim by stern produced by bow spray strips was greater; at high speed, the trim by stern produced by Ω-type freeboard was larger. The analysis shows that the difference was caused by the dynamic lift generated by Ω-type freeboard. Comparing the variation tendencies of 2 methods on heaving and trim by stern, we can find that the 2 methods were consistent with respect to the change of heaving and trim by stern with *Fn*, which should be determined by the hydrodynamic characteristics of the main hull. We can see from the above that, in addition to the anti-green-water effect, Ω-type freeboard can also produce additional dynamic lift, and the hull's navigational motion can be changed by changing the longitudinal curvature of Ω-type freeboard. If the sectional self-control of Ω-type freeboard is realized by control algorithm, the longitudinal curvature can be adjusted according to the required navigational motion.

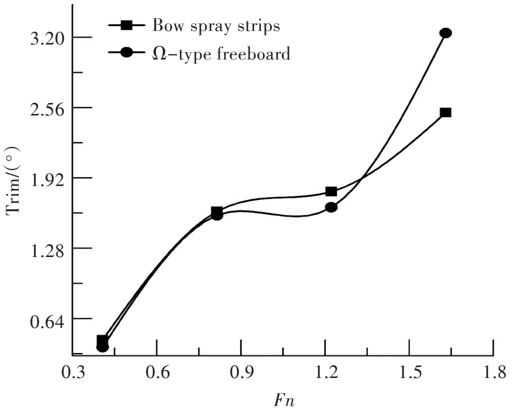
Besides, when $Fn = 1.630$, the drag of the hull



(a) Drag



(b) Heaving



(c) Trim

Fig.7 Comparison of hull drag and motion with two methods

with Ω-type freeboard was less than that with the design of bow spray strips, which is caused by the large uplift and trim of the hull. At the same time, it can be found that the wet surface area of the hull was reduced, which is also the direct cause of the decrease of drag. Through the analysis of the drag components of the hull by 2 methods at the speed node $Fn = 1.630$, we can see that: under bow spray strips, pressure drag per unit weight was 0.123, and viscous drag per unit weight was 0.229; under Ω-type freeboard, pressure drag per unit weight was 0.122, and viscous drag per unit weight was 0.214. Thus, the decrease of the hull drag by the Ω-type freeboard method was caused by the reduction of friction.

4 Initial stability and reserve buoyancy

Since the design of Ω-type freeboard increases the hull width above the waterline, in a certain range of draught, initial stability will be increased, but with the upward shrinking of the hull width, the radius of initial stability will decrease with the decrease of water plane and the increase of displacement volume. This conclusion has been verified by the calculation results of stability, as shown in Fig. 8. As can be seen from Fig. 8, because the shapes below the waterline are the same, the radius of initial stability of the 2 models at the designed waterline and below the waterline is the same. But beyond the designed waterline, the stability radius of high-speed boat with Ω-type freeboard was significantly greater than that with bow spray strips, which is very useful for slender ship form. Fig. 9 shows that the reserve buoyancy of boat with Ω-type freeboard was greater than that with the bow spray strips, which means that the high-speed boat with the Ω-type freeboard has the advantage of load and safety to some extent.

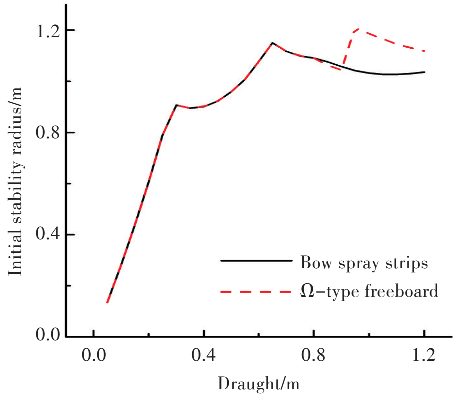


Fig.8 Comparison of initial stability with two methods

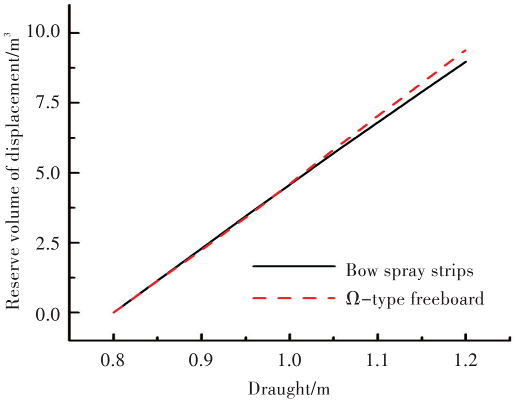


Fig.9 Comparison of reserve buoyancy with two methods

5 Restoring moment of heel at high speed

In Fig. 10, the restoring moment of heel of the models with 2 anti-green-water methods were compared at $Fn = 1.630$. When the model navigates at high speed, the restoring moment of heel generated by Ω-type freeboard method at different heel angles was larger than that generated by bow spray strips, with an increment of 53%-55%. A greater restoring moment means that the boat has a smaller heel angle when turning at high speed. It is no doubt beneficial to improve the maneuverability and safety of high-speed boats, especially some slender high-speed boats, by increasing the restoring moment of heel. Therefore, the Ω-type freeboard design is obviously better than the bow spray strips design in improving the boat's dynamic stability and safety. But the larger restoring moment of heel is not obtained by large reserve buoyancy, but hydrodynamic force generated by Ω-type freeboard. The comparison of 2 methods in high speed, wave-making with heel and hull wetness shows that, the design of Ω-type freeboard is of great help to the control of hull wetness with heel. Fig. 11 shows that when the heel angle was 15°, the midship and stern wetness of bow spray strips model was almost close to the deck side line, and Ω-type freeboard model controlled wetness very well below the freeboard knuckle line. Fig. 12 shows the hull's heel motion of the free-running model during high speed turning. It is found in the experiment that the free-running model can be rapidly converted from heel to the upright position.

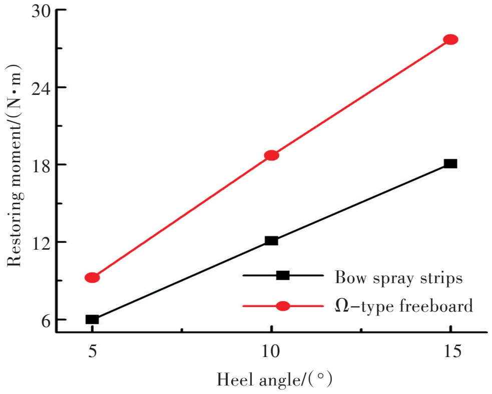
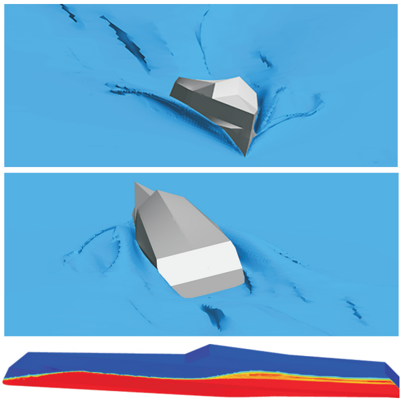
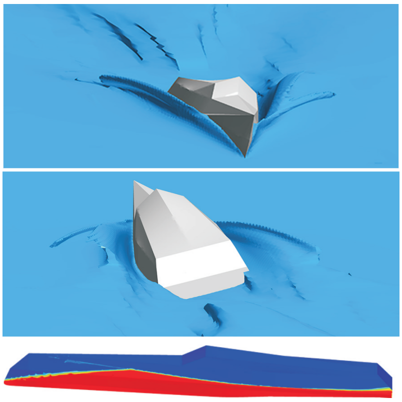


Fig.10 Comparison of hull restoring moment of heel at high speed with two methods (Fn=1.630)



(a) Bow spray strips



(b) Ω-type freeboard

Fig.11 Comparison between wave-making, spray and hull wetness with two methods (heel angle is 15°)

Fig.12 A free-running model turning at high speed

6 Conclusions

Through the studies, it was found that the bow spray strips and Ω-type freeboard can be used to control the bow and freeboard wetness, but the 2 methods also showed different characteristics and effects.

The bow spray strips have significant control effect on the bow green water and wetness, but with the increasing speed, after termination of wedge spray strips at the end of bow, water would rush out of spray strips and wet the freeboard. The design of Ω-type freeboard can control the freeboard wetness and green water in the range of boat length. Especially when there is a large trim by stern of the hull, the bow green water will not be obvious, and the Ω-type freeboard will play the most important role.

Generally speaking, the navigational drag difference caused by different ways of anti-green water is not obvious in the calculated speed range in this paper. If the speed continues to increase, the Ω-type freeboard solution probably can show greater advantage of rapidity. The effects of 2 methods are different on the boat's motion in still water, but the models of the 2 methods have consistent trend with the variation of Fn regarding heaving and trim by stern.

Compared to the bow spray strips, design of Ω-type freeboard can increase the hold capacity and reserve buoyancy without changing the hull below the waterline, and further improve the stability and safety of slender boats.

For the high-speed boat using Ω-type freeboard, the restoring moment of heel it generated at high speed is greater than that using the bow spray strips, which is favorable to improve the maneuverability and security of high-speed boats especially some slender boats.

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船艏及干舷压浪在高速艇上的应用对比

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摘　要： 快艇在高速航行时会产生剧烈的艏部兴波和干舷淹湿问题，通常需要采用适当的压浪措施来控制这些不利因素。为进一步研究干舷压浪技术在高速艇上的应用效果并与船艏压浪技术进行对比，基于某一细长高速穿浪船，对比这2种压浪技术对船体兴波、淹湿、运动、稳性和高速下横倾回复力矩的影响。船体淹湿、阻力和船体运动通过求解URANS方程和使用动网格技术获得，高速下的横倾回复力矩也通过求解URANS方程获得。计算结果表明，2种压浪技术均能有效控制船体淹湿，但干舷压浪设计能在船长范围内控制船体淹湿并具有更好的初稳性，在高速下也有更大的横倾回复力矩。自航模试验也验证了压浪干舷的可行性和良好性能。

关键词： 高速艇；干舷压浪；船体淹湿；稳性；横倾回复力矩；数值水池试验